Cryogenic Irradiation and Low Temperature Annealing of Semiconductor and Optical Materials

DISSERTATION

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By

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Abstract

A Cryogenic Irradiation Facility (CRIF) has been designed, fabricated, and tested for use in the pool of the Ohio State University Research Reactor (OSURR). This CRIF has supported *in situ* radiation induced damage experiments in optical and electronic materials at cryogenic temperatures and temperature controlled low temperature annealing experiments from cryogenic temperatures to above room temperature. The facility has been tested with liquid nitrogen and liquid helium out of the reactor pool. Temperature control has been demonstrated in the experimental volume of the CRIF from 4.2 K to above room temperature. The 10” Dry Tube, which will house the CRIF in the OSURR pool, has been inserted into OSURR pool and tested. The empty 10” Dry Tube and the CRIF have been simulated in a model of the OSURR using MCNP6 to understand the predicted radiation fields and total energy deposition in the empty 10” Dry Tube and in typical optical and electronic materials in the experimental volume of the CRIF. The radiation fields and the total radiation energy deposition have been used to predict experimental operating parameters for CRIF experiments, based upon desired dose calculations and time to boil-off for the liquid helium inside the CRIF.

The CRIF has been used for four sets of experiments on single-mode and multi-mode silica optical fibers, in conjunction with a Luna Optics Optical Backscatter Reflectometer and an optical transmission measurement system, and on GaN High
Electron Mobility Transistors, in conjunction with an integrated NI PXI Electronics Measurements System. These four experiments included (1) cryogenic materials characterization experiments without radiation, (2) gamma-only cryogenic irradiation experiments and low temperature annealing experiments, (3) reactor-on mixed field cryogenic irradiation experiments and low temperature annealing experiments, and (4) reactor-on mixed field room temperature irradiation experiments. These experiments were all completed at the OSU Nuclear Reactor Laboratory. The experiments demonstrated varying effects on the materials under test, depending on the temperature of the experiments and the radiation type, dose rate, and total dose of the experiments. The flexibility of the CRIF, in allowing for in situ measurements during cryogenic irradiation periods and during cooling/heating portions of the experiments, was shown to be vital in observing the complicated combined effects of the cryogenic irradiation.
Dedication

This document is dedicated to the many family members, friends, and mentors that have invested in my education and upbringing. I specifically want to thank my parents, Mariann and Keith Reinke, who have always supported me and engendered in me a passion for learning and a strong work ethic. I also want to thank my sister and brother, Brigitte and Blake Reinke who have always been supportive and encouraging, in all that I do. I want to thank Dr. Thomas Blue, my research adviser and mentor as a nuclear engineering researcher, who has invested countless hours in teaching, training, and supporting me. I would also like to thank Dr. Wolfgang Windl, who has served as a secondary research adviser and teacher, who has helped me understand radiation defect generation simulations. I want to thank Dr. Tunc Aldemir, our program chair, and Dr. Lei Cao for their service on this Ph.D. Examination Committee, and for their support and guidance as teachers and mentors as I look toward my career. I would also like to thank Dr. Christopher Hadad for his service on the dissertation committee as a representative of the graduate school. Finally, I want to thank the many other mentors I have had during my time at OSU, including professors like Dr. Beck, research advisers like Dr. Van Woerkom and Dr. Marx-Scouras, and extra-curricular mentors like Dr. Blake Thompson, who have helped me attain more than I thought possible during my time at OSU.
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Chapter 1: Introduction

1.1. **Purpose of the Proposed Research**

The purpose of this research was to develop and characterize a facility to understand the effects of cryogenic irradiation in mixed fields and the physics of defect generation and low temperature annealing phases of NASA relevant materials, specifically semiconductor materials and optical fibers. In order to understand these effects, the Ohio State University CRyogenic Irradiation Facility (CRIF) was constructed to allow for in situ measurements to be taken at the OSU Research Reactor. The described experiments use the CRIF as a vessel to complete *in situ* cryogenic radiation damage experiments of optical fibers and transistors simultaneously and *in situ* low temperature annealing experiments between LHe temperatures and room temperature.

1.2. **Objectives and Scope of Research**

The objective of this project was to establish a research facility that allows experimenters to understand the effects of mixed radiation fields on semiconductor materials and optical fibers at cryogenic temperatures and to understand annealing from cryogenic temperatures to room temperature. More specifically, the goals of this project included:

- Design and assembly of the CRIF
• Testing the CRIF with liquid nitrogen (LN2) from 77 K to above room temperature
• Testing the CRIF with liquid helium (LHe) from 4.2 K to above room temperature
• MCNP6 simulation of the 10" Dry Tube in the OSU Research Reactor (OSURR) pool
• MCNP6 simulation of anticipated materials in the CRIF in 10" Dry Tube in OSURR pool
• Estimation of radiation induced heating and bounds for expected operational parameters for future experiments in the CRIF
• Experiments from 4.2 K to above room temperature in the CRIF, testing the thermal response of the GaN packaged transistors, silica single-mode off-the-shelf optical fibers, and silica multi-mode off-the-shelf optical fibers.
• Experiments in the CRIF in the 10” Dry Tube in the OSURR shutdown field: gamma-only radiation damage experiments at LHe temperatures and low-temperature annealing to above room temperature in the CRIF on GaN packaged transistors, silica single-mode off-the-shelf optical fibers, and silica multi-mode off-the-shelf optical fibers.
• Experiments in the CRIF in the 10” Dry Tube in the OSURR pool with the reactor operating at 15 kW thermal power: mixed field radiation damage experiments at LHe temperatures and low-temperature annealing to above room temperature in the CRIF on GaN packaged transistors, silica single-mode off-the-shelf optical fibers, and silica multi-mode off-the-shelf optical fibers.

1.3. **NASA Priorities and Mission Needs**
NASA has the need to understand how electronics and communications equipment performs under irradiation and at cryogenic temperatures. Every large spacecraft, satellite, orbiter, rover, and deep space probe launched and controlled by NASA is placed in an extremely harsh environment. In space, electronics equipment and communications equipment, onboard these important research vessels, are subjected to temperatures near absolute zero (a few degrees Kelvin) and are subjected to varying levels of heightened irradiation (from Cosmic background radiation to solar flares, with no atmospheric shield). Therefore, the expensive and important equipment must be able to survive these harsh conditions while performing extremely delicate tasks. When launching spacecraft, each and every pound counts. Since necessary thrust is directly proportional to weight, the cost of a launch is directly associated with the weight of the spacecraft. Smaller modern and future electronics and communications devices weigh less and are more desirable due to speed, efficiency, and decreased weight.

However, these electronics devices and optical fibers, especially those based upon highly ordered crystalline materials, can be susceptible to radiation damage because of single-event upsets and because of the change in local electronic structure because of dislocations and vacancies. These defects can manifest as macroscopic damage, like decreased electron mobility in transistors, diodes, and circuits, and decreased optical transmission in fiber optic cables. Furthermore, individual defects can interact and cluster to create more complicated defects than simple individual vacancies or interstitials. At cryogenic temperatures, annealing is decreased, which may lead to the formation of different or more complex defects than those created at room temperature or high
temperatures. Therefore, if NASA is able to understand radiation damage in the harsh environment of space, it may be better able to optimize the selection of materials, when deciding upon electronics and communications devices for future spacecraft. Furthermore, NASA may be able to estimate radiation damage levels to current and future spacecraft electronics components and optical fibers to determine estimates of mission lifetime, based on radiation sources and dose rates.

Important materials in electronics and communications equipment include gallium nitride in electronics and silica in optical fibers. These materials are of particular interest to researchers at NASA and the cryogenic facility designed and tested in this project was designed to study these materials in future research. This facility will allow for tests in an environment more similar to the harsh conditions of space, than previous experiments found in the literature.

NASA has a long history of nuclear experimentation ranging from designing and building reactors meant for nuclear space propulsion to irradiation experiments of materials for use in spacecraft. While many of these projects have been shaped around NASA’s mission to “Drive advances in science, technology, and exploration to enhance knowledge, education, innovation, economic vitality, and stewardship of the Earth,” the unique interests of the extreme conditions of space have added to the nuclear and radiation science fields in far reaching ways. Furthermore, NASA has historically worked on cryogenic irradiation tests of materials. For example, at the decommissioned Plum Brook Research Reactor, previously operated by the NASA Glenn Research Center (formerly NASA Lewis Field), cryogenic irradiations of metals were done as part of the
HB-2 Cryogenic Experiment. Since the Plum Brook Research Reactor was decommissioned in 2008, few cryogenic radiation experiments have been completed by researchers in any field. Moreover, there has been very little cryogenic radiation research completed on highly ordered materials like gallium nitride, which have great potential for use as structural materials, electronics, and communication media. Furthermore, there are no operating cryogenic research facilities in any research reactors in the US, and most cryogenic irradiation experiments are completed using mono-energetic sources like ion beams or electron beams. Space is a mixed radiation environment with a myriad of radiation types and energies. This varying field causes different types and amounts of damage to a material, depending on the given conditions. Therefore the work being done to establish the CRIF in the mixed field of a nuclear reactor is both novel and a better approximation of the actual space radiation environment.

Not only is the creation of the CRIF relevant to NASA, but the materials being investigated are also highly relevant. For example, GaN is of particular interest to NASA because of its applicability to scientific instrumentation, computer circuits and as a radiation detector. This semiconductor material is well suited to NASA’s goals because of its large bandgap and associated electrical and material properties. Semiconductors like GaN may even become the base for all future radiation-hard circuit elements. These GaN devices will have to survive in high radiation fields at low temperatures in space. GaN transistors are currently being investigated by the NASA Glenn Research Center Opto-electronics group to create current and next generation RF Solid State Power Amplifiers for deep space probes. These GaN transistors will likely be the basic
constituents of future RF communications systems. They also offer low weight and high power amplification alternatives to traditional Traveling Wave Tube Amplifiers.

Communication systems are the most critical of technologies aboard any space mission. Without an ability to communicate with any given mission, whether a satellite in LEO, a rover on Mars, or a deep space probe, the mission objective cannot be attained.

Therefore, continued reliable operation of all communication equipment is necessary for the success of any mission. Unfortunately these materials, while thought to be radiation tolerant, may also suffer from failure in high radiation fields at cryogenic temperatures. Thus, a facility to complete cryogenic irradiation tests of these materials could yield insight into the operation of these devices in various space radiation fields.

Silica optical fibers are also of great interest because of their use as a communication medium or an intrinsic sensor in high data rate optical communication and scientific instrumentation, and because of their superior performance in measurement systems in harsh environments. Silica fibers are inexpensive and easily available for many uses. However, if silica fibers lose their functionality in low temperature environments, high temperature environments, or radiation fields, they will not be workable solutions for space. A much more expensive, and difficult to manufacture, alternative, sapphire optical fiber, may be the solution. Sapphire optical fiber has many of the benefits of silica optical fiber, like high data rate transfer and low weight, but has an added advantage as well. Sapphire optical fibers are single crystal in structure, like GaN, and have a much higher melting point than silica optical fibers. Materials that are single crystal structures are often more radiation tolerant, because of the increased likelihood of
correct realignment of atoms during annealing, and they are often operable at higher temperatures, because of their robust, low-energy state, highly ordered structural atomic alignment. Therefore, a test facility that can replicate the conditions of space, like the CRIF described herein, is necessary to properly characterize the behavior of both types of optical fiber. This facility can support tests of cheap silica fibers as well as sapphire fibers.

This research project specifically addresses a number of NASA’s Roadmap Technology Area Breakdown Structure challenges\(^1\). For example, the application of these experiments to the needs of TA03: Space Power & Energy Storage, TA05: Communication & Navigation, TA08: Science Instruments, Observations & Sensor Systems, TA11: Modeling, Simulation, Information Technology & Processing, and TA12: Materials, Structures, Mechanical Systems & Manufacturing. Furthermore, this research would be applicable to the goals of multiple research divisions within NASA.

1.3.1. **TA03: Space Power & Energy Storage\(^2\)**

Spacecraft, including rockets, shuttles, deep space probes, satellites, and space stations have always undergone an increased level of radiation damage due to the increased level of background radiation outside of the earth’s atmosphere. However, radiation damage becomes all the more important when the spacecraft is being powered by a radioactive source. For many years, NASA has researched nuclear propulsion because a nuclear reactor propulsion system is a great prospect for future generations of spacecraft. Additionally, much more simple radiation based propulsion systems are equally important. Successful missions have used radioisotope thermoelectric generation
in deep space probes like Voyager 1, Voyager 2, New Horizon, and Viking. In the TABS for TA03, there are two types of nuclear power production sources mentioned: Fission & Fusion. Both of these methods produce a mixed radiation field, including high energy neutrons. Neutrons can cause direct damage to structures, and electronics and communications systems, but also can be captured by various materials. Neutron capture causes neutron activation of target materials, producing radioactive daughter isotopes, which act as new radiation sources, of varying types and varying energies. In these environments, active electronics and communications systems are more vulnerable, and yet remain essential for maintaining control of fission or fusion reactors.

One further potential problem is within future generation solar cells. Solar power offers great promise for missions near the sun. However, radiation in space can create defects in solar cells which can change the functionality of the solar arrays. These solar arrays are built upon semiconductor materials and some future cells are being investigated in GaN specifically. Understanding radiation effects, especially in varied environments is critical to establishing the reliability of such materials.

1.3.2. TA05: Communication & Navigation

A few of the specific problems identified within the NASA TABS category TA05: Communication & Navigation include (1) avoiding communication becoming a constraint in planning and executing future missions, (2) minimizing user mass and volume while improving performance, (3) providing integrity and assurance of information delivery across the solar system. Specifically, the CRIF will support research that addresses two of the six major areas within TA05: (1) optical communication and (2)
navigation and radio frequency communication. In each of these major areas, emerging technologies must be able to overcome the three problems outlined above. They must not hold back future missions, they must limit mass and maximize performance, and they must assure the ability to communicate throughout the duration of their missions. Within these two potential methods, optical and RF communications, there is a need for materials that can last in the mission required environments: low/high temperatures and high radiation fields. One of the most simple modes of failure of an optical communication system is the darkening of any fiber used to communicate within the system, or used to pass light from one place to another before a communication leaves the system. The CRIF will support experiments of two types of fibers to assess their survivability and functionality in a radiation field at cryogenic temperatures. The other devices that will be supported by the CRIF are directly relevant to NASA RF communication devices. As previously described, GaN provides excellent potential for replacing many current materials in future RF communications systems, especially RF power amplification devices. These materials are likely candidates for power amplification transistors and they must also be tested to confirm their integrity in mixed radiation fields at varying temperatures.

1.3.3. **TA08: Science Instruments, Observations & Sensor Systems**

Within the NASA TABS category TA08: Science Instruments, Observations & Sensor Systems, there are two important uses of the materials that can be investigated in the CRIF. Optical fibers can be used for passing light to and from various light sources including as pass-throughs for various laser systems, which are used for scientific
missions. Second, NASA has a need for new radiation detectors which can survive the harsh environments of space and measure the diverse radiation field. SiC has been demonstrated to work as an alpha particle detector up to 500 C, by Timothy Garcia and the OSU research team under Dr. Blue and Dr. Windl. GaN is a wide bandgap semiconductor material like SiC, and may provide another material from which it is possible to build next generation radiation detectors. Researchers at the NASA Glenn Research Center have begun investigations to build multiple-detector systems to identify multiple types and energies of particles within a mixed radiation field like space. To make such detectors, wide bandgap semiconductors like GaN can be used. While much of this detection technology is in its infancy compared to other materials like silicon, the necessity of characterizing these detection materials for radiation damage is necessary before they can be deployed in space. The CRIF will support investigations of devices made from these semiconductors.

1.4. **Space Radiation Fields**

There is a substantial amount of data on radiation damage events from various experiments in space. According to Jim Kinnison's NASA Spacecraft Radiation Protection Course from 2004, in 1999 Koon put together a database of 299 attributable anomalies in space. Of these, 54.2% were electrostatic discharges, 28.4% were Single Event Upsets, and 5.4% were from radiation damage. Of these, roughly one-third of the anomalies are attributable to radiation effects. In nine cases, solar arrays failed due to radiation damage. By 1999 there were 11 total missions lost because of radiation damage.
These recorded events are important because they demonstrate many of the ways that space radiation can affect the missions undertaken by NASA. These events occur because of a variety of radiation sources in space. Depending on the flight path of a space mission and shielding of devices, electronics systems can be exposed to different particles at different energies. Again, according to Jim Kinnison of NASA, in space, total ionizing radiation dose for displacement damage can come from solar and trapped protons with energies ranging from 0.5MeV to 800MeV, and from trapped electrons with energies ranging from 0.1MeV to 10MeV. Additionally, Single Event Effects (SEE) can come from Galactic Cosmic Rays (GCRs), in which charged nuclei of any element can arrive with energies up to 10s of GeV and from Solar Protons and light ions, which are ejected during solar events from 1MeV to 500MeV. GCRs probably come from Supernovae, but are not fully understood. They may result in secondary particle production as well, but because of their high energy and relatively low flux, usually travel fully through an electronic device, causing SEE. On average, they are composed of 83% hydrogen (protons), 13% helium (alphas), 3% electrons, and 1% heavy ions. Finally, many current and future space mission are subject to man-made sources of radiation, including Radioisotopic Thermal Generation Sources, Fission Reactors, and Atmospheric Orbital Events.

1.5. Related research and facilities

There have been very few cryogenic neutron irradiation facilities operated in the world. Decades ago, there was a cryogenic reactor-irradiation research facility in the US, at the NASA Plum Brook station, in Sandusky, OH. This reactor was built as one of the
most powerful science experimental reactors in the world. It operated until 1973, when NASA was forced to shut down the reactor after the end of the Apollo missions. The reactor was officially decommissioned and deconstructed beginning in 1998. During operation, researchers wanted to understand the combined effects of cryogenic temperatures and mixed radiation fields on metals that were commonly used in space flights for structural materials. So private and public research projects were conducted at sub-30K temperatures in a reactor field.

There is currently only one cryogenic reactor irradiation facility operating in the world. It is a pneumatic tube insertion cryogenic irradiation facility at the University of Tokyo Research Reactor. This facility allows for irradiations at 10 K at a maximum power of 5 MW and corresponding fast flux of $4.77 \times 10^{11}$ n/(cm$^2$-s). Additionally, there is currently only one other cryogenic irradiation neutron source in the world. It is located in Grenoble France and is called the Grenoble SARA facility. The SARA facility is a 6MeV maximum neutron source, generated by a 20MeV deuteron beam, which impinges upon a Be target, producing a neutron beam. This is a mixed field, because there are also gammas, which account for ~22% of the radiation dose. This radiation source uses a liquid argon cryostat to irradiate electronic materials at ~90K. Neither of these sources constitute the extended capabilities that will be provided by the CRIF established in support of this thesis, which includes temperature control from ~4.2K to above room temperature.

Most current cryogenic irradiation experiments involve cryostats placed into an ion beam. There have been a number of experiments completed with heavy ions at
cryogenic temperatures (>100K) in the types of materials that are proposed for use in the CRIF. These experiments have shown a higher level of radiation induced defects at cryogenic temperatures, because of decreased annealing at low temperatures. Some experiments have even shown total amorphization of a crystalline structure after irradiation at cryogenic temperatures, at a lower fluence than amorphization at room temperature or elevated temperatures. While amorphous materials work in many applications, they do not work for all applications. Therefore, some applications require highly ordered crystalline materials. However, when a highly order crystalline structure is amorphized, the useful characteristics of the crystalline material are often destroyed. An example of this would be the bandgap of a semiconductor being decreased because of localized amorphization.

The CRIF will support irradiations of both amorphous and crystalline materials. Although single crystal sapphire optical fibers have been shown to withstand the combined effects of radiation and high temperature better than amorphous silica optical fiber, that may not be the case at cryogenic temperatures. The CRIF helped determine the applicability of amorphous silica optical fibers, for use at cryogenic temperatures in radiation fields. Other materials which will be tested in the CRIF will include wide-bandgap semiconductor materials, which are dependent upon their highly ordered lattice structures for their important electrical properties. The results of a typical cryogenic mono-energetic ion irradiation experiment in a wide bandgap semiconductor material are shown below in Figure 1. These results are from an ion implantation experiment in 6H-SiC, which shows dose levels required for amorphization in 6H-SiC as a function of
temperature, with various ions and energies incident upon the material. As shown, the amorphization dose decreases as a function of temperature. Although the greatest changes happen above 300K, there appears to be a small linear (on the log scale) change below 300K.

![Graph showing amorphization dose vs irradiation temperature for different incident ions with various energies](image)

**Figure 1:** Experiment showing the amorphization dose of 6H-SiC for different incident ions with various energies as a function of temperature (Weber et al. 1998). Weber, William et al. “Structure and Properties of Ion-Beam-Modified (6H) silicon carbide,” Materials Science and Engineering (1998).

Cryogenic irradiation experiments in the CRIF may prove to yield greater levels of induced defects and corresponding macroscopic damage. However, the ability to change the temperature of the experimental volume slowly may lead to more informative results during low temperature annealing. The effects of low temperature annealing may provide a better insight into the physics of defect formation, evolution, and annihilation. An example of a cryogenic annealing experiment is shown below in Figure 2. This
experiment shows the relative disorder of silicon atoms in 6H-SiC after radiation induced defects were increased in temperature from ~175K to ~875K. As seen in the plot, most of the annealing occurs between ~175K and ~300K, which demonstrates the value of in situ measurements during low temperature annealing after cryogenic irradiation experiments. The CRIF will provide opportunities for such in situ measurements to be made after mixed field irradiations. If experiments occur at cryogenic temperatures and then are allowed to heat back to room temperature (~300K), depending on the type of radiation, there can be residual radiation induced defects, however, the greatest level of annealing can occur as the material increases back to room temperature.

Figure 2: Experiment showing relative disorder of silicon in 6H-SiC for cryogenic ion implantation (using 550 keV Si and 2 MeV Au) and annealing as a function of temperature
1.6. **Accelerated Testing of Materials**

The last important possible outcome of research in the CRIF has been previously mentioned. When materials are irradiated at cryogenic temperatures, they exhibit increased radiation damage. When an incident radiation particle interacts with a lattice structure, it can force atoms from their lattice locations. The creation of Frenkel Pairs, interstitials and vacancies, is a reversible process, through annealing (defect annihilation). Within the first few picoseconds, most radiation-induced defects return to their lattice sites. The immediate defect recombination can be overcome by those atoms which have been removed sufficiently far from their original lattice sites to be shielded from the attractive electrostatic force of the resulting vacancy. Then, interstitial atoms can move throughout the lattice, governed by statistical processes, which are weighted towards low energy stabilization for the system. At high temperatures, the random steps that interstitials may take throughout the lattice are more likely to allow for annihilation with available vacancies. This process is decreased at cryogenic temperatures. Furthermore, the immediate annihilation of many defects, near the end of an incident ions track, may be decreased substantially at cryogenic temperatures. In fact, some experiments, like that shown below in Figure 3, suggest that total amorphization of a localized structure can be achieved during cryogenic irradiation. In these experiments by Devanathan, the critical temperature for most heavy ion amorphization was found to be ~170K (Devanathan 1998). This suggests that with some materials, cryogenic irradiations in the proposed experiments may demonstrate effects of amorphization in some materials.
Figure 3: Critical Amorphization Dose for Heavy Ions in Sapphire (Devanathan 1998)

All of the previously discussed factors suggest that cryogenic irradiation may be a way to conduct accelerated radiation damage tests. For two experiments with comparable dose levels, it may be possible to achieve much more advanced defect structures in a cryogenic irradiation, compared to a room temperature or high temperature irradiation.

The CRIF may allow for new types of accelerated damage studies to be conducted at the OSU Nuclear Reactor Lab, during which high levels of radiation induced defects can be generated for dose levels that are multiple orders of magnitude lower than those typically required. The ability to conduct such tests may be tempered by the competing problem of
gamma heating. Specifically, gamma heating in the CRIF materials in or near the experimental volume will increase the temperature of the materials under test. Therefore, gamma heating that raises the temperature of the materials under test greatly will be counter-productive, and may require operation of the OSURR at a lower power. Ultimately, the success of such accelerated radiation damage testing will be determined by the competing issues of maximum flux achievable within the CRIF and minimum temperatures achievable.
Chapter 2: Background

2.1. General Radiation Induced Defects

Motivation for this research lies within the derivation and interpretation of the Point Defect Balance Equations found in Was.\textsuperscript{10} Was states that although Frenkel pairs can arise from collisions of high-energy particles with lattice atoms, they can disappear through the recombination of interstitials and vacancies or through their loss to a defect sink in the lattice. From these basic acknowledgements, he derives a set of differential equations called the Point Defect Balance Equations that account for the loss of interstitial and vacancy defects uniformly distributed at a specific temperature as a function of space and time:

\[
\frac{dC_v}{dt} = K_0 - K_{iv}C_iC_v - K_{vs}C_vC_s \tag{1} \\
\frac{dC_i}{dt} = K_0 - K_{iv}C_iC_v - K_{is}C_iC_s \tag{2}
\]

with: \(C_v\) = vacancy concentration, \(C_i\) = interstitial concentration, \(K_0\) = defect production rate, \(K_{iv}\) = vacancy–interstitial recombination rate coefficient, \(K_{vs}\) = vacancy–sink reaction rate coefficient, \(K_{is}\) = interstitial–sink reaction rate coefficient. The rates of
recombination and loss to sinks are material dependent and are determined by the atoms within the lattice, the lattice shape, the temperature of the material, the defect sink types and size, etc. When these equations are solved, they provide a description of the evolution of point defects due to annealing within a material. Furthermore, Was goes on to describe specific cases of low and high temperature evolution and shows that at lower temperatures, interstitials and vacancies occur in higher quantities than at higher temperatures. This is logical considering the fact that lattice atoms have higher energy at higher temperature. Therefore it would follow from physical arguments that interstitials would annihilate with vacancies less when the atoms within the lattice have lower energies and are less likely to move from their sites, or to overcome local maxima to reach true minima. This provides a fundamental reason for why irradiations in space, at low temperatures, may cause more damage than at room temperature or at high temperature. This means that understanding such radiation damage at low temperature is all the more important for future NASA spacecraft applications, and that the CRIF addresses a critical area of materials research.

Although GaN and silica optical fibers show great prospect for use in spacecraft, it is nonetheless important to understand how their electrical and optical properties change under the influence of radiation. Specifically it is important to understand how damage is produced at low temperatures, like those in space. It is also extremely important to understand how irradiation induced damage can be repaired, by annealing effects that occur when the material temperature is increased.
2.2. **Optical Fibers**

Optical fibers are glass or highly ordered crystals that are cylindrical in shape with a length that is orders of magnitude larger than their diameter. These fibers act as a conduit through which light travels from a light source to a receptor. Optical fibers are used ubiquitously in the telecommunications industry as a means to transmit large amounts of data quickly. They are used often in harsh environments and are immune to induced electromagnetic noise. Finally, fibers can act as inherent sensors for point measurements or distributed measurements of strain or temperature.

2.2.1. **Optical Fiber Theory**

2.2.1.1. **Optical Fiber: Light Propagation and Total Internal Reflection**

Total internal reflection describes the method by which light passes down the length of an optical fiber. In an optical fiber, there is always a core which is made of a material with a high level of optical transmittance, such as glass or single crystalline materials like sapphire. There is often a clad around the outside of the fiber core and an outermost protective layer coating. This coating is meant to provide mechanical strength or protection from the local environment. If the materials of the core and clad are different, then there is a difference in the index of refraction of the materials, and some portion of the light is reflected from the interface surface. The light that is reflected back towards the inside of the fiber core is guided down the length of the fiber through a series of reflections from the core/clad interface. Thus, the core of the optical fiber acts like a waveguide. Snell’s law defines this behavior through a simple equation:
\[ \theta_c = \cos^{-1}\left(\frac{n_{clad}}{n_{core}}\right) \]

where \( n_{core} \) is the index of refraction of the core, \( n_{clad} \) is the index of refraction of the clad, and \( \theta_c \) is the maximum angle for which light is totally reflected and kept within the core. If the angle of approach of a photon \( \theta_z \) is less than \( \theta_c \), then all of the light is reflected and is guided down the length of the fiber, without loss. If the angle \( \theta_z \) is greater than \( \theta_c \), then some of the light is lost through refraction across the boundary surface. Figure 4 below provides a visualization of Snell's Law.

One way to increase the light passing through the fiber is to increase the index of refraction mismatch between the core and the clad. Specifically, by finding a material with a greater index of refraction for the core, in comparison to the material of the clad,
the maximum angle of total reflection can be increased. This is done in the telecommunications industry to decrease the loss of the signal as it passes down the length of a fiber. A second method to increase total light propagation down the length of the fiber, is to increase the diameter of the core. A larger core can act as a larger transportation medium and the cross-sectional area is directly proportional to the number of photons which can be passed along the fiber. Unfortunately, there are negative consequences of increasing the fiber diameter as well.

