DESIGN, CONSTRUCTION, AND DEMONSTRATION
OF A NEUTRON BEAMLINE AND A NEUTRON IMAGING FACILITY
AT A MARK-I TRIGA REACTOR

by

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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Nuclear Science and Engineering).

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ABSTRACT

The fleet of research and training reactors is aging, and no new research reactors are planned in the United States. Thus, there is a need to expand the capabilities of existing reactors to meet users’ needs. While many research reactors have beam port facilities, the original design of the United States Geological Survey TRIGA Reactor (GSTR) did not include beam ports. The MInes NEutron Radiography (MINER) facility developed by this thesis and installed at the GSTR provides new capabilities for both researchers and students at the Colorado School of Mines. The facility consists of a number of components, including a neutron beamline and beamstop, an optical table, an experimental enclosure and associated interlocks, a computer control system, a multi-channel plate imaging detector, and the associated electronics.

The neutron beam source location, determined through Monte Carlo modeling, provides the best mixture of high neutron flux, high thermal neutron content, and low gamma radiation content. A Monte Carlo n-Particle (MCNP) model of the neutron beam provides researchers with a tool for designing experiments before placing objects in the neutron beam. Experimental multi-foil activation results, compared to calculated multi-foil activation results, verify the model. The MCNP model predicts a neutron beamline flux of $2.2 \times 10^6 \pm 6.4 \times 10^5$ n/cm$^2$-s based on a source particle rate determined from the foil activation experiments when the reactor is operating at a power of 950 kW with the beam shutter fully open. The average cadmium ratio of the beamline is 7.4, and the L/D of the neutron beam is approximately 200±10.

Radiographs of a sensitivity indicator taken using both the digital detector and the transfer foil method provide one demonstration of the radiographic capabilities of the new facility. Calibration fuel pins manufactured using copper and stainless steel surrogate fuel pellets provide additional specimens for demonstration of the new facility and offer a comparison between digital and film radiography at the new facility. Comparison of the radiographs taken by the two methods reveals that the digital detector does not produce high quality images when compared to film radiography.
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NOMENCLATURE

Latin Symbols

\( A(t) \)  Activity at the end of irradiation
\( b \)  distance between an object and a detector when the umbra reaches zero
\( d \)  diameter of a cadmium wire used to measure L/D
\( d_o \)  distance between the object and the detector in neutron radiography; [cm]
\( D \)  effective diameter of the beamline entrance; [cm]
\( k_{\text{eff}} \)  effective multiplication factor for a fission chain reaction
\( L \)  length of a beamline; [cm]
\( L/D \)  length-to-diameter ratio; a measurement of the beam divergence or quality of collimation of a beamline
\( M \)  molar mass; [g/mol]
\( m \)  mass of an activation foil
\( N \)  number density; [atoms/cm\(^3\)]
\( N_A \)  Avogadro’s number; 6.02E23 [atoms/mol]
\( t_j \)  thickness of material layer \( j \); [cm]
\( t_{\text{irr}} \)  duration of exposure to neutrons
\( T_{1/2} \)  half-life of a radioactive isotope; in units of time
\( \bar{x} \)  mean free path; [cm]
\( u_g \)  geometrical unsharpness; [cm]
\( n:\gamma \)  neutron to gamma ratio for a radiation beam containing both
\( X(a,b)Y \)  Reaction notation, where particle \( a \) reacts with particle \( X \) to produce particles \( Y \) and \( b \)

Greek Symbols

\( \lambda \)  decay constant of a radionuclide
\( \rho \)  density; [g/cm\(^3\)]
\( \Sigma \)  macroscopic cross-section; [cm\(^{-1}\)]
\( \sigma \)  microscopic cross-section; [cm\(^2\)] or [b]
\( \sigma_a \)  microscopic absorption cross-section
\( \phi \)  flux; [number/cm\(^2\)-s]
\( \mu \)  attenuation coefficient; analogous to the macroscopic cross-section (\( \Sigma \)), but commonly used for gamma attenuation; [cm\(^{-1}\)]
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>BEPO</td>
<td>British Experimental Pile '0'</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge-Coupled Device (used with respect to CCD cameras)</td>
</tr>
<tr>
<td>CSNR</td>
<td>Center for Space Nuclear Research</td>
</tr>
<tr>
<td>CT</td>
<td>Computed Tomography</td>
</tr>
<tr>
<td>DOE</td>
<td>Department of Energy</td>
</tr>
<tr>
<td>GSTR</td>
<td>United States Geological Survey (USGS) TRIGA Reactor</td>
</tr>
<tr>
<td>INL</td>
<td>Idaho National Laboratory</td>
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<tr>
<td>MCNP</td>
<td>Monte-Carlo N-Particle</td>
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<tr>
<td>MCP</td>
<td>Multi-Channel Plate or Microchannel Plate; used synonymously</td>
</tr>
<tr>
<td>NEUP</td>
<td>Nuclear Energy University Programs</td>
</tr>
<tr>
<td>NDT</td>
<td>Non-Destructive Testing</td>
</tr>
<tr>
<td>SAR</td>
<td>Safety Analysis Report</td>
</tr>
<tr>
<td>TRIGA</td>
<td>Training Research and Isotope Production, General Atomics</td>
</tr>
<tr>
<td>USQ</td>
<td>Unreviewed Safety Question</td>
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ACKNOWLEDGEMENTS

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DEDICATION

This thesis is dedicated to the many mentors who have helped guide me through my life thus far. For my scoutmaster, my swim coach, my advisor, and my grandfather, who have been like fathers to me, portraying strong examples of character, integrity, academics, and faith. For their support, I am truly grateful.
CHAPTER 1

INTRODUCTION

The United States Geological Survey (USGS) TRIGA Reactor (GSTR) is a 1 MWt Mark-I TRIGA reactor located at the Denver Federal Center in Lakewood, CO. The GSTR is primarily used for neutron activation analysis of geological samples, and, as a Mark-I TRIGA Reactor, the original GSTR design did not include neutron beam ports. More recently, the GSTR has become an important educational facility for students at the Colorado School of Mines, leading to a variety of educational and research activities. With increased demand for use of GSTR facilities, expanding the capabilities available at the GSTR has become increasingly important.

The fleet of research and training reactors is aging, and no new research reactors are planned in the United States. Thus, there is a need to expand the capabilities of existing reactors to meet users’ needs. Adding new beamline facilities to existing research reactors is both rare and challenging, and this thesis project designed, installed, and characterized the MINes NEutron Radiography facility (MINER Facility) at the GSTR. The new beamline facility includes a beamline control system, a neutron beamstop, and a Monte-Carlo N-Particle (MCNP) model of the neutron beamline.

The MINER facility is a useful new research tool that provides non-destructive examination capabilities based on the unique properties of neutron attenuation in materials. All radiographic methods are based on the same general principle: that radiation is attenuated when passing through matter. While x-rays are attenuated by high density, high atomic number materials, such as bones and metals, neutrons are attenuated by low density, low atomic number materials, particularly hydrogenous materials such as water and plastics (Domanus, 1992). The difference between x-ray and neutron attenuation makes neutron radiography particularly useful for the non-destructive examination of materials such as explosives, fluids, rubber, adhesives, and plastics, even when they are contained in a metal casing (Berger, 1976a). The fact that some elements absorb neutrons better than they absorb x-rays permits neutron radiography, in certain circumstances, to examine specimens that cannot be satisfactorily examined by x-ray radiography (Thewlis, 1956). Thus, neutron radiography is a complimentary method to x-ray radiography.
Chapter 2 provides background information for the topics discussed in this work, including the history of neutron radiography, fundamentals of neutron imaging, neutron beams and sources, neutron imaging techniques and detection methods, radiographic artifacts, applications of neutron imaging, and the USGS TRIGA reactor.

Chapter 3 describes major facility subsystems, including a detailed discussion of the design and construction of the subsystems, the safety analyses supporting the addition of the new facility, and the current status of the facility. Major facility subsystems discussed include the neutron beamline, the beamstop, the gas pressure control system, motorized control of the sample and imager stages, the multi-channel plate detector, the computer control system, and the experiment station, safety enclosure, and safety interlocks.

Chapter 4 describes the development of an MCNP model of the neutron beamline, which provides a useful tool for researchers to develop experiments before putting any equipment into the neutron beam.

Chapter 5 describes the characterization and testing of the beamline, and provides a demonstration of the neutron radiography capabilities of the new facility. Suitable specimens for the demonstration of the capabilities are developed, and both digital and transfer method radiographs are compared.

The appendices provide supplemental information. Appendix A provides input decks for the MCNP models created for this project. Procedures for the safe installation, operation, and removal of the facility are included in Appendix B, which were developed in cooperation with the GSTR Safety Committee, reactor staff, and CSM faculty. Appendix C provides an analysis performed to determine if the addition of the new facility creates an unreviewed safety question and covers postulated accidents related to the new facility in detail. Appendix D includes circuit diagrams for the electronic systems (interlock and power systems) of the MINER facility.
CHAPTER 2
BACKGROUND

Radiography is a non-destructive testing method which produces an image using penetrating radiation, such as x-rays or neutrons, instead of visible light. The attenuation of a radiation beam passing through an object reveals clues about the internal structure of that object. The ability to non-destructively analyze the internal structure of an object has many applications. Medical applications use x-ray radiography and tomography to diagnose illnesses. X-ray radiography is commonly used to check the quality of welds for industrial applications (Bossi et al., 2002). Neutron radiography is used for the non-destructive interrogation of used nuclear fuel elements (Mayer, 1972; Richards and McClellan, 1979; Korneev et al., 1983). Other neutron radiography applications include inspection of explosive cords used in pilot ejector mechanisms; inspection of gaskets, seal and o-rings inside metallic valves; confirmation that coolant channels in jet engine turbine blades are free of blockages; and screening of aircraft panels to detect low-level moisture or early stage corrosion in the aluminum honeycomb (Bossi et al., 2002).

While x-rays are attenuated by high-density materials, such as bones and metals, neutrons are attenuated by light materials, namely hydrogenous materials such as water and plastics. This reversal from x-ray attenuation properties for neutrons has made neutron radiography particularly useful for nondestructive testing of hydrogenous materials such as explosives, fluids, rubber, adhesives, and plastics, even when they are housed in a metal casing (Berger, 1976a). Unlike x-rays, neutrons have high penetrating power in dense materials, so large samples can be investigated with little to no radiation damage, and light elements can be detected in an environment dominated by heavy elements (Winkler, 2006). Additionally, while some elements are relatively transparent to neutrons, others strongly attenuate neutrons (e.g. gadolinium, boron, cadmium). Neutron radiography can reveal details within high-density surroundings that cannot be revealed by other means (Bossi et al., 2002).

2.1 History of Neutron Radiography

Radiography began with Roentgen’s discovery of the x-ray in 1895, which led to the first demonstration of an image of the bones in a human hand. It was not until reliable x-ray sources
became available 20 years later that that x-ray radiography became widely applied (Barton, 1976). At about the same time, Becquerel and the Curies, working in France, discovered radioactivity, the precursor to gamma radiography (Barton, 1976). Chadwick discovered the neutron in 1932 by bombarding beryllium with alpha particles from the decay of polonium (Chadwick, 1932). The highly penetrating nature of neutrons was discovered, in a sense, before the neutron itself; Bothe and Becker in Germany, the Joliot-Curies in Paris, and Chadwick at Cambridge were all intrigued by the particularly penetrating nature of the radiation emitted when alpha particles from polonium impinged on beryllium, and it was this that led to the discovery of the neutron in 1932 (Barton, 1976). The discovery of the neutron significantly advanced nuclear physics and enabled the discovery of nuclear fission, the production of radioactive isotopes, and the development of neutron imaging.

Kallmann and Kuhn took the first neutron radiographs in 1935 in Germany, only forty years after the first radiographs were taken with x-rays, using an accelerator as the neutron source (Kallmann, 1948). World War II delayed the development of neutron radiography, and Kallmann and Kuhn’s work was not published until after the war for “racial reasons” (Thewlis, 1956). Soon after, a German scientist, Von Otto Peter, used a higher-power accelerator to produce sharper radiographs in only a few minutes time (Peter, 1946). Though they demonstrated the potential for neutron radiography using accelerator-based systems, the first neutron radiographs had poor resolution as a result of weak and uncollimated beams. This, coupled with the complexity of the apparatus and the long exposure time, hindered the early exploitation of neutron radiography (Domanus, 1992).

Thewlis and Derbyshire produced the first thermal neutron radiographs from a nuclear reactor in 1956, using an 8 MW, graphite-moderated BEPO (British Experimental Pile with the “O” added to create an acronym that refers to the popular Marx Brothers) reactor at Harwell (Thewlis, 1956). Higher neutron beam intensity from the nuclear reactor and better beam collimation produced significantly better neutron radiographs than those produced in previous works (Thewlis, 1956). That work demonstrated the usefulness of neutron radiography for specific non-destructive testing applications, including the quality control of Boral (borated aluminum) sheets and the discrimination of voids in uranium (Thewlis, 1956).

With the availability of high flux research reactors in the 1950s and 1960s, which provided neutron beams with significantly higher intensity than accelerators, neutron radiography
developed into a valuable new non-destructive analysis technique that compliments x-ray radiography. One of the first reactors used for neutron radiography in the United States was at the Armour Research Foundation in Chicago, where Watts performed valuable studies of the performance of the technique (Watts, 1960; Barton, 1976). Facilities specifically set up for neutron radiography at the 200 kW Juggernaut reactor provided the first application of neutron radiography to study radioactive nuclear fuel (Barton, 1976). Neutron radiography “service” centers entered service around 1968, offering neutron radiography to outside industries. Companies would send an item to a center to be radiographed for a small fee, and the center would return the original, undamaged item to the company with a neutron radiograph (Barton, 1976). As neutron radiography became more widely-available, the process needed established standards similar to other nondestructive testing techniques (Barton, 1976).

A review in Birmingham, England in 1973 began to address the clear need for coordination and standardization (Hawkesworth, 1973). In 1974, the American Society for Testing and Materials (ASTM) Committee E-7 formed Subcommittee E-7.05, specifically on neutron radiography. This subcommittee produced the first standards for neutron radiography including the Method for Determining Image Quality in Thermal Neutron Radiographic Testing (American Society for Testing and Materials International, 2005). A desire to inform the technical community about the advantages of neutron radiographic inspection and about the neutron standards work in progress led Subcommittee E-7.05 to suggest the first neutron radiography symposium (Berger, 1976a). Since a neutron radiography program had recently been initiated at the National Bureau of Standards (Hawkesworth, 1973), and that program was contributing to the development of standards, a collaboration in sponsoring the symposium came about naturally. The first symposium was held in Gaithersburg, USA in 1975 (Berger, 1976a). Also in 1975, Tyuyakov and Shtan published the first book on the principles of neutron radiography (Tyuyakov and Shtan, 1975). In 1977, the Atomic Energy Review published a special issue devoted entirely to neutron radiography (Atomic Energy Review, 1977). The first World Conference on Neutron Radiography convened in San Diego, California in 1981 (Barton and von der Hardt, 1981). Today, neutron radiography is an accepted method of non-destructive testing and the target of significant research and development.
2.2 Fundamentals of Neutron Imaging

X-ray and gamma radiation are attenuated through interactions with electrons; accordingly, the radiation attenuation coefficient is continuous with increasing atomic number (Domanus, 1992). Additionally, the photon attenuation coefficient is dependent on the photon energy. Neutrons, however, interact with nuclei rather than orbital electrons, and the probability of interaction is determined by both the incident neutron energy and the detailed structure of the target nucleus, which differs for each isotope (Hawkesworth and Walker, 1983).

The microscopic capture cross-section describes the probability that a neutron will be captured by an atom. The microscopic cross-section has units of area, typically written in either barns (b) or cm² (1 b = 10⁻²⁴ cm²). Like the area of a target, the larger the cross-section, the higher the probability of interaction. In terms of imaging, high neutron attenuation produces high contrast for thin materials, and low attenuation means thick materials can be easily penetrated (Barton, 1976).

The neutron attenuation cross-section can vary discontinuously with each element (and each isotope), and can change abruptly from one element to another, sometimes by orders of magnitude (Barton, 1976). Figure 2.1 depicts a qualitative representation of both x-ray and neutron capture cross-sections for some common elements. In each case, the area of the circle is proportional to the corresponding attenuation cross-section. Light materials, especially hydrogenous materials, attenuate neutrons well as a consequence of the high cross-section of

![Figure 2.1. Qualitative representation of x-ray and neutron cross-sections.](image-url)
hydrogen compared to other common elements, such as carbon, oxygen, and iron (Figure 2.1). While heavy elements, such as tungsten and uranium, have a large x-ray attenuation cross-section, their respective neutron capture cross-sections are relatively low (Figure 2.1).

Additionally, when considering neutrons with different energies, the cross-sections, and therefore the contrast between elements, differs (Barton, 1976). Cross-sections at thermal (low) neutron energies vary widely for each element (Figure 2.1), but these differences are less evident at higher neutron energies (Kallmann, 1948; Thewlis, 1956).

While some elements are relatively transparent to neutrons, others strongly attenuate neutrons. These elements (and isotopes) are commonly called neutron absorbers. Figure 2.2 depicts a qualitative representation of both x-ray and neutron capture cross-sections for some common neutron absorbers. Boron (typically as boron carbide) is commonly used in control rods for the operation of nuclear reactors (Craft and King, 2011). Cadmium strongly absorbs thermal neutrons, but not epithermal or fast neutrons, and is commonly used in the nuclear industry to provide epithermal and fast neutron beams. Gadolinium is the strongest absorber in Figure 2.2, and is an attractive spectral shift absorber for fast spectrum space reactors (King and El-Genk, 2006). Prompt gammas from neutron absorption in gadolinium can also allow for direct neutron radiography (Domanus, 1992). Indirect neutron radiography commonly incorporates dysprosium as a converter (Domanus, 1992).

Neutron capture cross-sections can also vary significantly between individual isotopes. Figure 2.3 depicts a qualitative representation of both x-ray and neutron capture cross-sections for

![Figure 2.2. Qualitative representation of x-ray and neutron cross-sections for neutron absorbers.](image-url)
various cadmium and uranium isotopes. Natural boron consists of ~20% $^{10}\text{B}$ and ~80% $^{11}\text{B}$; the strong neutron attenuation of natural boron comes largely from the high capture cross-section of the $^{10}\text{B}$ isotope. Likewise, natural uranium is 0.7 wt% $^{235}\text{U}$ and 99.3 wt% $^{238}\text{U}$, and the large capture cross-section of natural uranium comes largely from the $^{235}\text{U}$ isotope. Figure 2.3 also depicts the cross-sections of 5 wt% enriched uranium, which is a common fuel for nuclear power reactors, and 93 wt% enriched (weapon-grade) uranium. Because $^{235}\text{U}$ has a larger cross-section than $^{238}\text{U}$, the cross-section of uranium increases with increased $^{235}\text{U}$ concentration (enrichment).

As a neutron transverses through a material, it interacts in a probabilistic fashion indicated by the cross-section of that material. Consider a slab of material subject to an impinging parallel beam of neutrons with an intensity of $\phi(0)$ particles/cm$^2$-s (Figure 2.4). The intensity decreases with increasing $x$ as the neutrons interact with the material, such that $\phi(x) < \phi(0)$.

The total cross-section ($\Sigma_t$) of a material is the sum of the absorption ($\Sigma_a$) and scattering cross-sections ($\Sigma_s$), ($\Sigma_t = \Sigma_a + \Sigma_s$). Equation 2.1 describes the intensity of uncollided neutrons, $\phi(x)$ at a depth $x$ into a slab of material with absorption and scattering macroscopic cross-sections, $\Sigma_a$ and $\Sigma_s$, respectively (Harms and Wyman, 1986):

$$\phi(x) = \phi(0)e^{-\Sigma_t x}.$$  \hspace{1cm} (2.1)

Figure 2.3. Qualitative representation of x-ray and neutron cross-sections showing isotopic differences.
The total macroscopic cross-section is analogous to the attenuation coefficient, $\mu$ (cm$^{-1}$), commonly used for photon attenuation. Equation 2.1 applies to uncollided neutron flux, and does not include neutron scattering effects. Equation 2.1 also assumes the neutrons are either monoenergetic or have a small wavelength bandwidth (Kasperl and Vontobel, 2005).

The irradiated object is often heterogeneous, such as a multi-layered radiation shield. For an impinging flux, $\phi(0)$, on a series of layers of material $j$ and thickness $t_j$, the uncollided neutron intensity at the end of the material, $\phi(x)$, is given by Equation 2.2 (Shultis and Faw, 2000)

$$\phi(x) = \phi(0)e^{-\sum_{j}^{j} t_j}.$$  

(2.2)

The total neutron flux at a given $x$-coordinate consists of an uncollided component (Equation 2.1) and neutrons that have undergone scattering; the total flux is therefore given by Equation 2.3 (Harms and Wyman, 1986)

$$\phi_{\text{tot}}(x) = \phi_{\text{unc}}(x) + \phi_{\text{scat}}(x).$$  

(2.3)

A tabulated “build-up” function accounts for the scattered component, and is defined in Equation 2.4 (Harms and Wyman, 1986)

$$B(\Sigma_s, \Sigma_{\alpha}, x) = \frac{\phi_{\text{tot}}(x)}{\phi_{\text{unc}}(x)}.$$  

(2.4)
Incorporating the build-up function into Equations 2.3 and 2.4, the total flux is given as Equation 2.5 (Harms and Wyman, 1986)

\[ \phi_{\text{tot}}(x) = \phi(0)B(\Sigma_e, \Sigma_a, x)e^{-\Sigma_m x}. \] (2.5)

The build-up factor is most significant for materials with significant scattering cross-section, such as hydrogenous compounds, silicon, copper, nickel, and other metals (Harms and Wyman, 1986).

The mean free path \( \bar{x} \) is the average distance traveled by a neutron before undergoing an interaction with the material, and is the inverse of the macroscopic cross-section \( \Sigma^{-1} \) (Shultis and Faw, 2008). These mathematical relations (Described by Equations 2.1 to 2.5) are useful in many neutron imaging settings.

In neutron radiography, an object under examination is placed in a neutron beam; after passing through the object, the beam that remains enters a detector that registers the fraction of the initial intensity that has been transmitted by each point in the object (Domanus, 1992). Any inhomogeneity in the object or internal defect (e.g. void, crack, porosity, or inclusion) will show up as a change in radiation intensity reaching the detector (Domanus, 1992). The pattern of the penetrating radiation reveals clues about the internal structure of an object (Bossi et al., 2002).

