MODELING AND DESIGN OF A SILICON-BASED HIGH-PRESSURE $^3$HE REPLACEMENT NEUTRON DETECTOR

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by
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MODELING AND DESIGN OF A SILICON-BASED HIGH-PRESSURE $^3$HE REPLACEMENT NEUTRON DETECTOR

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University of Missouri-Kansas City, 2015

ABSTRACT

$^3$He has stood as a major isotope used for neutron detection for many years. Due to national concerns of a possible $^3$He shortage, significant effort has been put forth, in the form of $^3$He alternative research, to push the community to develop more cost effective and higher intrinsic efficiency devices. The major focus of this thesis is on how a Si-based microstructured neutron detector (MSND) assembly, of size and shape comparable to that of a commercially available high-pressure $^3$He-based neutron detector, can yield higher neutron detection efficiencies than its $^3$He-based counterpart. With careful consideration of MSND assembly geometry, along with clever utilization of neutron moderating high-density polyethylene (HDPE), a high-pressure $^3$He replacement (HP-HeRep) device, consisting of eighty tightly packed 1-cm2 MSND’s, has been designed and will be compared with a high-performance 8.3 absolute atmosphere $^3$He-based neutron detector.

The MSND, designed and developed by the S.M.A.R.T. Lab at Kansas State University, is a high purity Si-based, highly anisotropic pin structure diode (i.e., 350-μm by 20-μm trenches in a 525-μm thick substrate). Given the novelty and complexity of the MSND, little is known in regard to its electric field character and resultant charge sweep-out properties. As a first step toward the development of a thorough understanding of these
properties, this thesis also focuses on the equivalent circuit analysis and comparison of the MSND with a planar-type neutron detector, via impedance spectroscopy.
APPROVAL PAGE

The faculty listed below, appointed by the Dean of the College of Arts and Sciences have examined a thesis titled “Modeling and Design of a Silicon-Based High-Pressure $^3$He Replacement Neutron Detector”, presented by Brent Joyner Rogers, candidate for the Master of Arts degree, and certify that in their opinion it is worthy of acceptance.

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CONTENTS

ABSTRACT........................................................................................................................................ iii

LIST OF ILLUSTRATIONS.................................................................................................................. viii

LIST OF TABLES.................................................................................................................................. x

ACKNOWLEDGMENTS.......................................................................................................................... xi

CHAPTER

1. INTRODUCTION................................................................................................................................. 1
   Introduction to the Neutron and its Interaction with Matter................................................................. 1
   Primary Project Motivations................................................................................................................ 4
   Motivation for Impedance Spectroscopy.............................................................................................. 5
   Review of Neutron Detector Types.................................................................................................... 6
   $^3$He Market Analysis........................................................................................................................ 14
   Thesis Structure................................................................................................................................ 16

2. FIRST AND SECOND-GENERATION NEUTRON DETECTOR DESIGNS .................................. 17
   Introduction to MCNP........................................................................................................................ 17
   Effects of Human Scattered Neutrons on Detection Efficiency....................................................... 18
   First-Generation $^3$He Replacements................................................................................................ 23
   First-Generation Neutron Detector Assembly Study: Simulation, Setup, and Results .................. 24
   Second-Generation Neutron Detector Assemblies.......................................................................... 30
   Second-Generation: Experimental Setup, Results............................................................................ 35

3. HIGH-PRESSURE $^3$HE REPLACEMENT...................................................................................... 39
   Third Generation Design................................................................................................................... 40
   Simulation, Setup, and Results......................................................................................................... 42
   Final HP-HeRep Design.................................................................................................................... 45
4. IMPEDANCE SPECTROSCOPY ................................................................. 47
   General Circuit Response ................................................................. 47
   Planar Neutron Detector and MSND I.S. Characterization ......................... 51
   Experimental Setup and Results ......................................................... 53
   Conclusions .......................................................................................... 61

5. FUTURE WORK ..................................................................................... 62
   REFERENCES ......................................................................................... 63
   VITA ......................................................................................................... 68
## ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Illustration of the MSND diode showing the $^6\text{Li}(\text{n},\alpha)^3\text{H}$ reaction</td>
<td>10</td>
</tr>
<tr>
<td>2: Photograph of the HRM with top cover removed</td>
<td>12</td>
</tr>
<tr>
<td>3: Typical $^3\text{He}$ neutron responses</td>
<td>13</td>
</tr>
<tr>
<td>4: 2012 Segmentation of consumer radiation detection devices</td>
<td>15</td>
</tr>
<tr>
<td>5: (a) 3D image of the MIRD phantom</td>
<td>19</td>
</tr>
<tr>
<td>6: Normalized total, source, and scatter neutron intensities vs. tally box position</td>
<td>20</td>
</tr>
<tr>
<td>7: (a) $^{252}\text{Cf}$ total and source neutron intensity vs. neutron energy</td>
<td>21</td>
</tr>
<tr>
<td>8: $^{252}\text{Cf}$ Source, scatter, and neutron intensity vs. neutron energy</td>
<td>22</td>
</tr>
<tr>
<td>9: Image and side view of a Domino neutron detector</td>
<td>23</td>
</tr>
<tr>
<td>10: First-generation assembly description</td>
<td>25</td>
</tr>
<tr>
<td>11: (a) Drawing of the first-generation simulation setup. (b) Overhead photograph of a first-generation laboratory experiment in progress</td>
<td>27</td>
</tr>
<tr>
<td>12: First-generation neutron detector assembly efficiency</td>
<td>28</td>
</tr>
<tr>
<td>13: Counter circuit for detector assemblies</td>
<td>31</td>
</tr>
<tr>
<td>14: Two data display options on the iPod touch control</td>
<td>32</td>
</tr>
<tr>
<td>15: Second-generation neutron detector assemblies</td>
<td>33</td>
</tr>
<tr>
<td>16: Modifications to the HRM used to collect data for analysis and comparison with prototype handheld units</td>
<td>34</td>
</tr>
<tr>
<td>17: Second-Generation Experimental Setup</td>
<td>35</td>
</tr>
<tr>
<td>18: Count rate vs. distance from source for each source configuration</td>
<td>36</td>
</tr>
<tr>
<td>19: Second-generation angular dependence plot</td>
<td>37</td>
</tr>
<tr>
<td>20: Detector strips arranged in a cubical pattern to fit within a cylinder</td>
<td>41</td>
</tr>
</tbody>
</table>
21: 3D diagram of a single detector strip and a 5 strip assembly ................................................. 42
22: HP-HeRep efficiency simulation setup. ......................................................................................... 43
23: Simulated absolute efficiency for each detector assembly. .......................................................... 44
25: Two-dimensional cartoon of the MSND ......................................................................................... 52
26: (a) Agilent 4294A impedance analyzer. (b) EM shielded impedance spectroscopy test enclosure. .......................................................................................................................... 53
27: Total impedance and phase angle vs. frequency for the MSND and a planar type neutron detector. ........................................................................................................................................ 54
28: Real and imaginary impedance vs. frequency for the MSND and a planar neutron detector. ........................................................................................................................................ 55
29: (a) Planar detector equivalent circuit. (b) Illustration showing pin structure of the planar detector. (c) Complex impedance plot of the planar detector ......................................................... 57
31: Planar neutron detector equivalent circuit parameter values .......................................................... 59
32: MSND equivalent circuit parameter values. .................................................................................... 59
## TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1: HRM Radiation Detection Specifications</td>
<td>12</td>
</tr>
<tr>
<td>Table 2: HRM Device Specifications</td>
<td>12</td>
</tr>
</tbody>
</table>
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CHAPTER 1
INTRODUCTION

Introduction to the Neutron and its Interaction with Matter

Under the tutelage of Ernest Rutherford, who is sometimes called the father of nuclear science, James Chadwick is credited with the discovery of the neutron in 1932 [1, 2]. This discovery was a key development in the understanding of nuclear processes. Neutrons, so named for their electro-magnetic neutrality, are subatomic particles found in nearly all forms of matter. Because neutrons do not interact via the Coulomb force, virtually all methods for detecting neutrons depend on electromagnetic secondary reactions as a means of detection signal transduction. In the early days of radiation science, detection of free neutrons relied heavily on gas-filled detectors such as proportional counters, ionization chambers, and Geiger Müller counters. It wasn’t until 1945 that the first solid-state radiation detector, invented by the Dutch physicist P.J. van Heerden, was presented. Termed the crystal counter, van Heerden describes detection of gamma rays and alpha particles with the use of a solid ionization chamber composed of silver chloride [3]. Today, there exist numerous system types for detecting neutrons such as fast neutron scintillators [4], thermal neutron scintillators [5], gas-filled counters [6], thermoluminescent dosimeters [7], and thin-film-coated semiconductor diodes [8].

Free neutrons exhibit what is sometimes referred to as neutron temperature. Neutron temperature is an indication of a free neutron’s kinetic energy. Thermal neutrons have energy near 0.025 eV. Epithermal neutrons are generally said to be in the energy range of about 0.025 eV to 1 MeV. Fast neutrons are generally said to have energies above 1 MeV. The two
energy regimes of most concern to neutron detection scientists are the thermal neutron regime and the fast neutron regime. This will be discussed in more detail shortly.

Neutrons have a mass approximately 0.2% greater than protons and approximately 184,000% greater than electrons. The existence of neutrons, interacting via the strong nuclear force, contributes to the existence of all periodic elements except that of hydrogen. Within the atomic nucleus, neutrons exist in bound energy states. A number of nuclear interactions may occur that result in neutron ejection or generation. Free neutrons have a half-life of about 10 minutes before undergoing beta decay. As neutrons do not interact via the electromagnetic force, the majority of free neutrons pass through the empty space of most materials without incident. Neutrons that do interact with matter do so by one of two ways: scattering or absorption.