2.2.1.2. **Optical Fiber Modal Dispersion & Single- vs. Multi-mode Fibers**

When photons enter the fiber at different angles, the photons can travel along different paths, which can have different total path lengths to reach the end of the fiber. Specifically, a photon entering at a larger angle must reflect off of the surface a greater number of times while passing along the length of the fiber, thus causing a greater total path length. The differences in the path lengths of the photons can cause distortions in the signal as the light passes through the optical fiber. This effect, called modal dispersion, limits the bandwidth, or data transmission rate, of optical fibers. The telecommunications industry uses optical fibers to send high bandwidth data over great distances. Since long optical fibers increase modal dispersion, smaller diameter optical fibers are often used. Small diameter optical fibers are called single-mode optical fibers and large diameter optical fibers are called multi-mode optical fibers. Below, in Figure 5, is a diagram of the cross-sections of representative single-mode and multi-mode optical fibers; each is a specific types that will be used in this research.
In a single-mode fiber, the core/clad material interface is optimized, and the core diameter is optimized for a specific mode of light. This eliminates modal dispersion and allows for a single-mode signal to be propagated efficiently through the optical fiber. In order to use such an optical fiber efficiently, the small diameter core must be well-aligned to the light source and output measurement system. Furthermore, the light source must provide a strong signal centered around the specific wavelength for which the optical fiber is optimized. Single-mode fibers are used often in the telecommunications industry at two specific wavelengths 1300 nm and 1550 nm.

Multi-mode fibers are typically used with a broadband light spectrum source, for many reasons, including the high cost of tunable laser sources. Additionally it is difficult to couple small core diameter optical fibers to broadband sources and measurement systems. Multi-mode fibers are also appropriate in some applications where there is a shorter optical fiber cable length, and therefore less modal dispersion.
2.2.1.3. **Optical Fiber Instrumentation/Application**

There are many technologies that rely on optical fibers as a communication medium, including typical optical fiber communications systems, like those used in the telecommunications industry, or to transmit light for light-based sensing technologies, including laser ultrasound, borescopes, and laser-induced breakdown spectroscopy. Other applications include sensing technologies for changes in pressure, strain, or temperature. An optical fiber system, in which the optical fiber is both an integral part of the system and the medium for communication, but not the actual sensor, is called an extrinsic sensor. An example of an extrinsic sensor is a Fabry-Perot interferometric temperature sensor, in which a sensing element is fused to the end of an optical fiber. Light, which passes through the fiber to the sensing element reflects off of the fiber/element interface, and also off of the sensing element/air interface. An applied strain or a change in temperature causes a change in the size in the sensing element, which causes a change in the interference pattern of the reflected light signals. An example of such a system includes a sapphire wafer fused to sapphire optical fiber. A similar system can be used for measuring pressure, in which a diaphragm is placed at the end of the fiber, with a small air gap in between. When the pressure increases, the diaphragm is compressed and the interference pattern for the light reflected from the fiber/air interface and the air/diaphragm interface changes.

There are also some optical fiber systems, in which an optical fiber is both the sensing mechanism and the medium of signal communication, which are called intrinsic sensors. In these applications, optical fibers can be interrogated and used as a sensing
medium for temperature and strain. One example is a fiber Bragg grating sensor. In these sensors, a periodically varying refractive index profile is inscribed into a small section of an optical fiber. These Bragg gratings reflect only a certain narrow bandwidth of light, while the rest of the light passes through. This narrow bandwidth, centered around a peak characteristic wavelength is reflected back to a sensor. When the fiber is strained or the temperature is changed, in the location of the Bragg grating, the inscribed sections are moved relative to one another and the reflected peak wavelength changes. When properly calibrated, this change in wavelength can be monitored to determine the magnitude of changes in temperature or strain. Since these gratings can be inscribed in multiple locations along an optical fiber, distributing sensing along the length of the fiber is possible, depending on the percentage of light reflected at each Bragg grating.

In space, optical fibers can be used for a number of applications. In the most simple format, off-the-shelf silica optical fibers can offer a cheap light-weight alternative to metal wires for transmitting data between devices within any spacecraft, from geospatial satellites, to manned missions and deep space probes. In other applications, optical fibers could be used in on-board measurement systems for manned missions, rovers, or scientific satellites. Additionally, they may be useful in applications in fission reactor-powered spacecraft to measure temperature or pressure in the reactor core and in heat exchangers.

Work by David Hawn, investigating silica optical fibers in situ for the effects of radiation damage and high temperatures, has demonstrated survivability up to 1000 C in a reactor radiation environment. More recent work by Christian Petrie, investigating
sapphire optical fibers *in situ* for the effects of radiation at higher temperatures has demonstrated sapphire optical fiber survivability up to 1300 C in a reactor radiation environment, with minimal increases in optical attenuation. These results indicate a broad range of applicability for both extrinsic and intrinsic optical fiber sensing technologies in harsh environments.

2.2.2. **Silica Optical Fiber**

2.2.2.1. **Silica Optical Fiber Manufacturing Method and Applications**

Silica optical fibers are made of amorphous silicon dioxide, also called fused silica. Manufacturing highly pure fibers is very important because impurities cause scattering of light, and at higher concentrations, non-negligible attenuation of light. Silica is one of the common structures of bulk SiO$_2$ and can be purchased cheaply in highly pure forms because of the mature technologies.

In the manufacturing process, there is a glass "preform" made, which is larger in diameter than the fibers, but has the correct core and clad material compositions, with closely controlled refractive indices. In making silica optical fibers, the preform is made by chemical vapor deposition in one of three ways: inside vapor deposition, outside vapor deposition, or vapor axial deposition. In each case, there is a glass structure and gas flow of silicon tetrachloride (SiCl$_4$) which reacts with oxygen at a high temperature (1800-1900 K), forming SiO$_2$ particles. These particles form layers on a glass wafer. By heating and controlling the flow rate, very pure low-defect layers can be formed into a preform.
Finally, the preform is placed into a drawing tower and the tip is heated and pulled. By controlling the tension while pulling on the tip, the preform can be drawn out into a silica optical fiber with a well-controlled and consistent diameter. During this process, the fiber core and fiber clad are extruded together.

While the optical fiber is being drawn out, the coating is applied. These coatings are generally a UV-cured urethane acrylite composite, and are applied at high velocity and then cured with UV light. The optical fiber inner coating is often also covered by an outer coating. These coatings are intended to provide mechanical support, to protect the fibers during small-diameter bends and to protect them from the local environment.

For many uses, optical fibers must be cleaved and spliced to other optical fibers, or to sensing features or equipment. In each case, the coatings must be removed in the local vicinity and the fiber must be cleaved. Because of the amorphous structure and highly pure nature of silica optical fibers, they are easily cleaved and often have very straight edges, after a cleave. The fibers can then be easily fused to other fibers, especially other silica fibers, because of their similar amorphous structure.

2.2.2.2. Silica Structure (Amorphous)

The basic constituents of amorphous silica optical fibers are tetrahedral SiO$_2$ molecules. In this configuration, two oxygen atoms are attached to opposite sides of a silicon atom. If no purities or defects are present, each of the oxygen atoms is attached to three more silicon atoms. These tetrahedral molecules of SiO$_2$ are assorted in an amorphous glass structure.
During the manufacturing process, if the extruded SiO\textsubscript{2} liquid is cooled slowly, a crystalline structure can form, known as quartz. Since amorphous silica optical fibers are cooled from a liquid state quickly, crystallization does not occur and there is no overall order to the glass fiber, resulting in an amorphous structure.

In Figure 7 above, the structures are simplified two dimensional representations of the real three dimensional case. In the amorphous structure, the bond angles vary and the
number of oxygen atoms vary within closed loops of the structure. When extending to the three dimensional case, the third degree also allows for variance in bond angles and numbers of oxygen atoms within connecting loops. As seen in Figure 7, local densities differ within the amorphous structure and are dependent on the localized structure. These differences in local structures result in localized changes in optical attenuation within the amorphous silica fiber, which results in scattering that is referred to as Raleigh Scattering. Therefore, a highly pure silica optical fiber actually has inherent attenuation. This attenuation is increased when impurities or defects are introduced.

Because of the manufacturing process and structure of silica optical fibers, they exhibit good optical transmission over a wide range of wavelengths. Additionally, the process can be tailored to a specific application by increasing the optical transmission in certain regions. When the concentration of hydroxyl groups (OH) is kept low, very low attenuation is possible in the IR spectrum. Conversely, by increasing the concentration of OH in the SiO$_2$, very low attenuation in the UV region is possible. Furthermore, silica optical fibers are beneficial because they are easy to post-process after being manufactured. Specifically, they can be doped with germanium, aluminum, fluorine, or boron in order to change the refractive index of the fiber materials, allowing for more complex optical fiber geometries to be formed. They can also be easily inscribed with the previously mentioned fiber Bragg gratings for use as sensors, which will be discussed in further detail below.
2.2.2.3. **Theory of Attenuation and Inherent Defects in Silica Optical Fibers**

Attenuation is the loss of light along the length of a fiber. Attenuation in a fiber occurs in two categories: (1) geometry and (2) material. The geometric considerations that can cause attenuation include leakage of unbound photons from the fiber core and losses at fiber coupling interfaces. The experiments that are supported by the CRIF can investigate the effects of radiation at cryogenic temperatures on optical attenuation. Therefore, the experimental results will be recorded in terms of added attenuation, not total attenuation. This means that as long as the geometry is not changed, the results of the experiments do not depend on the geometric attenuation losses. Instead we will focus on the material losses, which include two major categories: (1) intrinsic attenuation, which results from inherent characteristics of an ideal optical fiber, and (2) extrinsic attenuation, which results from impurities and defects. Intrinsic attenuation occurs through Rayleigh Scattering, Brillouin scattering, Urbach absorption, and multi-phonon absorption. Extrinsic attenuation can result in the same scattering and absorption categories, but is dependent upon changed electron energy levels due to impurities and point defects. The mathematical representation of these attenuation mechanisms and the dependence of light intensity on absorption can be seen below in equations 4 and 5.

\[
\alpha_{Total}(\lambda) = \alpha_{Geometry}(\lambda) + \alpha_{Material}(\lambda)
\]

\[
\alpha_{Geometry}(\lambda) = \alpha_{leakage}(\lambda) + \alpha_{connection}(\lambda)
\]
\[
\alpha_{\text{Material}}(\lambda) = \alpha_{\text{scattering}}(\lambda) + \alpha_{\text{absorption}}(\lambda)
\]
\[
\alpha_{\text{scattering}}(\lambda) = \alpha_{\text{Rayleigh}}(\lambda) + \alpha_{\text{Brillouin}}(\lambda)
\]
\[
\alpha_{\text{absorption}}(\lambda) = \alpha_{\text{Urbach}}(\lambda) + \alpha_{\text{multi-phonon}}(\lambda)
\]

\[
I(\lambda) = I(\lambda) e^{-\alpha_T(\lambda) L}
\]

where \(I(\lambda)\) = linear optical intensity, \(\lambda\) = wavelength of light (nm), \(\alpha_T\) = the total optical attenuation coefficient from equation 4, and \(L\) = length of fiber (m).

2.2.3. Rayleigh Scattering in Silica Optical Fibers

Defects or density fluctuations are dependent upon the localized \(\text{SiO}_2\) structure along a fiber, as previously discussed. These defects are randomly distributed within a single-mode silica optical fiber because of the previously discussed amorphous structure of the glass. The local density fluctuations manifest themselves as a change in the refractive index of the glass at a local point. Therefore, as light interacts with the local structure through electron excitation, the light scatters across a location which has a different refractive index than the average refractive index of the silica glass. This localized scatter occurs randomly along the fiber at any of these randomized structures and is called Rayleigh scatter. A full description of Rayleigh scatter can be found in the work of Schroeder\textsuperscript{15} and Lines\textsuperscript{16}. The small percentage of the light that is backscattered from these local sites is of interest, and its application will be discussed below.
2.2.4. **Brillouin Scattering in Silica Optical Fibers**

Brillouin scattering occurs when photons inelastically scatter off of small density fluctuations within a material, that are caused by temperature dependent acoustic vibrational modes within the material. The effects of Brillouin Scattering are similar to Rayleigh Scattering. A more full treatment of Brillouin Scattering, including a derivation of the temperature dependent Brillouin Scattering coefficient was derived by Rich\(^{17}\).

2.2.5. **Urbach Scattering and Multi-Phonon Scattering in Silica Optical Fibers**

Urbach absorption occurs when very low wavelength photons directly promote electrons from the valence band to the conduction band. For most materials, the Urbach absorption coefficient has been shown to be temperature independent, however for silica the temperature dependent Urbach rule has been derived and a further treatment can be found in the work of Godmanis\(^{18}\). Multi-phonon absorption occurs when two or more phonons create an electric dipole that strongly absorbs photons with frequencies near the vibrational frequency of the dipole. Some of these vibrational modes are complex and occur in the infrared spectrum.

2.2.6. **Attenuation in Silica Optical Fibers**

As previously discussed, the total attenuation in silica is also dependent upon the extrinsic impurities and defects within the material. In silica, for example, various impurities may form. Modern manufacturing methods have virtually eliminated all other impurities except, OH impurities, which can arise based upon the concentration of
hydrogen in the manufacturing environment\textsuperscript{19}. OH impurities can be kept low, but not completely eliminated. OH impurities increase absorption peaks centered at 1383nm, 1246nm, and 943nm\textsuperscript{20,21}. Other intentional impurities are possible, but are not relevant to the fibers that were used in the CRIF experiments described herein. Silicon and Oxygen formations, other than SiO\textsubscript{4}, are defects that can exist within silica optical fibers and create extra available states within the electronic band structure. Most of these create attenuation peaks in the UV wavelengths, but some can create attenuation in the visible wavelengths\textsuperscript{22}. These defects can all exist without the presence of radiation, but may increase when irradiated. Below, in Figure 8, is a plot of attenuation in a silica optical fiber (in black) with an overlay of perceived contributions\textsuperscript{23}. Also, below in Table 1, is a list of the attenuation peaks due to OH and SiO formations compiled by Humbach\textsuperscript{24}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8.png}
\caption{Mechanisms Leading to Attenuation in Silica}
\end{figure}
Table 1: Summary of attributable attenuation, due to OH and SiO formations in silica

<table>
<thead>
<tr>
<th>Description</th>
<th>Optical Absorption</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Energy (eV)</td>
</tr>
<tr>
<td>OH</td>
<td>0.46</td>
</tr>
<tr>
<td>OH + SiOSi</td>
<td>0.56</td>
</tr>
<tr>
<td>OH + 2xSiOSi</td>
<td>0.65</td>
</tr>
<tr>
<td>2xOH</td>
<td>0.90</td>
</tr>
<tr>
<td>2xOH + SiOSi</td>
<td>1.00</td>
</tr>
<tr>
<td>2xOH + 2xSiOSi</td>
<td>1.09</td>
</tr>
<tr>
<td>3xOH</td>
<td>1.31</td>
</tr>
<tr>
<td>3xOH + SiOSi</td>
<td>1.41</td>
</tr>
<tr>
<td>3xOH + 2xSiOSi</td>
<td>1.50</td>
</tr>
<tr>
<td>4xOH</td>
<td>1.71</td>
</tr>
<tr>
<td>4xOH + SiOSi</td>
<td>1.81</td>
</tr>
<tr>
<td>4xOH + 2xSiOSi</td>
<td>1.90</td>
</tr>
<tr>
<td>5xOH</td>
<td>2.09</td>
</tr>
</tbody>
</table>

2.2.2.4. Uses of Scattering in Silica Optical Fibers

2.2.7. Backscatter-Based Intrinsic Sensors

Scattered light within an optical fiber can be recorded and processed in order to interrogate the fiber itself as an intrinsic sensor. Specifically a method called Optical Time Domain Reflectometry (OTDR) has been developed to use Brillouin and Rayleigh
backscattered light as a method to determine physical changes to the fiber based upon outside environmental parameters\textsuperscript{25}. Theoretical models of OTDR in single-mode fibers have existed since Nakazawa published a derivation of the percentage of light collected from OTDR in a typical single-mode fiber\textsuperscript{26}. Since then, there has been a great deal of development in understanding how individual defects scatter light. Furthermore, technologies have developed to the point that commercial products can interrogate tens of meters of fiber with a spatial resolution of \textasciitilde{}1cm\textsuperscript{27}. These techniques rely on the ability to map inherent defects within a fiber over a length of the fiber.

The method used in this research focuses on a packaged technology from Luna Optics, which uses the Rayleigh Backscattered optical signal to map the local index of refraction fluctuations along a fiber. The single-mode silica optical fiber is coupled to a tunable laser source, which emits light as it sweeps through a frequency range. As the light passes through the fiber, the light is scattered at points of different refractive indices. A small percentage of that light is backscattered and propagated back along the wave guide (optical fiber) to the OBR. Within the OBR, the backscattered light is diverted and travels to an internal photodiode to be collected. As Rogers and Handerek demonstrated\textsuperscript{28}, the backscattered light can be collected by a photodiode and used to understand physical changes in the vicinity of the fiber. Specifically, the amplitude and the phase difference of the backscattered light can be collected and the frequency can be determined. The variance of the frequency with time is dependent upon the spatial distribution of the local scatter points, and therefore the spatial variation of the birefringence of the fiber\textsuperscript{29}. Since the scattering results in changes to the birefringence, an
analogous way to consider the spatial mapping of the fiber is by considering the local fluctuations in permittivity. As Froggatt and Moore have discussed\textsuperscript{30}, since the spatial data contain both phase and amplitude data, one can compute the spectrum of a section of fiber by selecting the average difference of the permittivity over a specified region of the fiber, $\Delta\varepsilon^*/\varepsilon(x/2)$, and transforming it to the frequency domain, with $x = $ distance and $\varepsilon = $ permittivity. Froggatt and Moore discuss how these measurements of light phases and amplitude can be coupled to a signal from a well-calibrated reference reflector, and the resulting interference patterns can be used to determine the optical backscatter spectra at distinct points along the fiber. Furthermore, they discuss how a series of these measurements can be taken to determine changes within the fiber. Specifically, as the fiber changes temperature or is strained, the scattering locations move within the fiber. These changes are due to strain or thermal expansion/contraction. When the scattering points move, there is a noticeable shift in the optical backscatter spectra. Therefore, by complex cross-correlation of two spectra, one reference scan, and a second scan of the same section of fiber after applied strain or a temperature change, one can determine the spectral shift. By calibrating this spectral shift for various strains or temperature changes of a specific type of optical fiber and specific setup, the fiber can be used as an intrinsic sensor to make distributed measurements of strain or temperature.

2.2.3. General Radiation Induced Damage/Defects in Optical Fibers

As previously discussed, there are many methods by which light may scatter or be absorbed in an optical fiber. For example, incident radiation can change the local
Within an optical fiber, thus inducing further scattering or absorption losses. When neutrons impinge on a material, they can cause primary knock-on events, in which a freed ion moves through the material, causing further damage. These cascades create various point defects within the material, if they transfer greater energy to lattice atoms than the requisite displacement threshold energy.

Point defects have different local electronic structures than a perfect lattice. These differences in electron locations and densities result in new available electron energy states. Some of these point defects cause absorption losses, because incident photons are absorbed by lower level valence electrons from the new defect electron states, promoting them to higher energy states within the band structure. Defects that absorb optical photons are commonly referred to as color centers. Studying these color centers, among other defects is a very mature field of science. The effects of radiation on glass have been studied since the late 1800s when Roentgen noticed a piece of glass changing color after irradiation. Roentgen's experiments were prescient, since the color centers result from the same physical mechanism, photon absorption, as the many other types of attenuation resulting from radiation induced defects.

### 2.2.3.1. Radiation Induced Defects in Silica Optical Fibers

Although silica is an amorphous material, it nonetheless can have interstitials and vacancies. The interstitials and vacancies result in the formation of different molecules, instead of different crystalline structures. Radiation induced point defects in silica have been studied greatly, and listed below in Table 1 are the known defects for silica, as provided by Skuja.
### Table 2: Summary of major defects in silica

<table>
<thead>
<tr>
<th>Description</th>
<th>Optical Absorption</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Energy (eV)</td>
</tr>
<tr>
<td>Interstitial Chlorine Cl2</td>
<td>4.00, &gt;6.89</td>
</tr>
<tr>
<td>Chloride Groups ≡Si-Cl</td>
<td>4.07-3.76, &gt;7.75</td>
</tr>
<tr>
<td>Silanol Hydroxyl Groups ≡Si-O-H</td>
<td>&gt;7.29</td>
</tr>
<tr>
<td>Interstitial ozone molecule O₃</td>
<td>5.28-4.28, &gt;7.29</td>
</tr>
<tr>
<td>Interstitial oxygen molecule O₂</td>
<td>&gt;7.08</td>
</tr>
<tr>
<td>Peroxy linkage ≡Si-O-O-Si≡ (Interstitial O₂)</td>
<td>7.75-6.70</td>
</tr>
<tr>
<td>Oxygen Vacancy ≡Si-Si≡</td>
<td>8.00-7.08</td>
</tr>
<tr>
<td>Oxygen Vacancy (Divalent Si)=Si··</td>
<td>5.39-5.28, 7.08-6.70</td>
</tr>
<tr>
<td>Oxygen Vacancy (Dangling Si Bond)=Si·</td>
<td>6.20-5.28</td>
</tr>
<tr>
<td>Peroxy Radical ≡Si-O-O·</td>
<td>5.99-4.68</td>
</tr>
<tr>
<td>Dangling Oxygen Bond ≡Si-O·</td>
<td>2.00, 5.28-4.20, 7.75-5.99</td>
</tr>
</tbody>
</table>

Each of these known defects results in photon absorption centered around characteristic wavelengths. Specifically, the table shows various types of molecules that can form,
other than the typical pure SiO$_2$ molecular structure of an ideal silica fiber. These defects have characteristic absorption lines from the UV through the visible spectral range (155nm - 620nm), including multiple color centers in the visible spectrum.

2.3. **Semiconductors**

A semiconductor is a material which, for the same voltage, has greater electrical conductivity than an insulator and lesser electrical conductivity than a conductor. Specifically, a semiconductor has an electronic band structure that exhibits a gap between valence electrons and the conduction band. This bandgap makes semiconductors extremely useful in a number of applications in modern electronics, including transistors, solar cells, light-emitting diodes (LEDs), quantum dots, and integrated circuits. This bandgap means that electrons must be promoted to the conduction band in order to flow through the material as current. In order to tailor a semiconductor material to a given application, doping is employed, which changes the electronic band structure to allow for more or less electronic transitions. Specifically, depending on the type of doping, one can increase the electrons or holes available for the function of the device.

2.3.1. **Common Semiconductor Materials**

Silicon was used as the semiconductor material for the first semiconductor devices and still remains the most popular material for most semiconductor applications. Silicon has a diamond cubic structure, with a 1.12eV bandgap and a relatively high melting temperature. Silicon is useful in many environments, but cannot be used for certain niche applications, including operation at high temperature and operation in
radiation fields. Silicon was not investigated in the CRIF, because silicon has already been widely investigated for radiation tolerance and has proven to be insufficient for most radiation environments, even at room temperature. Therefore, devices made from materials with higher bandgaps like GaN were investigated in the CRIF.

Within a semiconductor, electrons can be promoted in a number of ways. For example, in a semiconductor-based radiation detector (or a solar cell), incident radiation interacts with the semiconductor medium, exciting the electrons as the radiation loses energy. This excitation generates electron-hole pairs. When an electric field is applied in the volume where the pairs are generated, the electrons and holes can be accelerated to oppositely charged junctions and collected, generating a pulse with a measurable current and voltage. The opposite of this function is a LED, in which a current pulse is provided to the LED and photons are released with characteristic energy.

Other applications include transistors, which are used to amplify and switch electronic signals. In a transistor, the semiconductor material has at least three terminals. An applied voltage or current can be applied to one set of contacts on the transistor to "turn on" the amplifying effect of the transistor. In this case, one pair of terminals receives an input current or voltage, which changes the output of another pair of terminals. In the case of three terminals, the pairs can share the ground signal. This effectively allows for a controlled "switch" which either amplifies a signal, or does not amplify a signal. Transistors switches are the basic building blocks of most modern electronic devices. The first working silicon transistor was developed at Bell Labs in 1954. Since then, transistors have allowed for cheaper, more lightweight, and smaller
devices of all types, including radios, cell phones, and computers. These technologies can be employed in space-applications for communication circuits, if they can be shown to survive in radiation fields and at varying temperatures.

2.3.2. **Applied Semiconductor Materials: HEMTs**

One specific kind of transistor is the High Electron Mobility Transistor (HEMT). HEMTs are also known as Heterostructure Field Effect Transistors (HFETs) and Modulation-Doped FETs (MODFETs). HEMTs are able to operate at higher frequencies than other transistors and are used in cell phones, satellite communications, radar equipment, and other space-frequency relevant applications. These devices are traditionally made of GaAs with AlGaAs, but various other configurations have been created, including many new applications of GaN HEMTs.

HEMTs avoid the slowing down of electrons via collisions with impurities (dopants) by using a highly-doped wide-bandgap n-type donor-supply layer heterojunction (traditionally the AlGaAs layer) with a non-doped narrow-bandgap channel layer (traditionally the GaAs layer). The name "high electron mobility" is derived from the specialized function of this geometry. Electrons generated in the n-type AlGaAs layer preferentially move to the GaAs layer because the heterojunction, created by the mismatched bandgaps of the two layers, causes a quantum well (very low energy state) on the GaAs side of the junction. Within this undoped GaAs layer, there are no impurities (dopants) to decrease the electron mobility, resulting in a high electron mobility (low resistance) two dimensional electron gas. This high electron mobility allows for very fast
switching and amplification of high frequency signals. Therefore, HEMTs, which were investigated in the CRIF are ideal for RF space communications systems.

2.3.3. **Wide-Bandgap Semiconductor Materials and Applications**

A wide-bandgap semiconductor material is a semiconductor material with an electronic band gap greater than 1eV. In practice, a semiconductor material is often referred to as having a wide-bandgap, when it is greater than one of two of the most common semiconductor materials: silicon (bandgap = 1.1eV) and gallium arsenide (bandgap = 1.4eV). These wide-bandgap materials are commonly used in optoelectronics devices and in power devices. These materials are usually much more difficult to make, because of the necessity of having a high-purity, highly-ordered crystalline structure, in order to achieve the macroscopic properties associated with a wide-bandgap. It is difficult to grow highly-homogenous samples of these materials, and therefore they are currently used in niche applications, for which a common semiconductor will not suffice. Specifically, these wide-bandgap devices are often used in high temperature applications.

2.3.3.1. **Semiconductor Material: GaN**

Gallium Nitride (GaN) is a binary III/IV direct wide-bandgap semiconductor commonly used in LEDs. The crystal structure of GaN is either that of Zinc Blende or Wurtzite, with lattice constants $a = 3.186\,\text{Å}$ and $c = 5.186\,\text{Å}$, and a tetrahedral coordination geometry. A diagram of the two polytypes is shown below in Figure 9. GaN is more difficult to manufacture in high crystalline-quality than other wide bandgap semiconductors like SiC, but may hold even greater potential for various applications.
GaN can be doped with silicon or oxygen for n-type doping, or magnesium for p-type doping. It has been used to make p-n junction LEDs, including blue/UV LEDs and violet laser diodes. It also has shown promise in making UV detectors and various high-speed field-effect transistors.

![Diagram of GaN Polytypes](image)

**Figure 9: Crystalline Structure of GaN Polytypes: (1) Zinc Blende (left) and (2) Wurtzite (right)**

Of the two polytypes of GaN, the Zinc Blende structure is slightly more appealing based upon the higher hole mobility. However, there is very little difference between the properties of the two polytypes overall. The properties can be seen below in Table 5, along with those of Si, and GaAs. GaN promises to be a very important material in the future, especially in high frequency communications systems. The CRIF was used to investigate the function of this material in cryogenic radiation environments.
Table 3: Properties of Various Semiconductor Materials\textsuperscript{35 36 37}

<table>
<thead>
<tr>
<th>Properties</th>
<th>Silicon</th>
<th>GaAs</th>
<th>GaN (ZB)</th>
<th>GaN (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cc)</td>
<td>2.33</td>
<td>5.32</td>
<td>6.15</td>
<td>6.15</td>
</tr>
<tr>
<td>$E_g$ (eV)</td>
<td>1.1</td>
<td>1.42</td>
<td>3.2</td>
<td>3.4</td>
</tr>
<tr>
<td>$\mu_e$ (cm$^2$/V-s)</td>
<td>1400</td>
<td>8000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>$\mu_h$ (cm$^2$/V-s)</td>
<td>450</td>
<td>400</td>
<td>350</td>
<td>200</td>
</tr>
<tr>
<td>$K$ (W/cm-K)</td>
<td>1.3</td>
<td>0.55</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>$E_b$ (V/cm)</td>
<td>3E5</td>
<td>1E5</td>
<td>5E6</td>
<td>5E6</td>
</tr>
<tr>
<td>$T_{max}$ (°C)</td>
<td>1200</td>
<td>400</td>
<td>2500</td>
<td>2500</td>
</tr>
<tr>
<td>$E_d$ (eV)</td>
<td>22 (C)</td>
<td>13-20</td>
<td>73 (Ga)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>35 (Si)</td>
<td></td>
<td>32 (N)</td>
<td></td>
</tr>
</tbody>
</table>

2.3.4. Radiation Induced Defects/Damage

2.3.4.1. Radiation Induced Defects in GaN

Radiation can induce common point defects in GaN, including vacancies, interstitials, and anti-sites. A list plot of common defects found in Wurtzite GaN can be
seen below in Figure 10: Common GaN Defect Formation Energies as a function of the electron mobility. These show a variance between the various types and ionizations of vacancies, as well as Si and O anti-sites, which can be fairly common in GaN. Unfortunately it does not include interstitials in Wurtzite, or any formation energies in the Zinc Blende structure.