Figure 2.5 shows a schematic of a representative neutron imaging system. A neutron radiography system typically consists of a neutron source, a collimator (sometimes including filter

![Figure 2.5. Schematic of a typical neutron radiography system.](#)
devices), a shutter system, an imaging system, and a radiation beamstop (Domanus, 1992). A neutron source, such as a nuclear reactor, usually produces neutrons traveling in all directions. Fast neutrons collide with a moderator and slow down to thermal energies. Because the thermal neutrons are dispersed over the source and moderator volumes, a collimator is necessary between the source and the object to provide a properly directed neutron beam (Bossi et al., 2002). An aperture/collimator absorbs neutrons that are not traveling in the desired direction, producing a shaped neutron beam (Figure 2.5). Filters within the collimator assembly can remove different energy neutrons and gamma-rays from the beam (Domanus, 1992). A shutter mechanism opens and closes the beam, and may be a simple slab of absorber material which can be moved into and out of the beamline. An imaging station consists of a method to hold the object in the beam and an imager or detector at the image plane (see Figure 2.5). Potential imaging technologies include activation foils, scintillating screens, and multi-channel plates (Berger, 1976b; Lehman, 2007; Tremsin, 2011). Finally, a beamstop placed behind the imaging station absorbs the radiation beam, and prevents excessive exposure from the beam.

Figure 2.6 qualitatively describes neutron intensity at the image plane. The neutron beam interacts through absorption and scattering with the object, which reduces the intensity of the neutron beam at the image plane. The object in Figure 2.6 has a large round void in its center, which has a lower (essentially zero) macroscopic cross-section than the bulk material of the object; this creates a higher intensity at the image plane behind the pore compared to the intensity

![Diagram](image.png)

Figure 2.6. Radiography setup showing the effect of a sample on the neutron intensity at the image plane.

11
behind the object where the beam did not pass through the pores. The same is true of a crack parallel with the neutron beam within the object. A neutron detector placed behind the object reacts with the impinging neutron beam, creating an image of the radiation intensity at the image plane. The technique of radiological examination consists of finding an efficient mode of detecting and visualizing these radiation intensity differences (Domanus, 1992).

2.3 Neutron Beams

Neutron beam divergence and beam intensity are the two most important factors when evaluating a neutron beam for imaging purposes. There are several other factors which limit the spatial resolution of a particular neutron imaging system. The main parameters that define the quality of radiographs and tomographic reconstructions include the beam properties, the background radiation, the detector spatial and temporal resolution, and other perturbing effects such as object movement during exposure (Lehmann et al., 2007).

A standard criterion to characterize beam quality is the L/D-ratio, where L is the length of a beamline (e.g. from the source aperture to the sample) and D is the effective diameter of the beamline aperture, typically a few cm (Winkler, 2006). A larger L/D-ratio indicates lower beam divergence, which corresponds to a clearer image. Thus, the L/D ratio is the main parameter which contributes to the image blurring due to the neutron beam properties. The degree of blurring is quantified as the geometrical unsharpness \( u_g \) (Equation 2.6)

\[
 u_g = \frac{d_o}{(L-d_o)/D} \approx \frac{d_o}{L/D} \tag{2.6}
\]

Decreasing the distance \( d_o \) between the object and the detector plane increases precision with respect to spatial resolution (Lehmann et al., 2007). When high spatial resolution is needed, object-detector distances on the order of ~1 cm are required (Lehmann et al., 2007). The collimator L/D ratio should be 10 or greater to give useful resolution, though ratios greater than 50 are recommended for most practical applications (Cutforth, 1976). The effective L/D for a particular radiography system differs from the physical length over diameter of the beam tube as a result of neutron scatter off of the beam tube walls (Morgan and King, 2011). The effective L/D can be measured using a “no umbra” device (American Society for Testing and Materials International, 2008).
A neutron source should provide at least $10^9$ n/cm$^2$-s at the source for practical applications, and at least $10^{12}$ n/cm$^2$-s for high-resolution radiography (Cutforth, 1976). A beamline originating at the source collimates the neutrons into a useful beam, and the beam intensity is directly proportional to the source intensity. A neutron beam flux of at least $10^6$ n/cm$^2$-s is generally required for most practical applications.

Thermal and epithermal (0.01 eV to 10 keV) neutrons are typically preferred for neutron radiography, since cross-section effects are more pronounced at thermal energies compared to fast energies; however, the higher penetrating power of fast (>100 keV) neutrons may be preferred if the object is very thick and/or hydrogen-rich (Winkler, 2006). Typically, thermal neutron beams contain a fast neutron component, which penetrates substances to a higher degree and is nearly impossible to completely remove by absorption. These fast neutrons always cause additional blackening or fogging of film in direct imaging methods (Kallmann, 1948). Multi-foil activation experiments can be used to determine the energy spectrum for a particular neutron beam (Morgan and King, 2011). Depending on the type of detector, gamma radiation within a beam can produce noise and reduce contrast in the image. Thus, the neutron-to-gamma ratio ($n:\gamma$) can offer an indication of the signal-to-noise ratio for some neutron radiographic techniques (e.g. direct neutron radiography). Direct radiography techniques typically require a $n:\gamma$ of around $10^5$ n/cm$^2$-mR for metal conversion foils and $10^4$ n/cm$^2$-mR for scintillation screens to produce radiographs with negligible gamma fogging (Cutforth, 1976).

Neutron beam designs can be very simple, or extremely complex, depending on the application. The well-engineered beamline designed for prompt gamma neutron activation analysis at the Oregon State University TRIGA reactor includes a borated-aluminum liner to collimate the neutron beam, a bismuth filter to attenuate the gamma radiation, and a single crystal sapphire to reduce the fast and epithermal neutrons (Robinson et al., 2010).

The quality of a neutron beam can be determined by comparing an image of a test object with an image of a similar object that contains a known artificial discontinuity, a defect standard, or a reference standard (Bossi et al., 2002; Morgan and King, 2011). In common practice, a fabricated resolution indicator, often called a sensitivity indicator, emulates defects of varying size, with gaps and holes placed beneath different thicknesses of plastic (American Society for Testing and Materials International, 2005).
2.4 Neutron Sources

Neutron radiography can be performed with almost any neutron source (Winkler, 2006). The applicability of a neutron source to neutron radiography depends on several parameters, including: neutron energy, neutron intensity, beam collimation, background radiation, size and portability of the particular neutron source, and cost (Cutforth, 1976). No one source is preferred in all of these categories, and the proper source requires careful evaluation to match the application requirements with the most applicable neutron source (Cutforth, 1976). In general, these requirements are contradictory; for example, neutron beam intensity usually conflicts with the cost and portability of the system (Cutforth, 1976).

The neutrons from almost all sources are born with high energies (~2 MeV for neutrons produced by fission reactors, and 14.1 MeV for neutrons produced by D-T fusion reactions); however, neutron radiography generally requires lower energies (0.01 eV to 10 keV) (Domanus, 1992). Neutrons in the thermal energy range exhibit the most interesting and useful attenuation characteristics and are more easily detectable and recordable (Cutforth, 1976). High-energy (fast) neutrons slow down to low (thermal) energies through scattering interactions with a moderator, a low-Z material with high scattering cross-section and low absorption cross-section, such as water, graphite, or beryllium (Domanus, 1992). The moderator not only reduces the energy of the neutrons, but also reflects some neutrons back toward the source and serves as shielding for surrounding personnel (Cutforth, 1976).

Possible neutron sources include high-intensity radioisotope sources, accelerator-based systems, and nuclear reactors. However, in most practical applications, neutron radiography is performed at dedicated facilities, typically nuclear reactors, that can provide a relatively high neutron intensity (>10^6 n/cm^2-s). The next sections describe the benefits and limits of radioisotope, accelerator, and nuclear reactor neutron sources.

2.4.1 Radioisotope Sources

Radioisotope-based systems are attractive owing to their reliability, semi-portability, and ease of operation (Domanus, 1992); however, the relatively low thermal neutron intensities available from radioisotope sources lead to low resolution and high exposure times (Domanus, 1992). Also, unlike accelerators and reactor systems, the neutron source continuously emits radiation and cannot be turned off.
One of the most attractive and commonly used radioisotope sources for neutron radiography is a $^{252}$Cf spontaneous fission source (Domanus, 1992). The spontaneous fission of californium provides an average neutron energy of 2.3 MeV (lower than the energies from most ($\alpha$,n) sources), which yields a high thermalization efficiency (Cutforth, 1976). Neutron intensity is limited by economic rather than technical reasons (since neutron intensity and cost are both proportional to the activity of the radioisotope source material), and the gamma background is low enough to allow direct neutron radiography (Cutforth, 1976). Most other neutron sources are a combination of an alpha-emitter and beryllium, which results in a $X(\alpha,n)$Be reaction. Common alpha-emitters for this purpose include $^{239}$Pu, $^{241}$Am, $^{226}$Ra, $^{227}$Ac, and $^{228}$Th (Domanus, 1992).

The quality of radiographs using isotopic sources is generally lower than those acquired using other neutron sources. However, these sources are especially useful for applications that require portability and can tolerate moderate image quality (Cutforth, 1976).

2.4.2 Accelerator-Based Systems

Accelerator sources typically provide less-intensive neutron beams than nuclear reactors, but are generally more intense than radioisotope sources. They are amenable to intermittent operation and may be portable, but have a short target life and are reasonably complex (Domanus, 1992). Modern trends in the application of neutron generators focus on the detection of explosives, fissile materials and other illicit materials for homeland security purposes (Chichester et al., 2006). However, neutron generators have been employed for neutron activation analysis, medical diagnostics, assay of nuclear waste, and high-energy physics (Chichester et al., 2006).

Useful radiographs have been produced using accelerators, but like radioisotope sources, the quality of radiographs produced is poor compared to those produced using nuclear reactors (Cutforth, 1976). Neutrons can be produced by positive ion bombardment of targets with accelerating voltages as low as 50 kW, but practical applications for neutron radiography require at least 150 kV accelerating potential (Cutforth, 1976). Some modern accelerators use D-T and D-D fusion processes to produce neutrons for neutron radiography (Chichester et al., 2006).

Common reactions include $^3$H(d,n)$^4$He, $^2$H(d,n)$^3$He, and $^9$Be(d,n)$^{10}$B. The $^9$Be(d,n)$^{10}$B reaction has the highest neutron yield for positive ion bombardment, but energies in excess of 1 MeV are necessary to obtain this high yield (Cutforth, 1976). Sophisticated equipment is required to supply these high accelerating voltages, and the investment for such equipment is substantial.
Accelerator-based systems consist of a fast neutron generator, a moderator, and a collimator to provide a thermal neutron beam suitable for neutron radiography. An example Van de Graaff accelerator system for neutron radiography is shown in Figure 2.7 (Domanus, 1992).

For many applications of neutron radiography, a 3 MeV Van de Graaff accelerator with a beryllium target (reaction is $^9\text{Be}(d,n)^{10}\text{B}$) can produce sufficient neutrons (Cassidy, 1976). A polyethylene block or water tank around the source slows fast neutrons to lower energies suitable for neutron imaging (Figure 2.7). A collimator seated in the moderator at a position with the highest thermal neutron flux provides a beam suitable for neutron imaging.

(Cutforth, 1976).
2.4.3 Nuclear Reactors

Nuclear reactors can provide significantly higher thermal neutron intensities than radioisotope and accelerator systems, and are thus the most common sources of neutrons for radiography and tomography applications. However, research nuclear reactors require high capital investments, are immobile, and require a license to operate (Domanus, 1992). Most nuclear reactors were originally built for purposes other than neutron radiography, and radiography is essentially a by-product of many reactors (Cutforth, 1976). However, some reactors were built specifically for neutron radiography, such as the neutron radiography (NRAD) reactor at the Idaho National Laboratory and the UC Davis McClellan Nuclear Research Center (MNRC), which is owned and operated by the University of California, Davis.

Nuclear reactors are commonly classified according to the energy of the neutrons that cause most of the fissions (Shultis and Faw, 2008). Neutrons born from fission have high energies (~1-2 MeV); fast reactors operate using these high-energy or fast neutrons. Fast neutrons can be slowed through scattering with surrounding material to speeds comparable to the thermal energy of the atoms of the surrounding material; thermal reactors operate using mostly these slow or thermal neutrons. The heart of every nuclear reactor is the active core, where the fission chain reaction is sustained (Shultis and Faw, 2008). A reactor core contains (1) the fissile fuel which produces the neutrons through fission, (2) a moderator in the case of thermal reactors, (3) coolant for heat removal, (4) structural material which maintains the physical integrity of the core, and (5) a means to control the fission chain reaction (Shultis and Faw, 2008). Figure 2.8 depicts the layout of an open-pool light water reactor, which is a common type of research reactor. A reflector typically surrounds a reactor core and scatters neutrons back to the core, reducing neutron leakage. A shield outside the reflector reduces the radiation levels to the surrounding facility. For open-pool light water reactors, the water usually acts as the moderator, coolant, and radiation shield.

Another potential neutron source for neutron radiography related to nuclear fission reactors is a subcritical assembly of fissile material. For this system, a neutron source, such as $^{252}$Cf, is surrounded by fissile material. The subcritical assembly has a multiplication factor near unity; neutrons from the $^{252}$Cf are multiplied in the assembly by a subcritical chain reaction. The amplification of the neutron source term depends on the multiplication factor ($k_{\text{eff}}$) of the assembly, and follows according to Equation 2.7.
For example, if the $k_{\text{eff}}$ of the system were 0.95, the system would amplify the number of neutrons by a factor of twenty. A subcritical assembly for neutron radiography should be inexpensive, small, semi-portable, and constructed in such a way that there is no chance of a criticality (Cutforth, 1976).

Radioisotope beam intensity is limited by the activity of the radioisotope and accelerator source intensity is limited by the power of the accelerator. Neutron beam intensity from a nuclear reactor is directly proportional to the reactor power; the reactor power is limited by the reactor’s license and by the ability to safely operate and cool the reactor. The fission chain reaction in a nuclear reactor can produce significantly higher thermal neutron fluxes than accelerator or radioisotope sources. The increased source intensity produces more intense neutron beams, which can result in better neutron radiographs. The following section discusses several techniques for acquiring neutron radiographs.
2.4.4 The United States Geological Survey TRIGA Reactor

The United States Geological Survey (USGS) owns and operates a 1 MW<sub>th</sub> Mark-I TRIGA reactor primarily for the primary purpose of neutron activation analysis (United States Geological Survey, 2010). The reactor, called the Geological Survey TRIGA Reactor (GSTR) is located at the Denver Federal Center in Lakewood, CO (United States Geological Survey, 2009). The GSTR is a light water cooled, graphite reflected reactor using ~19.75% enriched uranium-zirconium hydride TRIGA fuel elements (United States Geological Survey, 2009). The reactor has a maximum steady-state thermal power of 1.0 MW and can pulse to a peak power of 2,500 MW<sub>th</sub> (United States Geological Survey, 2009).

The GSTR core sits at the bottom of a 231 cm (7 ft 7 in) diameter, 757 cm (24 ft 1 in) tall stainless steel tank with ~6.1 m (20 ft) of water above the top of the reactor core (United States Geological Survey, 2010). The water acts as a moderator, radiation shield, and naturally convecting coolant (United States Geological Survey, 2010). The main safety feature of the TRIGA Mark-I nuclear reactor is the strong, prompt-negative temperature reactivity feedback coefficient of the U-ZrH fuel, which limits the achievable steady-state and peak power, thus preventing fuel damage from credible reactivity accidents (Simnad et al., 1976). The reactor is cooled by natural convection, and cannot operate if the water is above 60°C (United States Geological Survey, 2010).

Figure 2.9 shows a picture of the GSTR reactor taken from the surface near the southwest edge of the tank. The reactor core contains the fuel and control rods, and a graphite reflector surrounds the core to improve the neutron economy of the reactor. A lazy susan at the top of the core (Figure 2.9) serves as an irradiation facility capable of holding several samples at a time, rotating them around the reactor to achieve uniform exposure for each sample. The GSTR is a highly thermal reactor, and can provide an excellent source of thermal neutrons for neutron imaging.

While most neutron radiography facilities are located at nuclear reactors using existing beam ports, the MINER facility developed by this project includes a non-permanent beamline added specifically for neutron radiography. The Gulf General Atomic in San Diego added a very similar facility to a 250 kW<sub>t</sub> Mark-I TRIGA reactor in 1970 for neutron radiography (Whittemore et al., 1971). This facility consisted of a tangential beamline tube into the reactor tank positioned just above the graphite reflector, which included a conical collimator to provide neutrons for
radiography. The resulting flux was \(\sim 1.2 \times 10^6 \text{n/cm}^2\text{-s} \) with an L/D of 100 (Whittemore et al., 1971). The Gulf General Atomic facility primarily employed the transfer method using gadolinium foils for neutron imaging. Thus, particular attention was focused on reducing the gamma content of the beamline. This was accomplished by adding lead gamma filters to the source-end of the beamline (Whittemore et al., 1971). The beam tube, except for the 12” section nearest to the source, contained neutron absorbers to reduce neutrons scattered from the beam tube walls (Whittemore et al., 1971). The beamstop constructed for the Gulf facility contained a borax-paraffin mixture (two parts paraffin to one part borax) to attenuate neutrons and a 3” thick, 12” OD lead backstop to attenuate gammas (Whittemore et al., 1971).
2.5 Neutron Imaging Techniques and Detection Methods

Many neutron radiographic techniques are available, and the proper technique depends on the application and desired results. Techniques exist for static radiography, real-time/dynamic radiography (or radioscopy), and three-dimensional computed tomography. Unfortunately, neutrons typically cannot be used to directly produce an image, but can create secondary radiation (e.g. α-, β-, or γ-rays) that is often directly utilized (Thewlis, 1956). In general, imaging systems for neutron radiography include a converter or intensifier which interacts with incoming neutrons and emits a more directly detectable radiation, such as alpha, beta, gamma or visible light radiation (Domanus, 1992). The resulting secondary radiation is recorded on photographic or cellulose nitrate film, activation foils, or monitored by electronic detectors (Domanus, 1992).

Similar to x-ray radiography, most neutron radiographic methods use a film-based image detection and recording technique (Domanus, 1992). Neutron radiographic methods using conversion foils can be broken up into two categories: direct and indirect (or transfer) methods. Indirect methods use an intermediate detector or recorder, while in direct systems, the film is present in the neutron beam during the exposure (though the film still requires subsequent film processing) (Berger, 1976b). Table 2.1 lists some common conversion foil materials for thermal neutron radiography (Berger, 1976b). The appropriate converter material for each technique depends on the material’s cross-section, reaction mode, and half-life. Direct radiography techniques require materials with prompt (or extremely short) decay half-lives, while transfer methods require an extended half-life on the order of hours.

<table>
<thead>
<tr>
<th>Material</th>
<th>Useful Reactions</th>
<th>Thermal Neutron Cross-Section [b]</th>
<th>Half-Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>boron</td>
<td>$^{10}$B(n,α)$^7$Li</td>
<td>3,830</td>
<td>prompt</td>
</tr>
<tr>
<td>cadmium</td>
<td>$^{113}$Cd(n,γ)$^{114}$Cd</td>
<td>20,000</td>
<td>prompt</td>
</tr>
<tr>
<td>gadolinium</td>
<td>$^{155}$Gd(n,γ)$^{156}$Gd</td>
<td>61,000</td>
<td>prompt</td>
</tr>
<tr>
<td></td>
<td>$^{157}$Gd(n,γ)$^{158}$Gd</td>
<td>254,000</td>
<td>prompt</td>
</tr>
<tr>
<td>lithium</td>
<td>$^6$Li(n,α)$^3$H</td>
<td>910</td>
<td>prompt</td>
</tr>
<tr>
<td>indium</td>
<td>$^{115}$In(n,γ)$^{116}$In</td>
<td>157</td>
<td>54 m</td>
</tr>
<tr>
<td>dysprosium</td>
<td>$^{164}$Dy(n,γ)$^{165}$Dy</td>
<td>800</td>
<td>2.3 h</td>
</tr>
<tr>
<td>gold</td>
<td>$^{197}$Au(n,γ)$^{198}$Au</td>
<td>99</td>
<td>2.7 d</td>
</tr>
</tbody>
</table>
2.5.1 Direct Imaging Methods

In a direct imaging method, a converter foil such as gadolinium is closely coupled to a film during irradiation; the converter screen absorbs neutrons and immediately emits ionizing radiation (e.g. gamma and beta radiation), which exposes an adjacent film (Domanus, 1992). The film and converter foil are often placed in vacuum cassettes to ensure good contact between the conversion foil and the film (Domanus, 1992). In general, this method cannot be used to image radioactive (gamma-emitting) objects because the radiation from the object would also expose the film, resulting in a fogged image.

Figure 2.10 shows a schematic of the direct radiography process. The neutron beam interacts with the object, and the resulting neutron beam impinges on the converter foil, giving off secondary radiation in the pattern of the object, which exposes the film. Some direct radiography techniques are susceptible to gamma fogging, and require a gamma filter (e.g. lead or bismuth), which attenuates gamma radiation in the beam but is relatively transparent to thermal neutrons (Kallmann, 1948). The exposed film is removed after irradiation for development in a dark-room (Figure 2.10).

Gadolinium is the most common converter foil for direct neutron radiography. Thin gadolinium foils for the direct method are typically 25.4 µm (0.001 in.) thick (Berger, 1976b). In this method, a single-emulsion film is preferred to the typical double-sided emulsion (Berger, 1976b). The converter foil should be placed behind the film, and the emulsion-side of the film should face the foil. The film readily shields the low-energy internal conversion electrons emitted from the gadolinium upon neutron bombardment and exposes only the emulsion-side of the film facing the gadolinium (Berger, 1976b). Elimination of the second emulsion only slightly reduces the film response to thermal neutrons, but significantly reduces the gamma fogging of the film.

![Diagram of the direct neutron radiography process.](image)

Figure 2.10. Schematic of the direct neutron radiography process.
(Berger, 1976b). Typical neutron exposure for the direct method ranges from $10^8$ to $10^9$ n/cm$^2$, depending on the speed of the film (Berger, 1976b). A neutron fluence of $\sim 10^9$ n/cm$^2$ can give a high-resolution, high-contrast radiograph if careful, dust-free darkroom procedures are used (Bossi et al., 2002).

Another direct imaging technique does not use a foil at all, but rather a neutron-sensitive imaging plate, consisting of a thin phosphor layer containing a mixture of storage phosphor, neutron converter and an organic binder. Following neutron exposure, the plate is scanned by a thin laser beam which stimulates the emission of a pattern of light (Bossi et al., 2002). Advantages of this technique include wide dynamic range, direct availability of digital data for processing, converter efficiencies of 30 to 40 percent, and spatial resolution acceptable for many applications (Rant, 2001; Kobayashi and Satoh, 1999). Scintillation screens significantly reduce exposure times compared to gadolinium conversion foils, with a required exposure between $10^5$ and $10^6$ n/cm$^2$ compared to $10^9$ n/cm$^2$, respectively (Berger, 1976b).

For applications where gamma-insensitive direct imaging is required, a “track-etch” system is available that includes a combination of dielectric film (e.g. cellulose nitrate) and a converter that emits either alpha particles (e.g. $^6$Li, $^{10}$B) or fission fragments (e.g. $^{235}$U) (Domanus, 1992). Track-etch radiography most commonly utilizes a light- and gamma-insensitive cellulose nitrate film that can be exposed directly in the neutron beam (McClellan and Richards, 1984), though other dielectrics such as polycarbonate materials, glass, and mica could substitute for the cellulose nitrate film (Barton, 1976). A lithium tetraborate coating on the track-etch film absorbs neutrons and emits alpha particles, creating damage tracks in the cellulose nitrate film; the image is produced by subsequent etching using sodium hydroxide (McClellan and Richards, 1984). While the contrast of an image produced using the track-etch technique is very low, the resolution of the image is very high, making this a valuable technique for some applications where accurate measurements are required (McClellan and Richards, 1984). Also, because it is gamma-insensitive, the track-etch method is another technique that can be employed on radioactive objects, such as used nuclear fuel.