A free neutron that is involved in an event that alters its momentum, but is allowed to continue traveling, is said to have undergone a scattering event, a phenomenon exploited by proton recoil neutron detectors [9]. If the total energy of a scattering event is conserved within the system of interest it is said to be an elastic scatter. Free neutron elastic scattering events occur most frequently with low-Z nuclei, that is, nuclei with few atomic protons. It is also possible for a scattering event to occur in which the total energy of the system is not conserved within the system of interest, that is, energy is lost to a material in the form of nuclear excitation or phonon generation. This interaction is termed inelastic scattering and occurs when neutron energies are high enough to induce nuclear excitation (typically several MeV). In this case, it is possible for the target nucleus to return to its ground state, subsequently producing secondary radiation.
A second kind of neutron interaction is one in which a free neutron is involved in a nuclear absorption event, the products of which may be harnessed as contributions to neutron detection. Of the neutron absorption processes, the most applicable to neutron detection is neutron capture. This occurs when a free neutron is absorbed by particular elemental isotopes, resulting in a new isotope. Commonly, the resulting isotopes are unstable and secondary nuclear events occur.

Yet, another type of nuclear absorption is neutron-induced nuclear fission. This type of event occurs more commonly with high-Z target nuclei. In this instance, the energy of the free neutron excites the relatively heavy target nucleus, resulting in the nucleus splitting into two or more nuclei of smaller Z value. Some common particles emitted as a result of neutron-induced fission are protons, photons and additional neutrons. By this process it is possible to achieve self-sustaining neutron multiplication, which is the basis of both nuclear power reactors and nuclear weapons.

Neutron Interaction Cross-Section

The probability of interaction between a free neutron and a target nucleus is well-described by the concept of microscopic cross-section ($\sigma_i$). The cross-section is an empirical, energy-dependent quantity. This value tells the probability of a certain type of interaction, denoted by $i$, that will occur between a neutron of certain energy and a specific type of target nucleus. Its most common unit of measure is the barn ($1 \text{ barn} = 10^{-28} \text{m}^2$). One interpretation of microscopic cross-section is given by:

$$\sigma = \frac{R'}{\Phi \cdot N}$$
where \( R' \) is the rate of reactions per unit target volume, \( \Phi \) is the neutron flux, and \( N \) is the atomic density of the target volume. Through dimensional analysis we find that:

\[
L^2 = \frac{(L^{-3} \cdot T^{-1})}{(L^-2 \cdot T^{-1}) \cdot (L^-3)}
\]

where \( L \) is the length dimension and \( T \) is the time dimension. Note that the number of incident neutrons and the number of reactions are dimensionless quantities.

With a working knowledge of free neutron behavior and proper equipment, one is capable of detecting and locating neutron emission sources. The economic and technological evolution of radiation science has led to vast improvements in neutron detection over more antiquated methods, all of which will be discussed in the following sections.

Primary Project Motivations

The primary neutron detector used in this study is the silicon (Si)-based microstructured neutron detector (MSND) [10]. With the use of the Monte Carlo N-Particle transport code (MCNP), a sequence of neutron detector optimization simulations were performed with the objective of illustrating the detector configuration with the highest detection efficiency. The size constraints of the problem were defined by the neutron detection portion of one particular commercially available neutron-gamma ray dual detector. That detector, the handheld radiation monitor (HRM) is discussed in greater detail in the section immediately following. The HRM detects neutrons via an 8.3 absolute atmosphere (abs. atm.), helium-3 \((^3\text{He})\)-based proportional counter. With the looming shortage of the world supply of \(^3\text{He}\), significant effort has been expended to develop a suitable alternative neutron detection material. Semiconductor-based neutron detectors have been proven capable of not only adequately replacing \(^3\text{He}\), but also outperforming it, as will be presented.
Motivation for Impedance Spectroscopy

Impedance spectroscopy measures the dielectric response of a material to the application of a small AC signal. A common use of impedance spectroscopy is to characterize the complex impedance magnitude and phase of a system. There are numerous ways to view complex impedance data. A couple ways are: as real impedance vs. imaginary impedance, and as real or imaginary impedance vs. log-frequency. With these plots, a variety of conclusions may be made.

A complementary objective of this work was to reveal the microscopic electronic properties of the MSND. The simplest of Si-based neutron detectors are little more than $pn$-junction diodes, formed by joining p-type Si with n-type Si, coated with a solid-state neutron-reactive material. P-type semiconductors have an abundance of holes, which are the absences of electrons within an atomic lattice where they could possible exist. Similarly, n-type semiconductors have an abundance of electrons. For each semiconductor type, the more abundant charge carrier is known as the majority charge carrier (holes for p-type and electrons for n-type). By joining p-type and n-type semiconductor materials, the majority carrier of each semiconductor type diffuses into the opposite semiconductor, combining with their counterparts until thermal equilibrium is reached. The result is a volume near the p-type/n-type interface devoid of mobile charge carriers. This volume is known as the space-charge depletion regions (SCR). The mechanism that separates generated electron-hole (e-h) pairs within a Si-based neutron detector is the electric field within the SPR. Internal capacitances and resistances of these devices will affect the quantity of charge collected at the electrodes of the device, as well as the amount of time it takes to collect the charge. An
ideal detector of this type instantaneously collects the entirety of energy deposited by the neutron absorption daughter particles. A realistic planar type detector behaves quite differently and an MSND behaves more differently still.

Review of Neutron Detector Types

*Gas-Filled Neutron Detector Overview*

Gas-filled radiation detectors may be used to detect either thermal neutrons via nuclear reactions or fast neutrons via nuclear recoil interactions. Though the operating parameters (fill gas, operating voltage, etc.) are different for each type of gas-filled detector, the apparatuses are similar in material and construction. In general, a gas-filled neutron detector is composed of a sealed hollow metal cylinder, acting as the cathode; an axially centered conductive anode wire; and a connector (often coaxial) located at one or both ends.

If a free neutron interacts with the fill gas of a gas-filled detector, a portion of that neutron’s energy will be transformed into generation of electron-ion (e-i) pairs. If little or no voltage is applied to the counter, the majority of the e-i pairs will recombine without contributing to a readable signal. The region of low applied voltage, up to 50-V, is known as the recombination region.

If a moderate positive voltage (50–200-V) is applied to the anode the generated ions will be separated by the internal electric field and collected at the electrodes before recombination occurs. The region of moderate applied voltage is known as the ionization region.

In the high voltage region (200–800-V), a phenomenon known as gas multiplication or avalanche occurs. Due to the strength of the electric field, the first generation of electrons
gains enough kinetic energy to ionize additional gas molecules, spawning secondary and tertiary generations of e-i pairs. This process continues until the charged particles are drawn as current at the electrodes, amplifying ionizing events by \(10^1-10^4\) times. The high applied voltage region is known as the proportional region as the amount of charge collected by the electrodes is linearly proportional to the energy initially deposited in the gas.

In the region of very high applied voltage, known as the Geiger–Müller region, the proportionality between the initially deposited energy and the output signal is lost. This is mostly due to the anode becoming charge saturated, resulting in delocalization of the avalanche about the anode. Operating in the Geiger–Müller region can amplify weakly ionizing events by up to \(10^{10}\) times. The downsides of operating in this region are a limitation of accurately counting high reaction rates and an inability to differentiate the initial energy of the incident particles.

\textit{Gas-Filled Thermal Neutron Detectors}

Commonly used in proportional mode, gas-filled neutron detectors are relatively simple devices composed of a gas-filled ion chamber under pressure. Two of the more commonly used fill gases are \(^3\)He and boron-10 (\(^{10}\)B) in the form of boron trifluoride (BF\(_3\)). The neutron capture reactions for these elements are [11]:

\[^3\text{He} + n (0.025\text{eV}) \rightarrow ^3\text{H} + ^1\text{H} + 765\text{keV}\]

\[^{10}\text{B} + n (0.025\text{eV}) \rightarrow ^4\text{He} + ^7\text{Li} + 2.31\text{MeV} + \gamma (0.48\text{MeV}) (93.7\%)\]

\[^{10}\text{B} + n (0.025\text{eV}) \rightarrow ^4\text{He} + ^7\text{Li} + 2.79\text{MeV} (6.3\%)\]

Each of these reactions is exothermic. Simply put, they result in the release of energetic ions, and subsequent separable charge formation, within the chamber. \(^3\)He is a
highly thermal-neutron-sensitive isotope (i.e., it has a very high microscopic neutron-capture cross-section at thermal neutron energy) that produces moderately energetic reaction products upon neutron capture. When $^3$He is contained at higher than atmospheric pressures, the probability of an incident neutron encountering a $^3$He nucleus increases as well. Upon a neutron capture by a $^3$He atom, the particle is converted through a nuclear reaction into a proton ($^1$H) and a triton ($^3$H). The resulting charged daughter particles travel in opposite directions, depositing their energy in the $^3$He. The anode is a thin wire running through center of the tube’s long axis, while the cathode is the cylindrical inner shell. A voltage applied across these electrodes generates an electric field within the tube, from which the e-i pairs are separated. To ensure a negligible recombination of the e-i pairs, the applied electric field must be sufficiently high, typically 1200 to 2000-V. Once the e-i pairs reach the anode/cathode the electric potential peaks. These peaks are filtered and integrated by a voltage discriminator, generating the appropriate action on the user interface.

$\text{BF}_3$-filled neutron detectors operate under the same principles as $^3$He-filled detectors. At the occurrence of neutron capture, the $^{10}$B nucleus separates into a stable lithium ion and an alpha particle. The total sum of the energies of these daughter particles is 2.79 MeV 6.3% of the time. The remaining 93.7% of the time, the lithium nucleus is left briefly in an excited state. Upon decay of the excited lithium ion, a 0.48 MeV gamma ray is emitted, which is unlikely to deposit its energy within the chamber unless additional gamma-sensitive materials are introduced.
Gas-Filled Fast Neutron Detectors

Gas-filled fast neutron detectors operate under the principle of nuclear recoil by elastic scattering. This is achieved most successfully with the use of low-Z gasses. Upon an elastic scattering event, the traveling free neutron imparts a portion of its kinetic energy on the target nucleus, which—in turn—ionizes the proximate gas of the chamber. Helium-4 ($^4\text{He}$) and methane ($\text{CH}_4$) are two common fill gasses.