![Figure 10: Common GaN Defect Formation Energies as a function of the electron mobility](image)

Figure 10: Common GaN Defect Formation Energies as a function of the electron mobility\textsuperscript{38}
2.3.4.2. **Effects of Radiation Induced Defects in Semiconductor Materials:**

**Increased Resistivity - Decreased DC Amplification**

In all of these semiconductor materials, there are important electrical properties associated with the quality of the crystalline structure of the material. In each case, a device made with a given material is highly dependent upon the quality of that crystalline structure. Although some believe that high defect formation energies in SiC and GaN polytypes will make them less susceptible to radiation damage, it cannot be assumed. At cryogenic temperatures, decreased annealing may result in high defect densities, if not total amorphization of crystalline structure at localized points. As seen in the case of highly ordered semiconductors, these point defects can drastically change the localized electronic structure and properties of the material. Therefore, in a high-flux radiation field, it may be possible to change the bandgap or resistance of the material to the point that it no longer functions. The DC measurements completed in this work provide an indirect measurement of the gate-source functionality of the GaN HEMTs *in situ*, during the cryogenic irrigations and low temperature annealing. The results of these experiments demonstrate the functionality of these materials in the complex and harsh conditions of combined low temperatures and high radiation, which are similar to those found in space.

2.4. **Cryogenic Irradiation Facility Materials**

The cryostat will be exposed to high levels of neutron and gamma radiation. Because of this, all materials within the cryostat have to be carefully selected to support the experimental requirements without degrading significantly. Moreover, if the facility is
to be used more than once, it must not be limited by neutron activation of the cryostat materials. These requirements are important for electrical connections, structural materials, and cryogenic and vacuum support materials.

2.4.1. **Materials Degradation**

As previously described, when radiation interacts with a material, it can cause changes to the atomic structure of the material. Radiation can be captured by a target material, can slow down in the field of electrons within the target material, or can scatter off of atoms within the target material. These radiation interactions can cause local defects, which can cause macroscopic damage to the target material. This potential for damage of a material must be considered when selecting materials for a radiation environment. Specifically, some materials degrade in high gamma fields. The two structural materials of the CRIF, Al-6061 and G10 glass composite, are well established as robust structural materials that can maintain structural integrity during and after irradiation at high fluence in the mixed field of a nuclear reactor.

2.4.2. **Theory of Neutron Activation**

One specific type of radiation interaction with a target material, that can be very detrimental to the performance of the material and/or the future experimenter accessibility of the material, is neutron activation. When neutrons impinge upon a given target material, there is an associated probability that the neutron will be captured by the target nuclei, which is dependent upon a myriad of factors, including the target isotope, the neutron energy, and the local temperature. When the neutron is captured, the resulting
nucleus is now a new isotope of the original element, with one extra neutron. This new isotope has extra energy and an extra neutron, which often causes the nucleus to be unstable. An unstable nucleus must de-excite through emission of new radiation. The emission of radiation from the nucleus can change the unstable isotope to a new stable isotope of the same element, or a different element. Or, it can result in a subsequent unstable isotope, which must undergo a series of de-excitations to terminate as a stable, non-radioactive, isotope. This phenomenon, can happen at a high rate when in a high neutron flux region, which can change the target material macroscopic properties enough to cause component failure.

Many materials are constituted by common isotopes that have rather large neutron capture cross sections. The macroscopic neutron capture cross section is defined as the product of the number density of the target isotope and the microscopic cross-section:

\[ \Sigma = N \sigma \]

where \( \Sigma \) is the macroscopic cross-section of the target isotope, \( N \) is the number density of the target isotope, and \( \sigma \) is the microscopic cross-section of the target isotope.

### 2.4.3. Low-activation Materials

Any material used in a neutron radiation field must be able to continue to function. The chosen material must be constituted by isotopes with relatively low microscopic capture cross-sections. There are many materials that are well known for either their low microscopic capture cross-sections or short-lived daughter isotopes. Among these, the principle constituents of the cryostat, Aluminum 6061 and G10 glass.
composite, are well understood. Many of the other materials used in the CRIF were also chosen for their low activation or the relatively short half-lives of the resulting activated isotopes. These materials were examined during the course of the planning experiments and some were tested using neutron activation analysis, by removing small samples from the cryostat and irradiating them in the rabbit irradiation facility of the OSURR. These results will be discussed below in a subsequent section.

2.4.4. **Cryogen**

There are many ways to design cryogenic systems, which can cool experimental samples and control temperature in their vicinity. The CRIF relies on a liquid cryogen bath to support experiments. The CRIF can support experiments at various minimum temperatures using different liquid cryogens. These cryogens have different boiling points and different thermal transfer properties, which change some of the design parameters of experiments. Some of these cryogens require varying levels of supporting equipment for their safe handle and care, and for their efficient use within a system. The CRIF has been designed with two liquid cryogens in mind: liquid nitrogen (LN2) and liquid helium (LHe).

2.4.4.1. **Liquid Nitrogen**

Liquid Nitrogen (LN2) is simply nitrogen in a liquid state. Nitrogen exists naturally as a covalently bonded diatomic molecule of two nitrogen atoms (N2). LN2 is a clear liquid with a density of 0.807 g/cc, a boiling point of 77 K (-196 C or -321 F), and a thermal conductivity at 77 K of 1.39 mW/(cm-K). Liquid Nitrogen is manufactured
commercially by the cryogenic distillation of liquefied air or from the liquefaction of pure nitrogen gas. The relative ease of manufacturing keeps LN2 prices quite low. A liter of LN2 costs less than a liter of milk. Nonetheless, because it exists at ambient pressure near the boiling point or 77 K, it is very easy for LN2 to boil off, when in contact with room temperature air. Therefore, storage of liquid nitrogen is done in commercially available vacuum walled Dewars. Also relevant to the CRIF is the freezing point of LN2, 63 K. The freezing point is relevant in LHe pre-cooling, due to the fact that it is above the boiling point of liquid helium. This problem will be discussed in further detail below, in the experimental procedures sections.

2.4.4.2. Liquid Helium

Liquid Helium (LHe) is simply helium in a liquid state. Helium exists naturally as a noble gas, as a helium single atom free from molecular bonds. LHe is a clear liquid with a density of 0.125 g/cc, a boiling point of 4.2 K (-269 C or -452 F), and a thermal conductivity at 4.2 K of 0.27 mW/(cm-K). LHe is also manufactured commercially, but in a more complicated process. Unfortunately, gaseous helium is hard to come by, because it is typically extracted, along with natural gas from drilling wells. Some gas is stored by the US government in the National Helium Reserve, which has been decreasing in volume since the passing of the Helium Privatization Act of 1996. Since supplies are low, the gas has increased drastically in price. Additionally, the process of cooling liquid helium requires an iterative process in which the gaseous helium is compressed, then cooled, and finally decompressed. After repeating this process many times, the gaseous helium cools enough that it changes state and becomes a liquid. Due to the difficulties in
the supply of gaseous helium and in the manufacturing process, LHe is much more expensive than LN2. Because it exists at ambient pressure near the boiling point or 4.2 K, it is even easier for LHe to boil off, than for LN2, when in contact with room temperature air. Therefore, although LHe is also stored in robust commercially available vacuum walled Dewars, it still boils away fairly quickly. This short shelf life of LHe further exacerbates the high price problem.
Chapter 3: Cryogenic Irradiation Facility Equipment

The CRIF is a combination of three major pieces of equipment. The first is the OSU Research Reactor, which acts as the radiation source for all experiments. The second is a 10” Dry Tube, which sits beside the OSURR in the reactor pool and holds experimental setups. The third is the Cryostat, which is made up by a main Dewar, which holds liquid cryogen, and evacuated experimental facilities.

3.1. OSU Research Reactor

The Ohio State Research Reactor (OSURR) is an open pool type reactor which is licensed to operate at a maximum power of 500 kilowatts. The average thermal neutron flux at 500 kW in the core is 5E12 n/cm$^2$/s. The OSURR has 19.5% enriched U$_3$Si$_2$ plate-type fuel with aluminum cladding, and it sits in the bottom of a light-water pool. The OSURR is cooled by natural circulation. There are multiple experimental facilities in the OSURR pool, which allow for materials to be placed within the OSURR, or in close proximity to the OSURR. One of these facilities is a ten inch dry tube.

3.2. 10" Dry Tube in the OSURR Pool

The 10" dry tube is an all-aluminum 6061 vertical tube with a 10.5" OD, a 9.5" ID, a closed bottom, and an open top. The dry tube is made of 4 pieces, which connect
with bolted flange joints, with large O-rings between the pieces. The tube allows for the cryostat (9" OD) to be lowered via crane, into the bottom of the dry tube. There are steel plates at the bottom of the dry tube. The steel plates serve two important purposes. First, they help counter balance the buoyancy of the dry tube so that the tube sits on the bottom of the pool, but is relatively easy to lift and move within the pool. Second, the plates help align the cryostat and the inner experimental volume with the horizontal centerline of the OSURR core. On the outside of the dry tube is a welded aluminum box, which is aligned with the experimental facility of the cryostat. This aluminum box has a top and three side walls (the outer wall of the dry tube acts as the fourth wall), and an open bottom. There is a 1/4" OD aluminum tube which runs from the pool top to the bottom of this box, bends and opens up inside the box near the top. This box is referred to as the hard flux box. The 1/4" aluminum tube attaches at the pool top to a compressed air line. When compressed air is pumped into the box, water is expelled from the bottom of the box until the box is completely filled with air. By removing the water from the box, neutron moderation is decreased, because the hydrogen in water is a good neutron moderator and is at a higher density than the comparatively lower density air. Thus, by using the box, the neutron flux spectrum is shifted to a higher energy profile than when not in use. Below in Figure 11 is a diagram of the OSURR and the cryostat inside of the 10" dry tube.
Figure 11: Drawing of Cryostat inside of dry tube, beside the reactor core
3.3. Cryostat

Section 3.3. and all subsequent subsections will describe all of the equipment associated with the Cryostat vessel, which will be placed inside of the 10" Dry Tube, which is placed adjacent to the reactor core. The "Cryostat" will refer to the Main Dewar and all of the equipment, support structures, and experimental facilities contained within the confines of the Main Dewar.

3.3.1. Main Dewar

The cryostat, used in the CRIF was originally used over 20 years ago for a series of liquid helium based temperature characterization tests on thermal sensors, manufactured by Lakeshore Cryotronics. The tests were performed to determine the survivability of various thermal sensors in mixed radiation fields and were performed in the 10" dry tube in the OSURR pool. The cryostat has been fully refurbished and re-equipped for liquid nitrogen or liquid helium experiments on the relevant semiconductor materials and optical fibers. Within the cryostat, there are various parts that support experiments and some of these have been altered and/or re-characterized to constitute the new CRIF. The cryostat consists of a number of concentric parts. The outermost part is the main Dewar. The Dewar of the cryostat, shown below in Figure 12 (image (1)), is a 60" tall vacuum sealed Dewar. The outer walls, bottom and top are all made of aluminum 6061 to decrease problems with radiation activation of the materials. The inner walls of the Dewar are made of G10 plastic. Between the outer and inner walls is a vacuum region, which is nearly empty. Inside of this evacuated region is 60" tall cryogenic superinsulation, which is wrapped around the inner wall. Superinsulation is a proprietary
material sold by Lakeshore Cryotronics, which consists of a thin plastic film, with vapor deposited high-purity aluminum on one side. By wrapping the superinsulation, the aluminum layers are electrically and thermally isolated from one another because each aluminum layer of the film is separated from the neighboring layers by the plastic film. This material is used along with the vacuum as a thermal barrier. The vacuum decreases the thermal leakage from conduction and convection, whereas the superinsulation decreases the thermal leakage from radiative heat transfer, from the outside environment to the liquid nitrogen inside the main Dewar volume. There is a plunger type vacuum fitting on the top of the Dewar which allows for the volume between the walls to be evacuated, down to \(<10^{-6}\) Torr. This main Dewar provides an inner 10 L volume to hold the liquid cryogen (either nitrogen or helium) and the experimental facilities.

3.3.2. **Outer Canister and Vacuum Equipment**

All of the remaining parts of the cryostat are supported from the cryostat top. The cryostat top is a 0.75" thick piece of G10 plastic. Off-center there is a fill tube port, that allows for a liquid helium (or another cryogen) transfer tube to be inserted into the cryostat and for the cryostat to be filled. In the center of the top is a sealed and mounted KF-25 vacuum flange, shown below in the top of Figure 12 image (2). Centered on the bottom side of the G10 top is a G10 vacuum tube, which is also sealed. This vacuum tube has the same inner diameter as the KF-25 mounting flange on top and they are aligned. The vacuum tube runs down to the top of the outer canister and has a sealed connection to the outer canister top, and is shown below in Figure 12 image (2). Mounted along the length of the G10 vacuum tube are four aluminum discs that act as radiative heat
reflectors, which decreases heat transfer from the environment above the G10 top to the liquid cryogen.

The outer canister is an aluminum canister with a compressed indium seal between the top flange and the actual canister, also shown in Figure 12 image (3) (compression screws shown, but not actual indium seal). This outer canister contains a mounted concentric inner canister, which acts as the experimental volume (described in the next section). The outer canister is sealed to the vacuum line so that the entire inside of the outer canister can be evacuated. The cold bath of the liquid nitrogen provides the base temperature of operation, once the inner volumes are sufficiently cooled. The vacuum of the outer canister acts as a thermal barrier, to decrease the conductive and convective heat transfer, so that the inner canister temperature can be controlled. However, in order to have a more dynamic temperature response, after vacuum is pulled, a small amount of helium gas is inserted, so that the final pressure in the evacuated area is \( \sim 10^{-2} \) Torr. Finally, in order to complete experiments, it is necessary to provide electrical and optical connections to the experimental volume. Therefore, the electrical and optical leads run from feed-throughs in the top KF-25 flange, down through the central G10 vacuum tube, and into the volume of the outer canister.
3.3.3. Inner Canister/Experimental Volume

The inner canister is also an all-aluminum canister. The top of the inner canister is mounted to the bottom of the outer canister top, which can be seen above in Figure 12 image (3). This means that the inner canister hangs within the outer canister and the outer walls and the bottom of the inner canister do not make contact with the inner walls of the
outer canister. This mostly thermally isolates the inner canister from the outer canister. The inner canister mounts to the inner canister top via screw fitting, which can be seen above in Figure 12 image (4). Finally, there is a Lakeshore Cryotronics proprietary metal resistive heating wire called Manganin wrapped around the inner canister outer walls and secured with masking tape. Most of the electrical leads, which run through the central G10 vacuum tube, run through holes in the top of the inner canister. Two of the leads attach to the Manganin wire on the outside of the inner canister. This temperature control system will be discussed further below.

3.3.4. Mounting Platforms and Wiring

Inside of the inner canister, there is a cylindrical wire mounting block which has leads on either side and a low thermal conductivity in between. This block can be seen above at the top of Figure 12 image (6). It decreases the thermal conduction from the experimental volume, along the electrical wires. Below this is an aluminum mounting block with a mounted Zero Insertion Force (ZIF) electrical pin block. There is a corresponding ZIF block mounted to the cryostat top as well. These ZIF electrical connections have been mapped and the resistance across the two ZIFs and corresponding electrical wires have been recorded. The ZIF pin block allows for electrical pin leads to be plugged in quickly for fast removal after irradiation. The wire leads run down to two experimental mounting platforms. These platforms can also be seen above in Figure 12 images (5) & (6). These platforms are aluminum 6061 as well, and use aluminum 4-40 screws and washers to clamp down the Duroid board device mounts. Each platform is
mounted along a 1/4-20 aluminum threaded rod and separated by 1/4-20 aluminum nuts. The platforms can each support four Duroid boards and four HEMTs.

3.3.5. Fiber Mounts

Along with the HEMT tests, there will be optical fibers undergoing analogous experiments concurrently. The fibers will be run through feed-throughs in the cryostat top KF-25 flange and epoxied into place. They will run down the length of the central vacuum tube and will then pass through the outer canister top and the inner canister top, into the experimental volume. Inside the experimental volume, the optical fibers were placed into aluminum tubes. These tubes were epoxied to the mounting platforms vertically (perpendicular to the plane of the mounting platforms). The silica multi-mode fibers were spliced such that they form optical loops for attenuation tests. Single-mode silica optical fibers (off-the-shelf and FBGs) were run through the same channels, but do not complete full loops, since the OBR only requires one end of a fiber to be connected. The fibers (multi-mode silica and single-mode silica) can be seen above in Figure 12 image (6) mounted inside the experimental volume, in the optical fiber guide tubes. The mounting methods inside the vacuum tube and inner volumes were tested and the optical fibers were shown to work at room temperature (confirming no break points within the fibers) before beginning experiments.

3.4. Liquid Cryogen Equipment

There are multiple pieces of equipment that support the safe storage and transfer of both LN2 and LHe in the lab. This equipment is necessary for using the CRIF. Some
of the equipment is particular to the specific cryogen used: LN2 equipment vs. LHe equipment. Others, including safety equipment, are universal.

3.4.1. **Liquid Nitrogen Dewars and Transfer Line**

Commercially available Dewars are used to store the liquid cryogens and specialized transfer lines are used to transfer the cryogens to the cryostat. Because LN2 and LHe can boil off easily, gaseous pressure can build up inside of these commercial Dewars and cause an explosion, if they are not properly vented. Therefore, all commercially available Dewars have pressure regulators, which allow for N2 or He gas to escape. A diagram of a typical commercially available Dewar is shown below in Figure 13. For use with the CRIF, there is a Dewar that comes filled with LN2 from the OSU Gas Cylinder Warehouse. This Dewar is similar to that shown in the commercially available Dewar diagram. A photograph of the LN2 Storage Dewar used with the CRIF can be seen below in Figure 14.
Figure 13: Typical Commercially Available Liquid Cryogen Storage Dewar Side View and Top View
The LN2 is under pressure in the Dewar and exits the Dewar through a valve at the top of the Dewar. A LN2 transfer line, custom made by Precision Cryogenics is used to connect to this LN2 output port. This transfer line has a flexible hose, which is under vacuum to keep from boiling off LN2 during transfer. It connects to a 5 ft long rigid bayonet at a

Figure 14: LN2 Storage Dewar used for CRIF
right angle. This bayonet can be inserted into the fill tube of the cryostat from the cryostat top. Once connected, the valve is turned and LN2 flows through the flexible hose and down the bayonet, exiting at the bottom of the cryostat, where it begins to fill the main Dewar. A diagram of the LN2 transfer line can be seen below in Figure 15.

![Diagram of LN2 Transfer Line](image)

**Figure 15: Diagram of Transfer Line Used in LN2 Transfer from LN2 Storage Dewar to CRIF Main Dewar**

### 3.4.2. Liquid Helium Dewars and Transfer Line

The LHe is also stored in a separate commercially available storage Dewar, which is supplied by Praxair. The LHe storage Dewar is somewhat similar to the LN2 storage Dewar in functionality and design. A photograph of the LHe storage Dewar can be seen below in Figure 16.
Similar to the LN2 transfer line, there is a LHe transfer line, which has a 5’ flexible horizontal section, which is surrounded by a vacuum sealed wall, connected to a rigid bayonet. This transfer line has fittings that are appropriate for connection to the LHe storage Dewar. In this case, the LHe transfer line connection to the LHe storage Dewar is also a bayonet. The storage Dewar has a valve opening at the top, which accepts the bayonet and can be tightened down to create a seal. In this case, the storage Dewar is vented at a much lower pressure than the LN2 storage Dewar, for safety purposes. Therefore, there is not enough residual vapor pressure from LHe boil-off to allow for natural flow of the LHe out of the storage Dewar. In order to cause the LHe to flow out
and exit the transfer line, there is a secondary pressurization port on the top of the LHe storage Dewar. A compressed gas line is attached to this pressurization port and also attached to a He gas cylinder. The He gas flow rate is adjusted to a gauge pressure of a few psi and the He gas pressurizes the LHe storage Dewar to an appropriate level, such that the LHe begins to flow out of the transfer line and into the CRIF. Special precautions must be taken when handling LHe, because of the potential explosion hazards associated with using a LHe storage Dewar. These will be discussed in greater detail below in a subsequent section. A diagram of the LHe transfer line can be seen below in Figure 17 and a photograph of the transfer line can be seen below in Figure 18.

![Diagram of Transfer Line Used in LHe Transfer from LHe Storage Dewar to CRIF Main Dewar](image)

**Figure 17**: Diagram of Transfer Line Used in LHe Transfer from LHe Storage Dewar to CRIF Main Dewar
3.4.3. **Cryogenic Safety Equipment**

To properly handle all of the liquid cryogen transfer and the pre-cooling, proper safety equipment is necessary. During these procedures, two pairs of specialized cryogenic gloves, two cryogenic aprons, and two face shields that were purchased from Fisher Scientific were used, one by each of two experimenters. Pictures of this equipment can be seen below in Figure 19.
3.5. **Cryostat Temperature Monitoring and Control System**

Section 3.4. and the contained subsections will describe the equipment associated with controlling the temperature of the experimental volume of the cryostat. As previously described, the outer canister is in direct contact with liquid nitrogen or liquid helium, which establishes the lowest achievable temperature of the cryostat experimental volume. The description herein will provide the details of the temperature sensors, temperature monitoring system, the interface with the computer, and the control of the heating element, which is wrapped around the inner canister, and the vacuum pumping system.

3.5.1. **Temperature Sensors**

In all of the experiments, temperature in the experimental volume, inside the inner canister, must be well understood. These experiments are meant to characterize the
effects of radiation at cryogenic temperatures and well-calibrated thermometry is necessary. In order to properly record the temperatures of the experimental materials, there will be two Lakeshore Cryotronics Cernox Resistance Temperature Detectors (RTDs) (Model: CX-1030-SD-HT-1.4M) within the experimental volume, one mounted on each of the transistor mounting platforms. An RTD is a temperature measurement device that has a resistance which is dependent on the temperature of the RTD. The RTD is measured by a calibrated readout system that measures the change in resistance in the RTD and converts it to a temperature. These Cernox RTDs are useful from a minimum temperature of 0.1K to a maximum temperature of 420K. At 4.2K, they have a temperature error of only +/- 5 mK. They are also recommended for radiation environments and have been tested in neutron and gamma fields. The changes at various temperatures after neutron and gamma irradiation for a typical Cernox temperature sensor can be seen below in Figure 20. Also shown below in Figure 21, from the Lakeshore Cryotronics website, is a diagram of the specific Cernox sensor and packaging used in the experimental volume of the CRIF. Finally, a picture of one of the Cernox RTDs is shown below in Figure 22.
Figure 20: Lakeshore Cernox RTD Response in Neutron and Gamma Radiation Fields\textsuperscript{39}
General tolerance of ±0.005 in [±0.127 mm] unless otherwise noted

Figure 21: Lakeshore Cernox RTD Temperature Sensor Diagram
3.5.2. Thermocouple Readout Equipment and Positions

Two temperature readout instruments are employed to read the output resistance signal from the Cernox RTDs, convert it to a temperature measurement, and to record the temperature in a text file on a connected computer.

The Lakeshore Model 335 Temperature Controller is used to read the output signal of one of the Cernox RTDs. The Model 335 can read the Cernox RTD to a minimum of 300mK, well beyond the needs of the liquid helium based CRIF (minimum temp 4.2K). The Model 335 has an IEEE-488 port, a serial RS-232 port, and a USB port.
for communicating with the control computer. There are Labview drivers available to allow NI Labview remote control of the Model 335 through either the IEEE-488 or USB ports. The Model 335 communicates to the control computer using a NI Labview code, which controls the Model 335 and records the measured temperature in a text file. The Model 335 temperature controller also includes an internal PID controller, which changes the supplied current and voltage to a resistive heating element to maintain a set temperature. The Model 335 has output voltage and current commensurate with the needs of the Manganin wire resistive heating element wrapped around the inner canister. The Model 335 can operate with a maximum output power of 75W, with maximum current of ~1.41A and maximum voltage at 50V. The applied current and voltage is carried through a low resistance set of wires to the high resistance Manganin wire, which is wrapped around the inner canister of the CRIF. The Manganin wire heats up based on the applied current and voltage and the heat is transferred to the outer wall of the inner canister. This applied heat source allows for temperature control of the experimental volume inside the inner canister from 4.2K to above room temperature. Below in Figure 23 is a picture of the front panel and back of the Model 335 Temperature Controller.
Figure 23: Lakeshore Model 335 Temperature Controller

The output resistance of the other RTD is read and converted to a temperature by the Lakeshore Cryotronics 218 Temperature Monitor. This device records signals from up to eight cryogenic temperature sensors and interfaces to the control computer to record the temperature data. The Model 218 operates to a minimum temperature of 1.2K with the Cernox RTDs. The Model 218 also has an IEEE-488 port and a serial RS-232 port for communication with the control computer. In this case, only the IEEE-488 port is
supported for a NI Labview driver and a NI IEEE-488 to USB converter is employed to communicate with the control computer. This device is also controlled by the same NI Labview code, which is used for the Model 335. This integrated code records the measured temperatures from the Model 218 concurrently and writes them to the previously described text file. A picture of the front panel and back of the Model 218 can be seen below in Figure 24. A screenshot of the NI Labview code block diagram and the GUI, which controls the Model 335 and Model 218 can be seen below in.
3.5.3. **Vacuum Pumping System**

In order to control the temperature of the experimental volume, the Manganin wire resistive heating element must be able to provide more heating power than is removed through transfer to the cryogen bath. This allows the experimental volume temperature to be increased above the base temperature of the liquid cryogen. Therefore,
the thermal transfer to the cryogen bath must be minimized. In order to minimize this thermal transfer, the outer and inner canister volumes are evacuated. This is done by attaching a vacuum turbo pump line to the KF-25 mating flange on the cryostat top. The Pfeiffer Vacuum HiCube Eco is used to evacuate the central vacuum tube and concentric outer and inner canisters. This pump is a benchtop type integrated roughing and turbo pump, with a pumping speed of 35 l/s and a minimum pressure below 10⁻⁸ Torr. Below in Figure 25.

![Image of Pfeiffer Vacuum HiCube Eco Integrated Benchtop Turbo + Roughing Pump](image)

**Figure 25: Pfeiffer Vacuum Hi-Cube Eco Integrated Benchtop Turbo + Roughing Pump**

While the experiments are running in the CRIF, it is necessary for the central vacuum tube, outer canister, and inner canister to be evacuated, but it is not necessary to
continually pull vacuum on the system. Instead, between the vacuum line flange and the cryostat top flange, a KF-25 t-splitter is inserted, with a valve above and below it. The KF-25 t-splitter allows for a vacuum gauge to be placed on one of the splitter KF-25 flanges. The CRIF employs the Pfeiffer Vacuum Active Pirani/cold cathode transmitter (model: PKR 251, DN ISO-KF) (Vacuum Gauge). This Pfeiffer vacuum gauge has a broad range including the roughing and turbo pump ranges of a vacuum system that typically require two separate gauges. The full range of the Pfeiffer vacuum gauge is from ~5*10^{-9} Torr to 760 Torr (which equals 1 atm, or atmospheric pressure). A picture of the vacuum gauge can be seen below in Figure 26.

![Pfeiffer Active Pirani/cold cathode transmitter](image)

**Figure 26:** Pfeiffer Active Pirani/cold cathode transmitter (PKR 251, DN 25 ISO-KF) Vacuum Gauge
3.5.4. **Multimode Fibers**

The cryogenic experiments and cryogenic irradiation experiments were completed on silica multi-mode optical fibers. Silica multi-mode fibers (cheap off-the-shelf) were looped through the CRIF so that light could be passed through the fiber from a broadband light source and received by two spectrometers.

3.5.4.1. **Silica Fibers**

The multimode silica optical fibers that were used in the cryogenic irradiation optical attenuation experiments are low-OH Polymicro optical fibers, model FIP100120140. These optical fibers have low levels of hydroxyls (OH), which decreases attenuation losses from OH sites. These fibers have a silica core, with a 100μm OD, a doped silica clad, with a 120μm OD, and a polymide buffer, with a 140 μm OD.

3.5.5. **Single Mode Fibers**

Only one type of single-mode silica optical fibers as used in the cryogenic experiments and cryogenic irradiation experiments: cheap off-the-shelf single-mode silica optical fibers. In each of these experiments, the silica single-mode optical fibers were connected on one end to the Luna Optical Backscatter Reflectometer (OBR). The other end was placed into the experimental region of the CRIF.

3.5.5.1. **Off-the-shelf Silica Fibers**

The first type of fiber, Corning's SMF-28e+, is a relatively inexpensive optical fiber, commonly used in the telecommunications industry. It consists of a silica core, with an 8μm OD, a clad, with a 125μm OD, an acrylite protective coating, with a 245μm OD,
an aramid yarn buffer layer, with a 900μm OD, and a PVC outer jacket, with a 3mm OD. The coating layers are meant to provide mechanical strength to the optical fibers and to allow for tighter bending radii. The fibers have a nominal Rayleigh backscatter coefficient of -77 dB at 1310nm light and -82 dB at 1550 nm light. The index of refraction is 1.4676 at 1310nm light and 1.4682 at 1550nm light.

3.6. **Optical Fiber Equipment**

There are two main systems which can be used with the CRIF to support optical fiber experiments at cryogenic temperatures in radiation fields. Specifically, the first system was developed by Dr. David Hawn for automated attenuation measurements to be taken on the silica multi-mode optical fibers. This system includes a broadband multi-mode light source and a multiplexer attached to two spectrometers. This system is made of components from a number of different manufacturers. Therefore, Dr. Hawn wrote an integrated Labview program for characterization and data acquisition, including a graphical user interface. The second system was used to characterize single-mode silica optical fibers, in order to test optical fibers as temperature sensors in a cryogenic radiation environment. This Optical Backscatter reflectometer is an integrated system manufactured by Luna Technologies. These systems will be discussed in further detail below.