2.5.2 **Indirect Imaging Methods**

Indirect (or transfer) method neutron radiography involves the use of an intermediate detector, which produces an image upon subsequent processing. For this technique, a metal foil
(e.g. dysprosium, indium, gold) is used as the image recorder; the foil captures the image as activation of the foil material (Domanus, 1992). The transfer method is slower than the direct method (Domanus, 1992), but it offers the advantage that the film is not present in the neutron beam, thus offering complete discrimination against gamma ray fogging. The transfer method can thus be employed to image highly-radioactive objects, which give off significant gamma radiation that would fog the film in the direct method (Berger, 1976a; Richards and McClellan, 1979; Bossi et al., 2002).

Figure 2.11 shows a schematic of the indirect radiography process. An activation foil placed behind the object absorbs neutrons that penetrate through the object and subsequently becomes activated (Figure 2.11). After irradiation, the foil is taken to a dark-room where the activated foil is mated to an x-ray film, exposing the film according to the activity pattern of the activated foil (Figure 2.11). Subsequent development of the film produces a neutron image of the object.

In the indirect method, the converter foil material must have a high activation cross-section and appropriate half-life for the radionuclide formed by activation (Mayer, 1972). The half-life of the activated material must be long enough to allow for post-irradiation processing, but short enough for the foils to be reused. Dysprosium (T_{1/2} = 2.3 h) and indium (T_{1/2} = 54 m) both meet these requirements. Foil or film exposure beyond three half-lives gains little benefit, as ~90% of the saturation will have been achieved in each case; in practice, neutron exposure times are much less than this (about one hour) while film exposure is typically much greater than this (Thewlis, 1956). Dysprosium and indium are the most commonly used foils for indirect-method neutron radiography (Domanus, 1992). The thickness of dysprosium and indium transfer foils typically range from 125 µm to 250 µm (0.005 to 0.010 in.) (Berger, 1976b).

![Figure 2.11. Schematic of the indirect neutron radiography process.](image-url)
A dysprosium transfer foil can be combined with a cadmium foil and indium foils for simultaneous dual-image radiography (Bossi et al., 2002; McClellan and Richards, 1984). The foil cassette is loaded such that the first foil behind the object is dysprosium, followed by cadmium, then indium (McClellan and Richards, 1984). The cadmium strongly absorbs thermal neutrons, exposing the indium foil to only epithermal and fast neutrons. Thus, both epithermal and thermal neutron images can be produced with a single neutron exposure (McClellan and Richards, 1984). Indium has a large activation resonance at 1.46 eV, and has been widely used to detect these higher energy neutrons (Berger, 1976b). Other potential useful epithermal detectors include gold with a resonance at 4.9 eV and tungsten with a resonance at 18.8 eV (Berger, 1976b). Epithermal imaging techniques can be used to examine reactor fuels as the higher neutron energy provides greater penetration through $^{235}$U-enriched and plutonium-containing materials (Berger, 1976b).

Although film radiography can provide the highest spatial resolution, there are many drawbacks to these techniques. The exposure time required to obtain meaningful information is two to three orders of magnitude greater than modern digital systems, and development time must also be considered (Lehmann et al. 2007). The longer exposure time also makes tomographic reconstruction using multiple foil exposures prohibitively expensive (Lehmann et al., 2007). Additionally, in the case of neutron exposure, the risk of activation of the sample material is an important issue, and long irradiation times should be avoided to limit the activation of the sample (Lehmann et al., 2007).

2.5.3 Dynamic Neutron Radioscopy

Dynamic radioscopy produces an image during exposure, and thus could be considered a direct imaging technique; however, dynamic radioscopy is sufficiently different from static direct methods that it is described here as a separate technique. Techniques for dynamic neutron radioscopy provide a valuable capability for unique applications, such as lubricant flow through an operating jet engine, studies of absorption and compression refrigerator designs, studies of automotive parts in motion, and a large range two-phase flow studies (Bossi et al., 2002). Dynamic neutron radioscopy can produce frame rates that range from 30 fps (the typical frame rate of many televisions) to 1000 fps and up to 10,000 fps (Lindsay, et al. 2001; Takenaka et al., 2001).
Dynamic neutron radioscopy requires high-intensity neutron beams and detection equipment capable of producing the desired frame rate (Bossi et al., 2002). Producing high-speed, or flash, radiography requires a neutron source that is capable of producing an ultra-high intensity flash of neutrons lasting a few milliseconds, which can be achieved with a pulsed nuclear reactor (Domanus, 1992). Very high frame rate neutron radioscopy with a frame rate greater than 10,000 fps synchronizes the event to be studied, such as the burn cycle of a pyrotechnic event, to a neutron pulse (Bossi et al., 2002).

Neutron radiography usually requires a neutron exposure on the order of $10^9$ to $10^{10}$ n/cm$^2$ to produce an image of good quality (Chalmeton, 1973). Nuclear reactors typically produce beams of $10^6$ to $10^7$ n/cm$^2$-s (Chalmeton, 1973). In order to reduce exposure times, neutrons can be converted into useful, image-producing radiation (e.g. electrons, visible light) and amplified (Chalmeton, 1973). Scintillation screens and multi-channel plates can provide this amplification.

A common dynamic neutron radioscopy imager includes a high frame rate CCD camera coupled with a rapid response neutron-sensitive scintillation screen (Lehmann et al., 2007). Figure 2.12 shows an example setup for dynamic neutron radioscopy. Like other radiography systems, a neutron beam impinges on an object of interest before interacting with a detector. In this case, the detector is a light-emitting scintillator screen coupled to a CCD camera located outside the neutron beam. The screen typically consists of a mixture of lithium-6 and zinc-sulfide (Domanus, 1992). Lithium-6 absorbs neutrons and emits alpha particles, which interact with the zinc-sulfide to produce visible light (Lehman et al, 2007).

![Figure 2.12. Setup for dynamic neutron radioscopy using a CCD camera and scintillation screen.](image-url)
Almost all of the energy lost by an α-particle in a fluorescent substance is transformed into light energy (Kallmann, 1948). Generally, α-particles have an energy on the order of ~1 MeV and visible photons have an energy on the order of ~2-3 eV, so several hundred thousand photons will be emitted for every α-particle absorbed. Exposure to $10^5$ photons will create around $10^3$ blackened grains in a photographic emulsion (Kallmann, 1948). Not only can this light directly expose a film, but the fluorescent screen can also be coupled to a sensitive CCD camera for dynamic radioscopy (Lehman et al., 2007). The entire detection system is in a light-tight box to isolate the system from external light (Figure 2.12). Since radiation damages electronics, including CCD cameras, a mirror placed behind the scintillation screen reflects the image to the CCD camera placed outside the radiation beam. The camera connects to a computer that acquires and processes image data.

Neutron sensitive multi-channel plates (MCPs, synonymously used for microchannel plates) can also serve as imagers for dynamic neutron radioscopy (Cao et al., 2006). Originally developed as high-resolution electron amplification element for image intensification devices, MCPs have direct sensitivity to charged particles and high-energy photons (Wiza, 1979). MCPs have been used extensively in x-ray astronomy and many other photon-counting applications (Fraser and Pearson, 1990). High-efficiency, neutron-sensitive multi-channel plates capable of real-time neutron imaging provide significant advantages over many current technologies, with high spatial resolution (~10-15 µm) and rapid neutron timing resolution (~1 µs) that enable real-time high speed dynamic evaluation (Tremsin et al., 2011; Feller and Tremsin, 2010).

Microchannel plates are the same technology used in night-vision applications; in order to use a microchannel plate for neutron imaging, a converter must be included that converts neutrons to electrons (Chalmeton, 1973). The converter can be placed as a layer on the front-end of the MCP or incorporated into the bulk material of the plate. Incorporating the absorber into the plate increases the chance that the charged particles will promote secondary electrons in one or more channels (Fraser and Pearson, 1990).

Figure 2.13 depicts a qualitative schematic of a neutron-sensitive multi-channel plate showing a neutron interacting with an absorber in the bulk material of the plate to produce an electronic signal. The multi-channel plate contains an array of microchannels (~10 µm, with a wall thickness on the order of a few microns) and consists of glass doped with an absorber (e.g. $^{10}$B, $^6$Li, or Gd) to make it neutron sensitive (Tremsin et al., 2009). As shown in Figure 2.13, an
incident neutron is absorbed by $^{10}\text{B}$; the $^{10}\text{B}(n,\alpha)^{7}\text{Li}$ capture conversion process for thermal neutrons yields short-range charged particles, which in turn create free secondary electrons in the adjacent microchannel (Cao and Biegalski, 2007). Electrodes are deposited on the front and rear face of the MCP. When a bias voltage (~1 kV) is applied, the MCP acts as an electron multiplier (Fraser, 1983), amplifying the resulting electron signal as much as $10^6$ into a detectable signal (Cao and Biegalski, 2007). Imaging hardware then registers the burst of electrons emitted from the channels and constructs a digital image.

The secondary electron efficiency of MCPs has been studied in detail and the underlying theory is well understood (Fraser, 1983). Most of the electrical performance of a channel is neither a function of its length ($l$) nor diameter ($d$), but rather only a function of the ratio $l/d$; because of this, an almost arbitrary size reduction is possible (Wiza, 1979). A common image acquisition method involves scintillation of a phosphor layer and subsequent image capture with a video camera (Wiza, 1979). Alternatively, electrically independent conducting anode elements coupled to each channel can acquire an image by focusing the output charge of an individual channel on its anode element, which can produce an image with subsequent processing. This technique allows operation at high count rates since the anode elements act in parallel, but at the cost of electronic complexity (Wiza, 1979). Simpler anodes include two sets of orthogonal linear anodes (row and column), and event location is determined by the coincidence of row and column pulses (Wiza, 1979).
2.5.4 Computed Tomography

Computed tomography (CT) is a non-destructive imaging technique first developed for medical x-ray radiography in which a series of images are taken at uniform angles around a specimen and, using a computer program, reconstructed into a 2D or 3D image of the specimen (Domanus, 1992). Computed tomography is most commonly performed using x-rays, but any penetrating radiation, including neutrons, can be used to produce projections for tomographic reconstruction. Reconstruction estimates the linear attenuation coefficient ($\mu$) for x-rays and gamma rays, and the macroscopic cross-section ($\Sigma$) for neutrons.

The first tomographic images were taken in 1956 and used gamma-rays to reconstruct a two-dimensional slice of a fluidized bed to study differences in density (Bartolomew and Casagrande, 1957). The mathematics to determine the real function in a plane given by its line integrals provide the foundation for computed tomography (Cormack, 1963). Hounsfield reconstructed the first medical images in 1972, and Hounsfield and Cormack were awarded a Nobel Prize in 1979 for developing computed tomography (Baruchel et al., 2000). The development of computed tomography was slow through the 1980’s as a consequence of the large amount of data required for reconstruction, requiring high-speed, high-memory computers for acceptably fast reconstruction (Baruchel et al., 2000). The industrial benefits of computed tomography are numerous; potential applications range from small samples, such as characterization of composite materials displayed with 1 $\mu$m voxel size, to large samples, such as slices of a 1 m diameter riser with 5 cm pixel size (Baruchel et al., 2000). X-ray computed tomography offers the ability to better-distinguish between soft tissue types in medical applications and internal cracks and other internal features for material science applications compared to x-ray radiography.

Any detector that is capable of providing quality radiographs can be used for computed tomography. While it is possible to perform tomography with multiple radiographs acquired using foils, it is an expensive form of nondestructive testing and is not generally applicable to routine examination (McClellan and Richards, 1984). However, special applications may warrant the cost of tomography using the foil transfer method (Richards et al., 1982).

Because tomography requires multiple radiographs at different angles to the specimen, real-time detectors are preferred. With the advent of faster computers and real-time imaging technologies, such as scintillation screens and multi-channel plates, tomographic acquisition and
reconstruction requires significantly less time and may provide a viable nondestructive technique for routine examination.

2.6 Radiographic Artifacts and Image Processing

In neutron and x-ray radiography, projection images can be distorted by several artifacts resulting from imperfect imaging, measurement errors, and process errors (Kiss et al., 2006). Digital images taken by neutron or x-ray radiography generally require the application of image filters prior to radiographic analysis to increase the quality of the image prior to subsequent analysis. The following subsections discuss some of the more common artifacts present in radiographs, including nonuniformity of the beam, defects in the acquisition system, and beam hardening.

2.6.1 Nonuniformity

Some distortions are caused by the acquisition system itself. For example, if the detector is not uniformly sensitive in the field of view, some areas may be brighter than others. Nonuniformity in the neutron beam may cause a similar effect. A radiograph of the radiation field without a sample present, or flat-field image, can be used to create a filter that can be applied to simultaneously correct for both of these effects. This multiplication filter is applied pixel-by-pixel on each digital image in order to produce more constant images.

For some systems, the intensity of the beam or sensitivity of the camera may change during the acquisition period (Kiss et al., 2006). This may be caused by cold or warm camera electronic or fluctuations in the neutron beam intensity. As a consequence, brighter or darker images may be produced, which could cause artifacts in subsequent analysis (Kiss et al., 2006). To correct for this problem, each image should be multiplied by appropriate constants such that the average intensity of the background in each image is nearly the same (Kiss et al., 2006). Similarly, a reference object in each image can provide the reference intensity for each image, instead of the background.

2.6.2 Acquisition System Defects

To obtain a radiograph free of defects, the signal delivered by each pixel of the detector must be proportional to the neutron flux (Baruchel et al., 2000). Thus, high flux levels near the
upper limit of the digitization capability of the detector and near the lower limit of the background noise must be avoided (Baruchel et al., 2000). Also, some pixels of a detector may burn out, creating isolated noise points in each projection (Kiss et al., 2006). Threshold median filtering can be applied to correct the noise caused by these effects; in simple terms, this correction finds pixels that are not working and artificially sets its intensity to the median (or average) of the surrounding pixels.

2.6.3 **Beam Hardening**

A neutron beam from a nuclear reactor initially contains a polyenergetic spectrum. Since the macroscopic cross-section is a function of the neutron energy (typically with higher cross-sections for lower-energy neutrons), the lowest-energy neutrons are attenuated preferentially, leading to the gradual increase of the average neutron energy, or *hardening* of the neutron beam, along the direction of the neutron beam through a specimen (Baruchel et al., 2000). This leads to higher measured flux values than expected assuming a simple exponential attenuation law (Kasperl and Vontobel, 2005). Thus, beam hardening leads to flawed attenuation data. The beam hardening effects must be accounted for in radiographs of samples containing strong absorbers (e.g. cadmium, boron, gadolinium, etc.), samples with a high scattering cross-sections, or when analyzing good moderators using a cold neutron beam (Kasperl and Vontobel, 2005).

Beam hardening artifacts can be avoided by using a mono-energetic neutron beam, which can be difficult to achieve with a nuclear reactor. Thermal neutron filters placed at the source-end of the beam can pre-harden the neutron beam. Beam hardening can also be avoided when using (nearly) mono-energetic neutron sources, such as some accelerator and radioisotope sources.

For relatively homogeneous materials, radiographs can be corrected based on an image of a step-wedge made of the same material as the object of interest. The measured attenuation can be correlated to the actual material thickness, and an appropriate filter applied to the digital image (Baruchel et al., 2000).

The linearization technique is a well-known correction method for beam hardening, which uses a correction function to transform the projection data from poly-energetic to mono-energetic (Kasperl and Vontobel, 2005). This function is derived using a reference object made of the same material to be studied. The correction function \( H_{BH}(L) \) denotes the beam hardening characteristics and \( I_o \) and \( I_D \) are the intensity before interaction with the sample and the detected
intensities, respectively. The correction function is obtained by measuring $I_D/I_o$ for various known thicknesses of $L$ of the reference object (e.g. a step wedge) (Kasperl and Vontobel, 2005). Inverting the function $H_{BH}$ gives the desired correction function $H_{BH}^{-1}$ given in Equation 2.8:

$$H_{BH}^{-1} \frac{I_D}{I_o} = L.$$  (2.8)

For each measurement in a digital radiograph and for all projections of an object, the attenuation ratio is replaced by the path length, $L$, derived from Equation 2.8 (Kasperl and Vontobel, 2005).

One drawback of the linearization technique is that it is a noise-amplifying correction; however, the most considerable drawback of this linearization method are that it requires a reference object of the same material as the object, and that the measurements are only valid for a specific energy spectrum (Kasperl and Vontobel, 2005). The step wedge provides the same number of measured data as the number of steps on the step wedge, and the rest of the correction data is tabulated by interpolation between the measured data. Coarse interpolation can be problematic, and can be improved by increasing the number of examined step thicknesses.

2.7 Neutron Imaging Applications

The ability to non-destructively analyze the internal structure of an object is appealing for many applications. Neutron radiography and tomography offer tools for a wide variety of academic research and industrial applications. Neutron radiography can be used to study thermal-hydraulic phenomena, including: two-phase flow for water-cooled reactors; molten lead-bismuth flow over a slab; direct heat transfer phenomena between liquid lead-bismuth and water for steam generators for fast-breeder reactors; visualization of a cryogenic fluid heat exchanger using liquid nitrogen as the boiling fluid; two-phase flows in various components of a refrigerator (compressor, condenser, heat exchangers, etc); fluidized beds using dyes consisting of boron and/or cadmium to reveal flow patterns (Takenaka et al., 2001).

Though neutrons are capable of penetrating appreciable thicknesses of material such as steel and uranium, they can also be used to study small, delicate specimens, such as plants (Thewlis, 1956). Early radiographs of the structure of a plant taken in 1956 demonstrated the usefulness of neutron radiography to study organic specimens as a consequence of the high
attenuation of neutrons by hydrogenous materials (Thewlis, 1956). Neutron and x-ray tomography are also useful to study the internal structures of vertebrate remains (Schwarz et al., 2005). Neutron tomography can also image fossils, as neutrons can penetrate thick sections of rock and fossilized bone more deeply than x-rays (Schwarz et al., 2005).

Neutron radiography using a Van de Graaff accelerator can examine explosives contained within metal casings to locate discontinuities, cracks, voids, and high and low density areas; the condition of O-rings and other internal organic materials can also be determined (Cassidy, 1976). Johnson (1976) examined electro-explosives and internal hardware using $^{252}$Cf sources with a scintillation imager, and thicker and denser production items using nuclear reactors at Battelle Memorial Institute and the CP5 Reactor.

One of the most valuable applications of neutron imaging is the non-destructive analysis of nuclear fuel. No other non-destructive testing technique provides a comparable amount of comprehensive information on the condition of nuclear fuel (Domanus, 1983b). Neutron radiography of nuclear fuel can visualize inclusions, cracks, migration effects, central voids, fabrication errors, deformations, et al. (Domanus, 1983a). Accurate, non-destructive measurements of gaps, cracks, and displacements can provide vital information for optimizing fuel manufacturing (Notea et al., 1983).

Some boiling water reactor cores include gadolinium as a burnable absorber to compensate for excess reactivity. Neutron radiography offers the ability to analyze the gadolinium concentration in fresh and used nuclear fuel elements (Mayer, 1972). The gadolinium at the axial center of the fuel pins is depleted, while it is almost fully present at the axial ends of the fuel rod. In the middle, there is a conical transition zone in which it is possible to follow the radial burnup of the gadolinium (Mayer, 1972).

Hydridization of zircaloy cladding causes embrittlement of the cladding, which can produce cracks and allow fission products to migrate outside of the fuel element. Numerous investigations have aimed at detecting the formation of these hydrides in the zircaloy cladding tubes of nuclear fuel rods (Mayer, 1972). Hydride formation on the fuel clad cannot be easily detected visually, and neutron radiography makes it possible to identify the location of hydride formation for subsequent metallographic examination (Mayer, 1972). Experiments show that it is possible to detect differences in hydrogen concentration in zircaloy as low as 600 ppm (Mayer, 1972).
There are several methods for studying cracks in structures, and crack visualization can employ neutron radiography for a number of applications (Pugliesi and Andrade, 1997). Many structures of interest consist of materials with low neutron cross-sections, which will produce low contrast radiographs and poor visualization of cracks. A neutron-opaque substance applied to the surface of a suspect part penetrates into damaged areas via capillary action, and results in sharp contrast between the damaged regions and the bulk material of the structure (Poeth et al., 1996). The properties of contrast agents vary widely, and the best agent for an application depends on its ability to penetrate into cracks, appropriate neutron cross-section, and ease of removal after imaging (Brenizer et al., 1999).

Useful contrast agents range from simple hydrogenous materials to complex compounds, some containing rare-earth salts (Brenizer et al., 1999). Most practical contrast agents rely on the high scattering cross-section of hydrogen or the high absorption cross-sections of boron, lithium, cadmium, gadolinium, samarium, or europium (Brenizer et al., 1999). Hydrogenous materials (e.g. water, alcohol, oil, liquid penetrants) can be effective contrast agents if the defect is large and the interaction cross-section of the matrix is small (Brenizer, 1999). Gadolinium has an absorption cross-section three orders of magnitude larger than that of water, and thus offers the ability to resolve significantly smaller defects than possible with water (Brenizer, 1999).

Of all the contrast agents used for neutron radiography, those containing gadolinium are the most common, as gadolinium has the highest absorption cross-section of all the elements (Brenizer, et al., 1987). Chloride and nitrate salts of gadolinium have higher cross-sections than many alternative contrast agents (Poeth et al., 1996), and are generally very soluble in water but are often hygroscopic and corrosive (Brenizer et al., 1987). Gadolinium salts have been used to detect blockages in turbine blade cooling channels (Bossi et al., 2002). Alternatively, gadolinium oxide has been added to bulk ceramic material, which provides significant contrast (Brenizer et al., 1999).

The MINER facility contains a number of subsystems, and the following chapter describes the design and installation of these subsystems in detail.
CHAPTER 3
MAJOR FACILITY SUBSYSTEMS

This chapter describes the major facility subsystems. Since the GSTR has no existing beamlines, this project includes design and construction of a neutron beamline (Section 3.1), along with design and construction of a beamstop to reduce dose levels from the neutron beam (Section 3.2). A gas pressure control system controls the water level within the beamline, using the water level as the beam shutter (Section 3.1.4). The experiment station sits atop an optical table, and includes a safety enclosure, motor stages, and associated electronics (Section 3.3). The imager is a neutron-sensitive, multi-channel plate detector with direct-readout capabilities (Section 3.4). A computer workstation remotely controls the gas pressure hardware, the sample and imager stages, and the detector (Section 3.5). All subsystems are designed based on detailed hand and/or computer calculations as described in the following sections.