Semiconductor-Based Neutron Detectors

Primarily implemented as $\text{pin}$-junction diodes, thin-film-coated semiconductor-based neutron detectors receive a thin neutron-reactive coating on the top surface that acts as a neutron conversion layer. Early $\text{pn}$-junction-based neutron detectors consisted of an appropriately doped Si wafer, coated on one surface with an appropriate neutron-reactive material. Common neutron-reactive materials are lithium-6 fluoride ($^6\text{LiF}$), boron-10 ($^{10}\text{B}$), and gadolinium (Gd). As is the case with gas-filled neutron detectors, the neutron detection transduction process is dependent on ionized secondary reaction products. One of the most common thin-film coatings is $^6\text{Li}$. The lithium isotope has a reasonably large thermal neutron absorption cross-section of $\sigma_a = 940$ barns. The highly energetic ions produced in this absorption reaction make it a good candidate for use in solid-state thermal neutron detector. The $^6\text{Li}$ neutron reaction is:

$$^6\text{Li} + ^0\text{n} \rightarrow ^3\text{H}(2.73 \text{ MeV}) + ^4\alpha (2.05 \text{ MeV}), Q = 4.78 \text{ MeV}$$

where $^3\text{H}$ is a triton, $\alpha$ is an alpha particle, and $Q$ is the quantity of energy released by the reaction. Given the low energy of the incoming neutron, the alpha particle and the triton are ejected in opposite directions. This is important when considering how to best collect the
maximum possible energy from the motion of the charged daughter particles. The theoretical maximum intrinsic efficiency for planar type neutron detectors is limited by the mean free path of a single charged daughter particle.

The MSND

The MSND, designed and developed at S.M.A.R.T Lab at Kansas State University, is constructed by first etching high-aspect-ratio micro-structured trenches into a high purity, 18 kΩ-cm, and lightly doped n-type silicon substrate. Following the micro-structuring process, conformal diffusion of a p-type dopant within the micro-structures, as well as n-type dopant diffusion on the back side, forms the pin junction. The micro-structures are then backfilled with $^6\text{LiF}$, and a back contact of titanium-gold (Ti-Au) is evaporated on the backside of the wafer [12].

![Illustration of the MSND diode showing the $^6\text{Li}(n,\alpha)^3\text{H}$ reaction](image)

Figure 1: Illustration of the MSND diode showing the $^6\text{Li}(n,\alpha)^3\text{H}$ reaction

One pitfall of Si-based neutron detector technology is the existence of thermally induced current (thermal noise) and leakage current. These phenomena create an undesirable current on top of the transduction signal line. A limiting factor of the maximum efficiency of the MSND is dependent on the peak current of the noise. A lower level discriminator (LLD)
is used to filter out the undesirable portion of the signal. The value of the LLD is set such that minimal noise passes through the signal line, leaving only the current resulting from a neutron interaction event. An improvement on planar type detectors, MSND’s have the ability to capture energy of both reaction products (Figure 1) which results in greater ionization of the semiconductor, and therefore, a greater peak signal amplitude. Earlier-generation MSND’s yielded thermal neutron detection efficiencies of approximately 20% [13]. Recent improvements in the MSND fabrication process have reduced the leakage current and capacitance resulting in 4 cm$^2$ MSND’s with a thermal neutron efficiency of 30% [13, 14].

The Handheld Radiation Monitor

The handheld radiation monitor (HRM) was used extensively for this research. Manufactured and distributed by Sensor Technology Engineering, the HRM (Figure 2 and tables 1, 2) is a neutron and gamma-ray detector, and is the primary radiation detection instrument used by special U.S. Navy teams during primary screening visit, board, search, and seizure (VBSS) operations. Within the scope of general radiation detection operations, the HRM is primarily used to monitor illicitly transported nuclear materials.
Table 1: HRM Radiation Detection Specifications

<table>
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<tr>
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<th>Gamma Detector</th>
<th>Neutron Detector</th>
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<tr>
<td>CsI(Tl)</td>
<td>0.5 inch dia. (1.3 cm) by 1.5 inches long (3.8 cm)</td>
<td></td>
</tr>
<tr>
<td>8.3 abs. atm. $^3$He</td>
<td>0.75 inch dia. (1.9 cm) by 4.8 inches long (12.2 cm), 1.81 cubic inch volume</td>
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Table 2: HRM Device Specifications

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</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>8.3 inches (21.2 cm) by 2.0 inches (5.1 cm) by 1.2 inches (3.0 cm)</td>
</tr>
<tr>
<td>Weight</td>
<td>13 oz. (369 g) w/ battery</td>
</tr>
<tr>
<td>Operation Temp. Range</td>
<td>-13 °F (-25 °C) to 122 °F (50 °C)</td>
</tr>
<tr>
<td>Battery</td>
<td>3 V lithium CR123, 1 month continuous operation</td>
</tr>
<tr>
<td>Gamma energy Cutoff</td>
<td>≈ 45 keV</td>
</tr>
<tr>
<td>Integration Time (Response Time)</td>
<td>&lt; 1 second</td>
</tr>
</tbody>
</table>
The gamma detection portion of the HRM is comprised of a gamma-sensitive thallium-doped cesium iodide crystal (CsI(Tl)); a miniature photomultiplier tube (mini-PMT), which amplifies the photon-induced current of the scintillator; and the necessary pulse handling electronics. The neutron detection portion of the HRM is comprised of an 8.3 abs. atm. \(^3\)He tube, a high-voltage boost converter, necessary for functionality of the \(^3\)He tube; and necessary pulse handling electronics. The entire assembly is powered by a single CR123 battery.

![Neutron Kinetic Energy vs Neutron Wavelength](image)

*Figure 3: Typical \(^3\)He neutron responses as a function of pressure and neutron wavelength. At 8.3 abs. atm., the neutron conversion efficiency for \(^3\)He is approximately 82%*

At 8.3 atm, the \(^3\)He tube currently in use in the HRM has an approximate 82% thermal neutron conversion efficiency (Figure 3). Even though this is a high efficiency for any neutron-sensitive material, being a non-moderating type neutron detector limits the HRM’s detection ability to a relatively small window of possible neutron energies.
U.S. Radiation Detector Market Analysis

According to IBISWorld, a long-range industry forecasting market research organization, the annual radiation measurement device manufacturing industry revenue had risen to $938.1 million in the year 2012 [21]. The industry demand for radiation detection products tends follow the rise and fall of national economic performance. This effect is offset, to a smaller degree, by demand from medical and governmental sectors which are less susceptible to economic hardships. Following the 2011 tsunami in Japan and meltdown of the Fukushima power plant, radiation detector revenue increased by 19.6% within a year. IBISWorld also forecasted that the annual revenue of the radiation device manufacturing industry will increase by an average rate of 3.5% per year from 2012 to 2017. This is a substantial increase over the reported growth rate of 0.6% from 2007 to 2012. With continued national economic improvement, nuclear science related industries are likely to expand budgets, leading to increases in research and development funding and device production.

In 2012, sale of handheld/portable type radiation detectors accounted for 42% of the radiation detection market (Figure 4). Since then, the handheld radiation detection industry continues to gain market share. This is due to a variety of factors including: increased technological advancement, increased reliability, increase in private consumer purchases, and increased portability.
U.S. $^3$He Market Analysis and Drawbacks

The primary source of national demand for $^3$He comes from national security applications and other neutron detector applications. The U.S. weapons program’s stockpile of $^3$He reached roughly 235,000 liters in 2001. That same year, $^3$He demand began to exceed its production. In 2010 the increase in demand of $^3$He reduced the US stockpile to roughly 50,000 liters [22]. There are various sources for increasing nation $^3$He supply, including production in light-water and heavy-water nuclear reactors, production in particle accelerators, and importation from other countries. Projections indicate that US demand for $^3$He will continually be beyond any increase in supply in the near future.

Continued national use of $^3$He-based neutron detectors carries with it some foreseeable and existing issues including, but not limited to, an inability to field service the device and the likelihood of decreased future supply. Field servicing the device requires a thoroughly trained operator to work with the necessarily high voltages (approximately 1400 V) associated with a high-pressure proportional counter. Further, the production/collection of $^3$He is continually decreasing due to depletion in supply and a lack of production from tritium decay, a major method for producing $^3$He.
Since 2003, the Department of Energy (DOE) has resumed tritium production at the Watts Bar reactor in Tennessee. Given the half-life of tritium ($\approx 12.3$ years), it would take some time to replenish $^3\text{He}$ stockpiles. Currently, the Watts Bar irradiation site accounts for approximately 8,000 liters of new $^3\text{He}$ per year. It should be noted that since the call for $^3\text{He}$ alternative technology the auction cost has decreased, indicating a nontrivial decrease in consumer demand.

**Thesis Structure**

The remainder of this thesis is laid out in the following manner: Chapter 2 presents the tools and methods used to efficiently and relatively accurately design a variety of MSND handheld neutron detectors via simulation and empirical methods. It will present the “Domino” neutron detector, which has stood as the basis of nearly all first-generation designs, along with each of the first-generation detectors and their components. The second-generation detectors are also presented in Chapter 2. The third chapter will present the third-generation handheld neutron detector assembly design along with a more detailed discussion of the effects of elastic scattering of free neutrons by hydrogen-rich materials. Chapter 4 presents the experimental method of impedance spectroscopy and its application to the pin-junction-based neutron detector. Finally, the fifth chapter presents a number of goals for future work.
CHAPTER 2

FIRST AND SECOND-GENERATION NEUTRON DETECTOR DESIGNS

This chapter will present much of the work that lead to the high-pressure $^3$He replacement (HP-HeRep) neutron detector. Numerous simulations were performed in order to determine the most appropriate means of comparing many neutron detector assembly designs against one another. The primary purpose of the HP-HeRep is to aid a user in the location of neutron emission sources. As such, a method was derived in order to determine the effect on the neutron detection efficiency by an operator. Once the testing method was finalized, a series of first-generation handheld neutron detection assemblies were assembled and compared to simulated analogues, along with an existing high-pressure $^3$He neutron detector.