3.6.1. **Broadband Multi-mode Optical Fiber Transmission Measurement System**

The broadband multi-mode light source is a custom source manufactured by NKT Photonics. The light source is connected to one of two multiplexers. Two identical optical
fiber multiplexers (model FOM-IR400-2x8) were purchased from Avantes Inc. and allow for multiple fibers to be interrogated automatically and in quick succession during an experiment. Inside of each multiplexer, an internal optical fiber is connected to one main outside port on one side and to a mechanically rotating system on the other side. As the rotating fixture moves, the fiber is aligned with one of 16 connectors to allow for automated interrogation, in serial, of multiple optical fibers. The first multiplexer allows for light to be distributed from the light source to multiple fibers and the second multiplexer allows for light to be collected from multiple optical fibers.

The optical signal, which passes through the second multiplexer is measured by two spectrometers. The first spectrometer is an extended-range near-infrared (NIRX) spectrometer (model NIRX-SR-1024), manufactured by StellarNet. The second is an ultraviolet-visible-near-infrared (UV-vis-IR) spectrometer (model BLK-C-SR), also manufactured by StellarNet. Both of the spectrometers use a fixed diffraction grating to separate the optical spectrum spatially onto a linear CCD. The NIRX spectrometer has a 25μm slit and a 1024 pixel linear indium gallium arsenide (InGaAs) CCD, sensitive between 900nm and 2300nm. The UV-vis-IR Spectrometer has a 50μm slit and a 2048 pixel linear CCD (Sony ILX511), sensitive between 200nm and 1080nm. The InGaAs CCD operates with a thermoelectric cooler and has a 8nm resolution. The Sony CCD operates at room temperature and has a resolution of 2nm. The input optical fiber connector for both spectrometers is a SMA905 and the output communicates to a computer through USB. The entire measurement system is automated in the NI Labview program. Therefore, the output spectral data are collected and plotted in NI Labview,
before being written to a text file. The relative sensitivity of each of the spectrometers is shown below in Figure 27.

![Figure 27: CCD Sensitivity in UV-vis-NIR [78](L) & NIRX (R) Spectrometers](image)

Due to problems with heating in the spectrometers, both spectrometers were placed in a mini-refrigerator. Holes were drilled in the sides of the mini-fridge to act as optical fiber pass-throughs. The mini-fridge allows for more accurate optical attenuation measurements in both spectrometers.

Finally, there is a fiber-coupled optical power meter within the integrated system. This Newport model 918D-IS-1 is sensitive from 410-1650nm. A custom connector was fabricated for this readout system. This power meter does not differentiate between light wavelengths and instead measures the wavelength-integrated total optical power. The nominal sensitivity of the power meter, as provided by the manufacturer, is shown below in Figure 28.
A schematic of the light source, the power meter, the multiplexers, and the spectrometers can be seen within the system schematic below in Figure 29 and photographs of each can be seen below in Figure 30.

Figure 28: Spectral Sensitivity of Power Meter

Figure 29: Block Diagram of Experimental Setup
3.6.2. Luna Optical Backscatter Reflectometer

Fiber-as-sensor experiments in the CRIF were supported by the Luna Innovations' Optical Backscatter Reflectometer (OBR) model 4600, which is a swept-wavelength optical frequency domain reflectometer. As previously described, OTDR can be used to interrogate single-mode fibers as intrinsic sensors to determine changes in strain or temperature in the local environment. This method allows for distributed sensing at discrete locations, along a fiber of tens of meters. The OBR is a commercially available, well-calibrated, integrated system which allows for such measurements. The OBR includes both a tunable laser light source and a spectrometer. The light is passed down the length of a fiber and, after reflection, is collected within the integrated system box. In
order to allow multiple fibers to be interrogated in quick succession, the OBR is coupled to an optical switch (model FOS008), which has connections for up to eight optical fibers. The OBR can be used to characterize the temperature sensing capability of single-mode silica optical fibers in the mixed radiation field at cryogenic temperatures. Below is a photograph of the Luna OBR and optical switch in Figure 31.

Figure 31: Optical Backscatter Reflectometer Equipment in OSU research lab
3.7. **Transistor Equipment**

The transistor cryogenic experiments and cryogenic irradiation experiments were completed on GaN HEMTs, and were interrogated *in situ* by an computer controlled National Instruments benchtop electronics measurement system.

3.7.1. **Transistors**

3.7.1.1. **GaN HEMTs**

The GaN High Electron Mobility Transistors (HEMTs) used in this research are CREE model CGH40006S GaN HEMTs. They are high efficiency, low noise, broadband high gain amplifiers that operate in the frequency range of 0.5 to 6.0 GHz. These are packaged in 3x3mm 440203 plastic packaging. They can be used for 6W RF power amplification to +13 dB output gain at 2.0 GHz and 11 dB output gain at 6.0 GHz. The gain amplifier is rated for 28 V operation. These GaN HEMTs are commonly used in broadband amplifiers, 2-Way Private Radio, cellular communications, and test instrumentation for RF applications. These GaN HEMTs have also been mounted on Rogers model 8100 Duroid Board substrates. The GaN HEMTs were mounted in a configuration for in situ DC tests. The GaN HEMTs can be seen below in Figure 32.
### National Instruments PXI System

An integrated National Instruments PXI electronics testing system was used for the *in situ* testing of the HEMTs. The NI PXI System is based on a single electronics measurement system chassis (model NI PXI-1033: 5-Slot PXI Chassis with Integrated MXI-Express Controller) that interfaces with the control computer through one USB port.
The chassis supports individual electronic device modules that slip into card-type slots in the chassis. The electronics instruments do not have a high functionality physical interface for setup and control. Instead, they are controlled remotely by National Instruments Labview software on the computer. This software can be changed to fit the specific needs of a given experimental setup. In the case of these experiments, the PXI system is setup with two Precision Source Measure Units for PXI (SMU) (model: NI PXI-4231), and one 32-channel (2-Wire) switch, which allows for fast switching of consecutive measurements across 16 devices. The SMUs provide voltage/current and can measure voltage/current with a maximum of +/-100 V, with a resolution of 500 µV, and current of up to 100 mA, with a resolution of 5 µA. At low current, the SMUs can operate at 10 µA with a resolution of 500 pA. The PXI switch allows for up to 300 V 4-wire measurements to be taken on up to 16 different devices (total of 64 ports). For the cryogenic and cryogenic irradiation experiments on the GaN-based HEMTs, each HEMT as connected to the switch through two ports (for two-wire measurements) to one of the SMUs. The SMUs provided appropriate source-to-gate voltage in individual steps and measured the current across the G-S junction. This produced an I-V curve and a simple measurement of DC amplification.

This PXI system can also allow for C-V and other electronic measurements to be made, if required by future experiments. The C-V measurements can be made with the PXI 6 1/2-Digit PXI Digital Multimeter (DMM) and LCR Meter (model: NI PXI-4072 FlexDMM and LCR Meter). This DMM/LCR is also a card-slot type electronics instrument that fits within the PXI chassis. This DMM/LCR can function in DC or AC
modes and has a maximum output voltage of 300 V, with a maximum capacitance range of 10,000 µF, with 1 µF resolution, and a minimum capacitance range of 300 pF, with a resolution of 0.05 pF. This DMM/LCR can also use the switch and be controlled by NI Labview on the control computer. The integrated NI PXI system can be seen below in Figure 33: (1) National Instruments PXI-1033 Integrated MXIe with 5 Peripheral Slots, using two NI PXI-4132 Precision Source Measure Units, one NI PXI-4072 FlexDMM and LCR Meter and one PXI-2527 64-Channel 300V CAT I Multiplexer Figure 33.

Figure 33: (1) National Instruments PXI-1033 Integrated MXIe with 5 Peripheral Slots, using two NI PXI-4132 Precision Source Measure Units, one NI PXI-4072 FlexDMM and LCR Meter and one PXI-2527 64-Channel 300V CAT I Multiplexer
Chapter 4: Modeling/Simulation Methodology

4.1. MCNP6

MCNP6 is the most current version of the Monte Carlo Neutral Particle Transport Code developed by researchers at Los Alamos National Laboratory. This code is used to simulate various nuclear processes, including fission and propagation/tracking and interactions of radiation particles through a material. There is a validated MCNP model of the OSURR, which has been developed over many years by graduate students and the OSUNRL staff. This model simulates the operation of the OSURR and contains geometric models of all of the radiation test facilities within the reactor pool, except for the 10\" dry tube. Therefore, the work completed herein includes the addition of the 10\" dry tube and the CRIF to the OSURR MCNP model. This model simulates the neutron flux and neutron interaction events at detectors defined within the volume and location of (1) the empty 10\" Dry Tube and (2) proposed materials under test in the CRIF.

Specifically, the geometries of the entire CRIF including the mounting platforms and the optical fibers and HEMTs were added to the simulation.

In addition to the neutron simulations, MCNP can also be used for gamma and electron simulations. Typically, these are not relevant to neutron irradiation experiments. However, the gamma and electron flux can contribute to heating within the system. Since
this is a temperature controlled CRIF, it is important to know how much heat will be
generated in the CRIF materials. The previous experiments (by Lakeshore Cryotronics)
that used much of the equipment comprising the current CRIF, which used LHe at 4.2 K,
were conducted ~7-8 K at 500W reactor power (temperature increase due to radiation
induced heating). These tests were completed before the reactor was licensed to increase
the maximum operating power to 500kW. This means that it is necessary to predict the
level of radiation induced heating while operating the reactor at 500 kW, in order to
estimate LHe boil-off.

The simplest gammas and electrons to simulate, are those that result directly from
fission. By turning on gamma and electron tracking, in MCNP6, in the geometric cells
relevant to the experiments (reactor core, 10" dry tube, and cryostat), the gammas and
electrons can be tracked to the relevant materials. These prompt fission gammas and
electrons are the most significant source by multiple orders of magnitude and are the
most important for the heating simulations.

A second source that is relatively easy to track in MCNP6 are the gamma and
electrons produced from neutron activation. As neutrons are born from fission in the
reactor, they propagate through a number of materials. Those that reach the experimental
volume and the materials under test have likely been scattered during their lifetime. Other
neutrons are absorbed by the materials in the reactor pool, causing an unstable nucleus in
the new isotope. These activated radioisotopes decay in a number of ways. For the
activated materials near the materials under test, the activated isotopes can produce
gammas and electrons that may reach the materials under test and provide a noticeable
dose. Additionally, the materials within the cryostat that are activated may provide a significant source of gamma and electron heating.

4.1.1. Model of 10" Dry Tube in OSURR Pool

The first step in building the MCNP6 model was to incorporate a model of the 10" Dry Tube into the previously validated MCNP model of the OSURR. This model included the geometry of the flanges of the 10" Dry Tube, the Hard Flux Box (filled with compressed N2 gas to a density matching the pressure required to expel water from the Hard Flux Box), and the steel plates (filling the bottom of the 10" Dry Tube). In the past, simulations have been run with the inclusion of a 7" Dry Tube in the reactor pool, beside the reactor core. However, the placement of the 10" Dry Tube in the reactor pool necessitates the removal of the 7" Dry Tube. Therefore, first the 7" Dry Tube was removed from the model, then the 10" Dry Tube was placed into the model in the proper location to match the physical location of the 10" Dry Tube in the reactor pool when in use. In this model, air detectors were placed along the axial (z-axis) centerline starting adjacent to the steel plates and at height intervals of 1" to a maximum height of 56" above the reactor core horizontal centerline. The MCNP6 simulation was run with tracking of neutrons, photons, and electrons (i.e. Mode N P E). In this simulation, the Surface Source Write (SSW) card was used and a small shell (0.00001 cm outside the walls of the universe) was created around the universe that was placed inside the 10" Dry Tube to record all particle tracks coming across this shell boundary. The SSW run was completed on a single core (MCNP6 does not allow multi-core threading) for 61,000,000 source particles over a period of ~10 days and recorded a total of 10,840,068 radiation
tracks on the SSW surface. Then the track file was used in a subsequent Surface Source Read (SSR) with the F4 tally used in the air detectors for tracking neutrons, to understand the flux spectrum of neutrons along the z-axis of the 10" Dry Tube. The SSR run was completed for many iterations of the SSW output tracks on 44 cores on a computer cluster to reach a maximum of 1,000,000,000 (nps in MCNP6) source particles. A SSR run can be completed for multiple iterations of a source file consecutively, without giving the same results, because the random number seed counter in MCNP6 continues, instead of restarting, the simulation with the same initial seed. VisEd images of the geometry of the empty 10" Dry Tube simulations can be seen below in Figure 34 and Figure 35.

Figure 34: Side View of the MCNP6 Model of the Empty 10" Dry Tube in the OSURR Pool
Figure 35: Top View of the MCNP6 Model of the Empty 10" Dry Tube in the OSURR Pool

The results of these simulations can be found below in section 7.1.1.

4.1.2. Model of CRIF in 10" Dry Tube in OSURR Pool

After completing the model of the 10" Dry Tube, the CRIF geometry was added into the 10" Dry Tube in the MCNP model of the OSURR Pool. The Main Dewar was filled with LHe in the model, and all components inside the CRIF simulated using the temperature card, set so that the material temperature were was 4.2 K. As before, the CRIF model filled the universe inside the 10" Dry Tube and the same outer shell was used to record particle tracks in a SSW run. Again the model was run in a mode to track neutrons, photons, and electrons. The SSW run was again completed for 61,000,000 source particles over a period of ~10 days on a single computer core. All particle tracks
were used in the subsequent SSR run and F4 tallies were recorded in characteristic models of a typical GaN HEMT for neutrons. This SSR run completed many iterations of the SSW output file tracks for a total of 1,000,000,000 source particles (nps in MCNP6). Additionally, the F6+ tally was employed to record the radiation energy deposition in each of the structural materials and devices under test inside the CRIF, including the liquid cryogen. This tally was used in the subsequent radiation heating calculations to determine the time to boil-off for the liquid helium volume. A VisEd image of the CRIF in the 10” Dry Tube in the OSURR Pool can be seen below in Figure 36 and Figure 37.
Figure 36: Side View of the MCNP6 Model of the CRIF in the 10” Dry Tube in the OSU RR Pool
4.1.3. **Total Radiation Induced Heating Calculation**

In the previously described MCNP6 simulation of the CRIF in the 10" Dry Tube in the OSURR Pool, the F6+ tally was employed. This tally was used in each material/structure inside the CRIF, including in the LHe. The F6+ tally records the energy deposition from all available types of radiation as they pass through a given cell, provided in MeV/g. By multiplying the output values by the mass of each cell and summing each of these contributions, a total value for energy deposition was attained in MeV. This was converted to MeV/s for a given reactor power level, based on the total number of neutrons available in the core, as source neutrons, per second. Finally, the energy deposition rate was converted from MeV/s to J/s (or Watts). This energy
deposition rate, or heating rate, was then compared to the boil-off energy required to boil LHe that is at ambient pressure. The total initial volume after a LHe fill is known to be 10 L. Therefore, the initial volume was divided by the rate of LHe boil-off to achieve a conservative estimate of total time to complete boil-off of LHe. This estimate is a conservative estimate for a number of reasons. First, there is an assumption made that the thermal conductivity between all of the materials in the CRIF and the LHe is essentially infinite. This assumes that all of the heat that is generated through radiation energy deposition is completely free to flow into the cold LHe bath and is not limited. This is not a true scenario, because there will be some temperature gradient at steady state operation of the reactor, limited by the heat conduction path from each of the materials to the LHe bath. Furthermore, this assumes a continuous rate of energy deposition in the LHe. However, the LHe is continually boiling off. Therefore, although the energy deposition rate per unit mass will remain the same in the LHe, the total mass of the LHe will continually decrease. This means that the total energy deposition rate will decrease with time as the LHe boils away. This simple calculation for LHe boil-off is meant to provide bounds for experimental planning and conservative estimates are beneficial. The results of these calculations can be seen below in Section 7.2.
Chapter 5: Simulation Results

5.1. MCNP6 Results

The results from the previously described MCNP6 simulations can be seen below in the subsequent subsections.

5.1.1. Empty 10 inch Dry Tube Characterization

In order to compare against a foil activation experiment to determine the axial flux profile and the flux spectrum at the peak fast flux location, the MCNP6 simulation placed air detectors along the axial (z-axis) centerline of the empty 10" Dry Tube (foil activation experiment is underway by a fellow graduate student). The results from these simulations can be seen below in Figure 38.
As seen in the above figure, despite the use of the previously described Hard Flux Box to shift the spectrum of the neutrons to a higher energy range, the dominant component of the total flux is still the thermal flux. The fast flux peaks at -1 in, which is the same location as the total flux. We believe that this is due to the presence of the steel plates in the bottom of the 10" Dry Tube. We believe that the steel plates act as a more efficient neutron reflector than the air above. Therefore, there is a slight shift in the axial profile such that the peak total neutron flux, thermal neutron flux, epi-thermal neutron flux, and fast neutron flux all are located just below z = 0 (the reactor core horizontal centerline). These results are important for planning future experiments in order to line up the peak
fast neutron flux with the experimental volume of the CRIF, or any other experimental apparatus placed within the 10" Dry Tube.

The point of the highest fast neutron flux was examined more closely, since this would likely be the point planned for alignment with future experiments. The neutron flux energy profile can be seen below in Figure 39 plotted as differential flux*energy*Ln(10) vs. energy for a reactor power level of 450 kW.

![Figure 39: MCNP6 Model of the Empty 10" Dry Tube in the OSURR Pool, showing the Differential Flux*Energy*LN(10) for the neutrons in the air detector of the peak flux location \((z = -1)\)](Image)

The neutron flux profile clearly shows a large thermal neutron peak and a smaller fast flux peak. The fast flux for 450 kW is \(3.6 \times 10^{11}\) neutrons/(cm\(^2\)-s). The statistics of the simulation suffer because of the inclusion of photons and electrons and the computational time necessary to simulate these radiation types along with neutrons. Despite the visible
evidence of a need for better statistics, the simulation passed all ten of the statistical checks built into MCNP6. Future work should include a similar set of simulations without photons or electrons to achieve better statistics. These simulations will require a larger number of neutrons recorded on the SSW surface, which dominates the statistical issues seen in these simulations.

5.1.2. **Experimental Volume of CRIF inside 10" Dry Tube**

The second set of MCNP6 simulations included the geometry of the CRIF inside the 10" Dry Tube in the OSURR Pool. In these simulations, detectors were placed with F4 tallies for neutrons in characteristic transistors and in optical fibers mounted inside the geometry of the CRIF experimental volume. The GaN HEMT that was modeled is expected to be used inside the CRIF in future experiments. The results for the flux energy profile were again plotted as differential flux*energy*Ln(10) vs. energy for a reactor power level of 50 kW (this choice of 50 kW instead of 450 kW will be explained below for expected future experimental parameters) and can be seen below in Figure 40.
Figure 40: MCNP6 Model of the CRIF inside the 10" Dry Tube in the OSURR Pool, for operation at 50 kW, showing the Differential Flux*Energy*LN(10) for the neutrons a detector placed in a representative GaN transistor mounted inside the experimental volume of the CRIF.

As seen in the simulation above, there is again a large thermal neutron peak and a smaller fast neutron peak. The statistics again suffer from the previously described issues. However, again the simulation passed all of the ten statistical checks performed by MCNP6. The results demonstrate that a maximum fast neutron flux of $4.05 \times 10^{10}$ neutrons/(cm$^2$-s) is expected at a reactor power of 50 kW. This important for planning future experiments in the CRIF and for understanding the total fast fluence of a given experiment.

Finally, the optical fibers, as simulated in the MCNP6 model, were broken into sections as they run from the bottom of the experimental volume to the top of the CRIF. These sections were not of equal length. The sections in and closer to the experimental
volume are more important because they are in a volume of higher radiation flux than those closer to the top of the CRIF. Therefore the sections get larger as they increase in z position (i.e. closer to the CRIF top). The results for the average total flux, as determined by the F6 neutron tally in the MCNP6 simulation in the various sections of a typical silica optical fiber can be seen below in Figure 41.

![Figure 41: MCNP6 Model of the CRIF inside the 10" Dry Tube in the OSURR Pool, showing the Average Total Neutron Flux in various sections of a Representative Silica Optical Fiber Running from the Experimental Volume Through the Central Vacuum Structural Tube to the Top of the CRIF](image)

As seen in the figure above, the average total neutron flux is higher in the experimental volume of the CRIF and again peaks just below the reactor core horizontal centerline. The average total neutron flux then decreases as the z-position of the silica optical fibers increases. This is expected, since as z increases above 0 the silica optical fiber sections
are further away from the reactor core horizontal centerline. However, despite the decrease in average total neutron flux, there still remains a relatively large value of average total neutron flux to the CRIF top. This indicates that the lead-in and lead-out sections of optical fibers must be considered when planning experiments in the CRIF and when evaluating future experimental results. These higher sections of optical fiber will contribute to the total increase in optical attenuation from radiation damage.

5.2. **Total Radiation Induced Heating Calculation Results**

The final results from the MCNP6 simulations are the total radiation energy deposition (F6+ tally) results for each of the materials inside the CRIF, including the LHe. The results summed to a total of $5.31 \times 10^{-3}$ MeV deposited per source neutron in the simulation. For a reactor power level of 450 kW, this translated to a total radiation energy deposition rate of 32.4 W. Taking into account the latent heat of LHe at ambient pressure (20.754 kJ/kg), the density of liquid helium (125 g/L), and the total volume of the LHe (10 L), a conservative estimate of total time to LHe boil-off was calculated to be 13.3 minutes. Although this is a conservative estimate, for the reasons described in previous sections, this is an impractical amount of time for a given reactor experiment.

Specifically, the greatest contributing component to the radiation energy deposition calculation was the radiation energy deposition in the LHe (17.8%). As previously described, this number will decrease over time as the volume of LHe decreases in the Main Dewar, due to boil-off. Since 13.3 minutes is not a feasible irradiation period for a given experiment, two lower reactor power levels were used to replicate the previously
described calculations for conservative total time to full LHe boil-off. The results for all three reactor power levels (450 kW, 50 kW, and 5 kW) can be seen below in Table 4.

<table>
<thead>
<tr>
<th>Reactor Power</th>
<th>Time to Full Boil-Off</th>
</tr>
</thead>
<tbody>
<tr>
<td>450 kW</td>
<td>13.3 Minutes</td>
</tr>
<tr>
<td>50 kW</td>
<td>120 Minutes</td>
</tr>
<tr>
<td>5 kW</td>
<td>20 hours</td>
</tr>
</tbody>
</table>

Table 4: Conservative Calculations of Time to Complete LHe Boil-off for three reactor power levels

As seen in the above table, 50 kW provides a total irradiation time of two hours before total LHe boil-off. Since this is a very conservative estimate of LHe boil-off times, it is expected that some amount of LHe will remain in the Main Dewar post-irradiation. This means that low temperatures can be maintained post-irradiation for some period of time before a LHe refill is required. This allows for proper planning to complete post-irradiation low temperature annealing experiments, as previously described in the LHe experimental results sections.
5.3. **Flux and Displacement Dose in Silicon for Reactor Conditions of Reactor-on Cryogenic Irradiation Experiments and Reactor-on Room Temperature Irradiation Experiments**

For the actual cryogenic and room temperature reactor-on experiments that were conducted for this dissertation, a reactor power of 15 kW was chosen and a total irradiation time of 5 hours and 7 minutes. The explanation for this reactor power level and irradiation time period is given in subsequent sections. However, in order to match these results and to provide a predicted displacement dose, the output energy-binned neutron flux tally of the same MCNP6 simulation, discussed previously in section 5.1.2., was used to calculate the neutron flux spectrum for 15 kW operation. This neutron flux was then used to find the displacement dose in silicon. Unfortunately, there is not yet an accepted standard for a neutron displacement dose kerma factor in the materials studied within this dissertation, GaN and silica.

ASTM standard E722 explains how to convert a differential neutron energy flux spectrum into a displacement damage dose in silicon. This standard is often used to quantify the radiation dose for electronics radiation damage experiments in materials other than silicon. ASTM 722 dictates that the differential radiation displacement dose rate in silicon (rad(Si)/s) can be calculated by simply multiplying the microscopic kerma factor for silicon (differentially broken into energy bins and provided in the standard) by the flux for each energy bin (as calculated in this case by MCNP6). This differential displacement dose rate can then be integrated over all energy bins to find a total displacement dose rate in silicon for the given MCNP6 simulated neutron flux. This was
completed for the 15 kW simulation; and the total neutron flux of 1.07E11
neutrons/cm^2-s was converted to a neutron displacement dose rate in silicon of 2.95
rad(Si)/s and a total neutron displacement dose in silicon for the 5 hour and 7 minute
reactor irradiation period of 54.3 krad(Si).
Chapter 6: Experimental Methodology

The general plan for the experiments fit into six categories: (1) initial CRIF materials testing, (2) initial demonstration of the operability of the CRIF, (3) cryogenic testing of the optical fibers and transistors, (4) cryogenic gamma-only irradiation and low temperature annealing experiments, and (5) cryogenic reactor-on mixed field irradiation and low temperature annealing experiments, and (6) room temperature reactor-on mixed field radiation experiments.

6.1. Materials Activation Experiments

In order to estimate the effects of neutron activation within the materials that constitute the cryostat and some of the materials under test, an activation analysis was performed by irradiating small samples of the materials in the rabbit tube. Dr. Susan White completed these experiments and the results were post-processed and analyzed to determine the length of time required before the materials showed negligible radioactivity. These materials were the three types of wires found within the CRIF, a sample of the Duroid boards used to mount electronic materials, and superinsulation. The G10 and aluminum 6061 were considered to be well understood and samples could not be easily removed for the tests. Other materials not considered here, but important for materials activation, include the vacuum grease, epoxy, and indium high vacuum seal. These results will be discussed in the results section of this dissertation but at less length.

For a full treatment of the materials analysis, see the results sections of the thesis.

6.2. Initial Operability Testing of the CRIF with LN2 and LHe

The CRIF was tested using LN2 and LHe with and without different low pressure gas inserted in the experimental region (also including the central transfer tube, and the outer canister) of the CRIF. This testing was completed to understand the cooling down period of the CRIF experimental volume and the temperature control from 4.2 K to above room temperature. These experiments were completed sequentially to determine the necessary operation procedures and parameters for using the CRIF. These experimental results will be discussed briefly herein, in the experimental results section. However, a more full treatment of these experiments can be found in the previously mentioned MS Thesis by the author (cited in the previous section).

6.3. Cryogenic Materials Characterization Experimental Procedure

6.3.1. Initial Thermal Shock Testing of Transistors

There was an initial concern about the survivability of the internal packaging of the HEMTs, as well as the device mounts, when subjected to cryogenic temperatures. Specifically, because the materials of the device, the wire bonds, the pins, the plastic package, the Duroid board, and the soldered wire leads are all made of different materials, they have differing thermal expansion coefficients. These thermal expansion coefficients cause different amounts of thermal contraction of the materials under the
extreme conditions of LHe operation. There was a concern that differences in thermal contraction may cause enough stress at positions of mismatched material connections, that any of these important bonds may break under this stress. Therefore, in order to demonstrate the survivability of the devices at LHe temperatures, they were subjected to repeated thermal shock tests.

For these tests, wire leads were connected to one representative GaN HEMT. The other ends of the wires were inserted into the integrated NI electronics testing system and an I-V curve were taken. Then the device was thermally shocked to 77 K, by being placed directly into a LN2 bath. At this point, a second I-V measurement was made on the device. Then the mounted device was removed from the LN2 bath and allowed to warm back to room temperature. At this point a third I-V measurement was made at room temperature. This process was repeated three times, such that the device was cooled rapidly to 77 K three times and a before and after measurement was made at room temperature on the device. A photograph of the transistors dipped in a metal trashcan filled with LN2 during these thermal shock tests can be seen below in Figure 42. A photograph of a device extracted from the LN2, still cold, while warming back to room temperature can be seen in Figure 43.
Figure 42: GaN transistors being dipped into LN2 during thermal shock testing of the transistor packaging and Duroid board mounts

Figure 43: GaN transistor being removed from LN2, still cold, while warming back to room temperature
Additionally, the same test was repeated with the same device, but using LHe instead of LN2, so that the device was cooled rapidly to 4.2 K three times, with I-V curve measurements taken at 4.2 K and at room temperature before and after each thermal shock dip test. In this case a more robust Dewar was necessary to decrease the LHe boil-off rate. A photograph of the devices being dipped into this LHe filled Dewar can be seen below in Figure 44.

Figure 44: GaN transistor in Dewar filled with LHe

The mounted GaN HEMT demonstrated repeatable survivability in both sets of experiments. These results can be seen below in the experimental results sections.
6.3.2. Mounting of Materials Under Test

The materials under test were mounted into the cryostat inner volume prior to the four experiments: (1) cryogenic cooling to liquid helium temperatures followed by stepped increases in temperature to room temperature, (2) cryogenic cooling to liquid helium temperatures followed by gamma-only irradiation in the reactor shutdown field, followed by stepped increases in temperature to room temperature, (3) cryogenic cooling to liquid helium temperatures followed by mixed field irradiation with the OSURR running at 15 kW for five hours and seven minutes, followed by stepped increases in temperature to room temperature, and (4) room temperature mixed field irradiation with the OSURR running at 15 kW for five hours and seven minutes.