3.1 Neutron Beamline

While many research reactors were constructed with beam port facilities, Mark-I TRIGA reactors such as the GSTR have no existing beam ports. The addition of a new beamline facility at a nuclear reactor involves significant design, engineering, and safety challenges which must be addressed prior to installation of a new facility. The retrofitting of a beamline to an existing facility requires unique subsystems and design considerations. This section describes the design approach for the new beamline facility at the GSTR.

3.1.1 Beamline Design and Control

The first items to determine when designing a neutron beam facility are its intended purpose and where in the facility it will be installed. The primary purpose of the new neutron beam is neutron radiography, which, in addition to a relatively large and massive beamstop, requires a space for experimental setups. As a result of the limited space in the GSTR reactor bay, the new facility has to occupy a minimal footprint and be as unobtrusive to existing operations as possible.
Excavation in the basement of the GSTR facility for installation of a horizontal neutron beam, similar to beamlines at most other research reactors, is not a viable option. Instead, the beamline consists of an aluminum tube routing from near the GSTR core to the reactor bay near the reactor tank. Several locations in the reactor bay were options for the experimental-end of the beamline. Vibration characterization of the GSTR facility determined that the subfloor beneath the reactor safety grates has the lowest level of vibrational noise, which could become important for some experiments that may use the beam. For these reasons, the experimental enclosure for the new beamline is located at the southwest corner of the reactor safety grates and secured to the concrete subfloor (Figure 3.1).

Figure 3.1 shows a schematic of the GSTR and the new neutron beamline facility. The GSTR core sits at the bottom of a 231 cm (91 in) diameter, 757 cm (298 in) tall stainless steel tank with ~6.1 m (20 ft) of water above the top of the reactor core (United States Geological Survey, 2010). A lazy susan located around the top of the core (Figure 3.1) serves as an irradiation facility capable of holding several samples at a time, rotating them around the reactor during exposure to achieve uniform exposure for each sample (United States Geological Survey, 2010). Safety grates above the top of the tank allow personnel to work above the tank and also lock to prevent access beneath the grates. Safety grates are also located beneath the surface-section of the beamline facility, but they are absent from Figure 3.1 in order to show the lower section of the experiment enclosure support frame. The tank is surrounded by ~91 cm (~3 ft) of concrete, and the facility floor is also concrete. The area beneath the grates is ~3 m (117 in) square with ~46 cm (18 in) between the top of the grates and the concrete subfloor around the tank. The grates are often unlocked and opened for routine work, and the beamline facility does not prohibit access to areas that may need to be accessed on a regular basis. The new facility is also easily removable to allow for fuel manipulation and other major activities.

The experiment station sits on a vibrationally isolated optical table. The optical table frame consists of two parts. The lower frame is mounted to the concrete subfloor and is level with the safety grates so that the walking surface is flat when the facility is removed. The upper frame mounts directly to the lower frame. Three air cushions reduce vibrations to the optical table, which is connected to the upper frame by these isolators (Figure 3.1). The optical table top can rotate to accommodate different beamline locations, and, if a future user wanted to move the source-end of the beamline, the table could rotate to accommodate that beamline.
Figure 3.1. Cut-away view of the GSTR and radiography facility.
The beamline enters the experiment enclosure through a slot cut in the optical table top. An enclosure prevents access to the experiment station when the beamline is open (Figure 3.1). A neutron beamstop mounts to the top of the enclosure and is tilted to match the angle of the neutron beam. The beamstop is centered on the beamline using a laser attached to an aluminum sleeve that fits over the end of the beam tube.

The beamline operators must be able to remotely open and close the neutron beam. Typically, a neutron beam shutter consists of a block of shielding material that can be remotely positioned to obstruct the beam. The new neutron beam facility at the GSTR differs from this typical shutter design. The new beam tube is an aluminum pipe that is sealed at the top and open at the source-end. The beam is normally filled with water, which prevents neutrons from traveling to the experiment enclosure. When the beam tube is pressurized with helium gas, the water is evacuated and neutrons are able to travel through the beam tube. Thus, the water in the beam tube acts as the neutron shutter and adjusting the helium pressure within the beam tube controls the state of the beam.

The beam source location near the reactor determines the majority of the beamline properties, including energy spectrum, gamma content, and beam intensity; thus, careful selection of beam source location is an important early step of beamline design, which is discussed in detail for the new beamline in the following subsection.

3.1.2 Selection of the Beamline Source Location

The beam source location near the reactor determines the majority of the beamline properties, including energy spectrum, gamma content, and beam intensity. Generally, neutron intensity increases with proximity to the center of the reactor, where the neutron flux is the most intense; however, thermal neutrons are often preferred for neutron radiography, and the thermal-to-fast neutron ratio is lower near a reactor core than at its periphery. At the GSTR, a graphite reflector and the surrounding water moderate fast neutrons leaving the core, making locations outside the reflector desirable for a thermal neutron beam. Gamma contamination of the neutron beam is not desirable, since it both increases the dose at the surface and creates noise for some neutron imaging techniques. Most of the gamma radiation from the reactor is produced in the reactor core, and beamlines that have a direct line of sight to the core have higher gamma radiation contents. To avoid this, neutron beamlines are often placed tangential to the reactor core.
A placement study evaluated potential beam source locations using an existing detailed Monte-Carlo N-Particle (MCNP) model of the GSTR core and surrounding tank (Table 3.1) (Shugart and King, 2012). Potential source locations included the central thimble, in place of a fuel rod, above the fuel, above the reflector next to the lazy susan (far-side, near-side, and tangential), and tangent to the reflector (see Figure 3.2 and Table 3.1). The central thimble is an irradiation facility consisting of a stainless steel tube that routs vertically from the surface of the reactor bay to the center of the reactor core, which is the location of the highest neutron flux within the reactor core. While this facility is commonly used for neutron activation experiments, it could potentially be pressurized with helium and used as a neutron beam. The model for the central thimble model includes the reactor and central thimble tube filled with helium, with a flux tally at the surface-end of the central thimble tube. Each source location other than the central thimble is marked with letters A-G in Figure 3.2.

Figure 3.2. Potential beamline source locations.
thimble included an aluminum tube routed from the source location to the same point at the surface of the reactor tank. The beam tube models for each location other than the central thimble consisted of an aluminum tube, 5.08 cm (2 in) in outer diameter and 3.81 cm (1.5 in) in inner diameter. The beam tube was open at the bottom end and filled with pressurized helium. The material definitions in the models used the ENDF B-VI (.66c) cross-section libraries. Where available, the material definitions included the S(α,β) inelastic scattering cross-sections. The number of particles in each run was adjusted to provide standard deviations (σ) below 3% in each case. Table 3.1 describes the predicted beamline parameters for the beamline source locations shown in Figure 3.2.

The central thimble source location resulted in the highest thermal (E<1 eV) neutron flux (2.4*10^7 n/cm²-s) and highest total flux (6.1*10^7 n/cm²-s), but had the lowest thermal neutron ratio. This high neutron flux makes the central thimble an attractive location for a neutron beam; however, the central thimble is one of the most frequently used facilities for sample irradiation at the GSTR. Since one of the design goals of the facility is to be as least obtrusive as possible, other beamline options were more desirable for semi-permanent use.

Another location considered, which is similar to the central thimble in that the source is located within the reactor core, is a beamline source that replaces a fuel pin position. In this case, the modeled beamline produces the second highest total neutron flux of the locations considered (2.4*10^7 n/cm²-s) and a slightly better thermal neutron ratio than the central thimble, but had a relatively low thermal neutron ratio. The beamline tangent to the reflector produced the highest thermal neutron ratio (9.7), but one of the lowest overall neutron fluxes (1.8*10^6 n/cm²-s). The
neutron beams above the reflector near the lazy susan produce a good balance of properties. A beam at the far-side of the lazy susan would route too close to the control rod drives, which could produce safety concerns that would be avoided by using another source location.

Based on the model results, the source end of the new beamline is currently located tangent to the lazy susan (location D in Figure 3.2). This location yields high predicted thermal and total neutron fluxes \((3.2 \times 10^6 \text{ n/cm}^2\cdot\text{s} \text{ and } 4.6 \times 10^6 \text{ n/cm}^2\cdot\text{s}, \text{ respectively})\). The predicted thermal neutron ratio (2.3) is comparable to the other locations near the lazy susan, and the predicted gamma content (0.23 mR/10^6 neutrons) is the second lowest of the locations considered.

3.1.3 **Installation of the Neutron Beamline**

Several pieces of custom equipment are required to install the beamline in the selected position. The weight of the beam tube sits on an all-aluminum structure that ultimately rests on the bottom of the reactor tank (Figure 3.3). The beamline support structure holds the beam tube just over the reflector and close to the lazy susan without contacting either (Figure 3.3). A triangular structure supports the reactor and is positioned 1-1/8” above the bottom of the tank. The base of the beamline support is 25 mm thick (just less than 1”) and slides under the triangular support to prevent the beamline support from tipping.

The beamline consists of two long (~12 ft) sections of aluminum tubing (1-1/2 in inner diameter with ¼ in thick walls) and one 4 ft section, connected by 2 in stainless steel Swagelok connectors. The unions experience significantly lower flux than inside the beam tube, and

![Figure 3.3. Beamline and the beamline support shown from under water (left) and from above (right).](image)
activation of the stainless steel is expected to be low. The beamline weighs ~40 lbs when full of water, and ~25 lbs when evacuated; the beamline does not float when pressurized.

The upper end of the beam tube clamps to the side of the tank to keep the beam tube in position. The water temperature increase during operation can result in ~1 cm of beam tube expansion, and the clamp holds the beam tube with a PTFE insert to accommodate this thermal expansion. A safety grate with openings for the beamline and optical table supports replaced the existing safety grates. Once the upper optical table support frame is installed, the safety grate under the table cannot be opened, and the replacement safety grate has a small access panel to allow access to the beamline clamp beneath the grates.

Once the experiment station and beamline are installed, several components adjust to align the beam and the beamstop. Alignment is accomplished using a laser mounted concentric with the neutron beam, which, after adjustment, should point to the center of the neutron beamstop. The optical table turns so that the neutron beam enters the center of the slot in the optical table top. The beamline direction is adjusted by moving the position of the clamp that attaches the beamline to the tank. The beamstop angle is adjusted to match the angle of the beamline and it is centered on the neutron beam.

After the first installation of the beamline, an initial radiation survey verified that the radiation dose levels resulting from the new facility were within expected and acceptable levels (see Appendix B, Section D). The radiation survey began with the reactor at 5 Wı and measured both neutron and gamma dose rates at different distances from the beamline, around the enclosure, and around the beamstop. The radiation survey repeated at incrementally increasing power levels up to 950 kWı, just below the 1 MWı rated power of the GSTR. The radiation survey determined that the dose rates were within expected and safe values at all reactor power levels. The beamstop effectively attenuates the beam, with the lowest dose rates in the survey measured behind the beamstop. The gamma dose rate in the beam measures ~33 mSv/hr (3.3 rem/h) at 950 kWı. An additional enclosure, added around the beam tube between the safety grates and the experiment enclosure, prevents access to the slightly elevated dose levels around the beam tube. The beamline takes ~1 minute to fully pressurize to ~58.6 kPa (8.5 psi). Since it takes only ~1 m of water in the beam tube to effectively close the neutron beam, the beam effectively closes ~ 1-2 s after power to the pressure system is cut.

Characterization of the neutron beamline is described in Chapter 5. A beamline requires a
beamstop to attenuate radiation from the beam and reduce radiation dose rates to the surrounding environment. The following section describes the design and construction of the beamstop for the new beamline.

3.1.4 Gas Pressure Control System

The neutron beamline is normally filled with water, which shields the neutron and gamma radiation. When the beamline is pressurized with helium gas, the water is evacuated and no longer provides shielding. Thus, the water level in the beam tube serves as the neutron shutter. A gas pressure control system remotely controls the gas pressure in the beamline to adjust water level in the beam tube. Figure 3.4 shows a schematic of the pressure control system hardware.

A pressure regulator reduces the helium reservoir pressure to \(\sim 690\) kPa (\(\sim 100\) psi). An electro-pressure regulator further reduces the gauge pressure to 0-103 kPa (0-15 psi). Two solenoid valves offer remote opening and venting of the beam, and two manual valves allow manual closing and venting of the beam (Figure 3.4). Additionally, the solenoid valves ensure the system cannot pressurize until the system is energized, and also provide automatic closing of the beamline if power is lost. A rupture disk prevents over-pressurization of the beam in the event of a regulator failure, and a pressure gauge allows nearby users to ascertain the pressure of the beam (Figure 3.4). High pressure tubing connects the pressure system to the top of the beam tube.

![Figure 3.4. Layout of the gas pressure control system.](image_url)
Filters remove any particulates coming from the beamline when the beamline pressure is vented.

A control program, developed using LabView™ (http://www.ni.com/labview) and installed on a control computer (described in Section 3.5), operates the electro-pressure regulator and solenoid valves. The electro-pressure regulator accepts a command voltage from the command program and adjusts the pressure accordingly. The regulator contains a relief valve to vent pressure if the command voltage requires a decrease in pressure. The user-friendly LabView interface allows the user to control and monitor the pressure remotely. Hardware interlocks prevent access to an open beamline by cutting power to the gas pressure control system if 1) any of the four doors to the experiment station are opened, 2) the beamline becomes misaligned, or 3) the beamstop becomes misaligned. Photo-switches provide a positive signal for beamline and beamstop alignment. If any interlock switch is opened, power to the pressure system is cut, and the system will not reenergize until all interlock switches are closed and a reset button is pressed.

### 3.2 Radiation Beamstop

A beamstop is required to attenuate both neutron and gamma radiation in the radiation beam to prevent excessive radiation exposure in the surrounding areas. Detailed descriptions of beamstop design in literature are sparse, and this section provides a detailed description of the design of the neutron beamstop constructed for the neutron beam facility at the GSTR.

Though a beamstop should be simple to design, there are a number of design considerations that make the design of a beamstop for the new beamline more complex than many other shielding applications. Because the beamstop mounts above the experimental enclosure, the beamstop must be as light-weight as possible. Simply filling a large drum with neutron absorbers would produce a beamstop that is too large and heavy to comfortably mount atop the experiment enclosure. Thus, the mass of the beamstop must be optimized for the specific application. Design considerations for the development of the beamstop include radiation beam properties (energy spectrum, geometric size, and flux magnitude), activation concerns, dose limits, material costs, structural requirements, and procedural requirements.

#### 3.2.1 Beamstop Modeling and Design

A beamstop consists of neutron- and gamma-attenuating materials (Shultis and Faw, 2008). The materials should strongly attenuate neutron and gamma radiation and be available at a
reasonable cost. In the beamstop for the new beamline, lead at the back-end of the beamstop attenuates gamma radiation and borated paraffin (a mixture of sodium borate decahydrate (Na₂B₄O₇·10H₂O), commonly called “borax”, and paraffin wax) fills the bulk of the beamstop and attenuates neutrons. Borax, a white powder, is mixed with paraffin, which acts as a binder. Borated paraffin has a high hydrogen concentration, which efficiently thermalizes neutrons, and a high boron content for absorption of thermal neutrons. Activation of the elemental components of borated paraffin (H, B, C, O, and Na) does not produce significant amounts of long-lived radionuclides (sodium has a ~15 hour half-life). Neutron transport studies and the physical properties of different mixtures of borax and paraffin determined the optimal mixture for the beamstop.

The beamstop design considered the dose rates resulting from a radiation beam using the central thimble, which provides a neutron flux nearly an order of magnitude greater than any of the other beamlines considered for the neutron imaging facility (Table 3.1). Dose scales proportionally to the incident flux, so the expected dose levels for the imaging facility beamline are significantly less than the calculated dose levels for the beamstop in the central thimble. Thus, the beamstop is designed to shield the highest-flux radiation beam that could be produced above the reactor.

A representative beamstop model developed in MCNP determined the radiation attenuation behavior of different compositions of borated paraffin. The beamstop model, shown in Figure 3.5, includes the aluminum grates, the water surface, concrete, a representative sample, and the beamstop. The central thimble is normally filled with water, but is the model replaces the water with helium to allow radiation to travel to the surface. Radiation from the reactor travels through the central thimble, an aluminum tube that routs from the center of the reactor to the surface above the grates.

The existing model of the GSTR (Shugart and King, 2012) calculated the gamma and neutron fluxes, energy spectra and angular distributions for the beamstop model. Each beamstop model iteration tracked 2,000,000 source particles distributed evenly over a disc source placed in the beam tube 10 cm beneath the surface of the water. Removing the reactor from the beamstop model was necessary to reduce computer runtime. Table 3.2 presents the calculated energy spectra and Table 3.3 presents the angular distributions relative to the central thimble. The azimuthal distribution is assumed to be uniform. The predicted neutron and gamma fluxes are
6.1*10^7 n/cm²-s and 6.5*10^7 γ/cm²-s, respectively. The material definitions in the model used ENDF B-VI (0.66c) neutron cross-section libraries at room temperature with photon physics (phys:p) and S(α,β) thermal scattering cross-section libraries applied where relevant and available. The MCNP model calculated dose rates using the ICRP-21 flux-to-dose conversion factors (X-5 Monte Carlo Team, 2005) with a standard deviation (σ) less than 1% in each case.

Figure 3.6 shows the predicted neutron dose rate just above a representative beamstop for different concentrations (wt%) of borax in paraffin. While the final beamstop design is different than the representative beamstop used to calculate the data in Figure 3.6, the figure indicates that radiation attenuation increases with increasing concentrations of borax. However, high porosity and lack of structural integrity make pure powdered borax unusable as a beamstop fill material. Thus, paraffin must be added to decrease porosity and act as a binder to provide structural integrity. The mixture must also be liquid enough when heated to enable pouring of the mixture into the aluminum can of the beamstop.
Samples created with 50, 60, 70 and 80 wt% borax in paraffin provided information on the material properties of the various mixtures, including porosity, durability, and pourability (Figure 3.7). To create each sample, a measured amount of paraffin was melted, an appropriate amount of borax added, and the mixture poured before it solidified. High borax content (>70 wt%) mixtures did not pour as liquid slurries, but more like malleable clumps. Because the mixture is not liquid, high borax concentrations resulted in high porosities even if the mixture was packed while still malleable. The 50 and 60 wt% borax samples had little porosity and poured well. All of the samples were durable and withstood multiple impacts, so no cracking is anticipated during the beamstop’s service life.

A leaching test on the 60:40 borax:paraffin sample determined if the water-soluble borax could be dissolved in the event that water were to enter the beamstop (i.e. if the beamstop were to fall into the reactor tank). To test this, the sample was weighed, submerged in water for four
hours, dried, and weighed again. The sample lost 0.5% of its mass, indicating that the paraffin effectively seals the borax, and prevents it from dissolving in water. Considering the neutronics calculations and the tests described, the 60:40 borax:paraffin mixture offered the best balance of properties for the beamstop fill material.

The US Nuclear Regulatory Commission defines a radiation area as an area, accessible to individuals, in which radiation levels could result in an individual receiving a dose equivalent in
excess of 50 µSv (5 mrem) in 1 hour at 30 centimeters from the radiation source or from any surface that the radiation penetrates (10 CFR 20). The reactor bay and the roof are already posted as radiation areas. For a conservative beamstop, a dose rate limit of 50 µSv/hr (5 mrem/hr) for the reactor bay ensures that the presence of the neutron beam would not result in posting changes in the reactor bay, which is already posted as a radiation area. The same goal was set for the roof, but was not a hard limit, since access to the roof is restricted and monitored by the reactor staff.

The beamstop reduces the dose rates resulting from the neutron beam behind the beamstop; however, because radiation scatters in the beamstop instead of passing through to the ceiling, the presence of the beamstop actually increases the radiation dose rate in the reactor bay. The radiation beam contains both neutrons and gamma rays from the reactor and neutrons also interact with the beamstop materials to produce secondary gammas, all of which contribute to the total dose rate in the reactor bay. With the materials determined, the beamstop dimensions were iterated until dose limits are met with a compact beamstop. Figure 3.8 shows the calculated dose rate profiles for the central thimble radiation beam for neutron, gamma, and secondary gamma radiation. Neutrons are significantly attenuated by the borated paraffin, but also provide the majority of the scattered dose rate in the reactor bay (Figure 3.8a). At 1 MWt, the gamma

![Figure 3.8](image)

a) neutron dose rate  b) primary gamma dose rate  c) secondary gamma dose rate

Figure 3.8. Calculated dose rate profiles for the final beamstop design above the central thimble at a reactor power level of 1 MWt.
radiation penetrates through the borated paraffin and is mostly attenuated by the lead backstop (Figure 3.8b). The secondary gamma production results from neutron interactions, and is mostly produced at the representative sample and the front end of the beamstop where the neutron flux is the highest (Figure 3.8c). Secondary gamma production does not contribute significantly to the dose rates in the surrounding areas.

3.2.2 Construction of the Beamstop

Figure 3.9 shows a cut-away view of the final beamstop design. The beamstop is 101.6 cm (40 in) long, 30.48 cm (12 in) OD, with four $5.08 \times 10.16 \times 20.32$ cm ($2 \times 4 \times 8$ in) lead bricks as a gamma backstop. A $10.16 \text{ cm (4 in)}$, $20.32 \text{ cm (8 in)}$ deep cavity at the fore end of the beamstop reduces the dose rate within the reactor bay from scattered radiation (see Figure 3.8 and Figure 3.9). The lead bricks have a thin milled lip and are arranged such that there is no streaming path between the bricks. A steel lifting support at the back-end of the beamstop distributes the weight of the beamstop to four eyebolts; the neutron flux at the back-end of the beamstop is
sufficiently low that activation of the steel should be negligible. A cadmium sheet attached over the front of the cavity reduces backscatter that would produce noise in neutron images (see Figure 3.9), and an aluminum cover plate prevents access to the cadmium, which is toxic and carcinogenic. The steel lifting support and cadmium sheet were not included in the neutronics model from the previous section, but would further reduce the dose rates. The lower brim is 45.72 cm (18 in) in outer diameter (OD) and clamps firmly to the top of the experiment enclosure. The outer can for this beamstop is made of aluminum and is 6.35 mm (⅛ in.) thick with a 12.7 mm (½ in.) thick lower brim. Aluminum is a common structural material for near-core nuclear applications, as it has a low cross-section for neutrons and does not remain activated for long (T½ = 2.25 minutes).

The calculated dose rate in the reactor bay 1 m from the beamline is 47.5 μSv/hr (4.75 mrem/hr) from a beam produced using the central thimble with a reactor power of 1 MWt. The dose rate on the roof is 100 μSv/hr from the same beam. However, the expected fluxes for the beamline chosen for the neutron imaging facility are nearly an order of magnitude less than those expected from the central thimble beam, so the predicted dose rates are likewise proportionally lower.

Filling the beamstop with borated paraffin required approximately forty 1.5 kg batches consisting of 0.9 kg borax and 0.6 kg melted paraffin. An electric heater attached around the beamstop during pouring kept the mixture melted so that each pour bonded to the previous pour; this prevented voids between the layers of borated paraffin and provided reasonable homogeneity in the fill material. The final beamstop weighs 140.6 kg (310 lbs) and mounts to an aluminum support structure atop the optical table.