Introduction to MCNP

Monte Carlo methods are a class of computational algorithms that iteratively apply random number sampling to numerically approximate solutions to stochastic problems. These methods are particularly useful for simulating problems with high degrees of freedom. The Monte Carlo N-Particle transport code (MCNP), developed at Los Alamos National Laboratory, applies the Monte Carlo method to simulate sequential processes dictated by probabilistic events (neutron cross-section). The Evaluated Nuclear Data File (ENDF), which contains continuous-energy nuclear and atomic probability data, is the primary library from which MCNP operates. Additional libraries include: the Advanced Computational Technology Initiative (ACTI), the Evaluated Nuclear data Library (ENDL), the Evaluated Photon Data Library (EPDL), and the Activation Library (ACTL).
When preparing to perform a simulation with MCNP, the user defines every surface within all 3-dimenisonal space, as well as the material enclosed by those surfaces. Along with defining the material of the problem, the user defines which nuclear data file is retrieved. The next step is to define the radiation source and particle emission information, as well as what type of resulting data is presented. The process of scoring parameters in MCNP (e.g. surface current or flux, track length estimates of cell flux, pulse height, etc.) is known as tallying. For the work presented here, MCNP5 was used to carry out all time-independent simulations.

Effects of Human Scattered Neutrons on Detection Efficiency

The Medical Internal Radiation Dose (MIRD) phantom is an anthropomorphic computational phantom developed in the 1960’s at Oak Ridge National Laboratory. It is composed of more than 100 regions of interest, including all major internal organs, and is specifically designed for use in radiological science studies. We have postulated that during unknown neutron source search scenarios, the most efficient method for locating unknown illicit neutron sources is to take advantage of the moderating effects of the operator’s body. A series of simulations were performed with the objective of determining the position at which a handheld thermal neutron detector generally receives the most favorable neutron fluence as a result of human-induced neutron moderation.
Each simulation included the MIRD phantom, a planar neutron source, and nine tally boxes as depicted by Figure 5. The nine tally boxes, each with dimensions of 6 inches by 6 inches by 1 inch, have no matter within them and are used as a means of tracking position-dependent neutron fluence directly from the neutron source, and from neutrons scattered by the phantom. These tally boxes were placed in 6 inch increments from the surface of the torso of the phantom.

Two simulations were performed. The first involved neutrons of energies ranging from $10^{-9}$ to $10^{2}$ MeV. In this case, the possible neutron energies were binned in discrete, logarithmically increasing energy bins, each bin having an equal probability of emitting a neutron. The planar neutron source, which acts as an approximation of a realistic source very far away, had dimensions of 40 by 75 cm, the same as the torso of the phantom.

Figure 5(b) shows the path of neutrons that passed through one or more of the tally boxes out of the 250 emitted neutrons. The red tracks represent neutrons that came
unimpeded from the neutron source (henceforth referred to as source neutrons). The green tracks represent neutrons that have undergone one or more scattering events within the phantom before passing through one or more of the tally boxes (henceforth referred to as scatter neutrons). For this simulation, of the 250 emitted neutrons, 35 source neutrons were tallied and 7 scattered neutrons were tallied. Across all tally boxes, neutron fluence increased by approximately 20%, as seen in Figure 6.

![Figure 6: Normalized total, source, and scatter neutron intensities vs. tally box position.](image)

As was expected, the greatest fluence across a tally box occurred nearest the phantom and decreased with increasing distance from the phantom. The increase in neutron fluence at the tally box nearest the phantom was nearly 15% and dropped to about 5% at the tally box 6 inches from the surface of the phantom.
Figure 7: (a) $^{252}\text{Cf}$ total and source neutron intensity vs. neutron energy for all tally boxes. (b) $^{252}\text{Cf}$ scatter and source neutron intensity vs. neutron energy for all tally boxes.

By simulating the energy of each neutron as it enters a tally box, it is possible to compile energy spectra. The plots of Figure 7 display the energy spectra of total neutron fluence at each tally box (a), as well as the scattered neutron fluence at each tally box (b). For each plot in Figure 7, the low energy peak is due to the high elastic scatter microscopic cross-section of hydrogen in this region. The total neutron intensity plot indicates that the high-energy region is dominated by source neutrons. Comparing the difference between each plot reveals that high-energy neutrons are thermalized by the phantom and increase the thermal fluence at the tally boxes.
The plot of Figure 8 displays the total fluence, the source fluence, and the scatter fluence of the tally box at 6 inches from the surface of the phantom for a californium-252 (\(^{252}\text{Cf}\)) neutron source. The high energy region is dominated by fast moving free neutrons while the thermal and epi-thermal region involves both thermal source neutrons and thermalized fast neutrons. \(^{252}\text{Cf}\) emits far more high energy neutrons than it does thermal and epi-thermal neutrons. These neutrons are typically undetectable by thermal neutron detectors, unless thermalization occurs.

This result indicates that for scenarios where the location of a neutron source is unknown, or if one is present at all, it is beneficial to keep a handheld thermal neutron detector nearest the body of the operator.
First-Generation $^3$He Replacements

*Domino Neutron Detector*

Designed and developed by Radiation Detection Technologies (RDT) at Kansas State University, the Domino Neutron Detector, or “Domino”, is a semiconductor-$^6$Li indirect-conversion micro-structured neutron detector (Figure 9). Its thin form factor and high thermal neutron detection efficiency make it an ideal candidate as the fundamental detector of a solid-state handheld neutron detection assembly.

![Figure 9: Image and side view of a Domino neutron detector from Radiation Detection Technologies.](image)

Domino type neutron detectors have two key components: the electronics, and the $^6$LiF-backfilled MSND. Each essential electronic component is mounted onto an FR4-based printed circuit board (PCB). The electronics package converts the neutron detection signal to a digital output through standard front-end processing (preamplifier, shaping amplifier, discriminator, and analog-to-digital converter). Each Domino has one male and one female 10-pin connector for data read-out. Additionally, the 10-pin connectors allow Dominos to be “tiled”, cascading the signal of one Domino through another. This feature improves the Domino’s versatility by making it possible to collect the signal of a multi-Domino assembly through a single Domino output. The remaining pins, not reserved for signal transmission, are dedicated to power supply, threshold resistances, and ground lines. Physically, a single
Domino detector measures 3.945 by 2.545 by 0.514 cm and requires 2.8 to 5.5 VDC input to operate.

Each Domino is approximately 20% thermal neutron detection efficient at room temperature. Based on the Domino design, increases in ambient temperature result in thermal excitation of carriers which add to spurious activity of the output signal. For the Dominos used in the second-generation prototype assemblies, the static threshold voltage resistor was replaced with a user-controlled variable resistor, providing the user the ability to appropriately accommodate changes in ambient temperature. Although adjusting the threshold level reduces spurious/false counts, it also reduces the detection efficiency of the MSND. (Note: For the remainder of this thesis the term “threshold” or “threshold level” will be a direct reference to the resistance value used to increase the comparator level or lower level discriminator value that in turn reduces spurious/false detections.) To increase the energy range of possible detection events with a Domino-based system such as this, high density polyethylene (HDPE) is placed on or near the detectors. This has the effect of favorably scattering the neutron fluence such that an increased number of thermal neutrons are incident on the MSND’s, thus increasing the detection efficiency of the assemblies.

First-Generation Neutron Detector Assembly Study: Simulation, Setup, and Results

The initial design constraints were such that the assembled detectors must fit within the case of the HRM. Varying the orientation and number of Dominos, both with and without HDPE, MCNP was used to simulate the neutron sensitivity of each proposed detector configuration. Due to high computational resource demand of the simulated MSND, all MCNP simulations of the diode portion of the Domino detector were defined as a simple cube of dimensions equal to that of the MSND. The cube was comprised of the same
materials as the actual Domino diode, $^6$LiF and Si, with the $^6$LiF content adjusted for 22% normal incident thermal neutron efficiency. This method of approximation is herein referred to as the “block” approximation. Once simulated, each HRM replacement design configuration was replicated in the lab so that a comparison between simulated and empirical data could be made. The $^3$He tube of the HRM was also simulated and empirically tested for further comparison. Figure 10 depicts each first-generation detector assembly.

For each simulation, the assemblies were oriented in a similar fashion on the torso of the MIRD computational human phantom. Defined as a point source, the neutron emission source was placed 60 cm from the front surface of the phantom at chest height so that the detector assemblies were directly between the source and the phantom.

Figure 10: First-generation assembly description: (*Note: “bottom” refers to side nearest the phantom, “top” refers to side nearest the neutron emission source, and “center” refers to a position between detectors within a single detector assembly along an axis going from the source to the phantom). Individual assembly descriptions listed below.

1. HRM: $^3$He tube of the HRM. Long axis oriented vertically.

3. **16 Element**: A single un-modderated 16 Element detector board. Sixteen total 1 cm\(^2\) MSND’s.

4. **7SSD**: Seven stacked Domino detectors, each separated by 0.25 inches of neutron moderating HDPE. The entire assembly is also surrounded by 0.25 inches of HDPE. Seven total Domino detectors. Long axis oriented vertically.

5. **1x7**: A single row of tiled Dominos. Seven total Dominos. Long axis oriented horizontally.

6. **1x7 w/ HDPE**: A single row of tiled Domino detectors with 0.25 inches HDPE placed on the top of the Dominos. Seven total Dominos. Long axis oriented horizontally.

7. **3-4**: 2 stacked layers of four tiled Dominos on bottom and three tiled Dominos on top. Long axis oriented horizontally.

8. **3-4 w/ HDPE Top**: The same as the 3-4 configuration, with the addition of 0.25 inches HDPE placed on top of the detectors. Long axis oriented horizontally.

9. **3-4 w/ HDPE Center**: The same as the 3-4 configuration, with the addition of 0.25 inches HDPE placed between the two layers of Dominos. Long axis oriented horizontally.