The mounting procedure involved first soldering the GaN transistors onto the custom made DC Duroid Board mounts. These were very difficult to mount, due to the very small size of the GaN packaging pins. If similar experiments are done in the future, the devices under test should use packaging with larger pins, or a different mounting system should be devised. These Duroid mounts had copper leads running on the surface to the edge of the Duroid boards, at which point wire leads were soldered to the Duroid boards. Next, the GaN devices and their Duroid mounts were placed upon the bottom of two device mounting platforms in the experimental volume of the CRIF. Each Duroid board mount was affixed to the mounting platform by aluminum 4-40 bolts and washers, which held them against the aluminum mounting platform surface. Finally, the 2-wire leads from the Duroid boards were connected to the bottom ZIF block, which was wired to a corresponding ZIF block on the top of the Main Dewar top. Sets of twisted copper
wire pairs from a CAT-V cable were connected to the top ZIF block and to the NI PXI Electronics Measurement System, such that two electrical connections were made to each of the GaN transistors. There were two GaN devices that were successfully mounted into the CRIF experimental volume and tested in the four experiments. A photograph of the transistors mounted on the Duroid boards, attached to the experimental volume mounting platforms can be seen below in Figure 45. Also shown below, in Figure 46, is the set of wire leads attached to the transistors and Cernox RTDs inserted into the lower ZIF block, inside of the experimental volume of the CRIF. Finally, the electrical leads that run from the PXI Electronics Measurement System, Lakeshore Model 335 Temperature Controller, and Lakeshore Model 218 Temperature Monitor to the CRIF Main Dewar top, can be seen below in Figure 47 inserted (connected electrically) into the upper ZIF block.
Figure 45: GaN transistors mounted on Duroid boards, and attached to the mounting platforms (top platform further to the left in the photograph) of the experimental volume of the CRIF

Figure 46: Wire leads from GaN transistors & Cernox RTD temperature sensors inserted into the lower ZIF block inside the experimental volume of the CRIF
Figure 47: Wire leads from PXI Electronics Measurement System, Lakeshore Model 335 Temperature Controller, and Lakeshore Model 218 Temperature Monitor, inserted (connected electrically) into the upper ZIF block, mounted on the top of the CRIF Main Dewar Top

The optical fibers were also mounted inside of the experimental volume of the CRIF. Unfortunately, the optical fibers are all very fragile and do not already have leads running from the Main Dewar top to the experimental volume, through the central vacuum tube, like the transistors. In this case, the optical fibers were passed through a whole which was drilled in the Main Dewar top vacuum flange. The fibers were bound together to the tip of a long aluminum rod and were pushed down the central vacuum tube to the top of the inner canister, where the central vacuum tube hits a dead-end. There, the tape affixing the optical fibers to the aluminum rod was unbound using tweezers and the optical fibers were carefully passed through the side openings at this
juncture. The optical fibers were then passed through the small holes in the inner canister top and run through the fiber guide tubes to the bottom of the CRIF experimental volume. At this point, excess fiber length was pulled down past the bottom of the experimental volume. The pair of multi-mode silica optical fibers were spliced to create a loop for transmission experiments. The sections of optical fibers were carefully pulled out of the hole at the Main Dewar top vacuum flange until the looped fiber sections (silica multi-mode) were nearly taught across the bottom of the fiber guide tubes. Next, the single-mode silica sections were pulled so that some excess remained, and the excess was passed back up through the opposite fiber guide tube. This meant that all of the optical fiber sections were looped in a similar fashion with an identical bending radius from one optical fiber guide tube to the other, in the experimental volume. The fibers being looped out of the bottom of one optical fiber guide tube and into the other can be seen below in Figure 48.
Figure 48: Optical fibers mounted inside of the optical fiber guide tubes inside the experimental volume of the CRIF

At this point, the hole in the Main Dewar top vacuum flange was filled with a high grade cryogenic vacuum epoxy called Stycast 2850 Black. This epoxy was left to set over night. Finally, a custom made two-legged tower was mounted to the Main Dewar top. The optical fiber ends were spliced to optical fiber leads, that are long enough to run up the 10” Dry Tube and over to the optical fiber measurement systems. The splices to these long optical fiber leads were placed in a gap between two vertically mounted platforms on the Main Dewar top tower. Both ends of the spliced fiber were taped to these platforms to strain-relieve the optical fiber splices. Altogether, there were two of each type of optical fiber placed into the CRIF, single-mode silica and multi-mode silica.
The entire experimental volume of the CRIF, with all materials under test can be seen below in Figure 49.

Figure 49: Experimental Volume of CRIF with all materials under test mounted, just before closing up the inner canister and outer canister
6.3.3. Vacuum Preparation of CRIF

In order to prepare the system for use with a liquid cryogen, the inner canister and outer canister must be attached. Once the materials under test were all mounted and tested, the inner canister was screwed onto the inner canister top. Next the resistive heating element leads were connected to appropriate wires that ran up to the ZIF block on the top of the Main Dewar top. Finally, the outer canister was attached. In order to create a vacuum tight seal between the outer canister and outer canister top, ultra-pure indium is used to create a cold weld seal. In this case, there is a groove channel cut out of the outer canister mating flange, which matches the outer canister top flange allowing them to mate. A section of Indium wire was measured, so that if would fit perfectly within the groove channel of the outer canister. The indium wire was cut so that the two ends could be adjoined at 45 degree angles. Then they are pressed together so that the indium wire formed an indium torus. This indium torus was then placed inside the groove channel of the outer canister. Finally, the outer canister and outer canister top were aligned and the mounting bolts were tightened sequentially to ensure an even and gradual crushing of the indium torus in the groove channel. This crushed indium torus filled the volume of the groove channel and mated to the aluminum surfaces of the outer canister and the outer canister top, creating a cold weld seal.

Once the transistors and optical fibers were mounted and the connections were tested and the inner canister and outer canister were attached, it was necessary to pump down the central vacuum tube, outer canister, and inner canister to sub-roughing-pump vacuum levels. The Hi-Cube Eco was used to pull vacuum on these volumes down to a
sufficient pressure (~10^{-6} Torr). Next, the valve above the t-splitter was closed. The pressure was monitored to determine if there were any leaks within the system. Once it was determined that there were no leaks, especially at the epoxied hole in the Main Dewar top vacuum flange and the outer canister indium cold weld seal, these inner volumes of the CRIF were ready to be filled with low pressure helium gas. The gaseous helium transfer line was hooked up to a ¼” OD nozzle via a ¼” ID hose. The gauge on the gaseous helium cylinder was adjusted to a few psi and a small section of the hose was filled. Next, the section of hose was sealed off from the gaseous cylinder by closing an inline valve. Then, the port on the other side of the t-splitter, above the cryostat, was opened, allowing the small amount of gaseous helium to flow into the cryostat. This valve was subsequently closed. The pressure in the cryostat was observed. Since it was well above ~10^{-2} Torr, the valve above the t-splitter was opened, allowing the pump to suck out some of the gaseous helium, until a pressure of ~10^{-2} Torr was achieved. At this point, the valve above the t-splitter was closed and the pressure was observed to ensure there were no leaks. Finally, the valve below the t-splitter, attached to the Main Dewar top vacuum flange was closed, the pump was turned off and vented, and all components above this valve were disassembled. At this point, the cryostat was prepared for the Main Dewar to be filled with LN2.

6.3.4. **Data Acquisition Initialization**

Once the CRIF was completely prepared for cooling, it was important to begin data acquisition for all materials under test. Therefore, once the electrical and optical leads were all connected and tested, the measurement and data acquisition systems were
initialized and the GUIs for each systems were set up for automated data saving. First, the Lakeshore Model 335 Temperature Controller and Model 218 Temperature Monitor were set up to acquire temperature measurements at one second intervals and to save that data to a text file on the control computer. Then, the NI PXI Electronics Measurement System, the OBR, and the Optical Transmission Measurement System were set up to acquire data and save that data to their respective computers in one minute intervals. Finally, each of the systems was started at the same time so that the data acquisition and saving intervals would match. The materials under test, that were actively interrogated at this point included two GaN transistors, two single-mode silica optical fibers, and two multi-mode silica optical fibers.

6.3.5. **Liquid Cryogen Filling Procedure**

Once the data acquisition had commenced, the liquid cryogen filling and cooling procedure was started. First, the LN2 fill line was attached to the LN2 Dewar, the transfer line bayonet was inserted into the Main Dewar top and passed to the bottom of the Main Dewar through the transfer line guide tube. Below in Figure 50 the liquid cryogen transfer line bayonet can be seen after insertion into the top of the CRIF Main Dewar Top.
The LN2 transfer line was inserted into the bayonet and sealed. The LN2 storage Dewar valve was opened and the LN2 cryogen transfer process commenced.

In the beginning, cold LN2 gas flowed out of the line, because all of the transfer line components have to reach thermal equilibrium with the LN2 at 77 K before boiling
stops and LN2 flows out. Once equilibrium was reached, LN2 flowed steadily out of the transfer line and bayonet into the bottom of the Main Dewar. However, the Main Dewar was still warm at this point and caused rapid LN2 boiling until it was cooled to thermal equilibrium with the LN2 at 77 K. Once thermal equilibrium was attained for the contact surfaces of the Main Dewar, including the inner walls of the Main Dewar and the outer walls of the outer canister and central vacuum tube, the Main Dewar began to fill with LN2. Once the cryostat was filled, the temperature was monitored on the temperature acquisition system GUI. The cooling of the inner canister and experimental volume took much longer, because the low pressure helium gas (much lower than atmospheric pressure \( \sim 10^{-2} \) Torr) provided limited thermal conduction. Therefore, the temperature was monitored until the experimental volume was also in thermal equilibrium with the LN2 at 77 K. At this point, the LHe process could begin, however, due to the timing of the experiments, the CRIF was left to sit overnight filled with LN2 at 77 K, and the LHe filling process began the next morning.

To begin the LHe filling process, the LN2 first had to be dumped from the Main Dewar. A metal trashcan, with a large enough volume to receive the remaining LN2 was placed on the ground about 5 feet from the Main Dewar. The Main Dewar was strapped to a gas cylinder cart with ratchet straps. Two experimenters each donned cryogenic gloves, a cryogenic apron, and a cryogenic face shield. The two experimenters tilted the Main Dewar downward and lifted the top slightly so that a gap was made between the Main Dewar and the bottom of the Main Dewar top, allowing a pathway for the LN2 to flow out of the Main Dewar. The Main Dewar was tilted all the way down the metal trash
can, almost parallel to the ground and great care was taken to not break any of the optical or electrical leads. The LN2 was allowed to flow out of the Main Dewar until it was nearly empty and then the bottom of the cart was lifted to ensure that all LN2 had poured out of the Main Dewar. The cart and Main Dewar were carefully returned to an upright position and the volume of LN2 in the metal trash can was allowed to boil off until the trash can was empty. This LN2 dumping procedure can be seen below in Figure 51 and Figure 52.
Figure 51: Two experimenters pouring LN2 out of the CRIF and into a metal trashcan (where it was left to boil away)
With an empty Main Dewar, the CRIF was prepared for the LHe transfer process. First, the liquid cryogen transfer line bayonet was reinserted into the Main Dewar top and passed to the bottom of the Main Dewar through the transfer line guide tube. Next, the
LHe storage Dewar was prepared to receive the LHe transfer line. The helium gas
cylinder was brought near the CRIF and the valve on the helium gas cylinder was opened
to allow the flow rate to be adjusted to between three and five psi. The gas was allowed
to flow while the gas line was affixed to the LHe storage Dewar’s pressurization port.
Next, the low pressure relief valve on the LHe storage Dewar was closed, so that the LHe
storage Dewar could be pressurized above two psi. Then, the top port of the LHe storage
Dewar was opened (vertical port with inline valve) and pressurized cold gaseous helium
from LHe boil-off in the LHe storage Dewar was allowed to escape through the port. The
vertical section of the LHe transfer line was carefully inserted into the top port of the LHe
storage Dewar until the bottom tip of the transfer line was sufficiently below the level of
the LHe in the storage Dewar. Below in Figure 53 the LHe transfer line can be seen after
insertion into the vertical transfer line valve of the LHe storage Dewar.
Next, the other end of the LHe transfer line was inserted into the bayonet and sealed. Below in Figure 54 the connection of the LHe transfer line and the previously inserted bayonet (already in CRIF) can be seen.
Figure 54: Experimenter inserting opposite end of the LHe transfer line into the bayonet (which was already inserted into the CRIF) and sealing the two together for LHe transfer

At this point, the screw fitting was tightened on the vertical transfer line port of the LHe storage Dewar, causing the O-ring to compress against the LHe transfer line and pressurize the LHe storage Dewar. At this point the pressure within the LHe storage Dewar was enough to begin the flow of LHe through the transfer line. The tightening of
the screw fitting, pressurization of the LHe storage Dewar and LHe transfer line, and the flow of LHe can be seen below in Figure 55.

Figure 55: In foreground: experimenter tightening screw fitting on vertical LHe transfer line valve of the LHe storage Dewar, In background: Cold LHe gas and resulting condensation of air escaping from CRIF showing pressurization of LHe storage Dewar and LHe transfer line, and demonstrating an active LHe transfer

However, in order to increase the flow rate, the pressurization valve was opened so that helium gas from the gas cylinder could flow into the LHe storage Dewar. Then the pressure was adjusted on the helium gas cylinder to 5-10 psi. Finally, the very cold LHe gas at the exit of the transfer line began to fill the Main Dewar and cool the surfaces of the transfer line and the surfaces of the Main Dewar, until thermal equilibrium was reached with the LHe at 4.2 K, similar to the LN2 fill. This process took less time than the LN2 transfer process, because the surfaces of the CRIF were already pre-cooled to 77
K and had to only be cooled further to 4.2 K. Once thermal equilibrium was attained, the Main Dewar was filled with LHe and the experimental volume cooled to 4.2 K. At this point, the data acquisition software had continually taken data on each of the materials under test and the temperature of the experimental volume had also been monitored and recorded.

6.3.6. **Cryogenic Heating Experimental Procedure**

The final portion of the experiment involved heating the materials back to room temperature. In this case, the leads to the heating element were attached to the ZIF block at the Main Dewar top. The temperature set point was changed to 25 K and the PID controller of the Lakeshore 335 Temperature Controller output an appropriate power to the Manganin resistive heating wire. The data acquisition continued throughout this process at the previously described one minute intervals for all materials under test. The temperature was allowed to increase and stabilize at 25 K and then a timer was set so that data was taken for ten minutes at this temperature before heating again. This process was repeated in 25 K steps, with a stabilized data acquisition time of 10 minutes at each step, until 300 K was reached. This concluded the cryogenic materials characterization experiments. The results from these experiments can be found below in section 7.3.

6.4. **Gamma-Only Cryogenic Irradiation Experimental Procedure**

The gamma-only cryogenic irradiation experiments occurred within the CRIF and will be described within this section. However, in order to properly plan the gamma-only cryogenic irradiation experiments, it was necessary to understand the gamma shutdown
field of the reactor. Therefore, first an experiment was completed to analyze the shutdown gamma field of the reactor after operating the reactor at full power (450 kW) for one hour. This experimental procedure will be described herein. Then the gamma-only cryogenic irradiation experimental procedure will be described subsequently.

6.4.1. 10” Dry Tube Gamma Reactor Shutdown Field Irradiation Characterization Experimental Procedure

Gamma-only irradiation is really a misnomer. Based upon the operational history of the OSURR, there are a number of radioactive fission products and decay products, which produce a broad array of different types and energies of radiation. However, when the reactor has been recently operated and shut down, the vast majority of the radiation emitted from the reactor core are high energy gammas, resulting from the recent fission products and their daughter nuclei, which decay based upon their half-lives. The decay period can be described by an exponential decay function, and in this case was best fit by a double exponential in Matlab (this will be described later in the results sections). This decay field in the 10” Dry Tube for the reactor operating for one hour at full power, 450 kW, has been measured as part of this research project. A rig was designed with the help of fellow graduate students Travis Wander and Brandon Wilson. The rig was made of aluminum and placed a gamma dosimeter at the peak flux position of the 10” Dry Tube based upon MCNP6 simulations, which were previously described, and a neutron activation experiments previously conducted in the 10” Dry Tube. This position corresponds to a height within the experimental volume of the CRIF. The reactor was operated for one hour at 450 kW and then shut down. Upon the moment of the control
rods being completely inserted into the core, a timer was started and the 10” Dry Tube was moved beside the OSURR, to its correct position. The hard flux box had been previously evacuated and it was employed in this experiment. As soon as the 10” Dry Tube was appropriately positioned beside the reactor core, the gamma dosimeter was initialized and data acquisition began. This entire process took approximately 8 minutes to commence the data taking and the reactor shutdown field was measured for ~112 minutes. The gamma reactor shutdown field and curve fit can be seen below in the results section 7.4.

6.4.2. Mounting of Materials Under Test

Since the materials under test were mounted appropriately for the cryogenic materials characterization experiments, and due to time and budget constraints when using LHe, for the gamma-only cryogenic irradiation experiments the materials were left as mounted; i.e. the materials were not changed or remounted for the gamma-only cryogenic irradiation experiments that are described herein.

6.4.3. Vacuum Preparation of CRIF

After the cryogenic materials characterization experiments, the vacuum was maintained in the CRIF and the inserted helium gas was found to be at a functional level for the subsequent gamma-only cryogenic irradiation experiments. Therefore, it was not necessary to re-prepare the gamma-only irradiation experiments by pulling vacuum and re-inserting gaseous helium.
6.4.4. **Data Acquisition Initialization**

For the gamma-only experiments, the data acquisition systems were set up identically to the way they were set up for the cryogenic materials characterization experiments, with one exception. The voltage start-stop and number of data points were changed for the transistor experiments. Specifically, the collected GaN data points were changed to go further into the forward bias region. This new range was set to -4 V to +3 volts. The experiments were run on the two GaN transistors, the two single-mode silica optical fibers, and the two multi-mode silica optical fibers.

6.4.5. **Liquid Cryogen Filling Procedure**

For the gamma-only experiments, the initial cooling and preparation phases were identical to the cryogenic materials characterization experiment, including filling the Main Dewar with LN2, dumping the LN2, and filling the Main Dewar with LHe. These processes were again completed in the classroom of the OSU NRL. The subsequent experimental setup procedures were different, however.

6.4.6. **Loading of CRIF into 10” Dry Tube**

In order to conduct the gamma-only experiments in the OSURR, great care was taken during the loading procedure of the CRIF into the 10” Dry Tube. Specifically, the electrical leads were all disconnected from the CRIF top. Unfortunately, due to the mounting procedures, the optical fibers could not be disconnected at the CRIF top. Therefore, the optical leads were all zip-tied together and spooled, then disconnected from the optical measurement systems. These optical fibers were carefully carried behind
the CRIF, while the CRIF was wheeled on a cart from the classroom of the OSU NRL to the steps of the reactor bay. The cart was then lifted step by step by two experimenters, while a third carefully held the spooled optical fibers. Once the CRIF was at the reactor pool top, it was removed from the cart and set beside the reactor pool. Next, ropes were attached to two of the aluminum lifting loops at the top of the CRIF and care was taken to ensure no contact with any of the fragile optical fiber connections. Then the rope ends were tied together in a loop and lifted by the crane while experimenters aligned the CRIF with the opening of the 10” Dry Tube. Two experimenters guided the CRIF down into the 10” Dry Tube, while a third operated the crane. Once the Main Dewar top and the 10” Dry Tube top were roughly aligned, two aluminum rods were placed through the other remaining two aluminum lifting rings on the top of the Main Dewar of the CRIF. Then the crane was lowered so that the lifting rope went slack while the weight of the CRIF was held by the inserted aluminum rods. The CRIF rested this way at the reactor pool top inside the 10” Dry Tube.

Once the CRIF was resting at the top of the 10” Dry Tube, the electrical leads were all reconnected to the ZIF block on the Main Dewar top. The optical fibers were partially unspooled and reconnected to the optical measurement systems. Once the electrical and optical connections were all checked, the electrical wires and optical fibers were bound together by zip-ties before lowering the CRIF into the 10” Dry Tube. Finally, it was determined that the LHe needed to be replenished in the CRIF, and the 10” Dry Tube was moved to the far southeast corner of the OSURR pool.
6.4.7. **Liquid Helium Refilling Procedure**

In order to refill the CRIF with LHe before the experiment was completed, it was necessary to bring the LHe storage Dewar to the BSF pool top, which is adjacent to, but approximately five feet below the reactor pool top. It is not typically advisable to lift a LHe storage Dewar. Most often these Dewars are transported by elevator and they do not have any handles or lifting rings that are rated for bearing the weight of the storage Dewar. Unfortunately, the OSU NRL does not have an elevator. Therefore a custom strapping procedure had to be devised to lift the LHe storage Dewar to the BSF pooltop. This strapping configuration involved two long straps running under the LHe storage Dewar and connected to the crane above. These long straps were held tightly against the side of the LHe storage Dewar by two ratchet straps, which were tightly bound around the side walls of the LHe storage Dewar. This procedure was first tested with an empty LHe storage Dewar, to ensure safe operation. This whole process had been previously reviewed by the OSU Reactor Operation Committee and approved for use. Once the system had been tested and seemed sufficiently robust, a full LHe storage Dewar was lifted to the BSF pool top. From the BSF pool top, the LHe transfer line could reach the bayonet, inserted into the top of the CRIF, which was still being supported by the horizontal aluminum rods at the top of the 10” Dry Tube. The LHe fill process followed the operational procedure previously described for the cryogenic materials characterization experiments. The CRIF Main Dewar LHe refill can be seen below in Figure 56, showing the LHe gas escaping and water vapor condensation above the OSURR pool.
Figure 56: The CRIF Main Dewar LHe refill, showing the LHe gas escaping and water vapor condensation above the OSURR pool

After completing the LHe fill, the transfer line was disconnected, the bayonet was removed from the CRIF and the LHe Storage Dewar was moved to the south end of the BSF pool, away from the reactor pool. All valves on the LHe Storage Dewar were returned to their appropriate steady state positions (as previously described).
Finally, the 10” Dry tube was moved back to the middle of the OSURR pool and two experimenters lifted the CRIF by the lifting ropes, while a third experimenter removed the horizontal aluminum rods. Then the two experimenters slowly lowered the CRIF to rest upon the aluminum stand and steel plates at the bottom of the 10” Dry Tube, while the other experimenters carefully fed the electrical and optical leads into and down the 10” Dry Tube. Finally, the electrical and optical leads were tied off, and the experiment was ready for the reactor startup.

6.4.8. **Gamma Irradiation Experimental Procedure**

The gamma irradiation procedure in the reactor shutdown field followed a similar timeline to the previously described gamma reactor shutdown field characterization experiment. In this case, after the CRIF had been refilled with LHe, fully loaded into the 10” Dry Tube, and all optical and electronic leads had been tested, the 10” Dry Tube and CRIF were placed ~6 feet east of the reactor core in the OSURR pool. The reactor was powered up to 450 kW and operated at steady state for one hour. The reactor was shut down, and immediately following full control rod insertion, the data acquisition was commenced on the temperature measurement system and each of the materials under test. Then the 10” Dry Tube was moved beside the reactor core and placed into its proper alignment. The hard flux box had previously been filled with air and it was again employed during this experiment. The data acquisition systems continued to take data over night, for a total of ~14 hours, until the heating experiments began the next morning. During this experiment, the radiation induced heating caused the temperature in the experimental volume to jump from 4.2 K to ~ 9 K, once the 10” Dry Tube was put in
place. This temperature began to decrease over time, back to 4.2 K, as would be expected, following the decay period of the reactor shutdown field. This temperature data and all data acquired on the materials under test can be seen below in results section 7.5.

6.4.9. **Cryogenic Heating Experimental Procedure**

After irradiating the materials under test during the reactor shutdown field gamma-only irradiation experiment, the materials under test were heated within the experimental volume of the CRIF. Following a similar heating procedure to the Cryogenic Materials Characterization Experiments, the temperature was increased within the experimental volume of the CRIF in 25 K steps, to 300 K. Again, once a set temperature had been achieved, the temperature was maintained by the PID controller of the Lakeshore Model 335 Temperature Controller for 10 minutes while data was acquired on all materials under test. The data acquisition systems continued to operate throughout this time period, collecting data at the previously described intervals. All of the resulting data for each respective material under test for this heating portion of the reactor shutdown field gamma irradiation experiments can be seen below in section 7.5.

6.5. **Reactor-On Mixed Field Cryogenic Irradiation Experimental Procedure**

The reactor-on cryogenic irradiation experiments occurred within the CRIF and will be described within this section. However, in order to properly plan the gamma-only cryogenic irradiation experiments, it was necessary to understand the reactor mixed-field radiation inside the 10” Dry Tube. Therefore, first two experiments were completed to analyze the gamma field and the neutron field inside the 10” Dry Tube for steady-state
reactor operation at 15 kW. This experimental procedure will be described herein. Then the reactor-on cryogenic irradiation experimental procedure will be described subsequently.

6.5.1. **10” Dry Tube Reactor On Gamma and Neutron Radiation Fields**

**Experimental Procedure**

Although the MCNP6 model of the CRIF in the OSURR Pool provides a good estimate of the neutron and gamma radiation fields inside the CRIF, it is still necessary to validate the model. Unfortunately, due to the constraints of the system it is very difficult to complete a gamma dose measurement or a foil neutron activation measurement inside the CRIF. Specifically, there are a number of difficulties. First, due to size constraints, it was not possible to load our gamma dosimeter into the CRIF experimental volume. Second, loading of any foils inside the CRIF is problematic. First, most foil activation experiments require short lived daughter isotopes to be measured within a relatively short period after irradiation, on the order of minutes to hours. However, due to the prevalence of multiple structural materials inside the CRIF, it was deemed necessary for the CRIF to sit in the 10” Dry Tube for one month following reactor irradiation. This provides assurance that the activated materials will be safe for experimenter interaction, not providing a dangerous dose level. A one month activation cooling down period would make it nearly impossible to complete a common radiation foil activation experiment.

Since it was impossible to properly measure the neutron and gamma fields inside the CRIF, the next best possibility was to complete a gamma dose rate measurement in
the empty 10” Dry Tube and a neutron activation experiment in the empty 10” Dry Tube as well.

The neutron measurements were made by fellow graduate student Travis Wander using a custom rig. First a simple activation experiment was conducted with a long Ni wire to determine the location of the peak thermal neutron flux, which according to the MCNP6 model was ~ 2 cm below the reactor core centerline. The peak location was confirmed by these measurements. Next multiple foils were affixed at the peak flux location and a full neutron spectrum unfolding experiment was completed. The foils were then measured for radioactive daughters in a HPGe detector and the neutron spectrum was determined using SAND-II by Dr. Susan White of the OSU NRL. The results from the neutron activation analysis can be seen below in Section 7.6 with a comparison to the results of the MCNP6 simulations.

Following the previously described measurement scheme and using the same rig as that described above in Section 6.4.1., the gamma field for the empty 10” Dry Tube was measured, using the same gamma dosimeter. In this case, the gamma dose rate was measured at steady state for four reactor power levels (0 kW, 3 kW, 10 kW, and 30 kW) in the center of the 10” Dry Tube, at the height corresponding to the highest neutron flux level (as estimated by the MCNP6 model and confirmed by measurement). The gamma dose rate was then averaged for each of these four power levels and the four points relating gamma dose rate and reactor power were fit with a linear fit using Matlab. The gamma dose rates for these reactor power levels and the Matlab fit and the predicted gamma dose rate for relevant power levels can be found below in results section 7.6.
6.5.2. **Mounting of Materials Under Test**

Since the materials under test were mounted appropriately for the cryogenic materials characterization experiments and due to time and budget constraints when using LHe, for the reactor-on cryogenic irradiation experiments, the materials were left as mounted during the cryogenic materials characterization experiments and during the gamma-only cryogenic irradiation experiments; i.e. the materials were not changed or remounted for the reactor-on cryogenic irradiation experiments that are described herein.

6.5.3. **Vacuum Preparation of CRIF**

After the gamma-only cryogenic irradiation experiments, the vacuum was maintained in the CRIF and the inserted helium gas was found to be at a functional level for the subsequent reactor-on cryogenic irradiation experiments. Therefore, it was not necessary to re-prepare the reactor-on cryogenic irradiation experiments by pulling vacuum and re-inserting gaseous helium.

6.5.4. **Data Acquisition Initialization**

For the reactor-on cryogenic irradiation experiments, the data acquisition systems were set up identically to the way they were set up for the gamma-only cryogenic irradiation experiments. For the two GaN transistors, 10 data points were collected from -4 V to +3 volts. As in the gamma-only cryogenic irradiation experiments, there were two operable single-mode silica optical fibers. These were again set up to sample from 16 m to 20 m, taking data on one minute intervals. This time, there was only one multi-mode silica optical fibers that was tested, sampled at ~1 minute intervals. For each material
under test, the data acquisition systems were initialized while the CRIF and all constituent materials were at room temperature. The experimental data was taken for a period of ~30 minutes before beginning any cooling, to ensure good baseline data averages for the reactor-on cryogenic irradiation experiments. The data was collected continuously throughout the cooling, irradiation, heating, and post-heating periods of the experiments.