3.3 Experiment Station

An experiment station houses any experiment equipment that is exposed to the neutron beam. The beamline enters the experiment station through a slot in an optical table, and the beamstop mounts on top of a safety enclosure.

3.3.1 Optical Table and Vibration Isolation

An optical table provides a work surface for experiments using the neutron beam. The optical table upper support mounts to a lower support that anchors to the concrete subfloor (see
Figure 3.10). Holes cut into the safety grates allow the upper flange of the lower support to penetrate through and sit flush with the grates. The breadboard can rotate ~30° around the beamline, accommodating beamlines originating from different positions near the reactor.

Vibrations experienced by the imaging and sample stages could ultimately reduce the quality of the neutron image. Vibration characterization of the facility determined the location in the reactor bay with the lowest level of vibration for placement of the optical table. The characterization found that the concrete subfloor under the safety grates at the southwest corner of

Figure 3.10. Schematic of the optical table layout.
the reactor tank had, by far, the lowest vibrations.

The 10 cm thick optical table top spans 100 cm by 125 cm with a 50 cm by 15 cm cutout to accommodate experiments utilizing the neutron beam. The upper surfaces are stainless steel with a 25 mm square array of M6x1.0 taps to mount experimental components. The table mounts to passive vibration isolators, which are located on top of the upper frame and support the weight of the tabletop (118 kg, 260 lbs).

3.3.2 Experiment Enclosure

Safety is an important consideration throughout the design, development, and construction of the new facility. The facility includes safety hardware, and administrative and procedural safety features. This section summarizes these considerations.

One of the primary safety concerns is excessive radiation exposure to personnel, primarily from the new neutron beamline. The beamstop, previously discussed in Section 3.2, reduces radiation dose levels to the surrounding areas to well below target limits of 5 mrem/hr. The enclosure around the experimental station prevents personnel from accessing experiments while the beamline is open, and procedures also require verification that the beamline is closed before accessing the beamline.

Figure 3.11 shows the experiment station in the reactor bay. The experiment station sits on a vibrationally isolated optical table, and is controlled as a high radiation area. The beam tube penetrates through the grates and enters the experiment enclosure through a slot in the optical table top (Figure 3.11). A lower beamline enclosure prevents access to the section of the beam tube beneath the optical table, where there are slightly elevated dose rates (Figure 3.11). The experiment enclosure mounted to the optical table prevents access to the experiment station when the beamline is open (Figure 3.11). Four doors (two on each side of the enclosure) allow access to the enclosed area.

Snap-acting switches on each enclosure door determine if any one of the four doors has been accessed, and photo-switches mounted from the optical table to the beamstop and beamline determine if the beamstop or beamline have become misaligned. In any of these cases, the corresponding safety interlocks cut power to the gas pressure control system, venting the gas pressure in the beam tube and filling the beam tube with water, which closes the beam. An indicator light (Figure 3.11) provides a positive indication of the status of the beamline to the
reactor operator. The indicator light is off when the system is shut down. The light is green when the interlocks are engaged, the beam is not pressurized, and the beam is ready to be opened. The red light illuminates when the beamline becomes pressurized, which is determined by a pressure switch directly attached to the beam tube.

The interlocks are tested before operation of the facility per facility procedures (Appendix B, Section E). Appendix D shows a circuit diagram for the interlock system. If any interlock switch is opened, power to the pressure system is cut. The interlocks will not reenergize until all interlock switches are closed and a system-reset button is pressed.

Experiments using the neutron beamline are placed in the experimental enclosure before
the beam is opened. The optical table allows quick and simple installation and removal of experiments, which can be set up and mounted to a breadboard, and then mounted onto the optical table top. In Figure 3.11, the neutron radiography facility is installed within the experiment enclosure, the neutron beam is open, and the detector is acquiring digital radiographs.

The first time a new beamline is installed, or is installed after being removed, a radiation survey performed with the beam open determines if the resulting radiation areas are within expected values and if additional interlocks, postings, and safety systems are required. A number of the large/heavy components of the new facility could cause damage if they fall. When installing heavy items (e.g. the beamline, the optical table, or the beamstop), safety lines will be used when possible to prevent these items from falling into the reactor pool, at least two persons will be present, and the overhead crane will be used when practical. There will be no assembly or disassembly of the optical tabletop, beamstop, or beamline during reactor operation; however, experimental components may be assembled/disassembled during reactor operation. The beamstop is secured to a rigid structure (principally the overhead crane) by a safety chain to prevent the beamstop from falling toward the reactor if it becomes disconnected from the support structure.

The beamline rests on a beamline support at the bottom of the tank, and is clamped to the side of the tank at the surface. The beamline stability is tested after initial installation while the reactor is shut down by pressurizing the beamline with the coolant pumps both on and off.

An unreviewed safety question analysis resulted in the 10 CFR 50.59 Unreviewed Safety Question (USQ) document in Appendix C. The analysis included a variety of postulated safety accident scenarios in order to determine if the addition of this new facility produced a USQ. Accident scenario categories considered in the analysis included damage to the core or safety systems, loss of coolant flow, reactivity insertions, excessive radiation exposure due to experimental malfunction, and small objects falling into the reactor pool. The analysis found that all postulated scenarios were either bounded by existing analyses in the Safety Analysis Report (SAR) or did not produce a safety concern. No change was needed to the Technical Specifications (United States Geological Survey, 2010), Safety Analysis Report (United States Geological Survey, 2009), or facility procedures described in the SAR. The new facility does not result in an unreviewed safety question because it does not satisfy any of the circumstances from 10 CFR 50.59(c)(2) (Nuclear Regulatory Commission, 2007).
3.3.3 **Motorized Sample Stage**

Experiments using the neutron imaging facility mount to the optical table. Because the neutron beamline is angled, neutron imaging experiments mount to a separate bench plate that matches the angle of the neutron beam (Figure 3.12).

The sample stages have 150 mm (~6 in) of motorized translation available in the X- and Y-directions perpendicular to the neutron beam and 50 mm (~2 in) of manual translation in Z-direction, along the beam axis (Figure 3.12). The manual (non-motorized) translation in the Z-direction prevents an operator from remotely moving a sample into the detector, which could damage the detector. Before imaging, the sample is mounted to the stage and manually raised in the Z-direction close to the detector, since decreasing the sample-to-detector distance improves image quality. If remote manipulation of the sample in the Z-direction is required, one of the stepper motor drives could replace the manual drive; however, care should be taken not to collide the sample with any other hardware. A motorized rotation stage provides the ability to remotely rotate the sample (Figure 3.13). This stage allows an operator to take images of the same sample at different angles perpendicular to the neutron beam, which is required for computed tomography.

![Figure 3.12. Angled bench plate for imaging experiments.](image-url)
3.4 Neutron-Sensitive Multi-Channel Plate Detector

The detector for the neutron imaging system at the GSTR consists of two coupled multi-channel plates provided by Nova Scientific. Section 2.5.3 includes a discussion of multi-channel plates and how they work. Neutron sensitive micro-channel plates (MCPs) can serve as imagers for dynamic neutron radioscopy (Cao et al., 2006). Originally developed as a high-resolution electron amplification element for image intensification devices, MCPs are directly sensitive to charged particles and high-energy photons (Wiza, 1979). High-efficiency, neutron-sensitive multi-channel plates capable of real-time neutron imaging provide some significant advantages over many other neutron radiography technologies, with high spatial resolution (~10-15 µm) and rapid neutron timing resolution (~1 µs) that enable real-time high speed dynamic evaluation (Tremsin et al., 2011).

Microchannel plates are the same technology used in night-vision applications; in order to use a microchannel plate for neutron imaging, a converter must be included in the MCP that
converts neutrons into an electron signal (Tremsin et al., 2011). The converter can be placed as a layer on the front-end of the MCP or incorporated into the bulk material of the plate. Incorporating the absorber into the plate increases the chance that the resulting charged particles will promote secondary electrons in one or more channels (Fraser and Pearson, 1990).

Figure 3.14 depicts a qualitative schematic of a neutron-sensitive multi-channel plate showing a neutron interacting with an absorber in the bulk material of the plate to produce an electronic signal. The multi-channel plate contains an array of micro-channels (~10 μm, with a wall thickness on the order of a few microns) and consists of glass doped with an absorber (e.g. $^{10}$B, $^6$Li, or Gd), making the MCP neutron sensitive (Tremsin et al., 2009). As shown in Figure 3.14, when an incident neutron is absorbed by $^{10}$B, the $^{10}$B(n,$\alpha$)$^7$Li capture conversion process for thermal neutrons yields short-range charged particles, which in turn create free secondary electrons in the adjacent microchannel (Cao and Biegalski, 2007). Electrodes are deposited on the front and rear face of the MCP. When a bias voltage (~1-2 kV) is applied, the MCP acts as an electron multiplier, amplifying the resulting electron signal as much as $10^6$ into a detectable signal (Cao and Biegalski, 2007). Imaging hardware then registers the burst of electrons emitted from the channels and constructs a digital image.

The detector for the MINER facility, developed and constructed by NOVA Scientific, consists of two separate MCPs coupled together (see Figure 3.15). The boron- and gadolinium-
doped microchannel plates in the detector are 0.8 mm thick and 32.75 mm in outer diameter, with a hexagonal array of 8.5 \( \mu \)m OD channels with an 11 \( \mu \)m pitch. When energized, the plates have a bias voltage of -1500 V and -2000 V across the first and second plates, respectively (see Figure 3.15). Neutrons interact with the boron and gadolinium in the bulk plate material and produce electrons, which cascade down the micro-channels toward an anode readout system with a bias voltage of +400 V (see Figure 3.15).

The detector is contained within an air-tight stainless steel casing, and turbo and ion pumps hold the detector under a vacuum of \( \sim 10^{-4} \) Pa (\( \sim 10^{-6} \) mbar) during operation. The detector is theoretically capable of producing radiographs with pixel size of \( \sim 33 \) \( \mu \)m, but in practice the spatial resolution of the detector is limited to around 50 \( \mu \)m when well-tuned, which largely depends on beam properties and detector integration time.

A breadboard holds the detector perpendicular to the neutron beam within the experiment enclosure. Stepper motor stages attached to the detector allow for 50 mm of translation perpendicular to the neutron beam, which allows users to remotely position the detector in the center of the neutron beam. Optical mounts position samples in front of the detector, on stepper stages that provide remote positioning covering a 150 mm square in front of the detector. The detector provides images that are \( \sim 25 \) mm diameter; acquiring radiographs of samples larger than 25 mm diameter is made possible by remotely moving the sample position in front of the detector and subsequently combining multiple images of the sample. A nano-rotation stage allows users to remotely rotate the sample, which also allows for acquisition of images at multiple angles and in order to enable tomographic reconstruction.

In addition to the digital MCP system, the new facility is also capable of producing neutron radiographs with the transfer method, which is described in Section 2.5.2. After

![Figure 3.15. Qualitative schematic of a two-plate detector.](image-url)
irradiation, the foil is taken to a dark-room where the activated foil is mated to an x-ray film (such as Kodak Industrex T200 industrial radiography film), exposing the film according to the activity pattern of the activated foil. Following exposure, development of the film takes place in a dark room, producing a neutron image of the object. The MINER facility uses both indium and dysprosium foils for transfer method neutron radiography, often in combination with cadmium foils to produce both a thermal and epithermal radiograph.

The transfer method offers possible resolution advantages over the MCP detector, but requires additional processing to produce a radiograph and is not capable of real time image acquisition. The following section provides some of the first radiographs taken by the MINER facility, and compares radiographs taken by the digital detector and the transfer method.

3.5 Computer Control System

A LabView computer program controls the gas pressure system and motor stages. The gas pressure system, described in Section 3.1.4 includes two solenoid valves (one normally open and another normally closed) and an electronic pressure regulator. The control program energizes the solenoid valves and provides a control signal to the pressure regulator. The control program also manages the movement of the motorized stages described in Section 3.3.3, including the two linear stages (X- and Y-directions) and the rotation stage.

Figure 3.16 shows the user-friendly front panel. Once the program is started, the motors come online, after which the pressure system is activated, which energizes the solenoid valves. The startup process takes about twenty seconds, as initializing the motors takes some time. Once started, the operator can then operate several functions simultaneously. The pressure can be adjusted by clicking the increase and decrease buttons, or by typing in the target pressure under the command pressure. The electro-pressure regulator has a pressure transducer that reads pressure of the system, which is shown as a monitor pressure on the front panel. The motor stages include a control program through their manufacturer, Thorlabs. This program is imported into LabView and integrated into the control program to create a single operator interface for the entire system.

Figure 3.17 details the program behind the front panel. The three motor controls are included at the top of the program, and they activate before the lower program series in the while loop. The lower contents of the program control the gas pressure control system. Figure 3.18
shows a writing diagram for the gas pressure control system. An analog out (ao0) is the proportional control voltage (0-10 VAC) to the electro-pressure regulator. The electro-pressure regulator is capable of a 0-15 psi pressure range, and the control voltage is proportional to the pressure, so the program in Figure 3.17 converts the command pressure to the appropriate voltage. Two digital outputs energize the solenoid valves (Figure 3.17). A 5 VDC command voltage from LabView energizes two solid-state relays, which control the power supply to the solenoid valves (Figure 3.18).

The last program series in the loop is an analog voltage input, which reads a proportional voltage from a pressure transducer integrated in the electro-pressure regulator. The LabView program converts the input voltage to the appropriate pressure for display (Figure 3.17). Once initialized, the commands are in a while loop, offering continuous operation by the user until the program is stopped. The while loop adjusts for user changes every 100 ms. The program can be stopped by either clicking on the STOP button on the control panel (Figure 3.16), or if an error is
read from any of the pressure control hardware (Figure 3.17).

The power supply to the solenoid valves and electro-pressure regulator routes through safety interlock switches at the radiography station (shown in Figure 3.19). These interlocks break the circuit to the pressure control system if deactivated, resulting in flooding of the beamline, which closes the neutron beam. An electrical box attached to a computer cart where the control computer is located encloses the electrical wiring (Figure 3.18). Three cables connect the computer cart to the gas pressure control system, and one cable connects the cart to the interlock switches in the experiment enclosure.

With the system installed, the facility is available for various experiments. An MCNP model of the neutron beam developed as part of this project provides users the ability to design experiments before putting materials in the neutron beam. The development of the MCNP model of the beamline is discussed in the following section.
Figure 3.17. LabView program for the computer control system.
Figure 3.18. Wiring diagram for the control components at the computer control workstation.
Figure 3.19. Interlock wiring diagram for equipment on at the experiment station.

A - momentary switch (DPDT)
B - latching relay (DPDT)
C - relay (SPST, NO)
D - relay (SPST, NC)
E - photo-switch (NO, beamstop)
F - photo-switch (NO, beamline)
G - plunger switch (NO, enclosure doors)
H - pressure switch (beamline)
I - red indicator light
J - green indicator light

NO - normally open
NC - normally closed
SPST - single pole single toggle
DPDT - double pole double toggle

24 VDC power supply

pressure system power supply at control station
CHAPTER 4
MCNP MODEL OF THE BEAMLINE

An MCNP model of the neutron beamline at the GSTR provides a research tool for experiment design and facility analysis. The detailed model of the GSTR used to select the beamline source location contains many components that do not significantly affect the beamline. The beamline model, discussed in this section and provided in Appendix A, contains only the components that most impact the beam, making the input deck easy to understand and simple for users to modify. Figure 4.1 details the beamline model geometry, which includes the aluminum beam tube, tank water, and beamstop. The neutron beam tube is 6061 aluminum alloy and is 5.08 cm (2 in) in outer diameter and 3.81 cm (1.5 in) in inner diameter.

The neutron source is defined as a disk source at the bottom end of the beam tube. An existing MCNP model of the GSTR (Shugart and King, 2012), modified to include the source-end of the neutron beamline, calculated the energy and angular distributions at 50 cm from the reactor end of the beam tube. These distributions form the basis for the source card in the beamline MCNP model. Figure 4.2 shows the calculated energy distribution with equal-lethargy bins, which take the shape typically expected for thermal research reactors. Table 4.1 and Table 4.2 list the normalized energy bin probabilities and the normalized probabilities for the source angular distribution, respectively. The assumed azimuthal distribution of the beam is uniform about the source disc, with the axis for the angular distribution collinear with the central axis of the beam tube.

The model runs in MCNP5 (X-5 Monte Carlo Team, 2005) and the material definitions in the input deck use the ENDF B-VII (.70c) cross-section libraries. Where available, the material cards include the ENDF B-VII $S(\alpha,\beta)$ inelastic scattering cross-sections. The number of particles is adjustable by the user depending on the desired standard deviation and runtime.

To be useful, the MCNP beamline model must be verified with experimental data to show how well the modeled calculations match experimental results. The following subsection discusses the experimental verification of the MCNP model and the determination of an appropriate denormalization factor.
Figure 4.1. MCNP model of the neutron beamline.
Figure 4.2. Calculated energy spectrum for the beamline MCNP model.
Table 4.1. Energy bin distribution for the beamline model source card.

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<tr>
<td>5.96E-5 - 1.12E-4</td>
<td>4.831E-3</td>
<td>0.0139</td>
</tr>
<tr>
<td>1.12E-4 - 2.11E-4</td>
<td>4.655E-3</td>
<td>0.0137</td>
</tr>
<tr>
<td>2.11E-4 - 3.98E-4</td>
<td>4.548E-3</td>
<td>0.0138</td>
</tr>
<tr>
<td>3.98E-4 - 7.50E-4</td>
<td>4.395E-3</td>
<td>0.0142</td>
</tr>
<tr>
<td>7.50E-4 - 1.41E-3</td>
<td>4.311E-3</td>
<td>0.0145</td>
</tr>
<tr>
<td>1.41E-3 - 2.66E-3</td>
<td>4.190E-3</td>
<td>0.0148</td>
</tr>
<tr>
<td>2.66E-3 - 5.01E-3</td>
<td>4.079E-3</td>
<td>0.0149</td>
</tr>
<tr>
<td>5.01E-3 - 9.44E-3</td>
<td>3.905E-3</td>
<td>0.015</td>
</tr>
<tr>
<td>9.44E-3 - 1.78E-2</td>
<td>3.887E-3</td>
<td>0.015</td>
</tr>
<tr>
<td>1.78E-2 - 3.35E-2</td>
<td>4.311E-3</td>
<td>0.0138</td>
</tr>
<tr>
<td>3.35E-2 - 6.31E-2</td>
<td>4.234E-3</td>
<td>0.0143</td>
</tr>
<tr>
<td>6.31E-2 - 1.19E-1</td>
<td>4.420E-3</td>
<td>0.0127</td>
</tr>
<tr>
<td>1.19E-1 - 2.24E-1</td>
<td>4.975E-3</td>
<td>0.011</td>
</tr>
<tr>
<td>2.24E-1 - 4.22E-1</td>
<td>6.987E-3</td>
<td>0.0102</td>
</tr>
<tr>
<td>4.22E-1 - 7.94E-1</td>
<td>8.767E-3</td>
<td>0.0089</td>
</tr>
<tr>
<td>7.94E-1 - 1.50E+0</td>
<td>1.007E-2</td>
<td>0.0086</td>
</tr>
<tr>
<td>1.50E+0 - 2.82E+0</td>
<td>1.018E-2</td>
<td>0.0093</td>
</tr>
<tr>
<td>2.82E+0 - 5.31E+0</td>
<td>5.620E-3</td>
<td>0.0131</td>
</tr>
<tr>
<td>5.31E+0 - 1.00E+1</td>
<td>1.576E-3</td>
<td>0.0286</td>
</tr>
</tbody>
</table>
4.1 Experimental Verification of the Beamline Model

Multi-foil activations experimentally test the calculated energy spectrum for the beamline model. Table 4.3 lists the foils used for the verification experiments, along with the reactions of interest. A stack of foils (Cu, Au, MnCu, Dy and In, in this order) were placed at the end of the beamline with the copper closest to the reactor and irradiated for one hour with the reactor at 950 kW. After activation, the foil activity at the end of irradiation was measured for each foil using calibrated HPGe detectors. The experiment was repeated with a second stack of the five bare foils. Two stacks of four cadmium-covered foils (Cu, Au, MnCu and In, in this order) were also irradiated for two hours. The activity of each foil (listed in Table 4.5) at the end of irradiation, $A(t)$, is predicted by Equation 4.1 (Shultis and Faw, 2008).

$$A(t) = \frac{mN_A}{M} \sigma \varphi \left( 1 - e^{-\lambda t} \right)$$

(4.1)

### Table 4.2. Angular distribution for the beamline model source card.

<table>
<thead>
<tr>
<th>angle range (degrees)</th>
<th>normalized probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 0.2</td>
<td>1.461E-2</td>
</tr>
<tr>
<td>0.2 - 0.5</td>
<td>6.638E-2</td>
</tr>
<tr>
<td>0.5 - 1.0</td>
<td>2.240E-1</td>
</tr>
<tr>
<td>1.0 - 2.0</td>
<td>4.179E-1</td>
</tr>
<tr>
<td>2.0 - 5.0</td>
<td>1.322E-1</td>
</tr>
<tr>
<td>5.0 - 180</td>
<td>1.449E-1</td>
</tr>
</tbody>
</table>

### Table 4.3. Activation foils for verification experiments.

<table>
<thead>
<tr>
<th>foil</th>
<th>reaction of interest</th>
<th>half-life of radionuclide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>$^{63}$Cu(n,γ)$^{64}$Cu</td>
<td>12.7 h</td>
</tr>
<tr>
<td>Au</td>
<td>$^{197}$Au(n,γ)$^{198}$Au</td>
<td>2.7 d</td>
</tr>
<tr>
<td>MnCu</td>
<td>$^{55}$Mn(n,γ)$^{56}$Mn</td>
<td>2.58 h</td>
</tr>
<tr>
<td>Dy</td>
<td>$^{164}$Dy(n,γ)$^{164}$Dy</td>
<td>2.33 h</td>
</tr>
<tr>
<td>In</td>
<td>$^{115}$In(n,γ)$^{116}$In</td>
<td>54.2 m</td>
</tr>
</tbody>
</table>
Instead of using published thermal cross-sections to calculate the activity of the experimental foils, it is more accurate to use continuous energy cross-sections integrated over the entire energy spectrum (American Society for Testing and Materials International, 2010). MCNP readily accomplishes this, since it uses continuous energy cross-section libraries. The flux tallies (Column-A in Table 4.4) calculated by MCNP are multiplied by the pertinent isotope’s absorption cross-section, $\sigma_a(E)$ (reaction 102 in ENDF B-VII), giving the reaction rate ($\sigma_a \cdot \varphi$) (X-5 Monte-Carlo Team, 2005). Table 4.4 shows this reaction rate (Column-B), and the resulting energy averaged cross-section (Column-C). Equation 4.2 calculates the experimentally determined average flux for each foil (Column-D) using the measured activity of each foil and the energy averaged cross-section (Column-C) in Table 4.4.

$$\varphi = \frac{A(t)M}{mN_A \sigma_a} \left(1 - e^{-\lambda t}\right)^{-1} \quad (4.2)$$

The stacks of foils are also modeled in the MCNP beamline model. MCNP calculates the flux and activation rate averaged over each of the foils, which are placed at the end of the modeled beamline in the same position and order as in the experiments. MCNP reports all flux and reaction rate results normalized to the number of source particles (neutrons in this case) tracked in the calculation. The "sp" in the units in Table 4.4 reflects this. A source particle rate (SPR), which is a scalar multiplier, denormalizes the flux tally result given by MCNP. The SPR for each foil (Column-E) is the experimentally-calculated flux (Column-D) divided by the normalized MCNP-calculated flux (Column-A). The average SPR determined by this method is $2.38 \times 10^8$ ($\pm 6.9 \times 10^7$) source particles (neutrons) per second (Table 4.4).