10. **3-4 w/ HDPE Top & Center**: The same as the 3-4 configuration, with the addition of 0.25 inches of HDPE placed on top of the detectors as well as between the two layers of Dominos. Long axis oriented horizontally.

11. **Saw-tooth**: Row of six Dominos oriented such that each Domino’s planar orientation is 45° to the one next to it. Long axis oriented horizontally.
12. Saw-tooth w/ HDPE: The same as the saw-tooth, with the addition of HDPE filling the available cubical volume. Long axis oriented horizontally.

13. Wedge: Two columns of three tiled Dominos oriented such that the two columns’ planar orientation is 90° to the one another. Long axis oriented vertically.

14. Wedge w/ HDPE: The same as the wedge, with the addition of HDPE filling the available cubicle volume. Long axis oriented vertically.

![Figure 11](image)

Figure 11: (a) Drawing of the first-generation simulation setup. (b) Overhead photograph of a first-generation laboratory experiment in progress.

Through extensive study it was found that, in a general search scenario, the neutron detectors perform best when positioned on the chest of the phantom. Consequent to a neutron closely passing by the detector and entering the surface of the phantom, there is an increased probability that this neutron may undergo multiple scattering events within the phantom and pass back through the neutron detector, thus increasing the absolute detection efficiency of the assembly.

For laboratory testing of the prototype detector assemblies, a phantom stand-in was required. It was found that a water-filled container, approximately the same size as a human
torso, was a suitable analogue. Figure 11(b) is an overhead photograph of an experiment in process with the large container of water serving as a stand in for a human operator.

The Dominos of any particular assembly were either tiled (when possible) or connected via a wiring harness to one another, linking the power in and signal out components. For each detection event, regardless of which Domino the event occurred in, a pulse was sent to a Keithley model 776 programmable desktop counter/timer, giving a result of total detections in a given time period. Each Domino-based assembly was powered by a GW Instek GPS-18500 power supply. With the experimental time known, as well as the emission rate of the $^{252}$Cf neutron source, it was then possible to determine the absolute detection efficiency given by:

$$
\epsilon_{Abs} = \frac{\text{total detected neutrons}}{\text{total emitted neutrons}}.
$$

![Graph](image)

Figure 12: First-generation neutron detector assembly simulated and empirical absolutely efficiency. The table relates assembly name with assembly number.

<table>
<thead>
<tr>
<th>Device #</th>
<th>Device Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HRM</td>
</tr>
<tr>
<td>2</td>
<td>Single Domino</td>
</tr>
<tr>
<td>3</td>
<td>16 Element</td>
</tr>
<tr>
<td>4</td>
<td>7SSID</td>
</tr>
<tr>
<td>5</td>
<td>1x7</td>
</tr>
<tr>
<td>6</td>
<td>1x7 w/HDPE</td>
</tr>
<tr>
<td>7</td>
<td>3-4</td>
</tr>
<tr>
<td>8</td>
<td>3-4 w/HDPE Top</td>
</tr>
<tr>
<td>9</td>
<td>3-4 w/HDPE Center</td>
</tr>
<tr>
<td>10</td>
<td>3-4 w/HDPE Top &amp; Center</td>
</tr>
<tr>
<td>11</td>
<td>Sawtooth</td>
</tr>
<tr>
<td>12</td>
<td>Sawtooth w/HDPE</td>
</tr>
<tr>
<td>13</td>
<td>Wedge</td>
</tr>
<tr>
<td>14</td>
<td>Wedge w/HDPE</td>
</tr>
</tbody>
</table>

Figure 12 displays the simulated and experimental absolute efficiencies for all 14 prototype assemblies. The 3 assemblies with the highest detection efficiencies are the 16 Element, the HRM, and 3-4w/ HDPE Top & Center, in that order. There are a variety of
effects that have led to this result. Probably the most important factor is that, during testing, the neutron source was oriented normal to each assembly, therefore the 16 Element had the greatest detector surface area directly exposed to the neutron source without additional detectors or detector board FR4 absorbing neutrons or displacing the detector away from the human moderator interface. This exact configuration, however, is not practical in a real-life search scenario. When attempting to locate a hidden source, the orientation of the detection assembly relative to the source will vary. Because the 16 Element had no HDPE around it, when the source was placed to either side of the assembly, it performed relatively poorly.

For the same reason that the 16 Element performed well, one would expect that the 1x7 would outperform the 3-4 w/ HDPE Top & Center. The scattering effects of the HDPE must, to some extent, overcome the lack of directly exposed detector area in the 3-4 configuration. It is clear that placing one Domino in front of another has a detrimental effect on the total absolute efficiency of the assembly. This is primarily due to the fact that neutron absorptions by boron within the FR4 material of the front detector decrease the number of neutrons incident on the detector behind it. This detriment to efficiency, caused by stacking Dominos, does not decrease efficiency as much as increasing the number of Dominos increases efficiency.

There was also a very distinct discrepancy between simulated and experimental results. It is believed that this discrepancy is due to the simulated “block” approximation that was discussed above. The increase in neutron sensitivity due to the micro-structuring of the Domino detectors appears most profound at small angles normal to the surface of the detector face. For an incident neutron that happens to be perfectly normal to the detectors surface, there is somewhere under a 50% chance that the neutron will pass through the $^6\text{LiF}$ cap layer.
and directly into a Si column. These neutrons have a relatively poor probability of being detected. For neutrons that are not normally incident, if an interaction does not occur in the cap layer, there is still a relatively high probability of interaction within a $^6$LiF trench.

Based on the results of simulations and laboratory tests, three fully portable solid-state neutron detection assemblies were designed and assembled for second-generation testing.

**Second-Generation Neutron Detector Assemblies**

A primary objective, regarding the $^3$He replacement, was to design a neutron detector assembly that is fully portable and comparable in size and neutron detection efficiency to the HRM. Requiring full portability for the handheld neutron detector designs necessitated that the power supply component and the pulse handling component both be made portable.

**Digital Counter Board**

Designed and developed by a neutron detection system research and development company, U2D, a digital counter board was implemented to count the resulting pulses and display data to the user. The key components of the board are: 1) eight female 10-pin connectors that receive the Dominos, 2) a Bluetooth LE transceiver, 3) one 3.7 V lithium battery, 4) digital potentiometers for threshold adjustments by the user, 5) an LCD display, and 6) the necessary Firmware programming.

Each counting circuit board can receive up to eight individual Domino neutron detectors (although more may be tiled into the detectors) via the 10-pin connectors. In
addition to the signal lines, the connectors route redundant ground lines, the threshold resistance I2C communications, a 3.3 V supply voltage, and the neutron count signal. The readout and threshold resistance control links via Bluetooth to an iPod Touch acting as the handheld control unit.

The power required to operate the board and the Domino neutron detectors is supplied by a single CR123 battery with a 1500 mAh rating at 3.7 V. For an average current draw of 7 mA, a CR123 battery is capable of powering an 8 Domino assembly for ~200 hrs.

![Image of the board](image)

*Figure 13: Counter circuit for detector assemblies.*

Wireless reach-back to the user is achieved with integrated Bluetooth LE (Bluetooth 4.0) transceivers. The maximum range of communication with Bluetooth 4.0 is 40 ft. This allows the assembly to be placed in a high dose area while the user remains at a safe standoff distance. Neutron count data, internal assembly temperature, and remaining battery power may be viewed by the user in two ways. The primary interface is the aforementioned iPod Touch. Sent wirelessly, data is displayed in multiple formats (Figure 14). Software integrated into the iPod Touch may display real-time plots of the integrated neutron count rate for all connected neutron detectors, or it may be displayed in a numeric form as counts.
per second for each connected neutron detector. An alternative method for viewing real-time count data is via an LCD screen mounted directly to the counter board (Figure 13).

![Figure 14: Two data display options on the iPod touch control units for the handheld detectors. (a) Counts per second on individual detectors and summed counts. (b) Graph of total counts per second.](image)

The firmware of the digital counter board was written in embedded C and stored on an MSP430 chip. The MSP430 chip serves multiple purposes. The chip: (a) monitors the temperature of the counter board through a temperature sensor embedded in the Bluetooth LE chip; (b) handles the data passed via the Bluetooth transceiver; and (c) sends user command communications. The neutron counts are integrated by the firmware and displayed as counts per second for all connected neutron detectors. Neutron count rates and individual neutron counts are transmitted over Bluetooth and written into a CSV type file on the iPod Touch.
Second-Generation Si-Based Neutron Detectors

To broaden the scope of obtainable information, three very different handheld assemblies were built (Figure 15) as second-generation $^3$He replacement neutron detectors. Those assemblies are:

1. **Stacked**: This assembly consists of 3 stacks of 4 Dominos (12 total). The purpose of this assembly was to determine detection efficiency with the highest attainable MSND per unit volume that could possibly fit within our volume constraint. As discussed previously, the FR4 of each Domino decreases the absolute efficiency of the Domino behind it, yielding diminishing returns.

2. **4-2**: This assembly consists of 2 layers of 4 Dominos (8 total). Its 2 layers are encased in HDPE and 30° off parallel with one another. This angle slightly decreases the efficiency when a source is directly in front of the assembly but improves its angular detection efficiency. The entire assembly has approximately 170-cm$^3$ HDPE.

3. **16 Element**: A single 16 Element board containing 16 separate MSND’s. This assembly has the greatest amount of directly exposed MSND surface area. It was expected that when the full area of the MSND’s was exposed to a thermal neutron
source, it would have the greatest efficiency of all three assemblies. Because there is no HDPE to scatter neutrons into the assembly at large angles to a source, it was also expected that this assembly would realize the greatest decrease in efficiency as the angle between the plane of the detectors and the incident neutrons approached $90^\circ$.

Figure 16: Modifications to the HRM used to collect data for analysis and comparison with prototype handheld units.