6.5.5. **Liquid Cryogen Filling Procedure**

For the reactor-on cryogenic irradiation experiments, the initial cooling and preparation phases were similar to the cryogenic materials characterization experiment and the gamma-only cryogenic irradiation experiment, including filling the Main Dewar with LN2, dumping the LN2, and filling the Main Dewar with LHe. These processes were again completed at the ground level of the OSU NRL reactor bay. In this case, the CRIF was filled with LN2 and allowed to sit overnight as a pre-cool period. Although it is not necessary to wait this long before completing the LN2 dump and LHe fill, it is useful because of time constraints at the OSU NRL. Specifically, the hours of operation in the OSU NRL limit the available time in a given day for reactor operation. Therefore, it is useful to complete as much experimental prep as possible, including completing a LN2 precool, beginning the day before reactor operations. In this case, the LN2 dump was completed on the morning of the reactor operation, and the Main Dewar was immediately filled with LHe.

As previously mentioned, during reactor-on cryogenic irradiation experiments, as opposed to the previous two experiments, data was continuously taken on each of the
materials under test, throughout the cooling processes. This caused greater difficulty in the filling procedure, because the electrical and optical leads had to remain attached to the top of the CRIF and to the respective data acquisition equipment, while the LN2 filling, LN2 dumping, and LHe filling procedures were completed on the ground floor. In this case, great care was taken when handling the electrical and optical leads, so as not to break any of the leads or disconnect any of the leads, interrupting the data acquisition.

Once the CRIF experimental volume temperature stabilized at 4.2 K and the CRIF was deemed to be full, the CRIF was lifted to the BSF pool top using the crane. Finally, the CRIF was carefully loaded into the 10” Dry Tube for reactor operations.

6.5.6. **Loading of CRIF into 10” Dry Tube**

In order to conduct the reactor-on cryogenic irradiation experiments in the OSURR, great care was taken during the loading procedure of the CRIF into the 10” Dry Tube. Again, the electrical and optical leads were all zip-tied together and spooled, but were never disconnected from the optical measurement systems. The crane was used to lift the CRIF into the top of the 10” Dry Tube, while the bundle of electrical and optical leads were also lifted, to avoid strain. When the CRIF and 10” Dry Tube tops were properly aligned, aluminum rods were inserted into two of the CRIF lifting rings, so that the CRIF could rest, hanging from the aluminum rods, which were braced across the 10” Dry Tube top flange. Finally, the crane was disconnected from the other two CRIF Main Dewar lifting rings and ropes were attached, in their place.

Next, the crane was attached to two eye bolts on the 10” Dry Tube top flange. The CRIF and 10” Dry Tube were moved to the middle of the OSURR pool. At this point,
two experimenters stood above the CRIF at the OSURR pool top and used the ropes to
lift the CRIF, while a third experimenter removed the aluminum rods. The CRIF was then
carefully lowered by the two experimenters until it rested at the bottom of the 10” Dry
Tube on the steel plates and aluminum platform, while the third and fourth experimenters
fed the electrical and optical leads bundle down the 10” Dry Tube. Once the experiment
was in place and the electrical and optical leads were deemed to be strain-relieved, the
electrical and optical lead bundle was zip-tied at the OSURR pool top to a couple of
pipes. A final check of the electrical and optical lead connections was made.

The final step for safe operation of the OSURR at 15 kW was to insert the 7” Dry
Tube plug at the top of the 10” Dry Tube. In this case, the crane was attached directly to a
u-bolt on the top of the 7” Dry Tube plug. The crane was then used to lift the 7” Dry
Tube plug and to lower it into the top of the 10” Dry Tube, while a second experimenter
guided the 7” Dry Tube plug into the 10” Dry Tube and ensured that the plug was not
making contact with the electrical and optical lead bundle. At this point, the crane was
disconnected from the 7” Dry Tube plug and was reconnected to the two 10” Dry Tube
eye bolts. The crane was used to guide the 10” Dry Tube into place beside the OSURR
core and properly align the hard flux box with the core. The 10” Dry Tube was mounted
in place and the hard flux box was filled with compressed air, causing the water to be
expelled. The compressed air line was sealed off and the CRIF was finally ready for the
reactor-on cryogenic irradiation experiments.
6.5.7. **Reactor-On Cryogenic Irradiation Experimental Procedure**

Once the CRIF had been fully loaded into the 10” Dry Tube and the 10” Dry Tube was in place beside the OSURR core, the reactor was started. The reactor was brought up to 15 kW, in a typical fashion for safe operation and control of the OSURR core. The reactor was then operated for five hours and ten minutes while data was continually collected on all materials under test, at approximately 1 minute intervals. During this irradiation period, the temperature of the experimental volume was continuously monitored to ensure that there was sufficient cooling during the experiment and that there was no evidence of complete boil-off of the LHe. At the beginning of the irradiation period, the temperature jumped from 4.2 K to ~9 K and then settled relatively quickly back to ~6 K. 6 K was maintained in the experimental volume for the remainder of the reactor-on experiments. The original plan was to operate for six hours, based upon the previously described MCNP6 predicted results for total time to boil-off. However, a temperature transient was observed at five hours and seven minutes of operation at 15 kW. Although this transient included a very slow temperature increase, it was determined by the experimenters that it would be wise to shut down the reactor and finish the experiments ensuring that LHe was still present in the CRIF, rather than extending the irradiation period to the full six hours. When the five hour and ten minute irradiation was complete, the reactor was shut down. During the reactor shut down, the control rods were inserted into the reactor core, which took approximately five minutes. Once the rods were fully inserted, the experimenters reattached the crane to the 10” Dry Tube, cut the zip-ties holding the electrical and optical leads at the reactor pool top, and moved the 10” Dry
Tube (with CRIF inside) to the southwest corner of the reactor pool (away from the OSURR core), carefully ensuring strain relief of the electrical and optical leads. After reactor shutdown was complete, the temperature in the experimental volume of the CRIF began to decrease and it stabilized at 4.2 K. This meant that there was still LHe remaining inside the CRIF. In order to ensure that there was sufficient LHe remaining in the CRIF to complete the full set of heating experiments, the CRIF was lifted back to the surface of the reactor pool top and again suspended using the inserted aluminum rods at the top of the 10” Dry Tube. The experiment was allowed to sit for a period of ~ 1 hour, while preparations were made for a LHe refill. This resting period allowed for some residual radioactivity to decay away after the experiment, decreasing the dose to the experimenters for the remainder of the experiments. In order to gauge roughly how much LHe remained in the CRIF, the cryogenic transfer line end was inserted slowly into the fill port of the CRIF. As the transfer line enters the CRIF, the transfer tube begins to cool very rapidly from the ambient pressure cold boil-off He gas. Once the transfer line reaches the surface of the LHe, rapid boiling of LHe occurs and there is a noticeable increase in He gas and vapor being expelled from the CRIF top vent port. The height at which this rapid boil occurred was noted and it was estimated that the CRIF remained between one third and one half full of LHe. This indicates that a longer reactor irradiation period should be possible in subsequent cryogenic irradiation experiments.

The LHe storage Dewar was lifted to the reactor pool top. If the LHe storage Dewar is completely emptied during a LHe fill of the CRIF, the compressed He gas will continue to flow into the LHe storage Dewar, and then into the CRIF, causing warm He
gas to be inserted into the bottom of the CRIF, resulting in rapid boil-off of the LHe in the CRIF. In order to ensure that this did not happen, the LHe storage Dewar and a large scale were lifted to the BSF pool top. The LHe storage Dewar was placed upon the scale and the weight of the LHe storage Dewar was continuously monitored, to ensure that there was ample LHe remaining in the LHe storage Dewar. The weight was used as a proxy to measure the amount of LHe that was extracted from the LHe storage Dewar. Once it was determined that more than 10 L had been removed from the LHe storage Dewar, the CRIF was deemed sufficiently full. At this point, the LHe storage Dewar transfer lines were disconnected from the CRIF and the CRIF was ready to begin the heating experiments.

6.5.8. Cryogenic Heating Experimental Procedure

After irradiating the materials under test during the reactor-on cryogenic irradiation experiment, the materials under test were heated within the experimental volume of the CRIF. This heating experiment began ~ 2 hours after the reactor shutdown. Following a similar heating procedure to the cryogenic materials characterization experiments and the gamma-only cryogenic irradiation experiments, the temperature was increased within the experimental volume of the CRIF in 25 K steps, back to room temperature. Again, once a set temperature had been achieved, the temperature was maintained by the PID controller of the Lakeshore Model 335 Temperature Controller for 10 minutes, while data was acquired on all materials under test. The data acquisition systems were continually run throughout this time period, at the previously described one minute intervals. All of the resulting data, for each respective material under test for this
heating portion of the reactor-on cryogenic irradiation experiments, can be seen below in section 7.6.

6.6. **Room Temperature Reactor-On Mixed Field Irradiation Experimental Procedure**

After completing the reactor-on cryogenic irradiation experiments, it was determined that one final experiment should be completed. Although the reactor-on cryogenic irradiation experimental results are significant on their own, a comparison with more conventional results was desired. Specifically, an irradiation of the exact same period with the same materials, in the same irradiation field would provide an “apples-to-apples” comparison to determine whether or not more macroscopic radiation induced damage was evident during cryogenic irradiations at 6 K, than at room temperature. It was not possible to complete an exactly analogous comparison experiment, due to two important reasons.

First, the materials were already mounted, and due to time, safety, and budget constraints, it was not feasible to disassemble the CRIF and mount new materials. Specifically, after irradiation at cryogenic temperatures, the safety analysis was provided for leaving the CRIF in the 10” Dry Tube for one month, to ensure decay of activated materials, to ensure safety to the experimenters when disassembling the CRIF. Therefore, the materials that were previously irradiated during the reactor-on cryogenic irradiation experiments were the materials that were irradiated during the room temperature experiments. Although these were not virgin materials, the experiments involved starting with a baseline measurement pre-irradiation and continuously comparing the materials
performance during the irradiation to the materials performance for the baseline measurements. This means that results can be compared reasonably well.

Second, there is a difference in the radiation field at cryogenic temperatures, when compared to room temperature, because of the presence of the LHe during the cryogenic irradiation experiments. As previously discussed, the LHe has a high neutron cross section at ~2 MeV, which changes the incident radiation field when LHe is present. There is unfortunately no easy way to overcome this issue, other than to complete a slow irradiation experiment, in which the LHe is filled, but room temperature is maintained by use of the heating element. This would require a nearly continuous refill of LHe to ensure the presence of LHe during the reactor irradiation period. This would be very difficult to complete procedurally, but would also be extremely expensive, due to the amount of LHe that would be consumed.

6.6.1. Mounting of Materials Under Test and Vacuum Status of the CRIF Experimental Volume

For the purposes of the room temperature irradiation experiment, the materials were not remounted after the previous experiments. Therefore, the same materials were mounted in the same ways as in all previous experiments. Additionally, the CRIF experimental volume was not opened to ambient pressure. Therefore, the CRIF experimental volume was still under vacuum with inserted He gas at a relatively low pressure (~10^-2 mbar).
6.6.2. **Data Acquisition Initialization**

For the room temperature experiment, all of the data acquisition systems were initialized and began acquiring data about one hour before the reactor was started. The data was acquired during the process of lowering the CRIF into the 10” Dry Tube and moving the 10” Dry Tube into place.

6.6.3. **Loading of CRIF into 10” Dry Tube**

For these experiments, the CRIF was lowered into the 10” Dry Tube in the same ways as previously described for the gamma-only and reactor-on cryogenic irradiation experiments. Once in place, the hard flux box was again emptied of water upon being filled with compressed air. Finally, the 10” Dry Tube and CRIF were moved into place beside the reactor core. At this point, the reactor was started up.

6.6.4. **Reactor-On Room Temperature Irradiation Experimental Procedure**

In order to replicate the radiation conditions of the reactor-on cryogenic irradiation experiments, the reactor was powered up to 15 kW and maintained for the exact same irradiation period of five hours and seven minutes. During this irradiation period, data was acquired on all relevant materials under test continuously. Since there was no cooling period for this experiment, there was also no heating period. Therefore, once the reactor was shut down, the data acquisition was halted. The 10” Dry Tube was moved back to the southeast corner of the reactor pool, to begin the required safety resting period of one month in the 10” Dry Tube before removing the CRIF. At this point the electrical and optical leads were all disconnected and the experiments were complete.
Chapter 7: Experimental Results

Below in this chapter the results for the neutron activation experiments, the transistor thermal shock experiments, the cryogenic materials characterization experiments, the gamma-only cryogenic irradiation experiments, the reactor-on cryogenic irradiation experiments, and the reactor-on room temperature experiments can be found.

7.1. Neutron Activation of CRIF Materials

The results of the previously described neutron activation analysis can be found below in Tables 1-5. These results only cover some of the materials used in the CRIF; however, the other CRIF materials will be discussed qualitatively below.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Activity (uCi/mg)</th>
<th>Energy (keV)</th>
<th>Half-life (hours)</th>
<th>10 Half-lives (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na-24</td>
<td>0.001407</td>
<td>1368.55</td>
<td>14.97</td>
<td>6.238</td>
</tr>
<tr>
<td>Cu-64</td>
<td>3.458</td>
<td>1345.77</td>
<td>12.7</td>
<td>5.292</td>
</tr>
<tr>
<td>Hg-197</td>
<td>0.001928</td>
<td>68.8</td>
<td>64.13</td>
<td>26.72</td>
</tr>
<tr>
<td>Hg-197</td>
<td>0.001948</td>
<td>78</td>
<td>64.13</td>
<td>26.72</td>
</tr>
<tr>
<td>Hg-203</td>
<td>2.79E-05</td>
<td>279.2</td>
<td>1119</td>
<td>466.1</td>
</tr>
</tbody>
</table>

Table 5: Duroid board materials activation for mounted GaN HEMTs
<table>
<thead>
<tr>
<th>Isotope</th>
<th>Activity (uCi/mg)</th>
<th>Energy (keV)</th>
<th>Half-life (hours)</th>
<th>10 Half-lives (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na-24</td>
<td>0.006378</td>
<td>1368.55</td>
<td>14.97</td>
<td>6.238</td>
</tr>
<tr>
<td>Sb-122</td>
<td>0.0008517</td>
<td>564.08</td>
<td>65.28</td>
<td>27.2</td>
</tr>
</tbody>
</table>

Table 6: Superinsulation materials activation (wrapped between the inner and outer walls of the Main Dewar)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Activity (uCi/mg)</th>
<th>Energy (keV)</th>
<th>Half-life (hours)</th>
<th>10 Half-lives (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr-51</td>
<td>0.02207</td>
<td>320.07</td>
<td>664.8</td>
<td>277</td>
</tr>
<tr>
<td>Mn-56</td>
<td>0.06432</td>
<td>846.6</td>
<td>2.578</td>
<td>1.074</td>
</tr>
<tr>
<td>Co-58</td>
<td>0.0008658</td>
<td>810.75</td>
<td>1701</td>
<td>708.8</td>
</tr>
<tr>
<td>Ni-65</td>
<td>0.4564</td>
<td>1115.53</td>
<td>2.517</td>
<td>1.049</td>
</tr>
<tr>
<td>Ni-65</td>
<td>0.3408</td>
<td>1481.84</td>
<td>2.517</td>
<td>1.049</td>
</tr>
</tbody>
</table>

Table 7: Wire inside Cryostat materials activation (first of two wire types that runs through the cryostat central vacuum support tube to the experimental volume)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Activity (uCi/mg)</th>
<th>Energy (keV)</th>
<th>Half-life (hours)</th>
<th>10 Half-lives (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu-64</td>
<td>18.04</td>
<td>1345.77</td>
<td>12.7</td>
<td>5.292</td>
</tr>
</tbody>
</table>

Table 8: Wire inside Cryostat materials activation (second of two wire types that runs through the cryostat central vacuum support tube to the experimental volume)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Activity (uCi/mg)</th>
<th>Energy (keV)</th>
<th>Half-life (hours)</th>
<th>10 Half-lives (days)</th>
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<td>Mn-56</td>
<td>52.83</td>
<td>846.75</td>
<td>2.578</td>
<td>1.074</td>
</tr>
<tr>
<td>Mn-56</td>
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<td>1810.67</td>
<td>2.578</td>
<td>1.074</td>
</tr>
<tr>
<td>Cu-64</td>
<td>18.04</td>
<td>1345.77</td>
<td>12.7</td>
<td>5.292</td>
</tr>
</tbody>
</table>

Table 9: Manganin Heating Wire materials activation (wrapped around inner canister and used for heating the inner canister and experimental volume for temperature control from 4.2 K to above room temperature)
As seen above, most of the materials that are activated have relatively short half-lives. It is expected that after the experiments are completed, the cryostat can sit in the 10" Dry Tube for a period of ~30 days, which should be enough time for almost all of the residual activation to have decayed to negligible levels. The three isotopes of note, that have longer lived half-lives, are the Hg-203 from the Duroid board and the Cr-51 and Co-58 in one of the types of wires found within the wiring harness in the central vacuum support tube of the cryostat. The Hg-203 is already at an extremely low activity, because it is a trace contaminant isotope found in the Duroid board sample. This should not be an issue for handling the cryostat after irradiation. Furthermore, the Duroid boards can be easily removed from the mounting platforms of the experimental volume and stored or disposed of separately with any mounted electronic device. The Cr-51 and Co-58 exist in a wire type that constitutes only a few of the many wires that run down the central vacuum tube to the experimental volume. These are still at relatively low specific activity levels and are still relatively unimportant when multiplied by total mass. There was an expected Al-27 to Al-28 neutron capture event, for the superinsulation wrap. However, since the measurements were taken a day later, it appears that the short Al-28 half-life of 0.0375 hours, caused the Al-28 gamma emission to be negligible before measurement could be made in the HPGe detector system.

The other materials that were not considered here are the two major structural materials of the Main Dewar and inner structures of the cryostat and the devices under test. The Main Dewar and inner structures of the cryostat are Al-6061 and G10 composite. Al-6061 is commonly used at the OSU NRL for experimental structures and
is well understood from a radiation activation perspective. The longest lived activated isotopes of Al-6061 decay away in a period less than the proposed period of decay time for the Main Dewar to stay in the 10" Dry Tube (~30 days). The G10 is a glass composite that has been laminated in layers with a proprietary glue. The material is generally considered low activation based upon its main constituents: Si, O, Ca, Al, Mg, Na, and S. There are three expected long-lived isotopes to exist post-irradiation, however, based upon an activation calculation, the three isotopes have lower than pCi levels per mg.

Based upon the constituents of the optical fibers and previous experience irradiating silica optical fibers in facilities of the OSURR, it is expected that any optical fibers will have negligible activities after irradiation. Furthermore, optical fibers can be removed relatively easily from the experimental volume of the cryostat and pulled out of the central vacuum tube for disposal. Any electronic devices are expected to activate, however, they can also be easily removed, along with the Duroid mounting boards and stored or disposed of separately.

In conclusion, it is expected that after removal of the materials under test and allowing the cryostat to sit in the 10" Dry Tube for a period of ~ 30 days, it should be safe to bring back to Scott Labs and should be safe for handling for future experiments.

7.2. **Transistor Thermal Shock Experimental Results**

The GaN transistors survived both sets of thermal shock dip tests, dipping into LN2 (77 K) and LHe (4.2 K). In each case, the behavior of the transistors changed upon being submerged in the liquid cryogen, but then recovered after being allowed to warm back to room temperature. In each case, 21 data points were taken covering a range from
-10 V to +1 V. Since the transistors survived both sets of experiments, the data from the LHe dip tests, which was a more extreme condition, is presented herein, but the LN2 dip test data is omitted. The LHe dip test results for three successive dips are shown below in Figure 57. There are a total of seven I-V curves presented. In succession they are for an initial room temperature measurement, followed by 3 successive measurements, alternating between an I-V curve measurement with the GaN transistor submerged in LHe and a measurement after the GaN returned to room temperature.

![I-V Curve for GaN Transistor](image)

**Figure 57: LHe Thermal Shock Dip Tests for Direct Submersion (Rapid Cooling and Heating) of a typical GaN transistor**

As seen in the figure above, the transistors consistently returned to the original room temperature I-V curve shape after being allowed to warm to room temperature. This type of measurement is a worst-case scenario thermal shock measurement. In these
measurements, the GaN transistors were rapidly cooled through complete submersion in the LHe. Then they were pulled out of the LHe and allowed to warm rapidly in room temperature air. The thermal shock did not cause any of the leads or internal packaging to fail and the measurements were repeatable. This indicated that much slower cooling and heating, inside the CRIF would not likely cause failure of any of the electrical lead connections, the mount soldering of the GaN transistors, or any of the internal wire-bonds inside the GaN transistor package.

7.3. **Cryogenic Materials Characterization Experimental Results**

In the cryogenic materials characterization experiments, the CRIF was filled with LN2, then dumped and filled with LHe, before being heated back to room temperature, following the previously described procedure. In these experiments, the Cernox RTDs mounted inside the CRIF experimental volume, on the device mounting platforms were used to monitor and control the temperature inside the experimental volume. Generally, the two Cernox RTDs were in very close agreement in all of the experiments. The results from one of the Cernox RTDs, mounted to the lower of the two device mounting platforms can be seen below in Figure 58.
Figure 58: The CRIF Main Dewar Cernox RTD Temperature Measurements vs. Time for the Duration of the Cryogenic Materials Characterization Experiments, Showing all of the Temperature Regimes Associated with the LN2 Fill, LN2 Dump, LHe Fill, Stable Periods, and Heating Portion of the Experiments

In the Cernox RTD figure, there are visible indicators corresponding to the cooling and heating portions of the experiment. Starting at the left-hand side of the graph, the experiment begins at room temperature (~294 K) before any liquid cryogen has been inserted into the CRIF. At this point, all of the materials under test were mounted and the data acquisition for each experiment was begun concurrently with the temperature data acquisition. Next, when the CRIF was filled with LN2, the material inside the CRIF began to cool quickly and eventually the experimental volume of the CRIF (as measured by the Cernox RTDs) cooled completely and came into thermal equilibrium with the LN2 bath at 77 K. This occurred at ~5 hours.
The CRIF was left filled with the LN2 overnight, per the experimental procedure. The next morning, at ~20 hours, the LN2 was dumped, and there was a slight increase in temperature, noticeable on the Cernox RTDs. As quickly as possible, the CRIF was filled with LHe, which corresponds to the rapid drop in temperature from just above 77 K down to 4 K, which occurs just after 20 hours. This drop is evident on the graph and demonstrates how quickly the system was able to come into thermal equilibrium at LHe temperatures (4 K) after being pre-cooled with LN2 to 77 K. The system was left to rest and the temperature of the system was maintained at 4 K for ten minutes, while data was acquired on all of the materials under test. Next, the temperature was increased in the experimental volume, following the previously described procedure, in 25 K steps. At each step, the temperature was maintained for ten minutes, to acquire data on each of the materials under test. These 25 K steps are evident in the graph above, and begin just after 20 hours and conclude at the end of the experiment at ~ 26 hours. This data will be shown again in subsequent plots, to discuss the results of the Cryogenic Materials Characterization Experiments in the following subsections.

7.3.1. Cryogenic OBR Results

The Cryogenic Materials Characterization Experiments using the OBR followed the previously described procedures. Data was taken approximately every minute using the Luna OBR. The data collected was then processed in two separate ways. First, the OBR output data was reprocessed for spectral shift (in GHz). In this case, the OBR reprocessing software calculates the spectral shift across a 1 cm region of fiber. For each
of the four fibers that were connected during this experiment, the range 16 m to 20 m was investigated and reprocessed.

The second reprocessing method was the temperature sensing reprocessing method of the OBR reprocessing software. In this case, there is an internal calibration in the OBR software for silica single-mode fibers. This calibration works in the range from room temperature up to ~800 °C. Unfortunately, the calibration curve is not well suited to cryogenic measurements. Therefore, although a temperature was returned by the OBR showing a general trend in measuring lower temperatures that is concurrent with the cooling down period of the experiment, the reprocessed temperatures were non-physical. This indicates a need for a proper cryogenic calibration experiment for temperature vs. spectral shift. Below in Figure 59 are the results from the OBR Temperature Sensing of the OBR and the Cernox RTD Measured Temperature.
As previously discussed, the OBR temperature sensing mechanism is not well calibrated for cryogenic temperatures. However useful information can still be gleaned from this plot. As seen above, the OBR measures a temperature that is negative at LN2 temperatures and more negative at LHe temperatures. These negative temperatures are not physical, since 0 K is the minimum physical temperature. However, the general shape and trends of the plot, when viewed against the measured Cernox RTD temperatures are meaningful. It appears that when the temperature stabilized, after the LN2 fill, that the OBR temperature also stabilized. This indicates that the fiber is in thermal equilibrium with the liquid cryogen; however it does not definitively indicate that the temperature of the fibers is exactly 77 K. The fibers, as previously described, are mounted inside the
optical fiber guide tubes. These tubes make contact with the mounting platforms, upon which the Cernox RTDs are mounted. Therefore, the guide tubes should always be nearly the same temperature as the Cernox RTDs. The optical fibers make contact at various points within the guide tubes and thermal conduction occurs between these guide tubes and the optical fibers at these points of contact. Additionally, as described in the experimental procedures, a very low pressure He gas is inserted into the experimental volume of the CRIF after vacuum is attained. This low pressure He gas acts as a thermal medium, which helps maintain uniform temperatures in the experimental volume.

Finally, the optical fibers are quite small, they have a small mass and a narrow diameter. This means that the optical fibers should attain thermal equilibrium with their surroundings relatively quickly. This is indicated in the left side of the OBR temperature plot, where it is evident that the temperature of the optical fibers reaches steady state more quickly than the large mass of the aluminum mounting platforms and the mounted Cernox RTDs. Although all of the experimental volume should attain thermal equilibrium at the boiling temperature of the liquid cryogen, it is impossible to say with certainty, unless Cernox RTD sensors were mounted in direct contact with the optical fibers, that this occurred. However, the stability of the non-physical temperature measurement in LN2 at 77 K is an indication that, if properly calibrated, the OBR would be capable of measuring the temperature in these cryogenic regimes.

The second temperature drop coincides with the time when the CRIF was filled with LHe. In the plot above, it is evident that the OBR temperature decreases quickly after the LHe fill and the OBR optical fibers achieve thermal equilibrium with their
surroundings in a very short period. Again, it appears that the optical fibers achieved thermal equilibrium with the LHe more quickly than the mounting platforms and the Cernox RTDs. Again this is logical, since the cooling process transfers heat out of the experimental volume, through the inserted He gas. Once again, the non-physical temperature is very stable and indicates that when properly calibrated, the OBR could make a reliable temperature measurement down to 4 K.

In the first two decreasing temperature features, it appeared that the OBR temperature led the Cernox RTDs in time to equilibrium. However, in the heating portion of the experiment, the opposite is the case. This is because the cooling occurs from the large outside liquid cryogen bath, through the He gas in which the fibers are placed, and cools the relatively low mass optical fibers before the comparatively massive materials in the mounting platforms are cooled. However the heating occurs on the outside of the inner canister, which means that heat energy thermally conducts through the structural materials to regions of low temperature, instead of through the low pressure He gas as the heat energy flows in the cooling process. Therefore, the structural materials and mounting platforms can achieve a heating temperature set point sooner than the optical fibers, which must be heated through their limited thermal conduction contact points in the optical fiber guide tubes, or through the He gas, which must be heated against the constant cooling power of the LHe. The net result is a noticeable lag in the indicated temperature between the Cernox RTDs and the OBR, during the heating portion of the experiment. This means that a calibration curve cannot be created from this data. Unfortunately, the lag is too great to determine the exact corresponding Cernox RTD
temperature measurement for a given OBR spectral shift or OBR temperature measurement.

Unfortunately, the manufacturing methods used in making different types of silica optical fibers can cause complications in calibrating the spectral shift vs. temperature. For example, doping within the fiber may change the lattice packing at all temperatures of interest. Furthermore, the effects of the interface between the core/clad and effects of surface tension, which both depend on the diameters of the various portions of the optical fiber, can affect the thermal contraction of the optical fiber at cryogenic temperatures. These issues were discussed in detail by Boyd et al. of Luna Optics and studies were conducted to calibrate various optical fibers at cryogenic temperatures. Below in Figure 60 are the spectral shift data, measured by Boyd et al., for multiple types of commercially available silica optical fibers, which have different coatings applied, providing different surface strain under thermal contraction at cryogenic temperatures.
Figure 60: Spectral Shift vs. Temperature for Various Commercially Available Silica Optical Fibers

The spectral shift data demonstrate that the manufacturing methods of the silica optical fibers, including deposited coatings, can have a great effect on a calibration for the optical fiber spectral shift vs. temperature.

Additionally, the authors completed a more refined calibration measurement on a bare silica optical fiber. The calibration was fit in three separate regions for the measured data.
This calibration curve does not agree with the coefficient of thermal expansion for bulk silica, because it does not demonstrate the greatest rate of change in lattice size (and therefore spectral shift) with temperature at ~ 25 K. Taken together, these figures demonstrate that the physical characteristics of silica optical fibers (i.e. manufacturing methods, doping, and diameter of core/clad/coating) can have a significant effect on the thermal contraction and resulting calibration for spectral shift vs. temperature compared to bulk silica. Therefore, a high resolution calibration experiment must be completed for any given fiber that is to be used in a cryogenic environment to measure temperature. Unfortunately, this type of calibration curve was outside the scope of the research.
completed within this dissertation. However, such an experiment is encouraged for future work.