The normalized MCNP-calculated activities (using Equation 4.1) multiplied by the average SPR yield the calculated activities in Table 4.5, which also shows the experimentally measured activities for the bare and cadmium-covered foils. The activity of the cadmium-covered Cu-2 foil was below the measurement limits of the detector.

Figure 4.3 presents a plot of the experimentally measured and model-calculated activities. The model accurately predicts the activation of bare copper and dysprosium foils and cadmium-covered copper, gold and manganese-copper foils, while bare gold, manganese-copper, and indium are outliers. The low modeled activities of some of the bare foils compared to the higher
experimental values indicate that the modeled energy spectrum may be too hard. Increasing the thermal content of energy spectrum may better predict the experimental results.

To evaluate the accuracy of the model predictions, a chi-squared test determined how well the modeled results match the experimental data. This test shows with $\chi^2 = 0.71$ probability that the null hypothesis of independence can be rejected, and the differences between the modeled and experimental data occurred by chance rather than by real sources of error. Overall, the model reasonably predicts the experimental activities.

Table 4.4. Calculated fluxes, reaction rates, cross-sections, and source particle rate.

<table>
<thead>
<tr>
<th>foil</th>
<th>A (MCNP calculated flux)</th>
<th>B (MCNP calculated reaction rate)</th>
<th>C (MCNP calculated absorption cross-section)</th>
<th>D (Experimental activation flux)</th>
<th>E (Calculated source particle rate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu-1</td>
<td>1.18*10^2</td>
<td>2.65*10^2</td>
<td>2.25</td>
<td>2.77*10^6</td>
<td>2.35*10^8</td>
</tr>
<tr>
<td>Cu-2</td>
<td>1.18*10^2</td>
<td>2.65*10^2</td>
<td>2.25</td>
<td>4.08*10^6</td>
<td>3.47*10^8</td>
</tr>
<tr>
<td>Au-1</td>
<td>1.16*10^2</td>
<td>6.54*10^1</td>
<td>56.53</td>
<td>1.96*10^6</td>
<td>1.70*10^8</td>
</tr>
<tr>
<td>Au-2</td>
<td>1.16*10^2</td>
<td>6.54*10^1</td>
<td>56.53</td>
<td>2.11*10^6</td>
<td>1.82*10^8</td>
</tr>
<tr>
<td>MnCu-1</td>
<td>1.14*10^2</td>
<td>7.64*10^2</td>
<td>6.69</td>
<td>1.96*10^6</td>
<td>1.89*10^8</td>
</tr>
<tr>
<td>MnCu-2</td>
<td>1.14*10^2</td>
<td>7.64*10^2</td>
<td>6.69</td>
<td>2.02*10^6</td>
<td>1.77*10^8</td>
</tr>
<tr>
<td>Dy-1</td>
<td>1.11*10^2</td>
<td>1.35*10^1</td>
<td>1217.30</td>
<td>2.49*10^6</td>
<td>2.24*10^8</td>
</tr>
<tr>
<td>Dy-2</td>
<td>1.11*10^2</td>
<td>1.35*10^1</td>
<td>1217.30</td>
<td>2.25*10^6</td>
<td>2.02*10^8</td>
</tr>
<tr>
<td>In-1</td>
<td>1.02*10^2</td>
<td>1.16</td>
<td>113.52</td>
<td>1.07*10^6</td>
<td>1.05*10^8</td>
</tr>
<tr>
<td>In-2</td>
<td>1.02*10^2</td>
<td>1.16</td>
<td>113.52</td>
<td>1.12*10^6</td>
<td>1.10*10^8</td>
</tr>
</tbody>
</table>

average SPR (bare) = 1.94*10^8

<table>
<thead>
<tr>
<th>foil</th>
<th>A (MCNP calculated flux)</th>
<th>B (MCNP calculated reaction rate)</th>
<th>C (MCNP calculated absorption cross-section)</th>
<th>D (Experimental activation flux)</th>
<th>E (Calculated source particle rate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu-1</td>
<td>2.58*10^3</td>
<td>8.23*10^4</td>
<td>0.32</td>
<td>1.25*10^6</td>
<td>4.84*10^8</td>
</tr>
<tr>
<td>Cu-2</td>
<td>2.58*10^3</td>
<td>8.23*10^4</td>
<td>0.32</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Au-1</td>
<td>2.55*10^3</td>
<td>8.80*10^2</td>
<td>34.49</td>
<td>4.53*10^5</td>
<td>1.77*10^8</td>
</tr>
<tr>
<td>Au-2</td>
<td>2.55*10^3</td>
<td>8.80*10^2</td>
<td>34.49</td>
<td>5.96*10^5</td>
<td>2.33*10^8</td>
</tr>
<tr>
<td>MnCu-1</td>
<td>2.52*10^3</td>
<td>2.33*10^3</td>
<td>0.92</td>
<td>4.79*10^5</td>
<td>1.90*10^8</td>
</tr>
<tr>
<td>MnCu-2</td>
<td>2.52*10^3</td>
<td>2.33*10^3</td>
<td>0.92</td>
<td>2.07*10^6</td>
<td>8.21*10^8</td>
</tr>
<tr>
<td>In-1</td>
<td>2.41*10^3</td>
<td>1.15*10^1</td>
<td>47.91</td>
<td>2.38*10^5</td>
<td>9.87*10^7</td>
</tr>
<tr>
<td>In-2</td>
<td>2.41*10^3</td>
<td>1.15*10^1</td>
<td>47.91</td>
<td>2.42*10^5</td>
<td>1.00*10^8</td>
</tr>
</tbody>
</table>

average SPR (Cd-covered) = 3.01*10^8

average SPR (total) = 2.38*10^8
<table>
<thead>
<tr>
<th>foil</th>
<th>calculated activity [μCi]</th>
<th>relative uncertainty</th>
<th>measured activity [μCi]</th>
<th>relative uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu-1</td>
<td>8.70*10^{-3}</td>
<td>0.04%</td>
<td>8.59*10^{-3}</td>
<td>0.23%</td>
</tr>
<tr>
<td>Cu-2</td>
<td>8.85*10^{-3}</td>
<td>0.04%</td>
<td>1.29*10^{-2}</td>
<td>0.28%</td>
</tr>
<tr>
<td>Au-1</td>
<td>1.42*10^{-3}</td>
<td>0.07%</td>
<td>1.21*10^{-2}</td>
<td>0.08%</td>
</tr>
<tr>
<td>Au-2</td>
<td>1.41*10^{-3}</td>
<td>0.07%</td>
<td>1.29*10^{-2}</td>
<td>0.09%</td>
</tr>
<tr>
<td>MnCu-1</td>
<td>4.81*10^{-3}</td>
<td>0.04%</td>
<td>4.06*10^{-2}</td>
<td>0.20%</td>
</tr>
<tr>
<td>MnCu-2</td>
<td>4.85*10^{-3}</td>
<td>0.04%</td>
<td>3.84*10^{-2}</td>
<td>0.19%</td>
</tr>
<tr>
<td>Dy-1</td>
<td>7.41*10^{-1}</td>
<td>0.04%</td>
<td>7.01*10^{-1}</td>
<td>0.56%</td>
</tr>
<tr>
<td>Dy-2</td>
<td>7.46*10^{-1}</td>
<td>0.04%</td>
<td>6.37*10^{-1}</td>
<td>0.57%</td>
</tr>
<tr>
<td>In-1</td>
<td>5.64*10^{-1}</td>
<td>0.04%</td>
<td>2.15</td>
<td>5.10%</td>
</tr>
<tr>
<td>In-2</td>
<td>5.82*10^{-1}</td>
<td>0.04%</td>
<td>2.32</td>
<td>5.55%</td>
</tr>
<tr>
<td>Cu-1</td>
<td>5.26*10^{-4}</td>
<td>2.28%</td>
<td>1.07*10^{-3}</td>
<td>0.07%</td>
</tr>
<tr>
<td>Cu-2</td>
<td>5.35*10^{-4}</td>
<td>2.28%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Au-1</td>
<td>4.54*10^{-3}</td>
<td>1.45%</td>
<td>3.31*10^{-3}</td>
<td>0.02%</td>
</tr>
<tr>
<td>Au-2</td>
<td>4.57*10^{-3}</td>
<td>1.45%</td>
<td>4.34*10^{-3}</td>
<td>0.02%</td>
</tr>
<tr>
<td>MnCu-1</td>
<td>2.76*10^{-3}</td>
<td>0.23%</td>
<td>2.19*10^{-3}</td>
<td>0.01%</td>
</tr>
<tr>
<td>MnCu-2</td>
<td>2.78*10^{-3}</td>
<td>0.23%</td>
<td>9.55*10^{-3}</td>
<td>0.05%</td>
</tr>
<tr>
<td>In-1</td>
<td>7.36*10^{-1}</td>
<td>0.77%</td>
<td>3.05*10^{-1}</td>
<td>0.68%</td>
</tr>
<tr>
<td>In-2</td>
<td>7.14*10^{-1}</td>
<td>0.77%</td>
<td>3.01*10^{-1}</td>
<td>0.69%</td>
</tr>
</tbody>
</table>

* based on the total average source particle rate calculated using the data in Table 4.4
Figure 4.3. Comparison of experimental and modeled foil activation data.
CHAPTER 5
CHARACTERIZATION AND DEMONSTRATION OF THE NEW FACILITY

The following section describes the characterization of the new neutron beamline, including the determination of the cadmium ratio, beam flux, and L/D ratio. The following section also details the demonstration of the new neutron radiography capabilities of the new facility, including a comparison between digital and transfer method radiography capabilities.

5.1 Characterization of the New Beamline

Some metrics for the quality of a neutron beam include the beam’s neutron flux intensity, cadmium ratio ($R_{Cd}$), and L/D ratio (Bossi et al., 2002). An MCNP model without any samples in the neutron beam calculates the neutron flux, using the total average SPR calculated in the previous section (the last line in Table 4.4), as $2.2 \times 10^6$ $n/cm^2\cdot s$ with standard deviation ($\sigma$) of less than a 1%. The cadmium ratio is determined using the measured foil activation data in Table 4.5 by taking the ratio of bare activity to cadmium-covered activity for each foil (American Society for Testing and Materials International, 2010). The average cadmium ratio for all foils is $R_{Cd,avg} \approx 7.4$ (using Au, Cu, MnCu and In). Individually, the cadmium ratios for each foil material are $R_{Cd,Cu}=8.0$, $R_{Cd,Au}=3.3$, $R_{Cd,MnCu}=11.2$ and $R_{Cd,In}=7.4$.

The L/D ratio of a neutron beam is a numerical measure of the geometry of the neutron beam (American Society for Testing and Materials International, 2008). The standard method for measuring the L/D of a neutron beam uses the “no umbra” (NU) technique, which radiographs a NU device and subsequently analyzes the radiograph to determine the point at which the umbra shadow width reaches zero (American Society for Testing and Materials International, 2008).

Figure 5.1 shows a diagram of the no umbra image location. The distance ($b$) between the object (a cadmium wire of diameter, $d$) and the detector when the umbra reaches zero are measured and applied in Equation 5.1 to determine the L/D of the neutron beam.

\[
\frac{L}{D} = \frac{b}{d}
\] (5.1)
The NU device is intended for film-radiography and contains multiple cadmium wires on an angled aluminum substrate such that one film radiograph contains data for multiple distances from the detector ($b$) (American Society for Testing and Materials International, 2008). Since the radiography system in this case is a digital radiography system capable of taking radiographs quickly compared to film radiography, it is not necessary to have multiple cadmium wires at various distances in the images. Also, the NU device is larger than the new neutron beam diameter. Thus, the measurement of the L/D of the new neutron beam does not use the ASTM Standard NU device, but rather a single cadmium wire that is remotely positioned at different distances from the detector.

Cadmium strongly absorbs neutrons, and the neutron flux at the detector is lower behind the cadmium than elsewhere in the image plane. As the cadmium wire moves away from the detector and the umbra width decreases, the shadow becomes lighter until the umbra reaches zero (as shown in Figure 5.1). The detector takes digital images of the cadmium wire at various distances between the detector and the cadmium wire and the 32-bit images are analyzed to produce gray value profiles across the wire. Figure 5.2 shows gray value profiles across a cadmium wire for various distances between the wire and detector. The gray value profiles for cadmium wires that are closer to the detector show a darker peak than for wires farther from the detector (Figure 5.2).

Figure 5.3 shows the average peak gray value for different values of $b$ (the distance from the wire to the detector plane) with a cadmium wire diameter ($d$) of 0.5 mm. The average peak grayscale value in Figure 5.3 is the average of the five darkest pixels (33 µm each in width) from the grayscale profile across cadmium wire (such as those shown in Figure 5.2). The L/D of the
neutron beam is the point at which the umbra reaches zero and the average peak grayscale value attains a maximum value. The average peak grayscale value levels off at $b = 100 \pm 5$, corresponding to a beam L/D ratio of $200 \pm 10$.

Figure 5.2. Image intensity profiles for various distances between the cadmium wire and the detector.

Figure 5.3. Peak intensity as a function of wire distance from the detector surface.
5.2 Demonstration of the New Neutron Radiography Capabilities

The potential quality of an image produced with a neutron beam can be determined by comparing an image of a test object with an image of a similar object that contains a known artificial discontinuity, a defect standard, or a reference standard (Bossi et al., 2002). In common practice, a resolution indicator developed by the American Society for Nondestructive Testing and Materials, often called a sensitivity indicator (SI), emulates defects of varying size, with gaps between and holes placed beneath different thicknesses of acrylic resin (American Society for Testing and Materials International, 2005). The SI is an aluminum u-channel filled with alternating strips of methylmethacrylate and aluminum, which are milled into steps (Figure 5.4). The aluminum strips (M-S) simulate gaps and range from 0.0254 cm (0.010 in) thick to 0.00127 cm (0.0005 in) thick (American Society for Testing and Materials International, 2005). There are four methylmethacrylate shims beneath the thicker methylmethacrylate steps, and holes in these shims (A-L) simulate defects and range from 0.508 cm (0.02 in) to 0.0127 cm (0.005 in) in diameter (Figure 5.4) (American Society for Testing and Materials International, 2005).

A radiograph of the SI is taken and the quantitative determination of the radiographic quality is determined by visually inspecting the SI for the number of visible simulated defects (holes and gaps) and assigning a numerical quality value to the facility (American Society for Testing and Materials International, 2005). Another ASTM standard uses a beam purity indicator.

---

Figure 5.4. Schematic of the sensitivity indicator.
(BPI) to produce information concerning the neutron beam and imaging system parameters that contribute to overall image quality (Domanus, 1986). Formulas given in the standard calculate neutron beam components using optical density measurements of a radiograph of the BPI (American Society for Testing and Materials International, 2005). These ASTM standards assign a category classification to allow users to compare radiography facilities.

Figure 5.5a shows a digital image taken by the MINER facility of a sensitivity indicator fabricated according to the ASTM standard, and Figure 5.5b displays a gray value profile taken from this image showing peaks corresponding to the thin aluminum shims in the SI. The digital image shown in Figure 5.5a is of poor quality and displays artifacts caused by the detector system. All of the foil gaps in the SI are easily apparent by visual inspection, and the gray value profile in Figure 5.5b the radiograph also shows those gaps; however, none of the holes in the SI are discernible by visual inspection. Previous studies have shown that the SI is insufficiently selective, as all of the gaps are usually visible, while the number of visible holes rarely exceeds four (Domanus, 1986). Figure 5.6a shows a second image of the SI taken by the MINER facility using the transfer method with a dysprosium foil. Figure 5.6b displays a gray value profile

Figure 5.5. Digital neutron radiograph of a sensitivity indicator and a corresponding gray value profile.
Figure 5.6. Neutron radiograph of a sensitivity indicator taken by the transfer method with a dysprosium foil and a corresponding gray value profiles.

showing the resulting peaks corresponding to the thin aluminum shims in the SI, and Figure 5.6c shows a gray value profile showing the holes.

Like the digital radiograph of the SI in Figure 5.5a, all of the shims, including the smallest 12.5 µm shim, are visible in Figure 5.6a. Also visible are six of the holes in the SI, identified by the white arrows in Figure 5.6a, which are not visible in the digital radiograph in Figure 5.5a. The additional features visible in the film radiograph, that are not visible in the digital radiograph, suggest that the image quality produced by the digital detector is limited by the detector itself and not by the neutron beam.

The most valid sensitivity indicator is a material or component, equivalent to the part being radiographed, with a known standard discontinuity, inclusion, omission, or flaw (known as a reference standard comparison part) (American Society for Testing and Materials International, 2005). The SI shown in Figure 5.6 and Figure 5.5 was designed by ASTM to substitute for a reference standard to provide qualitative information on hole and gap sensitivity (American Society for Testing and Materials International, 2005). An alternative reference standard
constructed by the Neutron Radiography Working Group (NRWG) provided an image quality indicator specifically for radiography of nuclear fuel (Domanus, 1989). The calibration fuel pin (CFP) designed by the NRWG contained standard discontinuities such as pellet-pellet and pellet-clad gaps and central voids within the pellets (Segal and Trichter, 1989).

Similar image quality indicators constructed for the current project provide a useful and interesting demonstration of the MINER facility and provide additional specimens for a comparison of radiographs produced at the facility by both digital and transfer method radiography. The calibration fuel pins constructed for this demonstration use surrogate materials for the fuel pellets. Figure 5.7 shows a schematic of the calibration pins, and Table 5.1 lists the

![Figure 5.7. Schematic of a calibration pin.](image)

<table>
<thead>
<tr>
<th>Pellet</th>
<th>Total length (A) [mm]</th>
<th>Shoulder length (B) [mm]</th>
<th>Void depth (C) [mm]</th>
<th>Full dia. diameter (D) [mm]</th>
<th>Reduced dia. diameter (E) [mm]</th>
<th>Void diameter (F) [mm]</th>
<th>Gap width (G) [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P0</td>
<td>8.0</td>
<td>N/A</td>
<td>N/A</td>
<td>7.8</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>P1</td>
<td>10.0</td>
<td>2.0</td>
<td>5.0</td>
<td>7.8</td>
<td>7.75</td>
<td>3.00</td>
<td>25</td>
</tr>
<tr>
<td>P2</td>
<td>10.0</td>
<td>2.0</td>
<td>5.0</td>
<td>7.8</td>
<td>7.70</td>
<td>2.75</td>
<td>50</td>
</tr>
<tr>
<td>P3</td>
<td>10.0</td>
<td>2.0</td>
<td>5.0</td>
<td>7.8</td>
<td>7.60</td>
<td>2.50</td>
<td>100</td>
</tr>
<tr>
<td>P4</td>
<td>10.0</td>
<td>2.0</td>
<td>5.0</td>
<td>7.8</td>
<td>7.50</td>
<td>2.25</td>
<td>150</td>
</tr>
<tr>
<td>P5</td>
<td>10.0</td>
<td>2.0</td>
<td>5.0</td>
<td>7.8</td>
<td>7.40</td>
<td>2.00</td>
<td>200</td>
</tr>
<tr>
<td>P6</td>
<td>10.0</td>
<td>2.0</td>
<td>5.0</td>
<td>7.8</td>
<td>7.20</td>
<td>1.75</td>
<td>300</td>
</tr>
<tr>
<td>P7</td>
<td>10.0</td>
<td>2.0</td>
<td>5.0</td>
<td>7.8</td>
<td>6.80</td>
<td>1.50</td>
<td>500</td>
</tr>
<tr>
<td>P8</td>
<td>8.0</td>
<td>N/A</td>
<td>N/A</td>
<td>7.8</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 5.1. Pellet dimensions for the calibration pin shown in Figure 5.7.
specified dimensions of the surrogate pellets.

One of the manufactured calibration pins contains stainless steel (304-SS) surrogate pellets and the other contains copper pellets. Each pin contains nine pellets of surrogate material. The two outer pellets (P0 and P8 in Figure 5.7) are simple cylinders, with no simulated defects. The other seven pellets (P1-P7 in Figure 5.7) contain simulated defects including central voids and pellet-clad gaps of known dimensions (see Table 5.1). Aluminum shims of different thickness (25, 50, 100, 150, 200, 250 and 300 µm for shims 1-7, respectively), located between the pellets, simulate gaps between the pellets. A steel spring holds the pellets in position within a 304-stainless steel cladding tube. The cladding tube is 7.825 mm in inner diameter and 9.525 mm in outer diameter with a 0.85 mm wall thickness. The total length of the calibration pin is ~120 mm, including the end caps.

Figure 5.8a shows a composite of multiple digital radiographs taken using the MCP and combined to form a complete image of the calibration pin containing copper pellets. Figure 5.9a shows a similar digital image of the pin containing stainless steel pellets. Figure 5.8b and Figure 5.9b present a gray value profile through the center of the corresponding pin. Some of the central voids, radial gaps and shims are visible by visual inspection and in the pixel intensity profiles, but the quality of the images produced by the MCP is low, and the intensity profiles contain a significant amount of noise. Additionally, the radiographs produced by the digital detector contain non-linearities, making straight specimens appear curved and distorted. It is nearly impossible to extract dimensional measurements from these digital images.

Figures 5.10 and 5.11 show radiographs and gray value profiles through the center of the pin of the copper-pellet and stainless steel calibration pins, respectively, obtained using the transfer method with a dysprosium foil. The film radiographs (Figures 5.10 and 5.11) provide significant detail compared to the digital radiographs (Figures 5.8 and 5.9). Inspection of the gray scale profiles reveals that the film radiographs provide significantly better image quality than the digital radiographs for both the copper pellet and stainless steel pellet calibration pins. The higher image quality of the film radiographs also makes it possible to discern a significant amount of flux tilting in the neutron beam that is obscured by the poor image quality of the digital radiographs.

Figures 5.12 and 5.13 provide a side-by-side comparison of the radiographs of the calibration pins containing copper and stainless steel pellets, respectively, using both the digital
detector (Figures 5.12a and 5.13a) and the transfer method (Figures 5.12b,c and 5.13b). Pellet-clad gaps are apparent in the film radiographs and are not shown in the digital radiographs. The central voids are apparent in the film radiographs, but are not easily discerned in the digital radiographs. The pellet-pellet gaps, while apparent in both the digital and film radiographs, are much sharper in the film radiographs.