To determine the detection efficiency of the prototype designs relative to the HRM, a one-to-one comparison with the HRM was required. To achieve this, time-dependent neutron count data from the HRM was also collected and recorded. In order to capture the neutron count data of the HRM, a counter board from the prototype handhelds was re-purposed to record neutron data as detected by the HRM. As neutrons are detected in the $^3\text{He}$ tube, a converted power signal is sent to the LED of the user interface, illuminating it during single neutron detections. A jumper wire was placed in the signal path of the LED, re-directing the signal to the counter board (Figure 16). This temporary modification allowed real-time neutron data from the HRM to be recorded on an iPod and compared to data for the prototype replacement designs in the same source/moderator configurations without compromising the HRM.
Second-Generation: Experimental Setup, Results

Continuing the use of a human stand-in, during the second-generation experiments, each assembly was mounted to a water filled container (trashcan). Subsequently, each assembly (with water container) was then placed onto a platform so that each assembly was at the same height of the center of the neutron source. Figure 17 displays an experiment in progress. Tests were performed in an open field. Concentric rings were drawn about the neutron source at 50cm increments from 50 cm to 10 m. The neutron source was $^{252}$Cf with an emission rate of $4.43 \times 10^5$ neutrons per second placed within a moderating source container (MOD $^{252}$Cf). Data was collected for multiple source configurations: Bare MOD $^{252}$Cf; MOD $^{252}$Cf plus 1 inch of HDPE moderator; MOD $^{252}$Cf with $\text{H}_3\text{BO}_3$ improvised shielding; as well as MOD $^{252}$Cf with $\text{H}_3\text{BO}_3$ and 1 inch HDPE moderator.

![Second-Generation Experimental Setup](image)

Figure 17: Second-Generation Experimental Setup

Before collecting neutron count data, a thorough background was collected for each assembly. Background data was collected approximately 200 m from the MOD $^{252}$Cf source for upwards of 10 minutes. For each neutron detection experiment, total counts were recorded as a function of time. Readings were taken at distances ranging from 50 cm to 4 m in 50 cm increments. Data was collected with the handheld detector assemblies facing
directly toward the source, as well as with the assemblies pointing 90° and 180° away from the source.

Upon analysis, the source configuration which resulted in the highest neutron count rate occurred when the MOD $^{252}$Cf source had an additional 1 inch of HDPE on all sides. The $^{252}$Cf emitted neutrons undergo some moderation within the MOD $^{252}$Cf HDPE and undergo further moderation within the additional HDPE. The $^{252}$Cf energy spectrum is such that the vast majority of emitted neutrons are well above the thermal region. The additional moderation of $^{252}$Cf epi-thermal neutrons results in a substantial increase in free thermal neutrons.

For each of the source configurations, the 16 Element assemblies maintained the highest count rate. This confirms the previously proposed hypothesis that the 16 Element’s

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*Figure 18: Count rate vs. distance from source for each source configuration.*

Upon analysis, the source configuration which resulted in the highest neutron count rate occurred when the MOD $^{252}$Cf source had an additional 1 inch of HDPE on all sides. The $^{252}$Cf emitted neutrons undergo some moderation within the MOD $^{252}$Cf HDPE and undergo further moderation within the additional HDPE. The $^{252}$Cf energy spectrum is such that the vast majority of emitted neutrons are well above the thermal region. The additional moderation of $^{252}$Cf epi-thermal neutrons results in a substantial increase in free thermal neutrons.

For each of the source configurations, the 16 Element assemblies maintained the highest count rate. This confirms the previously proposed hypothesis that the 16 Element’s
high, uninterrupted MSND surface area is the most efficient solid-state configuration. These plots also indicate that the 4-2 assembly performed well when compared with the HRM.

The angular dependent count rate of each second-generation assembly was also collected. Using the bare MOD $^{252}$Cf source and the same source moderated with 1 inch of HDPE, each assembly was placed 1 m away from the source. Count rates were determined for detectors oriented at 0°, 90°, and 180° relative to the source.

As expected, the 16 Element assembly saw the greatest decrease in count rate at 90°. The stacked assembly also saw a decrease at 90°. Neither assembly includes additional moderating HDPE as part of the assembly. The 4-2 assembly also saw a relatively small decrease between 0° and 90°. This shows the beneficial scattering effect that the HDPE has on this assembly. At 180°, the highest data point occurred with a measurement by the 16 Element without HDPE around the MOD $^{252}$Cf source. This indicates that, at least for a
MOD $^{252}$Cf neutron source, there is an upper limit to the amount of moderation that may occur before an excessive number of neutrons are scattered from the system. Between $0^\circ$ and $90^\circ$, the HRM remained nearly constant due to its inherent symmetry.
CHAPTER 3
HIGH-PRESSURE \(^3\)HE REPLACEMENT

\(^3\)He proportional neutron counters of various sizes and pressures are commonly used for a wide variety of neutron detection and spectrometry applications. Proportional counters are often used as part of Bonner sphere spectrometers, large area portal monitors, and the previously mentioned HRM. A suitable high-pressure \(^3\)He replacement (HP-HeRep) must have the following requisites:

- high neutron conversion/detection efficiency
- low false count rate
- high gamma rejection
- low production/material cost
- low power consumption

\(^3\)He has one of the largest microscopic thermal neutron absorption cross-sections of applicable neutron conversion isotopes. At 8.3 atmospheres, it has a neutron conversion efficiency of about 85%. This value, however, stands as a theoretical maximum for total intrinsic detection efficiency of a \(^3\)He-based proportional neutron counter. In reality \(^3\)He proportional counters suffer from dead zones at each end of the detector, due to required internal insulting components, as well as a radially dependent distribution of neutron sensitivity about the tube’s axial central anode. This makes the active area of any proportional counter smaller than the assembly itself, sometimes up to 30%. Moderating type assemblies address these deficiencies by scattering otherwise undetectable neutrons into a detector’s active detection regions. Because hydrogen has one of the highest probabilities to elastically scatter free neutrons, and cause subsequent thermalization of epi-thermal incident
neutrons, inclusion of hydrogen-rich HDPE as part of a detection system greatly improves neutron detection efficiency. This is especially so, due to multi-scatter neutron reflection, if it is possible to completely encapsulate neutron detectors in HDPE.

In order to find the optimal detector configuration, a series of neutron detection efficiency simulations were undertaken with the MCNP5 software. The first step in simulating real world neutron detectors is adjusting theoretical efficiency maximums of the simulations. At the time of this process, the MSND’s were measured to have a thermal neutron intrinsic detection efficiency of 22%. This value is lower than the theoretical maximum due to the fact that most simulations do not account for thermal and electronic effects on the assemblies. In order to account for these effects, the atomic density of the $^6\text{LiF}$ was adjusted so that the thermal neutron detection efficiency of the simulated MSND was 22%.

Third Generation Design

The high-pressure $^3\text{He}$ replacement was designed in simulation with a cylindrical form factor. This form factor serves two purposes: first to demonstrate the possibility of replacing the $^3\text{He}$ tube of existing systems with Si-based neutron detectors, and second to allow for HDPE to surround the entire assembly as well as within the inner core of the assembly.
Based on previous work and the given space constraints, it was known that the cross-sectional view of the high-pressure $^3$He replacement would take the form of one of the two options presented in Figure 20. One question to be answered by the following simulations was in regard to the contribution to neutron detection efficiency of the central neutron detectors versus the value of having HDPE in the detectors’ place. A direct comparison was made between an assembly with a set of central detectors and an assembly without central detectors.

Another question to be answered was in regard to neutron detection efficiency versus the number of neutron detectors in the axial direction. It is obvious that increasing the number of included detectors increases the efficiency, yet having an analytic trend allows for a financial cost versus efficiency comparison to be made.
Neutron Detector Strips

Figure 21: 3D diagram of a single detector strip and a 5 strip assembly.

The simulated neutron detectors consisted of MSND’s with 400 μm deep and 20 μm wide trenches. Each MSND had dimensions: 1 cm by 1 cm by 500 μm. The HP-HeRep was populated by a number of axially oriented detector strips. Each detector strip is dual sided, populated with MSND’s on each of its two larger faces. The detectors were placed within a ceramic detector housing with outer dimensions of 1.2 by 1.2 by 0.175 cm. Each of the ceramic housings was then mounted directly to the PCB board with dimensions of 1.25 by 0.0508 cm by 1.25*n cm, where n is the number of MSND’s on one face of the detector strip. Figure 21 depicts a single detector strip with 16 total MSND’s, and an assembled HP-HeRep with 5 detector strips and 16 MSND’s per detector. In order to determine the benefit of including HDPE in the final assembly, each assembly was simulated with and without HDPE.

Simulation, Setup, and Results

In an attempt to make the simulation more realistic, simulated neutron emission sources were located in the center of an International Atomic Energy Agency (IAEA) type
source container. Composed of HDPE and lead, the IAEA container shields emitted source gamma rays and moderates emitted source neutrons. It is commonly used to approximate environmental scatter effects. The innermost layer,captaining the neutron source and air, is a cylinder with outer dimensions: 11.608 cm length by 3.556 cm diameter. The middle layer is a hollow lead cylinder with outer dimensions: 14.148 cm length by 6.096 cm diameter. The outermost layer is a hollow HDPE cylinder with outer dimension: 17.958 cm length by 9.906 cm diameter. The source container, along with a $^{252}$Cf omnidirectional point source, was placed 60 cm from the farthest edge of each neutron detection assembly.

As with the work discussed in Chapter 2, a human stand-in was included in the system to provide a more realistic comparison between assemblies (Figure 22). Due to excessive computational cost of the MIRD phantom, a cube of pure H$_2$O was employed in its

\[\text{Figure 22: HP-HeRep efficiency simulation setup.}\]
stead. The H$_2$O phantom has dimensions of 20 by 30.5 by 35.5 cm, similar to a human torso. The reflecting effects of the H$_2$O are similar to that of the MIRD phantom. By using H$_2$O, rather than the phantom, the simulated results are more easily compared to empirical results, as the MIRD phantom is a far more complex structure and not available in the laboratory setting.