In order to understand the full response of the OBR to the cooling and heating experiments, it is worthwhile to consider the 3D plots of OBR temperature vs. length along the fiber vs. time. The 3D plot for the OBR measured temperature can be seen below in Figure 62. In the plot, it is clear that the temperature decreases from lower length values to higher length values. The plotted region corresponds to a 1 m section of the optical fiber, running from the top of the CRIF down into the experimental volume of the CRIF. Looking at the time axis, the plot shows a behavior similar to the single position plot shown and discussed above. For a number of data sets in the range of 180 cm to 200 cm (which is the reprocessed data fiber lengths, corresponding to real fiber lengths of 17.8 to 18 m), which corresponds to the section of optical fiber inside the experimental volume of the CRIF, the spectral shift looks relatively spatially flat for each respective time. This means that the temperature is spatially constant in the optical fiber throughout the experimental volume.
In order to more clearly display the uniformity of the temperature over the CRIF experimental volume, the OBR reprocessed temperature at three positions within the CRIF experimental volume were chosen and plotted vs. time. As shown below in Figure 63, the OBR temperatures are all overlapping throughout the duration of the experiment.
Figure 63: Plot of OBR Reprocessed Data Measuring Temperature vs. Time for typical Single-Mode Silica Optical Fiber inside the Experimental Volume of the CRIF for Three Specific Locations along the Optical Fiber: 17.85 m, 17.9 m, and 17.95 m

Although it is informative to view the temperature sensing reprocessed data from the OBR, the fact that the system is not calibrated for the experimental temperature range means that it is not as useful as investigating the spectral shift reprocessed OBR data. A plot of the OBR reprocessing spectral shift data and the Cernox RTD temperature profile of the experiment vs. time can be seen below in Figure 64. Again, the Spectral Shift response to the LN2 cooling portion of the experiment and the LHe cooling portion of the experiment leads the Cernox RTD measured temperature. Also, the spectral shift as a function of time is very flat in the portions of the experiment corresponding to the steady state operation when the CRIF was full of LN2 and LHe. Finally, the OBR spectral shift
lags the Cernox RTD measured temperature for the heating portion of the experiment, as mentioned previously.

**Figure 64: Plot of OBR Reprocessed Data Measuring Spectral Shift vs. Time for typical Single-Mode Silica Optical Fiber inside the Experimental Volume of the CRIF**

Below in Figure 65 is a plot of the spectral shift of the same three positions (17.85, 17.9, and 17.95 m) along the same optical fiber, that were shown in the figure above. The spectral shift of the three measurements are in close agreement at each point in time. This indicates that the temperature was uniform throughout the experimental volume.
The final data that can be examined from the OBR optical fiber experiments is the reflected optical signal amplitude as a function of temperature. Because the reflected signal depends on the type and number of scattering points within the fiber, cooling should not change the amplitude of the reflected signal. Instead, the scattering points should move in relation to one another, which would be evident in the change in spectral shift as a function of temperature. This type of spectral shift change has been previously shown and discussed above. However, unless cooling to cryogenic temperatures introduces or activates new defects or scattering points, the reflected amplitude should not change. In order to determine whether or not such changes occurred, the amplitude of
the reflected signal for a 15 cm length of fiber inside the experimental volume of the CRIF was examined. The light amplitude reflected from each point was averaged to produce an average reflected optical amplitude over the region from 17.8 m to 17.95 m. This signal was saved for each OBR scan and plotted as a function of time, and therefore temperature. This average reflected optical amplitude vs. time plot can be seen below in Figure 66.

As expected and as seen in the figure above, the average reflected optical amplitude changes very little over the time period of the experiment. Ignoring the errant data points, the maximum variation in average reflected optical amplitude is < 1 dB. The scale shows that the average reflected amplitude during the experiment is ~ -124.5 dB. As expected,
the amplitude of the reflected light from a given point > 16.8 m down the length of an optical fiber is much lower than the amplitude of the light source. Although there are some points of transition within the above plot, where the amplitude dips for a period of time, they do not correspond to any changes in temperature. Therefore, these dips in average reflected optical amplitude may be from changes in the light source strength or in other changes within the setup, but do not appear to be correlated with temperature. In conclusion, the OBR can resolve a repeatable change in spectral shift as a function of temperature, but the average reflected optical amplitude does not appear to be a function of temperature as indicated by spectral shift.

7.3.2. Cryogenic Optical Fiber Transmission Results

The data for optical attenuation vs. time for the cryogenic materials characterization experiments was taken across a broad spectrum of wavelengths, from ~500 to 2000 nm, throughout the duration of the experiment. As described above in the OBR experiments, since the experiments only involve cooling the optical fibers and not irradiating them, there should not be an increase in defects or scattering centers within the optical fibers. Therefore any change in optical attenuation as a function of temperature would likely be caused by stress from thermal expansion and/or contraction at splice points, or at points within the experimental volume where the fiber was bent. The experimental data for the optical transmission measurements of multi-mode silica optical fibers during the cryogenic materials calibration experiment can be found below in a series of figures. In Figure 67, the experimental data is plotted as wavelength vs. time for three specific times during the cooling down portion of the experiment, corresponding to
Cernox RTD measurements of temperature at the steady state portions of the experiment: 293 (room temperature), 77 K (LN2 temperature), and 4.2 K (LHe temperature).

Figure 67: Plot of Added Attenuation vs. Wavelength for a Typical Multi-Mode Silica Optical Fiber inside the Experimental Volume of the CRIF during the Cryogenic Materials Characterization Experiment

As seen in the figure above, the added attenuation at each of the three times shows very little variation across the measured wavelength range. The largest variation is seen in the middle data set for 77 K and the variation in added attenuation is on the order of +/- 0.5 dB/m. This range is very low and within the noise range of the system. During these tests, the measurements were taken on a single multi-mode silica fiber inside the CRIF. The optical light source has a fluctuation in the output signal that is based upon the stability of the electrical power supply as well as temperature fluctuations inside the optical light source, and likely other factors. This fluctuation in the optical output signal is
unpredictable. However, the fluctuations can be accounted for by sampling a second optical fiber (a control fiber). This was overlooked for this experiment and the gamma-only cryogenic irradiation experiment, but was included for the reactor-on cryogenic irradiation experiment and the reactor-on room temperature experiment. Given the noise range of the measurement system, there is no observable trend between the data sets at the three temperatures for which measurements are presented above. Therefore the optical attenuation is seemingly uncorrelated with temperature.

The heating portion of the experiment was also examined. The data for four times, corresponding to the steady state heating portions for 4 K, 100 K, 200 K, and 300 K are plotted below as added attenuation vs. wavelength in Figure 68.

![Figure 68: Plot of Added Attenuation vs. Wavelength for a Typical Multi-Mode Silica Optical Fiber inside the Experimental Volume of the CRIF during the Cryogenic Materials Characterization Experiment](image)

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Again, the added attenuation at each time is very low and does not vary much beyond ~ +/− 0.5 dB/m, except for at 300 K at approximately 1,100 nm. The low variation in measured values for added attenuation and the lack of an observable trend as a function of temperature indicate again that the optical attenuation is not correlated with temperature.

The data was again plotted, this time for four wavelengths covering much of the observed range of the experimental data: 800 nm, 1000 nm, 1200 nm, and 1550 nm. 1550 nm was chosen specifically because it is the wavelength used for the OBR. This data is plotted below in Figure 69 as added attenuation vs. time and overlaid in black is the temperature profile of the experiment as measured by the Cernox RTDs and plotted as temperature vs. time.

![Figure 69: Plot of Added Attenuation vs. Time for a Typical Multi-Mode Silica Optical Fiber and Cernox RTD Measured Temperature vs. Time inside the Experimental Volume of the CRIF during the Cryogenic Materials Characterization Experiment](image_url)
Again, the measured values show very little fluctuation, less than +/- 1 dB/m vs. time. The measured values again do not demonstrate any dependence on temperature. Here, the fluctuations in the light source output may account for the variation of the observed signal.

Finally, the wavelength region that demonstrated the most variation in measurement, as was seen above in Figure 68, was centered around 1080 nm. Therefore, 1080 nm was plotted alone below in Figure 70 for added attenuation vs. time, again with the temperature profile of the experiment overlaid in black, plotted as temperature vs. time.

![Figure 70: Plot of Added Attenuation vs. Time for 1080 nm on a Typical Multi-Mode Silica Optical Fiber and Cernox RTD Measured Temperature vs. Time inside the Experimental Volume of the CRIF during the Cryogenic Materials Characterization Experiment](image-url)
In this case, 1080 nm light shows a much larger decrease in attenuation, ~ 3.5 dB/m, compared to the initial scan at two separate times within the measured data. At each of these times, the temperature within the experimental volume of the CRIF is measured to be in the range of 100-200 K. However, the transition at around 2.5 hours occurs during a cooling period and the transition at around 24 hours occurs during a heating period. Interestingly, the added attenuation returns to ~ 0 dB/m in the middle portion of the experiment when the temperature was at steady state 77 K and when the temperature was decreased and held at steady state at 4 K. There is not an obvious physical explanation for this behavior; however, this again may be accounted for by variations in the light source output. Unfortunately, because the measurement setup did not include a control fiber to account for the variation in the light source output, we cannot ascertain for certain whether or not this variation in measured signal at 1080 nm is caused by temperature effects. Despite this uncertainty, the overall signal variation is still low at 1080 nm and very low at all other observed wavelengths. Furthermore, there is again not an obvious trend in added attenuation at 1080 nm with temperature, similar to all other observed wavelengths.

7.3.3. **Cryogenic Transistor Results**

The cryogenic measurements on the GaN Transistors were conducted at the same time as the other materials and underwent the same experimental cryogenic procedures and the same cryogenic temperature experimental profile. The GaN transistors were mounted such that two-wire measurements were taken across the source and gate of the GaN packaged pHEMTs. This means that when a voltage was applied and the current
measured, the devices would behave like Schottky diodes. In the negative voltage region, the diode would be “off,” demonstrating essentially zero current flow. In the positive voltage region, the diode would turn on and the current would increase exponentially with increasing voltage in the positive voltage region near the turn-on voltage. This current would increase exponentially with increasing voltage until reaching a saturation current for the diode, which is the maximum current that can pass through this Schottky diode in the pHEMT. For the initial measurements during the Cryogenic Materials Characterization Experiments, the measurement range was chosen based upon the product manual for the transistors and based upon a concern that acquiring many data points in the forward bias region may induce heating within the devices. Because the current increases exponentially in the first few data points, there was concern that heating in the pHEMTs would cause the measurements to be inaccurate, because when the base temperature for a measurement is so low (4.2 K), any energy deposition may cause heating in the material to the point that subsequent measurements would be taken at elevated temperatures, instead of the theoretical experimental temperature of 4.2 K. This could likely be true if multiple measurements were taken in rapid succession in the forward bias region. Because of the high cost of LHe and the limited number of experiments that could be completed within the scope of the project, caution was taken in the initial measurements.

The measurements in this data set were taken to demonstrate at least one point in the forward bias direction. Therefore, practice measurements were taken at room temperature and the data acquisition system was set up to acquire 10 data points from -10
to +1 V with 100 millisecond intervals between acquired points. In each case, the applied voltage was applied to the leads outside of the CRIF and the current was measured. The samples were taken every one minute throughout the experiment. I-V curves for each of the two GaN transistors can be seen below in Figure 71 and Figure 72 for steady state temperatures during the cooling down and during the heating potions of the experiment.

![I-V Curve for GaN Transistor 1](image)

**Figure 71: I-V Curve for GaN Transistor 1 Across a Temperature Range of 4 K to 300 K during the Cooling and Heating Portions of the Cryogenic Materials Characterization Experiment (Ordered by Time Decreasing Down Legend)**
As seen in the two figures, the I-V curves in the first measurement (297 K) and last measurement (300 K) demonstrate a single point in the forward bias region, indicating the exponential increase in current where the diode “turns-on.” However, as the temperature is decreased, the curve shape changes and the applied voltage is not large enough to “turn-on” the diode. This behavior demonstrated the need to further bias in the forward direction in subsequent tests. Furthermore, the current flowing in the positive bias region did not increase the temperature measured by the Cernox RTDs by any noticeable amount. Unfortunately these cryogenic materials characterization measurements were not redone with more data points in the forward bias region because of the high cost of LHe and the limited supply in the lab at the time of the experiments.
Here, there was not a noticeable trend in the low measured current in the negative bias region as a function of temperature. However, one obvious feature is that all of the data points in the 300 K measurement, which was one of the last measurements made at the end of the heating portion of the experiment, were higher than the corresponding measurements made at 297 K, which was at the beginning of the experiment. This increase may have been caused by the cooling and heating of the devices or by some drift in electronic noise within the power supply or internal power of the NI PXI integrated electronics measurement system. Importantly, as previously in the thermal shock dip-tests, the transistors survived cooling to 4.2 K and heating back to room temperature and continued to demonstrate the expected behavior of a Schottky diode, typical of a pHEMT. These measurements informed the data acquisition plan for all subsequent measurements of the GaN transistors.

7.4. 10” Dry Tube Gamma Shutdown Field Experimental Results

In order to understand the gamma shutdown field dose rate as a function of time, a gamma dose rate measurement was completed for the same operating conditions that were used in the subsequent gamma-only reactor shutdown field cryogenic irradiation experiment. This experiment was previously described and involves measuring the gamma dose rate on the z-axial centerline of the 10” Dry Tube at a height corresponding to the location of the peak total flux (predicted by MCNP6 and confirmed via experiment). After operating the reactor for 1 hour at full power (450 kW), the reactor shutdown field was measured with a magnesium walled ion chamber for the dose rate in
tissue, from ~9 minutes after shutdown until 117 minutes after shutdown. The results of the measured dose rate can be found below in Figure 73.

![Gamma Shutdown Field Dose Rate vs. Time after 450 kW run for 1 hour](image)

**Figure 73: Measured Gamma Shutdown Field Dose Rate in krad/hr in the Center of the 10” Dry Tube after the Reactor was Operated for One Hour at 450 kW; Measured for Approximately Two Hours after Shutdown**

As seen above, the reactor shutdown field decreases in dose rate very quickly following an exponential decay. Since the gamma-only cryogenic irradiation experiment was planned to last longer than the measured time period, it was necessary to fit the measured data and extrapolate the fit to a greater time interval. The data was fit with a two-term exponential using Matlab’s curve fitting tool for a functional fit of the form:

\[
f(t) = a * e^{(b*t)} + c * e^{(d*t)}
\]
The fit had a R-squared value of 0.9998 and the fit coefficients were as follows:

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Coefficient Value</th>
<th>95% Coefficient Confidence Bounds (+/-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>49.22</td>
<td>0.12</td>
</tr>
<tr>
<td>b</td>
<td>-0.001102</td>
<td>0.000007</td>
</tr>
<tr>
<td>c</td>
<td>37.94</td>
<td>0.15</td>
</tr>
<tr>
<td>d</td>
<td>-0.0001793</td>
<td>0.0000007</td>
</tr>
</tbody>
</table>

Table 7: Fit values for Gamma Shutdown Field of OSURR

The fit was then extrapolated out from 0 hours to 14 hours. The extrapolated fit for the gamma shutdown field can be seen below in Figure 74.
As seen in the fit above, most of the radiation dose is imparted in the first ~5 hours.

Finally, the gamma-only cryogenic irradiation experimental period of the extrapolated gamma shut-down field fit was integrated to find the total integral dose in tissue for the subsequent experiments, 246.2 kRad.

Also of interest is the gamma dose rate for the operation of the OSURR under experimental parameters matching the reactor-on cryogenic irradiation experiments. Therefore, a previously described experiment was completed to measure the reactor-on gamma dose rate at the same height along the z-axial centerline of the 10” Dry Tube for four reactor power levels.
<table>
<thead>
<tr>
<th>Reactor Power Level (kW)</th>
<th>Gamma Dose Rate (krad/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.63</td>
</tr>
<tr>
<td>3</td>
<td>32</td>
</tr>
<tr>
<td>10</td>
<td>104.75</td>
</tr>
<tr>
<td>30</td>
<td>307.5</td>
</tr>
</tbody>
</table>

The four data points were fit with Matlab’s linear fitting function (poly1) to achieve a linear fit of the form:

\[ f(P) = m \times P + b \]

The linear fit has an R-squared value of 1.000 and calculates the coefficients to be:

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Coefficient Value</th>
<th>95% Coefficient Confidence Bounds (+/-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m = )</td>
<td>10.22</td>
<td>0.19</td>
</tr>
<tr>
<td>( b = )</td>
<td>1.389</td>
<td>3.034</td>
</tr>
</tbody>
</table>

Table 8: Linear Fit Coefficients for Gamma Dose Rate vs. Reactor Power
The linear fit for the gamma dose rate as a function of reactor power level can be seen below in Figure 75 plotted for 0 kW to full reactor power (450 kW). The dose rate can then be found using the linear fit for any reactor power operating conditions.

Figure 75: Gamma Field Dose Rate Linear Fit in the Z-Axial Centerline at a Height of -2 cm from the Reactor Core Centerline (Position of Peak Flux) in krad/hr at OSURR Power Levels between 0 kW and 450 kW

One interesting observation from these results is that the gamma shutdown field dose rate is equal in magnitude to the steady state operation of the OSURR at 15 kW (154.6 krad/hr) at 20.44 minutes. Therefore, steady state dose rate effects for the cryogenic irradiation reactor-on experiments operating at 15 kW can be compared to the gamma-only shutdown field cryogenic irradiation experiments at 20.44 minutes after reactor shutdown. Finally, for the reactor-on experiments operating at steady state for 5 hours and 7 minutes, the total gamma dose was 791.0 krad.
7.5. **Gamma-Only Cryogenic Irradiation Experimental Results**

In the gamma-only reactor shutdown field cryogenic irradiation experiments, the CRIF was filled with LN2, then dumped and filled with LHe, before the irradiation began. The experiment was irradiated overnight in the gamma shutdown field of the reactor before being heated back to room temperature, following the previously described procedure. In these experiments, the same Cernox RTDs were used to monitor and control the temperature inside the experimental volume. Again, the two Cernox RTDs were in very close agreement in all of the experiments. The results from one of the Cernox RTDs can be seen below in Figure 76.

![Figure 76: The CRIF Main Dewar Cernox RTD Temperature Measurements vs. Time for the Duration of the Gamma-Only Shutdown Field Cryogenic Irradiation Experiments: Beginning at 4 K During the Gamma Irradiation and Showing the Heating Portion of the Experiment to Room Temperature](image)

In these experiments, following the previously described procedure, the CRIF had been pre-cooled with LN2 and LHe, similar to the first cryogenic materials.
characterization experiments. After the reactor was run for one hour at full power and shut down, the data acquisition systems were all started. At 2 minutes after shut down, the CRIF inside the 10” Dry Tube was moved into place beside the OSURR core. Therefore in each data set, the first two or three measurements were completed at 4.2 K without any radiation presence. This can be seen in the measured Cernox RTD temperature above. The first few data points record a stable temperature of 4.2 K. However, as soon as the CRIF was placed beside the reactor core, the gamma induced heating of the materials inside the experimental volume caused the temperature to increase to ~9 K. This temperature then decreased, along with the gamma dose rate decrease, throughout the first hour of the experiment until returning to ~ 4.2 K. The temperature was then extremely stable throughout the irradiation period, before increasing during the heating portion of the experiment, starting at ~800 minutes.

7.5.1. **Cryogenic Gamma Irradiation OBR Results**

The gamma-only cryogenic irradiation experiments using the OBR followed the previously described procedures. Data was taken approximately every minute using the Luna OBR. The data collected was then processed for spectral shift, like in the cryogenic materials characterization experiments. Again, the silica single-mode optical fiber length range of 16 m to 20 m, which accounted for more total length than the full cold section of the optical fiber, was investigated and reprocessed. Also, the average reflected light amplitude of the optical fiber for a region within the experimental volume (17.8 m – 17.95 m) of the CRIF was again examined for the duration of the experiment. As previously discussed, the temperature sensing feature reprocessing software is poorly
calibrated for this temperature regime, and therefore the spectral shift and the average
reflected amplitude for data within the experimental volume of the CRIF are the only data
considered herein.

A plot of the OBR reprocessing spectral shift data at three optical fiber lengths
inside the CRIF experimental volume, corresponding to 17.85 m, 17.9 mm and 17.95 m,
and the Cernox RTD temperature profile of the experiment plotted vs. time can be seen
below in Figure 77.

![Figure 77: Plot of OBR Reprocessed Data Measuring Spectral Shift and Cernox RTD Measured Temperature vs. Time for typical Single-Mode Silica Optical Fiber inside the Experimental Volume of the CRIF for Three Specific Locations along the Optical Fiber: 17.85 m, 17.9 m, and 17.95 m](image)

The Spectral Shift response as a function of time is very flat in the portions of the
experiment corresponding to the steady state operation, when the CRIF was full of LHe
during the gamma irradiation portion of the experiment, until the heating portion of the
experiment began at ~14.5 hours. The steep vertical lines that appear to go to points off-scale in the plot, at ~14 hours occur during the process of moving the CRIF and 10” Dry Tube away from the reactor core, in preparation for the heating experiment. When the lead-in optical fibers were strained during the moving process, the reprocessed data was nonsensical. Similar to the cryogenic materials characterization OBR experiment, the response to the heating portion of the experiment lags the Cernox RTD measured temperature. Again this is due to a time delay in heating the low pressure gaseous helium within the experimental volume of the CRIF, which is the main thermal transfer path for heating the optical fibers. Again the three plotted lengths are in very close agreement for the spectral shift as a function of time, which indicates consistent temperature in the experimental volume as a function of time during the experiment.

In order to examine the effects of cryogenic gamma-only irradiation, the OBR reprocessed results for spectral shift for the same three optical fiber lengths were also plotted along with the gamma dose rate of the gamma shutdown field, which can be found below in Figure 78.
In the plot above, it is evident that the spectral shift was extremely stable at all three measured points within the CRIF experimental volume throughout the gamma-only irradiation period. With a continuously decreasing gamma dose rate during the irradiation period, this leads to two interesting observations. The OBR was demonstrated to be functional in a gamma-only field at various dose rates, including a maximum dose rate of \(~300\) krad/hr, for at least a very brief period (First few minutes after shutdown).

Therefore, from dose rate effects alone, the OBR could be functional in a gamma field up to at least a dose rate of 300 krad/hr; however it is important for subsequent experiments to demonstrate long-time survivability at such a gamma dose rate. Additionally, the cumulative dose effects also are negligible for the duration of the experiment, since a
consistent spectral shift was measured throughout the irradiation period. This suggests that the OBR spectral shift measurement can consistently measure the spectral shift for a corresponding cryogenic temperature for an integral dose of 246.2 kRad.

The final data that can be examined from the OBR optical fiber experiments is the reflected optical signal amplitude as a function of temperature. The average amplitude of the reflected signal for the same 15 cm length of optical fiber, from 17.8 m to 17.95 m, as the cryogenic materials characterization experiment, inside the experimental volume of the CRIF was examined. The light amplitude reflected from each point was averaged to produce an average reflected optical amplitude over the region. This signal was saved for each OBR scan and plotted as a function of time, and therefore temperature. This average reflected optical amplitude vs. time can be seen plotted below along with the gamma dose rate in the CRIF experimental volume vs. time, in Figure 79. Also, to consider any effects of annealing during the heating portion of the experiment, the same average reflected optical amplitude vs. time is plotted below in Figure 80 along with the OBR reprocessed spectral shift (which indicates change in temperature during the heating portion of the experiment).
Figure 79: Plot of OBR Average Reflected Optical Amplitude and Extrapolated Gamma Dose Rate vs. Time for a length (17.8 m 17.95 m) of Single-Mode Silica Optical Fiber inside the Experimental Volume of the CRIF

Figure 80: Plot of OBR Average Reflected Optical Amplitude and OBR Reprocessed Spectral Shift vs. Time for a length (17.8 m 17.95 m) of Single-Mode Silica Optical Fiber inside the Experimental Volume of the CRIF
As seen in the figures above, the average reflected optical amplitude changes very little over the time period of the experiment. The maximum variation in average reflected optical amplitude is $< 1$ dB, again centered around $\sim -124.5$ dB. Although there are some points, where the amplitude dips for a period of time, they do not correspond to any changes in gamma dose rate or temperature. Therefore, these dips in average reflected optical amplitude may be from random fluctuations in the light source strength or in other changes within the setup, but do not appear to be correlated with gamma dose rate, gamma dose, or temperature.

The gamma-only cryogenic irradiation experiments using the OBR to investigate the spectral shift of off-the-shelf silica single-mode optical fibers demonstrated reliable measurements, corresponding to stable temperature in thermal equilibrium with the LHe bath during the gamma irradiation portion of the experiment. The gamma irradiation did not show any effects on the ability of the OBR to resolve spectral shift during the gamma-only cryogenic irradiation due to dose rate or total dose. Furthermore, the average reflected amplitude did not change, which indicates that gamma-only cryogenic irradiation at the dose rates, and up to the total dose, considered during these experiments had little effect on the optical fiber in any scattering centers around 1550 nm. Finally, the heating portion of the experiment did not cause failure in the OBR reprocessing measurement for spectral shift, nor did it cause a noticeable change in the average reflected amplitude of the OBR reflected optical signal from the considered 15 cm section of optical fiber within the experimental volume of the CRIF. Moreover, the heating curve, observed in the spectral shift plot is very similar to that seen in the
cryogenic materials characterization experiments. This further confirms that there were no major changes in optically active scattering centers around 1550 nm in the silica single-mode optical fiber during the gamma-only cryogenic irradiation experiments. These results suggest that the OBR and silica single-mode optical fibers would function, if properly calibrated, as a measurement system for temperature or strain at cryogenic temperatures in gamma-only radiation fields comparable to the dose rate and total dose of these experiments.

7.5.2. Cryogenic Gamma Irradiation Optical Fiber Transmission Results

The data for optical attenuation vs. time for the gamma-only reactor shutdown field optical transmission experiments was taken across the same broad spectrum of wavelengths, from ~500 to 2000 nm, throughout the duration of the experiment. The temperature profile of the experiment was measured by the Cernox RTDs and has been previously discussed. The experiments occurred in the experimental volume of the CRIF and underwent the same gamma irradiation as described in sections 7.4 and 7.5.1 (exponentially decreasing gamma dose rate as a function of time). The experimental data for the optical transmission measurements of multi-mode silica optical fibers during the cryogenic materials calibration experiment can be found below in a series of figures. In Figure 81, the experimental data is plotted as added attenuation vs. wavelength for five different times during the first eight hours of the experiment, which occurred at LHe
temperatures (no added heating) during the gamma irradiation portion of the experiment.

![Plot of Added Attenuation vs. Wavelength for Multiple Times (0.1, 2, 4, 6, & 8 hours) During the Constant Temperature (4 K) Gamma Irradiation Portion of the Gamma-Only Irradiation Optical Attenuation Experiment](image)

**Figure 81:** Plot of Added Attenuation vs. Wavelength for Multiple Times (0.1, 2, 4, 6, & 8 hours) During the Constant Temperature (4 K) Gamma Irradiation Portion of the Gamma-Only Irradiation Optical Attenuation Experiment

As seen in the figure above, the wavelength region from 500 nm to 1000 nm shows the largest change in added attenuation during the experiment. During the irradiation portion of the experiment (constant temperature near 4 K), there is a dependence of the negative added attenuation with time. This indicates that the negative added attenuation in this wavelength region is due to the gamma irradiation. As time increases, the added attenuation becomes more negative, but appears to be asymptotically reaching a minimum value as a function of time. In order to investigate the time dependence of this wavelength region in greater detail, wavelengths in the 500 nm to
1000 nm range will be plotted below within this subsection, vs. time, and the negative added attenuation will be examined in greater detail.

The added attenuation at each of the five times shows the wavelength region is extremely flat between ~1300 nm and 1700 nm. The high wavelength region from ~1700 nm to 2000 nm shows some variation (< 1.5 dB/m); however it is relatively small and negative and there is not a definite trend with time (time corresponds to decreasing gamma dose rate and increasing total gamma dose). In the region of ~1000 nm to 1300 nm, there is a greater variation in the optical attenuation (up to ~ 2.5 dB/m). In this region, the optical attenuation increases noticeably after ~2 hours; however, the trend is not continually increasing with time. As in the cryogenic materials characterization experiments, the measurements were taken on a single multi-mode silica fiber inside the CRIF without a second optical fiber to compensate for random fluctuations in the light source. This was not originally known as a major issue during this experiment or the cryogenic materials characterization experiment, but was compensated for during the subsequent reactor-on cryogenic irradiation experiment and the reactor-on room temperature experiment. Therefore, the measured optical attenuation variation without a noticeable trend as a function of time, in the wavelength region from ~1000 nm to 2000 nm is suspect, and we cannot definitively conclude that there is a change in optical attenuation as a function of gamma dose rate or as a function of total gamma dose when the fiber is irradiated at cryogenic temperatures.

The heating portion of the experiment was also examined. The data for four times, corresponding to the steady state heating portions for 4 K, 100 K, 200 K, and 300 K (as
measured by the Cernox RTDs) are plotted below as added attenuation vs. wavelength in Figure 82.