Based on the images of the ASTM sensitivity indicator and the calibration fuel pins, the digital detector is not currently capable of producing quality radiographs. Since radiographs obtained using the transfer method are of reasonable quality, the image quality issues originate from the detector and not the neutron beam. Furthermore, the skewing and distortion of the images created by the image acquisition system most likely make it impossible to extract dimensional measurements from radiographs produced by the digital detector. Additionally, the problems with the digital detector preclude its use to obtain images for tomographic reconstruction, as the image quality problems would result in significant reconstruction artifacts.
Figure 5.8. Composite digital radiograph of the calibration pin with copper pellets and the corresponding gray value profile through the center of the pin.

a) Composite digital radiograph of the copper pellet calibration fuel pin.

b) Gray value profile through the center of the pin.
Figure 5.9. Composite digital radiograph of the calibration pin with stainless steel pellets and the corresponding gray value profile through the center of the pin.

a) Composite digital radiograph of the stainless steel calibration fuel pin.

b) Gray value profile through the center of the pin.
a) Transfer method radiographs of the calibration pin with copper pellets.

b) Gray value profile through the center of the pin.

Figure 5.10. Transfer method radiographs and gray value profiles of the calibration pin with copper pellets.
a) Transfer method radiograph of the calibration pin with stainless steel pellets.

b) Gray value profile through the center of the pin.

Figure 5.11. Transfer method radiograph and gray value profile of the calibration pin with stainless steel pellets.
Figure 5.12. Digital and transfer method radiographs of the calibration pin with copper pellets.
Figure 5.13. Digital and transfer method radiographs of the calibration pin with stainless steel pellets.
CHAPTER 6
SUMMARY AND CONCLUSIONS

The fleet of research and training reactors is aging, and no new research reactors are planned in the United States. Thus, there is a need to expand the capabilities of existing reactors to meet users’ needs. Adding new beamline facilities to existing research reactors is both rare and challenging, and represents a significant contribution to the nuclear science and engineering field. While many research reactors include beam port facilities, the original design of the United States Geological Survey TRIGA Reactor (GSTR) included no beam port facilities. The new Mines NEutron Radiography (MINER) facility installed at the United States Geological Survey TRIGA Reactor provides new capabilities for both researchers and students at the Colorado School of Mines. The facility consists of a number of components, including a neutron beamline, a beamstop, a gas pressure control system, an optical table, an experimental enclosure and safety interlocks, a computer control system, a multi-channel plate detector, and the associated electronics.

The new beamline facility at the GSTR includes a beamline control system, a neutron beamstop, and a neutronics model of the neutron beamline. The neutron beamline consists of a 5.08 cm (2 in) outer diameter, 3.81 cm (1.5 in) inner diameter 6061 aluminum alloy tube routed from above the reactor’s reflector to the surface of the reactor tank. Water normally floods the beam tube, which acts as a neutron shutter. A gas pressure control system pressurizes the beam tube with helium, which removes the water and opens the neutron beam. The neutron beam enters an experiment station, which is enclosed to prevent access to the open beam. A beamstop mounted above the enclosure attenuates the radiation beam. The neutron beamstop contains borated paraffin and lead to attenuate neutron and gamma radiation. Safety interlocks vent the helium pressure, and thus close the neutron beam, if the enclosure is accessed or if the beamstop or beam tube becomes misaligned.

The neutron beam source location, determined through neutronics modeling, provides the best mixture of high neutron flux, high thermal neutron content, and low gamma radiation content. Radiation surveys indicate that the dose levels in the reactor bay with the new beamline
and beamstop are within accepted limits.

An MCNP model of the neutron beam provides researchers with a tool for designing experiments before placing objects in the neutron beam. Experimental multi-foil activation results, compared to calculated multi-foil activation results, verify the model. The modeled and experimental activation results are in reasonable agreement with an 86.5% likelihood that the differences result from random error. The neutronics model predicts a neutron beamline flux of $2.2 \times 10^6 \pm 6.4 \times 10^5$ n/cm$^2$-s based on a source particle rate determined from the foil activation experiments when the reactor is operating at a power of 950 kW with the beam shutter fully open. The average cadmium ratio of the beamline is 7.4, based on copper, gold, manganese and indium foil activation data. The L/D of the neutron beam, calculated using a digital neutron radiography system and a single cadmium wire to produce an umbra, is approximately 200±10.

The experiment station mounts to an optical table positioned above the reactor tank. The neutron beamline routes from the reactor to the experiment station through a slot in the optical table. The enclosure and interlock system prevents access to the neutron beam while the beam is open. A multi-channel plate detector system provides direct digital readout in real time which forms a digital radiograph. A computer control station remotely operates the beamline facility, positions the sample using stepper stages, and controls the digital multi-channel plate detector.

Radiographs of an American Society for Testing and Materials sensitivity indicator taken using both the digital detector and the transfer method with dysprosium and indium foils provide a demonstration of the radiography capabilities of the MINER facility. A comparison of the radiographs taken by the two methods reveals that the digital detector produces lower quality images than the transfer foil method. Additionally, the image acquisition system produces a number of artifacts in the resulting digital images.

Calibration fuel pins manufactured using copper and stainless steel surrogate pellets provide a second demonstration of the new facility and a further comparison between digital and film radiography. The calibration pins contain simulated defects of known dimensions, including pellet-clad gaps, pellet-pellet gaps, and central voids within the pellets. Digital radiographs of the calibration pins are of poor quality, and do not provide the level of detail that the film radiographs provide. The problems with the digital images are a product of the digital imaging system and not the neutron beam. Additionally, the digital images contain non-linearities and distortions that likely prevent extraction of dimensional data and hinder qualitative evaluation of specimens.
CHAPTER 7
RECOMMENDATIONS FOR FUTURE WORK

There are a number of improvements that can be made to the neutron imaging facility. The new beamline created by this work is a first iteration beamline and could be improved significantly. This first beamline provides a path by which future beamlines and other radiation facilities could use the GSTR. Other improvements could include the imaging technology itself.

The current beam tube pressure readout comes from a pressure transducer in the electro-pressure regulator that is separated from the beam tube by ~20 ft of hose and other hardware. The pressure reading given to the operator while the pressure is increasing or decreasing does not reflect the actual pressure in the beam tube, as the pressure farther up the line lags behind the pressure in the tube. To improve this, a pressure transducer should be attached directly to the beamline, which would provide a more accurate pressure readout in LabView. While the electro-pressure regulator provides an accurate pressure reading during steady pressure, a pressure transducer attached to the beam tube next to the pressure switch would provide a more accurate pressure indication during pressure changes.

The open source-end of the beam tube allows the pressurizing gas to escape, bubbling out of the bottom of the beam tube if the pressure is too high. The beamline operator currently sets a pressure, and then visually examines the beamline to see if the pressure is too high, leading to gas bubbles coming out of the end of the beam tube. Not only does this design waste some gas, but it also yields an inconsistent water level within the beam tube. An upgraded beamline should include a dip tube that goes over the side of the reflector so that the operator could fully pressurize the beam tube without having to worry about releasing bubbles out the bottom. There are other mechanisms to accomplish this, but a dip tube is a simple and elegant solution.

It is apparent in the film images that the beam has a relatively significant amount of flux tilt. It is likely due to the large aperture (3.81 cm diameter) and the fact that the source is not uniform within the aperture. While this is likely the main cause, the extent of the flux tilt cannot be fully explained by this alone. To improve the flux tilt, the aperture diameter should be decreased. While this would decrease the beam intensity, it would also improve the already high
L/D ratio.

An upgraded beamline should also have an increased beam size. The aperture diameter should be decreased, but the beamline could increase in size further up the beam tube, such that the beam size at the experiment enclosure could be 100-150 mm in diameter. This would enable transfer-method radiography of larger samples. Increasing the beam size would require adjusting the beamstop cavity to accommodate the larger size beam and the addition of shielding material around the lower-end of the beamstop to make up for the removal of shielding material from the cavity. As an alternative, a second beamstop could be constructed. The section of this work describing the design of the beamstop should be helpful in this case.

Additional beamline improvements will almost always be possible. Single-crystal sapphires could be added to filter fast neutrons. A lead or bismuth filter could filter gamma content from the beam. The system is designed to accommodate other beam source locations near the reactor. The beam could be placed over the fuel and filtered with cadmium to create a fast neutron beam for fast neutron radiography. A cold neutron beam could be produced with a liquid helium system.

The central thimble could provide a neutron beam with significantly higher neutron flux than other beam locations. This could allow for real-time neutron radioscopy. This project considered using the central thimble for a neutron beam, but this was abandoned because the facility would sit over the center of the reactor grates, preventing them from being opened. The facility would have to be removed daily to access the grates for morning checks before operation. However, a more easily removable facility could be designed that would allow for routine operation using the central thimble and be easily removable with the overhead crane.

The beamline facility and associated control system has a relatively small footprint, especially compared to beam facilities at other reactors, which typically have a dedicated room for the facility. While the footprint is already small, it could be decreased, and some components could be removed from the reactor bay. The computer control system, which is currently in the reactor bay, should be moved or made remotely accessible from outside the reactor bay. This would decrease the dose received by the beamline operator who currently operates the beam from inside the reactor bay. However, the operator would still have to enter the reactor bay to adjust the sample object and other facility hardware before taking an image. If the control station is located outside the reactor bay, the operator would have to enter the bay to make such adjustments, which
would increase demand on the reactor staff to let them into the bay.

The digital multi-channel plate detector does not produce quality images. Other universities that have nearly the same detector from the same company have also had significant issues with this detector. These issues were not well known when the digital imaging technology was selected. In hindsight, a scintillation screen with a coupled camera would have been a better digital radiography system than the MCP. Improvements to the facility should include a better imaging system such as a scintillator/camera system, which would enable dynamic radioscopy. Other imaging technologies exist for radiography, such as phosphor screens. Foil and film transfer method radiography, while one of the first radiography methods developed, still has significant advantages, and this capability should be maintained.

A system for underwater radiographic examination of reactor fuel and control rods would provide useful knowledge to both the reactor staff and the academic community. Systems for underwater radiography have been created before. Such a system could be constructed that would fit within the GSTR tank, using aperture slits to increase the L/D of the beam. The source-end of the device would be located next to the reflector. Once in the tank, a fuel rod could be removed and placed into the device. Transfer foils would also be loaded into the device. Pressurization of the air-tight device would remove the water and allow neutrons to pass through the fuel element and activate the transfer foil. After exposure, the fuel would be placed back into the core and the activated transfer foils removed from the tank and taken to a dark room for film exposure. This process could be repeated several times a day, analyzing the entire fuel inventory in roughly two weeks.
REFERENCES


APPENDIX A – MCNP Model of the Neutron Beamline
This is the input deck for the MCNP model of the beamline described in Chapter 4 for the modeled activation of the activation foils. The model includes the activation foils at the end of the beam tube.

```
c Beamline Model 8/20/2012
c
c Cell Cards
c******************************************************************************
c--- multi-foil stack ---
11 11 -8.96 -10 -11 209 imp:n=1 imp:p=1 $ copper foil
12 12 -19.30 -10 11 -12 imp:n=1 imp:p=1 $ gold foil
13 13 -7.7076 -10 12 -13 imp:n=1 imp:p=1 $ Mn-Cu foil
14 14 -8.54 -10 13 -14 imp:n=1 imp:p=1 $ dysprosium foil
15 15 -7.31 -10 14 -15 imp:n=1 imp:p=1 $ indium foil
c
c--- beam tube ---
201 102 -2.7 200 -209 (210:208) -211 imp:n=1 imp:p=1 $ Al beam tube
202 104 -2.551e-4 200 -208 -210 imp:n=1 imp:p=1 $ He in beam tube
203 101 -1.0 -201 -220 290 (211:200) imp:n=1 imp:p=1 $ water
c
c--- beam stop ---
250 102 -2.7 251 -254 263 -265 imp:n=1 imp:p=1 $ Al brim
251 102 -2.7 (255:264) -252 254 -261 imp:n=1 imp:p=1 $ Al can
252 105 -11.34 -255 256 -271 272 -273 274 imp:n=0 imp:p=0 $ lead backstop
253 106 -1.2804 254 -255 -264 (253:262) (+256:
    271:272:273:274) imp:n=0 imp:p=0 $ borated paraffin
254 107 -8.65 -254 257 -263 imp:n=0 imp:p=0 $ Cd cover plate
255 102 -2.7 -257 258 -263 imp:n=1 imp:p=1 $ Al cover plate
256 103 -1.0467e-3 -253 254 -262 imp:n=1 imp:p=1 $ air in cavity
257 103 -1.0467e-3 251 -258 -263;252 254 261 -265 imp:n=1 imp:p=1 $ air around beamstop
c
c--- other ---
260 103 -1.0467e-3 201 -220 -291 (209:211)
    (252:265:251) (+209:10:15) imp:n=1 imp:p=1 $ air in bay
299 0 220:290:291 imp:n=0 imp:p=0 $ external void
c
Surfaces
c******************************************************************************
c--- experiment, 100-series resserved ---
c foils
10 cz 0.635 $ foil radius (1/2" OD)
11 pz 0.0127 $ copper foil 0.005"
12 pz 0.01778 $ gold foil 0.002"
13 pz 0.02286 $ Mn-Cu foil 0.002"
14 pz 0.0254 $ Dy foil 0.001"
15 pz 0.0508 $ In foil 0.010"
c
--- neutron beamline ---
200 pz -760.0 $ source-end of the beam tube
201 pz -150.9 $ water surface
208 pz -0.15875 $ 1/16" cap of beam tube
```
209 pz 0.0 $ top-end of the beam tube
210 cz 1.905 $ beam tube inner diameter
211 cz 2.54 $ beam tube outer diameter

--- beam stop ---
251 pz 100.000 $ bottom outer surface of beam stop
252 pz 201.600 $ 40" long top outer surface of beam stop
253 pz 120.954 $ 8" Cavity depth = s103 - s251
254 pz 101.270 $ 1/2" more than s251
255 pz 200.965 $ 1/4" less than s252
256 pz 190.805 $ 4" thick Pb plug bottom
257 pz 101.190625 $ 1/32" less than s254
258 pz 101.11125 $ 1/32" less than s257
261 cz 15.240 $ 6.00" OR of beam stop
262 cz 5.397 $ Cavity 4" diameter
263 cz 10.16 $ bottom opening boundary
264 cz 14.605 $ 5.75" Al can inner radius
265 cz 22.86 $ beamstop brim OD
271 px 10.16 $ lead boundary
272 px -10.16 $ lead boundary
273 py 10.16 $ lead boundary
274 py -10.16 $ lead boundary

--- other ---
220 cz 200.0 $ outer diameter of the model
290 pz -800.0 $ bottom of the model
291 pz 300.0 $ top of the model

Data Cards

MODE n p
NPS 1e8
SDEF PAR=1 POS=0 -760.00 ERG=D1 ARA=11.40091828
   AXS=0 0 1 RAD=D2 EXT=0 VEC=0 0 1 DIR=D3
   c SII 1e-12 1E-8 1E-7 1E-6 1E-5 0.001 0.01 0.1 1.0 4.0 20.0
   c SPI 0.04439 0.7449 0.8460 0.8650 0.8850 0.9027 0.9203 0.9344 0.9650 0.9925 1
9.23712E-01  
9.28585E-01  
9.34771E-01  
9.41739E-01  
9.51524E-01  
9.63756E-01  
9.77893E-01  
9.92130E-01  
1.00000E+00

c
SI2  0.0    1.905
SP2  -21  1
c
SI3
  0.0
  0.996194698
  0.999390827
  0.999847695
  0.999961923
  0.999993900
  1.0

SP3
  0.0
  0.1448842
  0.2771287
  0.6950270
  0.9190148
  0.9853936
  1.0000000
c
--- MATERIALS ---
c******************************************************************************
c copper (V=1.608796e-2 cc; rho=V/mass of the foil; purity=0.9999335)
c (Cu-E m=0.1467, rho=9.1186 g/cc)
c (Cu-F m=0.1492, rho=9.2740 g/cc)
M11  29063.70c  0.6915
     29065.70c  0.3085
c******************************************************************************
c gold (V=6.435185e-3 cc; rho=V/mass of the foil; purity=0.9995)
c (Au-A m=0.1210 g, rho=18.8029 g/cc)
c (Au-B m=0.1206 g, rho=18.7407 g/cc)
M12  79197.70c  1.0
c******************************************************************************
c Mn-Cu (81.3%) (V=6.435185e-3 cc; rho=V/mass of the foil; purity=0.99988)
c (MnCu-M m=0.0496 g, rho=7.7076 g/cc)
c (MnCu-N m=0.0500 g, rho=7.7698 g/cc)
M13  25055.70c -0.813
     29063.70c -0.128056
     29065.70c -0.058944
     28058.70c -0.002016
     28060.70c -0.000803
     28061.70c -3.55e-5
     28062.70c -0.000115
     28064.70c -3.03e-5
c dysprosium (V=3.2175925e-3 cc; rho=V/mass of the foil; purity=0.999267)
c   (Dy-G m=0.0319 g, rho=9.9142 g/cc)
c   (Dy-H m=0.0317 g, rho=9.8521 g/cc)
M14  66156.70c 0.0006
    66158.70c 0.001
    66160.70c 0.0234
    66161.70c 0.1891
    66162.70c 0.2551
    66163.70c 0.2490
    66164.70c 0.2818
c
c indium (V=3.2175925e-2 cc; rho=V/mass of the foil; purity=0.9999+)
c   (In-K m=0.2519 g, rho=7.8288 g/cc)
c   (In-L m=0.2444 g, rho=7.5957 g/cc)
M15  49113.70c 0.043
    49115.70c 0.957
c
m101  1001.70c 0.6666
    8016.70c 0.3333
mt101 lwtr.10t          $ water S(a,B) card
c
m102  12024.70c -0.006236001
    12025.70c -0.000822409
    12026.70c -0.000941595
    13027.70c -0.986000000
    14028.70c -0.003674938
    14029.70c -0.00192726
    14030.70c -0.000132337
    24050.70c -2.08689E-05
    24052.70c -0.000418497
    24053.70c -4.83680E-05
    24054.70c -1.24943E-05
    29063.70c -0.001027189
    29065.70c -0.000472812
mt102 al27.12t          $ aluminum S(a,B) card
c
m103  8016.70c -0.23
    7014.70c -0.77

c Lead (density=11.34 g/cc)
M105  82000.42c 1.0
Parafin (40wt%) and Borax (60wt%) Density = 1.2804348 g/cc
M106   11023.70c -0.07233999
      5010.70c -0.01253961
      5011.70c -0.05549603
      8016.70c -0.42790885
     6000.70c -0.34056000
     1001.70c -0.09115569

Cadmium (8.65 g/cc, pure)
M107   48106.70c 0.0125
       48110.70c 0.0089
       48111.70c 0.1249
       48112.70c 0.1280
       48113.70c 0.2413
       48114.70c 0.1222
       48115.70c 0.2873
       48116.70c 0.0749

Copper (for tallies)
M111   29063.70c 1.0

Gold (for tallies)
M112   79197.70c 1.0

Mn-Cu (for tallies) (81.3% TD)
M113   25055.70c 1.0

Dysprosium (for tallies)
M114   66164.70c 1.0

Indium (for tallies)
M115   49115.70c 1.0

--- TALLIES ---
F4:n 11 12 13 14 15
FM4 8.51E9 $ 2.4 n/fiss, 950 kW, 185 MeV/fiss
FC4 "Flux in foil cells 11, 12, 13, 14, 15"

F114:n 11
FM114 1.0 111 102
FC114 "Cu-E, multiplied by absorption XS for Cu-63"

F124:n 12
FM124 1.0 112 102
FC124 "Au-A, multiplied by absorption XS for Au-197"
FC134 "MnCu-M, multiplied by absorption XS for Mn-55"
FC144 "Dy-G, multiplied by absorption XS for Dy-164"
FC154 "In-K, multiplied by absorption XS for In-115"
APPENDIX B – Procedures for the Neutron Imaging Facility
The procedures are separated into sections, which are listed below. The procedures should be read through and well understood before they are carried out.

Section A: Installation of the beamline.
Section B: Installation of the optical table.
Section C: Installation of the beamstop.
Section D: Initial Beamline Startup and Radiation Survey.
Section E: Routine opening and closing of the beamline.
Section F: Pre-Start Checklist Template
Section G: Removal of the beamline.
Section H: Miscellaneous Procedures.
Section A) Beamline Installation

This section describes the process of installing the 2.0” O.D. neutron beamline in the GSTR tank.

1. Thoroughly clean the beamline tubes before inserting them into the reactor pool. The final stage of cleaning shall be a thorough rinsing with either fresh potable or deionized water.
   a) When the beam tube sections are in the reactor bay and out of the tank, be careful to keep them from contacting the central thimble tube, control rod drives, or lazy susan unload tube.

2. Unlock and lift grates into their upright positions as needed.

3. The beamline support must be in place prior to installation of the beamline.

4. Attach a safety line onto the bottom section of the beam tube and have a person hold this line to prevent the beamline from falling to the bottom of the tank.

5. Insert the first beamline section vertically into the reactor pool at the side of the tank (not over the reactor) and near the beamline support. Use caution not to impact the reactor tank or any reactor components with the beamline when lowering it into the tank.

6. Using appropriate tools, attach the second beamline section to the first. After this section has been secured, attach a temporary safety line to the upper beamline section, keeping the safety line attached (see above) to the lower section of the beamline.

7. Continue lowering the beamline vertically and carefully place it onto the beamline support, keeping the safety lines taut. The final positioning may require a tipping of the beamline from its vertical position.

8. Tilt the beamline to position the surface-end of the beamline into the beamline clamp, which should be attached in its desired position on the top lip of the reactor tank, and tighten the clamp to secure the beamline. Be cautious to ensure that the bottom of the beamline does not come off of the bottom support. The upper safety line should now be removed and the lower safety line shall be secured to the side of the tank.
   a. Make sure the clamp is tightly fastened to its desired location.
   b. The clamp position may be adjusted after the beamline is fastened in the clamp, but care must be taken to ensure the beamline is not dislodged from the bottom support.

9. Remove the beamline-access grate and lower the large grate over the beamline.

10. Attach the top section of the neutron beamline.
11. Replace and lock down the beamline-access grate.

12. With the reactor shutdown, test the beamline stability by pressurizing the beamline. Ensure the beamline is stable in this evacuated condition, both with the primary cooling pump off and on. Remove the gas and re-flood the beamline, observing again that the beamline is stable and fixed in position.

   a. Appropriate radiation monitoring must be performed when the beamline is pressurized.

13. If the beamline is not stable, correct this problem before reactor operation or remove the beamline from the beamline support.

NOTE: The beamline may be stored at the side of the tank, in a vertical position, if properly secured to the side of the tank.
Section B) Installation of the Optical Table

This section describes the process of installing the optical table. This section assumes:

- The beamline is installed before the optical table, since the grates under the optical table cannot be opened after the optical table frame is in place.
- The grates are closed.
- The reactor is down during installation.

1. Bolt the upper optical table upper frame to the lower frame.

2. Using the overhead crane and lifting straps, lift the optical tabletop and place it on top of its upper frame. Exercise caution not to set the weight of the table on the beamline, or to impact the beamline.
   
   a. At least two people must be present during installation of the tabletop. The crane operator counts as one of the two people.