The source energy spectrum was defined to be that of a $^{252}$Cf point source placed at the center of an IAEA source container. A series of detector strip geometry simulations were run with the objective of maximizing the theoretical absolute neutron detection efficiency.

![Graph](image)

**Figure 23: Simulated absolute efficiency for each detector assembly.**

Figure 23 displays the absolute neutron detection efficiency results for each simulated HP-HeRep geometry configuration as well as that of an 8.3 atm $^3$He proportional counter. It is evident that maximizing the number of detectors per detector strip yields the greatest increase in neutron detection efficiency. Beyond that, including HDPE in the assembly and
maximizing the number of detector strips within the assembly further improves neutron detection efficiency. The assembly with the greatest efficiency, of $\varepsilon_{th}=4 \times 10^{-5}$ with the phantom, was the assembly with five detector strips, eighteen detectors per strip, and HDPE. The simulated absolute detection efficiency of this assembly was 2.8 and 2.4 times the absolute efficiency of the 8.3 atm $^3$He tube, with and without the phantom respectively.

Final HP-HeRep Design

The final HP-HeRep design features eight 1 cm$^2$ MSND’s, grouped in two series’ of four detectors per side of a PCB strip. Each PCB has six layers for a total of 0.0032 inches in thickness, and 0.510 inches in width. The ceramic detector housing has dimensions: 0.510 by 0.079 inches and is backfilled with a neutron transparent, visible light opaque epoxy. Once assembled the entire strip has a cross-sectional dimensions: 0.510 by 0.190 inches. When the strips are arranged in the final cylindrical geometry the outer diameter of the assembly is 1.050 inches.

There are conducting traces run throughout the layers of the PCB which are used for passing signal for bias, threshold, and discrimination output. Each strip has four single ended, differential output trans-impedance amplifiers which convert the generated e-h pair current to a voltage. Each strip also holds four semi-Gaussian, unipolar output shaping amplifiers which act as the third step of the pulse transduction process. The shaping amplifiers increase the signal voltage, simultaneously reducing the signal-to-noise ratio. The final step in the transduction process is an LLD, one mounted on each detector strip, which outputs a digital signal high when its input signal is above a desired threshold voltage.
CHAPTER 4

IMPEDANCE SPECTROSCOPY

Impedance Spectroscopy (I.S.), was initially developed to determine the double-layer capacitance, which is an effect that occurs when an insulating separator is placed between two electrode materials [23, 25], and in AC polarography of various polarizable systems [26, 27]. In recent years its use and analysis methods have greatly increased, expanding its applicability to characterization of complex interfaces and electrode charge-transport processes [28, 29]. Although I.S. is a powerful tool for characterization of a multitude of devices, it is valuable mostly as a complementary method to be used in conjunction with other characterization methods. For most systems some a priori information is required; such as a detailed knowledge of the geometric structure of the system, doping profiles, and leakage current characteristics.

General Circuit Response

Let us consider an arbitrary electric potential $V(t)$ applied to a resister $R$ and a capacitor $C$ in series. By Ohm’s law and the electric potential equation for a capacitor, we have:

$$V(t) = i(t) \cdot R + \frac{Q(t)}{C} = i(t) \cdot R + \frac{1}{C} \int_0^t i(t) dt$$  \hspace{1cm} (4.1)

The Laplace transform is a common method for solving difficult integro-differential equations. By direct application of the Laplace transform, considering parameter $s$ to be real ($s$ is generally complex), we have:

$$V(s) = i(s) \cdot R + \frac{i(s)}{s \cdot C}$$  \hspace{1cm} (4.2)
By expressing the ratio of electric potential over current, we define the new quantity, impedance, as:

$$Z(s) = \frac{V(s)}{i(s)}$$  \hspace{1cm} (4.3)

The impedance function is a transfer function which transforms the value of applied voltage in the value of current. Combining the impedances of contributing components is analogous to the addition of resistance. For the case of a resistor and capacitor in series, impedance may be written as:

$$Z(s) = R + \frac{1}{s \cdot C}$$  \hspace{1cm} (4.4)

During application of I.S., one is concerned with the frequency-dependent response of a system, $I(t) = I_0 \cos(\omega t + \varphi)$, to an applied sinusoidal potential, $V(t) = V_0 \cos(\omega t)$. By Fourier analysis we may find the real parts (indicated by the single hash mark) and imaginary parts (indicated by the double hash mark) of the frequency-dependent voltage and current:

$$V'(\omega) = \frac{1}{T} \int_0^T V(t) \cos(\omega t) \, dt$$  \hspace{1cm} (4.5)

$$V''(\omega) = -\frac{1}{T} \int_0^T V(t) \sin(\omega t) \, dt$$  \hspace{1cm} (4.6)

$$I'(\omega) = \frac{1}{T} \int_0^T I(t) \cos(\omega t) \, dt$$  \hspace{1cm} (4.7)

$$I''(\omega) = -\frac{1}{T} \int_0^T I(t) \sin(\omega t) \, dt$$  \hspace{1cm} (4.8)

Finally, we write the real and imaginary parts of impedance as:
The complex impedance of our example can now be written as:

\[ Z(\omega) = Z' + iZ'' = R - \frac{i}{\omega C} \quad (4.11) \]

One of the more common ways of displaying complex impedance information is with a complex impedance plane plot, also known as a Nyquist plot. The Nyquist plot is a plot of \( Z'' \) versus \( Z' \), that is the imaginary part of impedance versus the real part of impedance plotted for a range of frequencies. In general, the complex impedance of any circuit may be written as the sum of impedance contributions of resistors, capacitors, and inductors, and applying standard laws of circuit analysis.

The real part of the complex impedance is simply \( R \), and is always purely resistive. As such, the real part of the impedance is not dependent on the frequency. The complex plane plot for a series RC connection consists of a straight line, parallel to the imaginary axis (Figure 24(a)).

For a resistor in series with a resistor and a capacitor in parallel, the complex impedance is written as:

\[
Z(\omega) = Z' + iZ'' = R_1 + \left( \frac{1}{R_2} + i\omega C \right)^{-1}
\]

\[ = R_1 + \frac{R_2}{1 + \omega^2 R_2^2 C^2} - i \frac{\omega CR_2^2}{1 + \omega^2 R_2^2 C^2} \quad \text{(A12)} \]
The limit of the magnitude of total impedance as \( \omega \to 0 \) is: \(|Z| = R_1 + R_2\). The limit as \( \omega \to \infty \) is: \(|Z| = R_1\). The complex plot shows a semicircle with radius \( R_2 \), centered at \( R_1 + R_2/2 \) on the real axis.

\[ \text{Figure 24: Complex impedance plot for resistor and capacitor circuits.} \]

All of the impedance and phase angle information is displayed in the complex impedance plane plot. The phase angle between current and voltage (\( \alpha \)) is shown by the angle between the real impedance axis and each data point for all frequencies. The complement to the phase angle is the loss angle, and is used to find the dielectric loss in the form of heat, for the system. The mean relaxation time in a distribution of time constants, e.g. the time constant (\( \tau \)), is shown by the peak in the increasing imaginary impedance direction. For a simple RC circuit with a series resistance, shown in Figure 24(b), which may represent a realistic dielectric-filled parallel-plate capacitor, the relaxation time constant is given by:

\[ \tau = RC \]
where $R$ is the parallel resistance, $C$ is the parallel capacitance. With the application of a time-varying electric field, the dielectric relaxation process signifies the change in polarization of the material. This change in polarization is a result of the rotation of dipoles back to their state of equilibrium after an electric field is applied.

A useful method used to determine the existence of multiple relaxation frequencies is to analyze the phase-angle vs. frequency plot. For a circuit, or dielectric system, without inductive components, the current resulting from an applied voltage leads the voltage by 0 to 90° (phase-angle). If several phase-angle maxima exist, they each correspond to a different relaxation frequency.

The following sections discuss, in more detail the process of impedance spectroscopy and its application to characterization of a planar type, Si-based neutron detector, and a micro-structured, Si-based neutron detector.

**Planar Neutron Detector and MSND I.S. Characterization**

The development of MSND’s has yielded a considerable increase in solid-state thermal neutron detection efficiency, improved gamma-ray discrimination, and reduced leakage current when compared to previous generations of similar technology [14]. Recently, the major advancements in the field of solid-state neutron detection have been focused on fabrication, geometry and implementation of the detector [15]. Currently, it is not fully understood how the microscopic properties of a micro-structured device differ from its planar type counterpart. As an early step toward the solution of this question, impedance spectroscopy has been carried out on an MSND and a commercial planar type neutron detector.
Developed by the Department of Mechanical and Nuclear Engineering at Kansas State University, in conjunction with Electronics Design Laboratory, at Kansas State University, the MSND is a high efficiency, silicon (Si)-based pin solid-state neutron detector. The particular device used for this study has an area of 1 cm$^2$. The micro-structuring consists of a series of 350 μm deep and straight 30 μm wide vertical trenches separated by 20 μm thick Si fins. A high concentration p-type dopant is conformally diffused into the top surfaces and the microstructures, completing the pin structure. For neutron detection operations, $^6$LiF is backfilled into the etched trenches. It is assumed that the $^6$LiF has no effect on the electronic properties of the device because it is external to the contacts (Figure 25). The second device being studied is a planar, Si-based pin type device. The manufacturing procedure for the planar device is similar to that of the micro-structured device except that the planar device has no micro-structuring. It measures 2 by 2 cm. To function as a neutron detection device, the top layer of the planar device is coated with $^6$LiF. For the planar device, it is again assumed that $^6$LiF has negligible effect on the electronic properties of the device.
As discussed previously, I.S. is the process of measuring the response to DC and small signal AC perturbations of a nonlinear electric system. The information obtained is useful for determining dielectric and charge transport properties of various materials/electronic devices [30].

Experimental Setup and Results

Figure 26: (a) Agilent 4294A impedance analyzer. (b) EM shielded impedance spectroscopy test enclosure.