3. Visually adjust the rotation of the table so it lines up with the beamline. Bolt the tabletop to the upper frame.

4. Attach the beamstop support/enclosure to the tabletop.
Section C) Installation of the Beamstop

This section discusses the installation of the beamstop. This section assumes:

- The optical table and beamstop support are installed prior to installation of the beamstop.
- The grates are closed.
- The reactor is shut down.

1. Measure the angle of the beamline, and adjust the beamstop support hinges to match that angle.

2. Position the beamstop support hinges to a position such the beamstop will be nearly in line with the beamline once it is lowered onto the support. This reduces the adjustment of the beamstop position once it is installed.

3. Using the overhead crane and lifting chains attached to the beamstop, lift the beamstop and place it in position on the beamstop support.
   a. At least two people must be present during installation of the beamstop. The crane operator counts as one of the two people.
   b. Align the beamstop with the beamline.

4. Firmly attach the beamstop to the beamstop support.

5. Once the beamstop is installed, a safety chain should attach the beamstop to a rigid structure in the reactor bay, such that the beamstop is prevented from falling toward the reactor safety grates.
Section D) Initial Beamline Startup and Radiation Survey

This section applies to a new beamline to determine radiation levels and appropriate safety measures to ensure the safety of facility staff. This section assumes:

- Radiation levels from the neutron beamline are not yet known.
- Additional defense-in-depth interlocks are not yet known.
- The neutron beamline is already installed per the installation procedures.

1. Open the manual valve on the pressure regulator and close the manual vent. Pressurize the beamline to 5 psi, and verify that the beamline indicator indicates that the beamline is open. Then, vent the pressure, and verify that the beamline indicator indicates that the beamline is not open.

2. With the reactor shutdown, pressurize the beamline until some gas bubbles out the end of the beam tube. This is expected to require between 9 and 12 psig. Reduce the pressure incrementally until the bubbles stop flowing from the beam tube.

3. Take neutron and gamma dose readings at each of the following locations, shown in the adjacent figure.
   
i) 5 m, 2 m, and 1 m from the experimental enclosure.
ii) At the sides of the experimental enclosure.
iii) In contact with the neutron beamline (position 1).
iv) On the optical table surface 30 cm from the beam (position 2).
v) At the base of the beamstop (position 3).
vii) Above the beamstop (position 4).

4. If the predicted dose rates are determined to be safe at the next higher power level, repeat step 2 with the reactor at 1 W, 100 W, 10 kW, 100 kW, 500 kW, and 1 MW. If any point in accessible areas is measured or predicted to be above 100 mr/hr, the reactor bay shall be controlled as a high radiation area for the remainder of this test. The Senior Reactor Operator-In-Charge or Reactor Health Physicist may stop the test at any point based on safety concerns.
5. After the highest power level is reached, a complete dose rate survey shall be performed and documented for the reactor bay and the bay roof.

a. After the detailed radiation survey, set a radiation monitor near the beam. Then flood the beamline, and determine the time response of the beam "turning off". This time (in seconds) will then be used to set an administrative limit on how soon the beam access doors can be opened during normal operations.

b. Then, the beamline shutter will be closed and the reactor may shut down.

6. Appropriate facility radiation postings and safety measures should be determined in accordance with 10 CFR 20 regulations using dose levels measured with the reactor at 1 MW.

7. The pre-start checklist for the new beamline will be developed before operation using Section E as a template.
Section E) Pre-Startup Checklist Template

This procedure describes a template for the pre-startup checklist, which is to be completed before pressurization of the beamline, described in Section F.

1. The appropriate postings and protective measures are in place in accordance with 10 CFR 20 regulations. This includes:
   - Appropriate postings
   - Protective measures
   - Other items, as deemed necessary

2. Verify that the beamstop is lined up with the neutron beamline.
   - NOTE: This can be accomplished visually, using lasers, or another reliable method.

3. Verify interlocks are operational
   - Access interlocks
   - Beamline position interlock
   - Beamstop position interlock
   - Additional interlocks may be required for new beamlines, which should be determined using data from Section D.
Section F) Routine Opening and Closing of the Neutron Beamline

This section covers pressurization and depressurization of the neutron beamline for routine operation. This procedure assumes:

- The neutron beamline is already installed per the installation procedures.
- The “New Beamline Startup and Radiation Survey” procedure has previously been followed for the beamline being operated and appropriate postings and protective measures are in place.

1. Complete the appropriate pre-startup checklist (described in Section F) prior to performing an experiment that requires opening of the neutron beamline.

2. Open the manual valve on the pressure regulator and close the manual vent. Pressurize the beamline to 5 psi, and verify that the beamline indicator indicates that the beamline is open.

3. Vent the pressure, and verify that the beamline indicator indicates that the beamline is not open.

4. Pressurize the beamline until some gas bubbles out the end of the beam tube. Reduce the pressure incrementally until the bubbles stop flowing from the beam tube. Note this pressure setting for future pressurization.

5. When it is not necessary for the beam to be open, vent the pressure in the beamline. Once the beamline is vented, close the manual valve on the pressure regulator and open the manual vent.
Section G) Beamline Removal

This section describes the process of removing the 2.0” O.D. neutron beamline from the GSTR tank.

1. Unlock and lift grates into their upright positions as needed.

2. Attach a clean safety line onto the upper section of the beamline and have a person hold this line to prevent the beamline from falling to the bottom of the tank. If a lower safety line is attached, have someone hold this line as well.

3. Loosen the beamline from the clamp and tilt the beamline vertical above the beamline support. Lift the beamline off of the beamline support and move the beamline to the side of the tank for removal.

4. The presence of the Reactor Health Physicist or his designee is required prior to removal of the beamline from the reactor tank.

5. Remove the first beamline section vertically from the reactor pool at the side of the tank (not over the reactor). Use caution to not impact the reactor tank or any reactor components with the beamline during removal from the tank.

Use either procedure 5a. or 5b.

5a. The beamline may be stored at the side of the tank, in a vertical position, if properly secured to the side of the tank. If the beamline is stored in the tank, the following step can be disregarded.

5b. The beamline may be removed from the reactor bay. Appropriate radiation monitoring must be performed when removing the beamline from the tank. Using appropriate tools, detach the top section from the bottom section and remove the two sections from the tank. Dry the sections as they are removed from the tank so that reactor tank water does not drip on the bay floor or on electrical components. Control contaminated or activated areas as needed. When the beamline sections are out of the tank, be careful to keep them from contacting the central thimble tube, control rod drive mechanisms, or lazy susan unload tube.
Section H) Miscellaneous: Operation of the Neutron Imaging Facility

This section describes routine operation procedures for operation of the neutron imaging facility not specifically covered by other procedures.

Miscellaneous Instructions:

1. There shall be no assembly or disassembly of the optical table, beamline, or the beamstop during reactor operation. Experimental components atop the optical table may be assembled, disassembled, etc. during reactor operation.

2. Prior to accessing the experimental station or removal of any safety systems, verify that the beamline is closed and cannot pressurize by either:
   a. Verify that the manual valve on the pressure regulator is closed and the manual vent is opened.
   b. Verify that the pressure hose is disconnected.

3. The gas tank should be either on a gas cylinder cart or fastened to a gas cylinder station, according to standard cylinder storing practices.

4. Verify that the gas used to pressurize the beamline is helium.

5. When moving large heavy objects (e.g. beamstop, beamline, optical tabletop), safety lines should be attached whenever possible. At least two persons will be present when moving heavy objects near the reactor pool and the overhead crane will be used whenever practical.
APPENDIX C – 50.59 Review for a Neutron Imaging Facility at the GSTR
1) **Addition of a Neutron Imaging Facility**

a) This proposal is to add a neutron imaging facility to the GSTR. The new facility will provide new research capabilities for a variety of applications. A description of the facility is included in Section 2 of this report. Section 3 covers the procedures associated with the facility. Section 4 discusses the accident analysis conducted in support of this review, and Section 5 discusses 50.59 considerations related to the new facility.

2) **Description of the Neutron Imaging Facility**

a) Figure C-1 depicts an overall schematic of the proposed facility. The water level in the neutron beamline serves as the shutter, which is controlled by adjusting the pressure in the beamline using a gas pressure control system. A beamstop reduces the radiation dose to the environment that would otherwise result from the neutron beam. A support that sits on the bottom of the tank will support the weight of the beamline. The optical table supports and vibrationally isolates the experimental setup and the beamstop. The major hardware components are discussed separately in the following subsections.

   i) **Beamline**: The neutron beamline is supported at the bottom by a beamline support, and clamped to the lip at the top of the tank. The location of the beamline on the reactor-end can vary. The current proposed location is positioned tangential to the reactor, above the reflector, outside the lazy susan, and near the southeast side of the reactor. The beamline extends to the experiment station in the reactor bay at the southwest corner of the reactor tank. The expected neutron flux at the imaging-end of the beamline is \( \sim 10^6 \text{ n/cm}^2\text{-s} \). The beamline does not route near the control rods. The weight of the beamline is held by the beamline support and does not sit on the reflector or lazy susan. The all-aluminum support sits on the bottom of the tank and has 1” of clearance above the reflector. The predicted deformation of the beamline support from the \( \sim 40 \text{ lb load} \) from the beamline is negligible.

   ii) **Gas Pressure System**: The water level in the beam serves as the neutron shutter. A gas pressure control system remotely controls the gas pressure in the beamline to adjust water
level. Figure C-2 shows a schematic of the pressure control system. The helium reservoir is required with a pressure regulator and a manual valve to lower the pressure to between 0-100 psi. An electro-pressure regulator further lowers the pressure to 0-15 psi. Solenoid valves ensure the system cannot pressurize until the system is energized, providing an automatic shutdown on loss of power. A control computer operates the electro-pressure regulator and solenoid valves. A 100 psi rupture disk protects against over-pressurization. A manual pressure relief valve is included as a safety precaution. Filters are in place to remove any particulates coming from the beamline when the beamline pressure is released.

Figure C-2. Schematic of the Gas Pressure System.

iii) **Beamstop:** A beamstop attenuates the radiation beam to prevent excessive dose outside the facility. The beamstop was designed to attenuate a radiation beam produced by pressurizing the central thimble, which would provide a neutron flux an order of magnitude higher than the current proposed beamline location will provide. The dose rates calculated for the beamstop at the central thimble are ~4.75 mrem/h at 1 m, 0.85 mrem/h at 3 m, and 10 mrem/h at the roof (which is already marked as a radiation area). Doses scale linearly with the incident flux, and thus the doses calculated for the central thimble are a magnitude greater than those expected for the proposed beamline, so the beamstop is expected to provide more than sufficient radiation attenuation. Figure C-3 shows a schematic of the beamstop.

Borated paraffin (60:40 wt% borax to paraffin) fills the aluminum shell of the beamstop to attenuate neutrons. Four lead bricks at the back end of the beamstop reduce gamma radiation. The beamstop weighs ~310 lbs. Finite element calculations indicate that the
beam stop mounting plate can easily withstand this expected loading. A structure mounted to the optical table supports the beamstop.

As an added safety measure, a safety chain attached to the beamstop prevents the beamstop from falling into the reactor pool. Procedures require verification that the beamstop is in line with the beamline prior to operation to prevent unexpected radiation areas. Alignment interlocks will depressurize the beamline if the beamstop becomes misaligned during operation.

iv) *Experiment Station*: The experiment station includes an optical table, experimental hardware, beamstop support structure, and interlocks.

The optical table frame consists of two parts. The lower frame is mounted to the concrete underneath the safety grates and is level with the grates (Figure C-4). The upper frame is mounted to the lower frame, and the optical table top is mounted to the upper frame. The table top weighs ~260 lbs and is installed using the overhead crane.

![Figure C-4. Safety Grates with Lower Frame Installed.](image)

The beamstop support is constructed from aluminum extrusions. It not only supports the weight of the beamstop, but is also enclosed, preventing access to the radiation beam during operation. Interlocks will cut power to the pressure system when the access doors are opened, flooding the beam tube with water, which closes the beam.

3) **Procedures: 2” Beamline Installation, Operation, and Removal**

Procedures are included in Appendix A
4) **Accident Analysis**

In support of this review, a meeting was held between CSM faculty, CSM graduate students, and the GSTR staff to brainstorm and discuss possible accident scenarios that could result from the addition of this new facility at the GSTR. A list of the resulting scenarios follows, along with a discussion of each.

a) **Damage to Reactor Equipment**

This new facility includes large, heavy objects placed near the reactor pool, primarily the beamstop and optical tabletop. A postulated accident entails one of these heavy objects falling and sinking into the reactor pool, damaging reactor components. When the reactor is not operating, this scenario is bounded by the 6000 lb shipping cask, which is lowered into the reactor pool for transporting fuel. The damage that could possibly result from the cask falling into the pool exceeds that which could be caused by the new facility components. The beamstop, beamline, and optical table installation procedures require that the reactor is shut down during installation. Also, safety lines will be attached whenever possible, the overhead crane will be used when practical, and at least two persons will be present when moving heavy objects near the reactor pool.

The analysis also considered the possibility of a large component falling into the pool during reactor operation. The components near the reactor pool are fastened together to make one rigid piece which is larger than the opening at the reactor pool top. The beamstop is rigidly fastened to a support structure, which is bolted to the optical tabletop. The tabletop is bolted to the upper frame. The upper frame is bolted to the lower frame, which is bolted and grouted to the concrete surrounding the reactor tank. A safety chain attaches the beamstop to a rigid structure in the reactor bay (e.g. the crane I-beam structure). The top-heavy beamstop is tilted away from the pool, reducing the chance that the beamstop could fall toward the pool. Additionally, the grates under the optical table cannot be opened with the optical table frame installed. Considering all of this, the analysis concluded that the possibility of a large facility component falling into the reactor pool during operation is not credible.

Additionally, if a large object falls on the end of the beam tube, jamming the beam tube downward, the reflector could be damaged. While this could lead to significant monetary damage, it is not a safety accident with respect to criticality or core cooling. Once assembled, the optical table prevents beamstop from falling on the end of the beam tube. Installation of the optical table top requires more than one person to carefully set the tabletop into position, taking care not to set the weight of the tabletop on the beamline. The maximum weight on the end of the beam tube from experimental components is ~20-30 lbs, which will be supported by the bottom support of the beamline.

If both pressure regulators simultaneously fail open, pressurized gas could vent through the end of the beamline, potentially causing the beam tube to lift off of the beamline support. If this occurs, there is a possibility that the beamline could contact a control rod connecting rod. This contact could possibly bind the control rod in such a way that the control rod could no longer be inserted into the reactor core. Multiple failures must occur simultaneously for this to be plausible. This scenario is prevented by the following safety features. The beamline
position interlock would sense that the beamline had shifted, cutting power to the pressure system, venting the pressure of the beamline. Also, a rupture disk in the gas pressure system will keep the beamline pressure below 100 psi to prevent high-pressure gas from the tank from blowing through the beamline. Such a failure would be loud and quickly noticed by staff, who could respond quickly to shut off the gas tank. In the highly unlikely scenario that these systems fail, along with the simultaneous failure of both regulators, and a control rod cannot be inserted into the core, the reactor can be shut down by inserting the other three control rods.

Finally, the beam tube fittings could come loose, the two long tube sections separate and swing into reactor components, resulting in damage to the reactor. This does not create an exposure concern, since the tubes would be filled with water upon separation. This situation is similar to other items falling into the tank during operation (e.g. the 8” beam tube, shepherd’s hook, etc.). The top section of the beamline is supported by the beamline clamp at the tank lip. The top end of the lower section of the beamline would rest against the tank since it is ~12 feet long in an 7’-8” diameter tank; the bottom end may fall to the bottom of the tank if it comes off the support. The support line will limit the potential motion of the bottom section of the beam line.

b) Loss of Coolant Flow/Reactivity Insertion

Over-pressurization of the beamline resulting from simultaneous regulator failures could have other consequences. If high-pressure gas causes the beamline to come off the beamline support, the beamline could fall under the reactor core, causing the helium to flow through the core. If the gas flow rate is large enough, the core could be voided of water. This scenario is bounded with respect to cooling by a LOCA (Section 13.2.3 of the SAR), which states that the core could remain sufficiently cool to prevent fuel damage at 1.5 MW when completely dry. The LOCA scenario also bounds disrupted cooling that would result from the beamline lifting off its support and landing on top of the reactor, blowing helium down on top of the core.

Reactivity insertion could also result if the beamline falls under the reactor core, blowing helium through the core. The voids would decrease reactivity, and the regulating rod could be withdrawn automatically try to compensate for this reactivity change. The regulating rod is worth a total of $3.88 reactivity (SAR, Table 13.8). When at full power, the regulating rod has less than $2 of reactivity worth left that it could insert from further withdrawal; thus the regulating rod would be limited to automatically adding no more than $2 reactivity to compensate for void reactivity loss. Assuming the automatic control remains active (it might shut off in response to power fluctuations), subsequent instantaneous flooding of the core could produce a maximum $2 reactivity insertion. This is, however, less than the reactivity insertion limit for a pulse of the reactor ($3). Also, this $2 reactivity insertion is less than the $3.49 reactivity insertion that would yield a worst case peak fuel temperature of 1000 °C (SAR, 13.2.2.2.1). It is also less than the $2.31 pulse that yields a very safe peak fuel temperature of 345 °C (SAR, 13.2.2.2.1).

c) Experiment Malfunction – Unnecessary Radiation Exposure
In a scenario where the beam access interlocks fail, and the beamline remains open, a worker could receive excessive dose. Hardware and administrative failures must happen for this scenario to occur. Access procedures include verification that beam is depressurized. To reduce the likelihood of hardware failure, interlocks will be verified to be functioning correctly before operation, per the routine operation procedure (Section E.1.c).

If the beamline or beamstop is bumped and shifts, the radiation beam might not be attenuated by the beamstop. This could result in unplanned radiation areas or exposure of persons at the facility. Interlocks are in place that sense if the beamstop or beamline have shifted, cutting power to the pressure system, which closes the beam. These interlocks are verified to be functioning correctly prior to operation of the facility, per the appropriate pre-start checklist (Section E).

Unplanned radiation fields and possible exposures could also result from the shifting of the beamline resulting from thermal expansion/contraction during normal operation (15° C to 60° C), which could change the length of the beam tube by approximately 1 cm. Also, if the beamstop falls, unplanned high radiation areas could be created. Again, interlocks sense that the beamstop and/or the beamline have shifted, cutting power to the pressure system, which closes the beam. The beamstop is also bolted to the optical table during operation. A safety chain and the tilt of the beamstop away from the reactor pool make it improbable that the beamstop would fall toward the reactor. Multiple systems must fail simultaneously for these scenarios to occur.

In the event that an incorrect or impure gas is used to pressurize the beamline, an activated gas could vent into the reactor bay, causing unplanned radiation fields and possible exposure. Procedures are in place to verify tank is helium before operation (Section H.4). Also, discussions between the GSTR staff and the compressed gas distribution company reveal that distribution of a mislabeled gas cylinder is extremely unlikely due to company operating procedures.

d) Miscellaneous

There are many small objects associated with the new facility that could fall into the reactor tank. The new facility will be used to analyze a variety of samples. Samples will be treated as individual experiments, which require reactor staff approval (Technical Specifications, Appendix A, Section H.1). Approved sample types will be cataloged for reference and more efficient future approval. Caution will be taken to reduce the likelihood of a sample falling into the reactor tank. The reactor operator will be notified immediately if a sample falls into the tank during reactor operation.

For other small objects, there is no existing reactor safety concern for small-objects falling into reactor pool, and objects related to the new facility will be treated similarly. The reactor operator will be notified immediately if a sample falls into the tank during reactor operation.
5) **Evaluation of 50.59 Requirements**

The proposed facility does *not* involve any of the following:

- Change to the Technical Specifications
- Change to the Facility as described in the Safety Analysis Report
- Change to the procedures described in the Safety Analysis Report
- Does not produce an unreviewed safety question as defined by 10 CFR 50.59(c)(2).

No change is needed to the Technical Specifications, Safety Analysis Report, or facility procedures described in the SAR. The new facility does not produce an unreviewed safety question because it does not satisfy any of the following circumstances from 10 CFR 50.59(c)(2):

i) Result in more than a minimal increase in the frequency of occurrence of an accident previously evaluated in the final safety analysis report (as updated).

An accident analysis was performed in support of this review (Section 4). The accident scenarios identified were bounded by accidents evaluated in the SAR, and were determined not to produce even a minimal increase in the frequency of accidents evaluated in the SAR.

ii) Result in more than a minimal increase in the likelihood of occurrence of a malfunction of a structure, system, or component (SSC) important to safety previously evaluated in the final safety analysis report (as updated).

This new facility does not impact SSC’s evaluated in the final SAR. Thus, the addition of this facility should not increase the likelihood of a malfunction of an SSC previously evaluated in the final safety analysis report.

iii) Result in more than a minimal increase in the consequences of an accident previously evaluated in the final safety analysis report (as updated).

An accident analysis was performed in support of this review, and the accidents postulated for the new facility were found to be bounded by the accidents previously evaluated in the final safety analysis report. The consequences of accident scenarios analyzed in the SAR will not increase as a result of the addition of this new facility. (See Section 4 of this report)

iv) Result in more than a minimal increase in the consequences of a malfunction of an SSC important to safety previously evaluated in the final safety analysis report (as updated).

This new facility does not alter SSC evaluated in the final SAR. The consequences of a malfunction of an SSC evaluated in the final SAR are not increased by the addition of this new facility.

v) Create a possibility for an accident of a different type than any previously evaluated in the final safety analysis report (as updated).
An accident analysis was performed in support of this review (Section 4). The accident scenarios identified by the analysis are bounded by accidents evaluated in the SAR. The analysis did not identify any accidents of a different type than those evaluated in the SAR.

vi) Create a possibility for a malfunction of an SSC important to safety with a different result than any previously evaluated in the final safety analysis report (as updated).

This new facility does not impact SSC evaluated in the final SAR. The consequences of a malfunction of an SSC evaluated in the final SAR are not increased by the addition of this new facility, and the results of the evaluated SCC malfunctions are not altered.

vii) Result in a design basis limit for a fission product barrier as described in the FSAR (as updated) being exceeded or altered.

This new facility does not affect the reactor core, and thus does not result in approaching any of the design limits related to fission product barriers described in the SAR.

viii) Result in a departure from a method of evaluation described in the FSAR (as updated) used in establishing the design bases or in the safety analyses.

The analysis methods employed in the accident analysis for this review (see Section 3) do not depart from the methods used in the SAR.

6) **Determination of Changes to Facility Drawings**

No changes are needed to existing facility drawings. Drawings of the beamline, beamstop, and optical table will be added to facility files.

7) **Determination of Additional Procedures, Logs, or Training Material May Be Affected**

No existing procedures, logs, or training material will be affected by this new facility. New procedures associated with the use of the new facility have been created and will be added to facility files. We will need to add an item to the daily prestart checklist and also to the daily shutdown checklist to check the placement/status of the beamline at the beginning and end of each day.

8) **List of Drawings, Procedures, Logs, or Other Materials To Be Changed**

No changes to existing procedures, logs, or training material will be affected by this new facility. New procedures associated with the use of the new facility have been created and will be added to facility files. Drawings of the beamline, beamstop, and optical table will be added to facility files.