For data collection, each pin junction device was placed within an EM shielded, four BNC terminal test enclosure. I.S. measurements were carried out with an Agilent 4294A precision impedance analyzer (Figure 26(a)) which employs the four-probe AC measurement method [24]. Data was collected at room temperature for -1 to -9 V bias at 1 V steps over a frequency range of 40 Hz to 80 MHz. Each device was placed within its own test enclosure (Figure 26(b)). The enclosures were electromagnetic (EM) shielded, nullifying any possible ambient electromagnetic interference. In order to mitigate the effects of stray leakage currents and capacitances of the test fixtures, each setup was open and short compensated as well as cable length compensated as discussed elsewhere [25].
Figure 27: Total impedance and phase angle vs. frequency for the MSND and a planar type neutron detector.

The total impedance and phase shift for the micro-structured device and the planar device is shown in Figure 27 for an applied reverse bias of -1 V. The applied small signal AC potential ranged from 40 Hz to 80 MHz. In the low-frequency region the total impedance of each device is due entirely to the capacitive reactance, indicated by the $1/\omega C$ trend. For the planar device, there are two easily identifiable dielectric relaxation time constants, one in the low frequency region and another at about 5 MHz, as indicated by the multiple points of inflection.
Figure 28: Real and imaginary impedance vs. frequency for the MSND and a planar neutron detector.

Figure 28 shows the real and imaginary impedance behavior for increasing reverse bias. For the micro-structured device the real part of the impedance shows a strong dependence on applied reverse bias. The planar device demonstrates a bias dependence as well, but to a lesser extent, implying that the planar device is near fully depleted at low reverse bias.

It can be seen that, for the micro-structured device, the real impedance is dependent on frequency through the entire applied frequency range. At lower frequencies (<500 kHz), the real impedance increases with increasing reverse bias and has a noise contribution at low reverse bias. At high frequencies, the real impedance decreases with increasing reverse bias. It appears that for each reverse bias value, each real impedance line has a similar shape, with
low reverse biases having a greater peak magnitude, at lower frequencies. Increasing the reverse bias decreases the peak value and shifts it to high frequency. The imaginary impedance of the micro-structured device decrease logarithmically with increasing frequency above 40 Hz to 1 kHz, depending on applied reverse bias. The peak of imaginary impedance follows the same trend of real impedance, decreasing in magnitude and increasing with applied reverse bias.

For the planar device, the real impedance logarithmically decreases with increasing frequency up to approximately 10 kHz. Between 100 kHz and 20 MHz the real impedance shows no dependence on frequency. Above 100 kHz, the real impedance has no dependence on applied reverse bias. The imaginary impedance also decreases logarithmically with frequency up to about 5 MHz. At about 20 MHz a broad high frequency peak occurs, which shows no dependence on reverse bias.
Neutron Detector Equivalent Circuit Analysis

The electrical impedance properties of the planar and micro-structured devices have been compared through impedance measurements. Impedance spectra were collected at reverse bias potentials of -1V, -3V, -5V, -7V, and -9V. Illustrated by Figures 29(c) and 30(c) are commonly used Nyquist plots of experimental data and complex non-linear least squares (CNLS) simulated data. Regarding the planar device, the Nyquist plot shows a limited frequency range, implying a time constant at a frequency below 40 Hz. The planar device also shows a more classical capacitor-like behavior when compared to the micro-structured device. The radius of each complex impedance arc (e.g. resistive component) for the planar device shows little dependence on bias while its capacitance shows a relatively strong
dependence on applied reverse bias. The radius of each complex impedance arc for the planar device shows little dependence on bias. This indicates that the net relaxation frequency shifts to higher frequencies with increasing reverse bias.

The Nyquist plot of the micro-structured device appears to be composed of a series of single semicircles with decreasing radius as a function of increasing applied reverse bias potential. Not distinguishable on the Nyquist plots, each device has unseen features in the very high frequency region, which support the addition of RC parallel components to our equivalent circuits. These features are trivial except that they support the idea of each device having multiple relaxation time constants.

By modeling an equivalent impedance circuit on data that was collected from the MSND and the planar-type neutron detector, we were able to make predictions about what electronic features of each device play a significant role in their charge transport. The designation of an equivalent circuit must be based in the real structure of each device. Numerous equivalent circuit models were proposed and fits to the experimental data were attempted. The fits with the least error are those illustrated in Figure 29(a) for the planar device, and Figure 30(a) for the micro-structured device. A typical \textit{pn}-junction equivalent circuit consists of single resistor-capacitor (R-C) parallel component in series with a parasitic resistance. The proposed equivalent circuit for the planar device includes a second time constant, which indicates the possibility of charge insertion or absorption phenomena within the quasi-neutral region.

These models are analogous to intrinsic resistances and capacitances of each device. Figure 29(b) shows a diagram of the \textit{pin} layers of the planar device. For this device, the
The proposed equivalent circuit is a function of the resistivities and capacitances of the SCR and the p-type layer. The p-layer/n-layer interface can be described by $R_{a}C_{a}$ parallel components. The space-charge region can be described by the $R_{b}C_{b}$ parallel components. $R_{S}$ is the series resistance associated with the electric contacts of the device.

The micro-structured device, represented by Figure 30(b), was modeled as two planar devices of different thicknesses placed in parallel. Two R-C parallel components in series are subsequently placed in parallel with two additional R-C parallel components in series. The $R_{1}C_{1}$ and $R_{2}C_{2}$ parallel components represent the resistance and capacitance of the micro-structure fin and trench, respectively. The $R_{3}C_{3}$ and $R_{4}C_{4}$ parallel components represent the SCR resistance and capacitance of the micro-structure fin and trench, respectively.

![Figure 31: Planar neutron detector equivalent circuit parameter values.](image1)

![Figure 32: MSND equivalent circuit parameter values.](image2)

Figures 31 and 32 show deduced resistance and capacitance values for the planar device and micro-structured device, respectively. Regarding the planar device, the series resistance, $R_{S}$, generally increases ohmically with increasing reverse bias. Capacitance $C_{b}$, which corresponds to the capacitance of the SCR, decreases as expected with increasing reverse bias potential. The resistance $R_{b}$ remains relatively constant through the applied
reverse potential range. It is believed that $R_β$ is acting as a shunt resistance, which accounts for increased leakage current with increasing reverse bias. $R_α$ decreases with increasing reverse bias potential while $C_α$ increases. This increase in capacitance implies the existence of an oxide layer at the metal contacts interfaces.

Regarding the micro-structured device, it is assumed that the trench region behaves most similarly to the planar device. It is thought that $C_1$ and $R_1$ correspond to the SCR of the trench region. $C_1$ is relatively small for this device, and decreases with increasing reverse bias. This may indicate that the electric field of this region is relatively uniform in magnitude and charge separation here is most efficient. $R_1$ is very large at low applied reverse bias, decreasing substantially as reverse bias is increased. In this case, large resistance values indicate a good ability to prevent thermally induced noise current. $C_3$ and $R_3$ are thought to correspond to the interface of the trench region. Each show a relatively weak dependence on applied reverse bias.

The column region of the devices may have the most interesting features. $C_2$ and $R_2$ are thought to correspond to the SCR of the column region. Each of these components behaves very similarly to $C_1$ and $R_1$. The resistance is approximately an order of magnitude than the resistance of the trench region. This may indicate that some thermal noise current may be generated in this region but it certainly is not the primary contributor. $R_4$ is thought to be the resistance of the column region interfaces. $R_4$ increases slightly with increasing reverse bias and is very small. It is likely that this is the primary contributor to noise and leakage current. This effect may be a result of inconsistent diffusion and oxidation of the p-type dopant. $C_4$ is also small and may slightly increase with increasing reverse bias.
Conclusions

It has been shown that the planar device used in this study yields a much lower capacitance and higher resistivity than the micro-structured device. The planar device likely has an oxide layer at an interface as indicated by the small $R_a$. Etching micro-structures changes significantly the electric properties of the device, yielding an equivalent resistance on the order of $1000\, \text{M}\Omega$ for low reverse bias. The micro-structured device also shows a much stronger dependence to applied reverse bias than the planar device. The micro-structuring and diffusion processes, necessary for the construction of the MSND, are likely the biggest contributors to the quantity of defects at the interfaces and within the bulk of the MSND’s. Currently, significant effort is being expended in the pursuit of understand the charge transport properties of the MSND. Members of S.M.A.R.T. lab at are analyzing the leakage current properties and the complex electric field of these devices.
CHAPTER 5

FUTURE WORK

A great deal of work remains to develop the HP-HeRep for consumer production. Upon construction of the device, it will be necessary to perform rigorous testing procedure to determine its performance. Goals of the tests include: validate thermal and fast neutron detection efficiency, determine appropriate LLD settings, determine optimal use configuration, and ensure high gamma rejection. It will also be necessary to determine the device’s sensitivity to changes in ambient temperature, and to determine the most beneficial temperature dependent LLD settings.

The HP-HeRep has the potential to be more than a handheld neutron detection device. Used in conjunction with gamma detectors, the device becomes more powerful in its ability to locate radiation sources. It is possible, too, to implement multiple HP-HeRep’s as part of a larger system, possible yielding spectroscopic and source localization information.

To improve the efficiency of the MSND, continued effort should be put forth to understand its charge transport properties. A number of experimental and data analysis methods can contribute to this understanding. Temperature dependent impedance spectroscopy can reveal, in more detail, the major contributors to leakage current. Analysis of leakage current data, in conjunction with complex capacitance analysis, can reveal which electron emission processes are dominant, i.e. Schottky effect, Poole-Frenkel effect, etc.
REFERENCES


VITA

Brent Joyner Rogers was born the 25th of May, 1983 at the Kansas University Medical Center in Kansas City, KS. After graduating from Jefferson City, MO high school in 2001, he began his college career by studying business finance at Park University in Parkville, MO. Upon his graduation from Park, he found a lucrative position within the finance industry. After two years of dispassionately managing other peoples’ riches he decided to leave the world of finance and continue to his education. He eventually developed a passion for the physical sciences and has never looked back.