![Added Attenuation vs. Wavelength for Multiple Times](image)

**Figure 82: Plot of Added Attenuation vs. Wavelength for Multiple Times (14.4, 15.75, 19.05, & 21.6 hours) During the Heating Portion of the Gamma-Only Irradiation Optical Attenuation Experiment Corresponding to Temperatures of (4, 100, 200, & 300 K)**

Again, the added attenuation at each time between ~1000 nm and 2000 nm when compared to time zero varies by less than 2.5 dB/m. Furthermore, the change as a function of time is nearly negligible, during this time period (after the end of the irradiation period and during the heating period). The region from 500 nm to 1000 nm shows a large decrease in added attenuation for the lower wavelengths, compared to the initial (time = 0) scan. The minimum of ~17.5 dB/m occurs around 500 nm and increases back to 0 dB/m at around 1000 nm. This negative added attenuation remains nearly
unchanged throughout the heating portion of the experiment. Overall, the low variation in measured values for added attenuation and the lack of an observable trend as a function of temperature indicate again that the optical attenuation is not correlated with temperature.

The data was again plotted, this time for five wavelengths covering the lower wavelength region, where the negative added attenuation was observed in the plots above. Below, Figure 83 presents plots for the added attenuation vs. time for five lower wavelengths (600 nm, 700 nm, 800 nm, 900 nm and 1000 nm) with the gamma shutdown field plotted vs. time.

![Figure 83: Plot of Added Attenuation and Gamma Dose Rate vs. Time for Multiple Wavelengths (600, 700, 800, 900, & 1000 nm) During the Gamma-Only Irradiation Optical Attenuation Experiment](image-url)
In the figure above, the added attenuation as a function of time is negative, but relatively negligible for 1000 nm. It becomes more negative more strongly with time for shorter wavelengths. At all wavelengths, the decrease of attenuation with time occurs with a shape resembling exponential decay, which matches the shape of the gamma dose rate. Unfortunately, it is difficult to draw conclusions about whether the added attenuation is a function of the gamma dose rate or accumulated gamma dose, since the dose rate is exponentially decaying. Interestingly, the gamma dose rate and accumulated total gamma dose for gamma-only irradiation at cryogenic temperatures appear to increase the optical fiber transmission. This is dissimilar to the effects of gamma-only irradiation at room temperature and at higher temperatures, such as that of Hawn et. al. As shown below in Figure 85, Hawn found that gamma-only irradiation at room
temperature and higher temperatures caused an increase in added attenuation at wavelengths below 1000 nm.

![Thermal & Co-60 Gamma Induced Attenuation at Specified Temperatures for Low-OH Polymicro Fiber](image)

Figure 85: Plot of Added Attenuation vs. Wavelength from Hawn for Heating and Gamma-Only Irradiation Experiment

In the gamma-only cryogenic irradiation optical transmission experiments, the multimode silica optical fibers were irradiated at or near 4.2 K to an integral dose of 246.2 kRad. Therefore differences between the two experiments should be expected. As discussed in section 2.2.2 and seen in Figure 8, there are a number of optical attenuation mechanisms in the wavelength range less than 1000 nm. Specifically, the dominant attenuation mechanisms at these wavelengths are Rayleigh scattering, UV absorption, and nonbridging oxygen hole centers (NBOHC) absorption.
As previously discussed in section 2.2.2, there are many defects that are optically active in the wavelength region from 500 nm to 1000 nm, seven provided in Table 1 (section 2.2.2.). These defects are mostly OH and SiO defects. At cryogenic temperatures, the defects that were present in the optical fiber from the manufacturing process may be changed by the gamma-only irradiation. For example, OH bonds in the lowest wavelength regions (4xOH and 5xOH) could be broken via ionizing radiation (splitting the O from the H after promotion of an electron) and thus decrease the number of active scattering or absorption centers during the irradiation period.

The wavelength 1550 nm was examined in greater detail, because it is the wavelength that has been investigated in the gamma-only cryogenic irradiation OBR experiments on single-mode silica optical fibers and because it is of interest to the telecommunications industry. Below in Figure 86 and Figure 87 are the plots for added attenuation vs. time for 1550 nm light plotted respectively along with the gamma dose rate for the gamma shut down field of the OSURR and plotted along with the temperature in the CRIF experimental volume, measured by the Cernox RTDs.
Figure 86: Plot of Added Attenuation and Gamma Dose Rate vs. Time for 1550 nm During the Gamma-Only Irradiation Optical Attenuation Experiment

Figure 87: Plot of Added Attenuation and Cernox RTD Temperature vs. Time for 1550 nm During the Gamma-Only Irradiation Optical Attenuation Experiment
In both of the plots above, the added attenuation shows very little deviation (< +/- 0.1 dB/m) from the baseline measurement as a function of time. As seen in these plots, the added attenuation is nearly zero at all points in time, despite the presence of gamma radiation, while the fiber was at cryogenic temperatures, and despite the rise in temperature during the heating portion of the experiment. This indicates that gamma radiation, at the dose rates within these experiments, does not create or activate scattering centers or defects that are optically active for 1550 nm light. Furthermore, any scattering centers or defects that are optically active at 1550 nm light do not change due to changes in temperature in the range of cryogenic temperatures experienced in these experiments.

These results are in agreement with the results from the gamma-only cryogenic irradiation OBR experiments in that there and both the cryogenic materials characterization experiments for the OBR with single-mode silica fiber and for the optical attenuation system with multi-mode silica fibers. In all cases, there was not a noticeable change in reflected or transmitted optical amplitude as a function of temperature at 1550 nm. For the two gamma-only irradiation experiments, there was also not a change in reflected or transmitted optical amplitude as a function of gamma dose rate or total gamma dose at 1550 nm. Although, we cannot say for certain that these optical fibers would not have an increase or decrease in optically active scattering centers at 1550, under a much higher radiation dose rate or total dose at cryogenic temperatures, these results suggest that 1550 nm light in single-mode or multi-mode silica optical fibers may be a successful method for sensing temperature or strain and for communicating optical signals under the combined extreme conditions of cryogenic gamma-only irradiation.
7.5.3. **Cryogenic Gamma Irradiation Transistor Results**

The gamma-only cryogenic irradiation transistor experiments underwent the same cooling and radiation periods as the previously described gamma-only experiments. In this case, the NI integrated electronics system was used to measure the two GaN devices under test. The GAN HEMTs were again biased from the gate to the source and I-V curves were taken, by choosing a voltage range and taking 10 individual point measurements of the current at the voltage points within the range. During the cryogenic materials characterization transistor experiments, it was determined that there was not too much self-heating when forward biasing the GaN HEMTs. Therefore, the voltage range was extended into the forward bias region to measure more points within the positive exponential curve. These I-V curves were taken at approximately one minute intervals throughout the duration of the experiment. Therefore, there is an I-V curve for each data point that can be fit to understand the difference of the behavior of the GaN HEMTs as a function of gamma-only irradiation and as a function of temperature during the heating portion of the experiment. When biased in this manner, only the Schottky diode behavior of the gate of the GaN HEMTs was investigated. Therefore, the I-V curves had a similar shape to a Schottky diode in the positive region and were analyzed by fitting with the Schottky diode equations for the ideality factor and the saturation current. The fitting algorithms will be discussed in further detail below.

One problem that was determined after the data was taken when attempting to fit the data was how to properly account for the lead wire resistance. Typically, measurements of this type could be done pre-irradiation and post-irradiation with a well
calibrated benchtop electronics characterization system. However, do to the nature of the desired in situ measurements in the CRIF during irradiation, it was necessary to use very long lead-in and lead-out wires. Additionally, inside the CRIF there are wires that were originally installed by Lakeshore Cryotronics. These are low thermal conductivity and low neutron-activation wires and are therefore desirable for the experiments. Unfortunately the wires are made of Evanohm, which is a metal alloy with a relatively high resistivity. Therefore, the combination of the long lead-in and lead-out copper wires, which run to the top of the CRIF, with the high resistance wires within the CRIF, that run from the top into the experimental volume provide a relatively high resistance to any applied voltage. In order to take into account the effects of these wires, the following diagram, in Figure 88 below, was considered.
In the diagram above, the resistors represent the four lead-in or lead-out wire components as such:

\[ R_1 = 17 \, \Omega = \text{Lead-In Wire Constant Resistance} \]

\[ R_2(T) = 458 \, \Omega - \Delta R(T) = CRIF \text{ Wire In Variable Resistance} \]

\[ R_3(T) = 458 \, \Omega - \Delta R(T) = CRIF \text{ Wire Out Variable Resistance} \]

\[ R_4 = 17 \, \Omega = \text{Lead-Out Wire Constant Resistance} \]

As seen above in Equations 10, the Lead-In and Lead-Out copper wires are considered to be constant in resistance, since these are always at room temperature. On the other hand,
the wires inside the CRIF, made of Evanohm alloy, have a resistance that changes as a function of temperature. In order to determine the resistance at a given temperature, the resistance across the wire was measured as the resistance from one mounting ZIF block at the top of the CRIF to the other ZIF mounting block inside the experimental volume of the CRIF. The actual resistance at room temperature is measured in this scenario, but unfortunately it is impossible to account for some of the other potential partial resistances that contribute to this total resistance. For example, a contributing factor would be the soldered points for the wires, the resistance within the ZIF blocks and the resistance across the low thermal conductivity wire pass through in the outer canister. These all account for some of the series resistance that was measured, but the change in these resistances was considered negligible in comparison to the relatively high resistivity of the Evanohm wires and the change in resistivity resulting from the change in temperature and the temperature dependence of the Evanohm wire. Thus the total resistance was scaled with temperature based on an approximation that the room temperature resistance was for only Evanohm wire. In order to determine the temperature dependence of the Evanohm wire, the resistivity of Evanohm alloy as a function of temperature was found in the literature. Hust published the percent resistance of 273 K Evanohm wire resistance as a function of temperature for 5 K to room temperature\textsuperscript{44}. His published data can be seen below in Figure 89.
Table I. Resistance ratio $R(T)/R(273 \text{ K})$ of Evanohm wire.

<table>
<thead>
<tr>
<th>$T$</th>
<th>$R(T)/R(273 \text{ K})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.9928</td>
</tr>
<tr>
<td>10</td>
<td>0.9926</td>
</tr>
<tr>
<td>15</td>
<td>0.9927</td>
</tr>
<tr>
<td>20</td>
<td>0.9928</td>
</tr>
<tr>
<td>25</td>
<td>0.9929</td>
</tr>
<tr>
<td>30</td>
<td>0.9930</td>
</tr>
<tr>
<td>35</td>
<td>0.9931</td>
</tr>
<tr>
<td>40</td>
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</tr>
<tr>
<td>45</td>
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</tr>
<tr>
<td>50</td>
<td>0.9935</td>
</tr>
<tr>
<td>60</td>
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</tr>
<tr>
<td>70</td>
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</tr>
<tr>
<td>80</td>
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</tr>
<tr>
<td>90</td>
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</tr>
<tr>
<td>100</td>
<td>0.9949</td>
</tr>
<tr>
<td>150</td>
<td>0.9963</td>
</tr>
<tr>
<td>200</td>
<td>0.9977</td>
</tr>
<tr>
<td>250</td>
<td>0.9991</td>
</tr>
<tr>
<td>300</td>
<td>1.0005</td>
</tr>
</tbody>
</table>

Figure 89: Table of Evanohm Wire Percent Resistance of 273 K Evanohm Wire Resistance for Temperatures from 5 K to 300 K, published by Hust

In order to use these values, they were multiplied by our known value of Resistance at room temperature. Then the lead-in (constant $R_1$), lead-out (constant $R_4$), and CRIF in and out ($R_2[T]$ & $R_3[T]$) wire resistances were summed and the total was plotted as a function of temperature, and fit to a line. The plot of the data points can be seen below in Figure 90.
Figure 90: Plot of Total Wire Resistance of all Wire Leads for Temperatures from 5 K to 300 K

The linear fit was made into a function in Matlab. Next, the recorded values, previously presented in this sub-chapter for the Cernox RTD measured temperature during the gamma-only cryogenic irradiation experiments were used as the input temperature vector for the functional fit of the lead wire total resistance as a function of temperature. The resulting lead wire resistance as a function of time throughout the experiment can be seen below in Figure 91.
Figure 91: Plot of Total Wire Resistance of all Wire Leads vs. Time for the Duration of the Gamma-Only Cryogenic Irradiation Transistor Experiments

As seen in the figure above, the shape of the resistance matches that of the temperature of the experiment, which makes sense since the resistance depends linearly on temperature. This resistance demonstrates a maximum difference of ~7 Ω across the temperature range considered in these experiments (4 K to room temperature).

The resistance as a function of time throughout the experiment is known and can be coupled with Ohm’s Law:

\[ V = I \times R \]

Together, they allow for a simple calculation of the voltage drop across the four lead wires. Unfortunately, we could not take into account the resistance of the Duroid board mounts and the soldered connections to the packaged devices. This should have been
estimated somehow before the experiments began, but was not properly measured and cannot be measured now due to the radioactivity of the packaged devices post-irradiation. Furthermore the series resistance of any of the wire bonds inside the packaged HEMT and the series resistance of the bulk GaN is not known. This series resistance would have to be measured directly for the packaging and for the substrate, which would require the measurements to be made during the manufacturing process, or would require destruction of the packaged device. Since these were not feasible options, these series resistances (R_s) were not accounted for and are a major source of error within the experiments. Further elaboration on the effects of such series resistance on final calculated diode equation terms will be discussed in greater detail below.

For the known resistance of the lead wires, Ohms equation was applied for the sum of the resistances in series, for each I-V curve measurement during the experiment, accounting for the temperature dependence of R_2 and R_3, to achieve a voltage drop across the lead wires.

\[ V(T)_{Lead\_Drop} = I \times (R_1 + R(T)_2 + R(T)_3 + R_4) \]  

Then this was subtracted from the voltage applied by the NI PXI integrated electronics system, \( V_{NI,\text{PXI}} \), to find the voltage applied to the packaged and mounted transistor, \( V_D \), as a function of temperature, T (\( V_D \) is used because it is the common terminology for diode voltage, when using the Schottky diode equations).

\[ V(T)_D = V_{NI,\text{PXI}} - V(T)_{Lead\_Drop} \]
This new voltage was then used to recreate the I-V curves, plotting the measured current I vs. \( V_D \), instead of measured current I vs. \( V_{NI,PXI} \). Below in Figure 92 and Figure 93, are I-V curves before and after applying the lead wire voltage drop, respectively, for five different temperatures during the heating portion of the experiment, after the gamma-only cryogenic (4.2 K) irradiation portion of the experiment.

Figure 92: Plot of Current (I) vs. NI PXI Integrated Electronics System Applied Voltage (\( V_{NI,PXI} \)) for GaN Transistor 1 at Various Temperatures After Gamma-Only Cryogenic Irradiation at 4.2 K, During the Heating Portion of the Experiment
In general, the data measured for the two GaN Transistors was very similar. In order to visualize the similarities, the same I-V curves, accounting for the voltage drop across the lead wires, for the second GaN HEMT are shown below in Figure 94.
As seen in all three figures above, there is an obvious dependence on temperature. As the temperature increases, the diode current is higher for a given voltage. With a goal of understanding the effects of temperature and gamma-only cryogenic irradiation, a fitting scheme is necessary, to numerically quantify the change in behavior of the GaN HEMTs.

Because the measurements for current vs. voltage have been made across the gate and source of the packaged GaN HEMTs, the behavior of the devices can be described by the standard Schottky diode equations. The Schottky diode equation can be seen below in Equation 14 for a simple Schottky diode:

\[ I_D = I_S \left[ \exp\left(\frac{qV_D}{nk_BT}\right) - 1 \right] \]
In equation 14, $q$ is the charge of an electron (1.602E-19 C), $k_B$ is Boltzmann’s constant (1.38E-23 J/K), $T$ is the temperature (in K), $n$ is the ideality factor of the diode (typically between 1 and 2, dimensionless), $V_D$ is the voltage applied to the diode, $I_S$ is the saturation current of the diode, and $I_D$ is the current passing through the diode. In this formulation, the ideality factor is 1 if the diode behaves fully according to thermionic emission theory. On the other hand, electron tunneling through the Schottky barrier and other processes can make a Schottky diode behave in a less than ideal fashion, which is indicated by an ideality factor closer to 2. The diode saturation current, $I_S$, can be written as a function of temperature and Shottky barrier height as well:

$$I_S = A A^* T^2 \exp \left( -\frac{q \varphi_B}{k_B T} \right)$$

In the equation for the saturation current, $A$ is the Schottky contact area, $A^*$ is the Richardson’s Constant, and $\varphi_B$ is the Schottky Barrier Height. The other terms have already been defined above. In this model, if the saturation current is measured or fitted using equation 14 above, the Schottky Barrier Height can be determined.

In the case of a packaged HEMT, the diode behavior of the device is more complicated, because the diode is not simply a Schottky metal contact on bulk semiconductor material. Instead, there can be multiple Schottky contacts, there can be multiple stacked semiconductor materials, and the effects of wire bonds and other internal device packaging affect the Schottky behavior of the HEMT. These combined effects can cause the ideality factor of the packaged HEMT to be higher than 2. Peifeng Hu discussed this possibility in greater detail\textsuperscript{45}:
"… the ideality factor was greater than 2.0. However, for a perfect metal-semiconductor interface, the ideality factor closes to 1.0 since the main current is thermionic emission theory. Jay M. Shah[6] thought that the rectification in unipolar heterojunctions as well as metal-semiconductor junctions could increase the ideality factor to values greater than 2.0. Therefore, for Schottky contact which contains the AlGaN/GaN heterojunction, it can be divided into the actual GaN p-n junction diode, unipolar AlGaN/GaN heterojunction diodes and a Schottky diode at the metal/AlGaN junction. The externally measured ideality factor is greater than 2.0 since it is the sum of the ideality factor of each individual junction."

Such behavior has been seen in a number of studies on GaN HEMTs, including Hu’s work, which used an AC I-V measurement to determine the ideality factor for some GaN HEMTs formed on SiC, from room temperature at the lowest value of n = 3.6, down to 4 K at the highest value of n = ~4.3. These values indicate that the ideality factor increases with decreasing temperature, which means that they do not function under the assumption of thermionic emission theory only. Other studies have confirmed this type of temperature dependence of the ideality factors of GaN HEMTs. For example, Salah Saadaoui measured I-V curves for packaged GaN HEMTs and fit the forward bias region to determine the ideality factor, n, as a function of temperature. He also determined the Schottky barrier height for the same temperature range and plotted both vs. temperature together, which can be seen below in Figure 96.
As seen in the plot above, there appears to be an exponential increase in the ideality factor as a function of decreasing temperature to a maximum value of ~6.5 at the lowest measured temperature, 50 K. On the other hand, the Schottky Barrier Height increases as a function of temperature.

Similar temperature dependence of the ideality factor of was even observed in simple Schottky Diodes (not packaged HEMTs). J. Oswald fit the diode equations for the ideality factor, $n$, for simple GaN Schottky diodes, and plotted those values vs.
temperature, from 80 K (using LN2 as a cold source) to 300 K\textsuperscript{46}. The plot can be seen below in Figure 96.

![Figure 96: Plot of Ideality Factor vs. Temperature for simple GaN Schottky Diodes measured by Osvald et. al](image)

As seen in the figure above, despite operation with an ideality factor in the normal range (1 to 2) for both the Ga-face polarity and N-face polarity of the GaN Schottky Diodes, for temperatures above 200 K, there is a seemingly exponential increase in ideality factor as a function of temperature as the temperature decreases toward 80 K. Osvald described this increase:
“Ideality factors for Ga-face structures are for higher temperatures also compatible with thermionic theory (Fig. 4). However for the temperatures below 200 K ideality factors start to be so high that it is not more in accordance with the thermionic mode of current transport. We assume that at low temperatures another mechanism starts to control the current flow. This mechanism is with very high probability tunneling.”

In all of these studies, the ideality factor decreases as a function of temperature. This behavior is also evident in the data presented within this dissertation below.

In order to properly fit the Schottky diode equations in the forward direction, it is also necessary to know any further sources of resistance within the system. As previously discussed, the resistances of the lead-in and lead-out wires were accounted for and converted to a change in applied voltage using equation 13. However, there are resistances associated with the mounting on the Duroid board mounts, including soldered connections to the device packaging pins, which were very small. There are also resistances within the GaN package from the wire bonds between the various metal contacts and packaging pins. Finally, there is a resistance associated with the bulk semiconductor material. All of these resistances sum in series and provide a series resistance drop in voltage across the mounted and packaged HEMT. In similar research, the series resistance, $R_s$, of the semiconductor bulk material is accounted for by direct measurement of the device before packaging. A typical formulation of the effect of the series resistance, $R_s$, can be seen below in Equation 16.
As seen in Equation 16, the series resistance can be multiplied by the diode current and subtracted from the applied voltage to the diode, $V_D$, to correct Equation 14. This allows for a fit to be completed and the ideality factor to be properly calculated. This series resistance can be quite large for GaN based HEMTs and/or Schottky diodes. In the previously discussed study by Saadaoui, the series resistance was measured for the temperature range from 50 K to above room temperature and can be seen below in Figure 97.
As seen in the figure above, the series resistance in the GaN bulk is quite substantial and can have a noticeable effect on the actual voltage applied across the Schottky contact of the GaN HEMT, and the resulting fit value for the ideality factor.

Due to the requirements of the research completed within this dissertation, it was impossible to open a device package and/or to measure the other components of the resistance associated with the packaging or device mounting as a function of temperature throughout the range from 4 K to room temperature. Therefore, it is understood that these resistances could not be fully accounted for in the diode equation fits. The various
unknown resistances can be summed and treated as one unknown resistance across the packaged and mounted GaN HEMT, $R_{\text{HEMT}}$.

$$R_{\text{HEMT}} = R_S + R_{\text{Packaging}} + R_{\text{Duroid, Mount}} + R_{\text{Other}}$$  \hspace{1cm} (16)

The resistance, $R_{\text{HEMT}}$, can be substituted for the series resistance, $R_S$, from equation 16 to establish the effective diode equation used for the experiments considered herein. This formulation of the effective Schottky diode equation is seen below in Equation 18.

$$I_D = I_S \left[ \exp \left( \frac{q(V_D - I_D R_{\text{HEMT}})}{n k_B T} \right) - 1 \right]$$  \hspace{1cm} (17)

In order to understand the effect on the ideality factor fit, due to this added factor $I_D R_{\text{HEMT}}$, we can consider Ohm’s equation and the voltage drop associated with the resistance, $R_{\text{HEMT}}$.

$$I_D R_{\text{HEMT}} = V_{\text{HEMT}}$$  \hspace{1cm} (18)

This voltage drop $V_{\text{HEMT}}$ can be substituted into the exponential in Equation 18, and the terms can be rewritten to consider the effective ideality factor that will be fit. Below in Equation 20, we can see that accounting for the voltage drop, $V_{\text{HEMT}}$, affects the determination of the value of the true ideality factor of the diode, $n$. If the $V_{\text{HEMT}}$ is not known, the ratio of $V_D/n'$ can be considered, where $n'$ is the uncorrected ideality factor.

$$\frac{V_D}{n'} = \frac{V_D}{n} \left( 1 - \frac{V_{\text{HEMT}}}{V_D} \right)$$  \hspace{1cm} (19)

Since the resistance $R_{\text{HEMT}}$ is not known, and $V_{\text{HEMT}}$ cannot be calculated, the uncorrected ideality factor, $n'$, can be substituted into Equation 18 to reach the form of the diode equation used for fitting the data measured in this research.
\[ I_D = I_S \left[ \exp \left( \frac{qV_D}{n'k_BT} \right) - 1 \right] \quad 20. \]

Equation 21 above, the modified diode equation, describes the measured I-V curves for the GaN devices. Since values for \( I_D, V_D, k_B, q, \) and \( T \) are known, it is possible to fit the equation to the measured data to calculate values for \( n' \) and \( I_S \). In this fitting scheme, terms are rearranged, an approximation is made to simplify the diode equation, a linear fit is completed to find estimate values for \( n' \) and \( I_S \), and finally a least squares fit is completed with the estimate values as initial guesses for the modified diode equation (Equation 21) to calculate final fit values for \( n' \) and \( I_S \). First, the natural log of both sides of Equation 21 is taken.

\[
\ln(I_D) = \ln \left( I_S \left[ \exp \left( \frac{qV_D}{n'k_BT} \right) - 1 \right] \right) \quad 21. \]

\[
\ln(I_D) = \ln(I_S) + \ln \left( \exp \left( \frac{qV_D}{n'k_BT} \right) - 1 \right) \quad 22. \]

Next we understand that for the temperatures considered in this research, \((4 \text{ K} < T < 300 \text{ K})\), in the positive forward bias, the exponential should be larger than one.

\[
\exp \left( \frac{qV_D}{n'k_BT} \right) \gg 1 \quad 23. \]

Therefore the approximation made above in Equation 24 can be made and substituted into Equation 23 to achieve Equation 25 below.

\[
\ln(I_D) \approx \ln(I_{S,Estimate}) + \ln \left( \exp \left( \frac{qV_D}{n'_{Estimate}k_BT} \right) \right) \quad 24. \]
Equation 25 can be simplified to the form of a linear equation, \( y = m \cdot x + b \), where \( x \) is \( V_D \) and \( y \) is \( \ln(I_D) \).

\[
\ln(I_D) \equiv \ln(I_{S\_Estimate}) + \frac{qV_D}{n'_{Estimate}k_BT}\tag{25}
\]

In Equation 26 above, a linear fit can be made, to find values of \( b \) and \( m \). Once \( b \) and \( m \) are known, they can be set equal to the constant terms in Equation 26.

\[
b = \ln(I_{S\_Estimate}) \quad \text{&} \quad m = \frac{q}{n'_{Estimate}k_BT}\tag{26}
\]

Finally, the terms can be rearranged to determine the initial estimate values for the saturation current and ideality factor, \( I_{S\_Estimate} \) and \( n'_{Estimate} \).

\[
I_{S\_Estimate} = \exp(b) \quad \text{&} \quad n'_{Estimate} = \frac{q}{mk_BT}\tag{27}
\]

For the gamma-only cryogenic irradiation experiments, there were I-V curves taken at \(~1\) minute intervals, with the temperature recorded at the same time. Therefore, there were many data sets for the measured current and voltage. After making the previously described corrections for the lead-in and lead-out wire voltage drop, the fitting scheme described above was completed on the five pairs of measured values for \( I_D \) and \( V_D \) in the forward bias direction (voltage range of \(~0.6 \text{ V} \rightarrow 2.2 \text{ V}\)) for each I-V measurement throughout the duration of the experiment. At this point, the resulting values for \( I_{S\_Estimate} \) and \( n'_{Estimate} \) at each time were known for the duration of the experiment. Finally, these calculated fit initial estimate values were put back into Equation 22 and a least squares fit was completed in Matlab for each data set to find the final fit values for \( I_S \) and \( n' \) at each time throughout the experiment. The calculated values for \( I_S \) can be seen plotted along with the gamma shutdown field dose rate vs. time below in Figure 98.
As seen in the figure above, there appears to be a linear decrease in the saturation current during the first ~14 hours of the experiment. This decreasing saturation current corresponds to the gamma-only cryogenic irradiation period of the experiment, before the heating portion of the experiment. The gamma shutdown field is decreasing exponentially throughout this period. Since the decrease in saturation current does not follow an exponential curve of any time, it is difficult to distinguish whether or not the linear decrease is a function of gamma dose rate or total accumulated gamma dose. Instead, it is likely a more complicated effect, depending on some combination of the effects of gamma irradiation with the accumulation and release of trapped charges, on electron
tunneling through the Schottky barrier, or on other surface or bulk effects. Regardless, it appears that irradiating these GaN HEMTs with gamma radiation at 4.2 K causes a decrease in the saturation current of the devices, which over an extended period of irradiation at 4.2 K or at a higher dose rate, may eventually cause failure of the devices.

The saturation current for the full duration of the experiment, including the heating portion of the experiment can be seen below in Figure 99, plotted along with the Cernox RTD measured temperature vs. time.

![Graph of Saturation Current vs. Time](image)

**Figure 99: Plot of Saturation Current (I_s) and Cernox RTD Temperature vs. Time for the Duration of the Gamma-Only Cryogenic Irradiation GaN Transistor Experiments**

In this figure above, we can see the previously discussed linear decrease in saturation current during the gamma irradiation portion of the experiment up to ~14.5 hours. Then after 14.5 hours, the heating portion of the experiment begins and the temperature
increases in 25 K steps back to 300 K. At the beginning of the heating experiment, through ~ 15 hours (corresponding to ~75 K), there is an increase in saturation current to values above those seen even before irradiation. This increase in temperature may allow for an increase in the release rate of trapped charge in the device. After ~ 16.5 hours (corresponding to ~125 K), however, the saturation current returned to a nearly flat value of saturation current of ~0.25E-6 A. This indicates that the gamma irradiation induced decrease in saturation current was not recovered by heating back to room temperature over a period of ~7.5 hours and that gamma-only cryogenic irradiation may have long term effects on GaN HEMTs.

In order to investigate the saturation current further and determine whether or not the fit values for the saturation current were reasonable, the reverse bias portion of the I-V curve measurements was examined. As seen in Equation 21, as the voltage becomes negative, there should be an exponential decrease in the measured current. As the exponential becomes very small, the -1 becomes the dominant term, and the measured current becomes the negative of the saturation current.

\[
\text{As } \exp\left(\frac{qV_D}{n'k_BT}\right) \to 0 : \quad I_D = I_S \left[ \exp\left(\frac{qV_D}{n'k_BT}\right) - 1 \right] \quad \Rightarrow \quad I_D = -I_S
\]

Therefore, the measured values of the steady state reverse current were averaged for each measurement. A plot of I-V curves in the reverse bias region for times corresponding to the heating portion of the experiment at temperatures through the heating range (4 K, 50 K, 100 K, 200 K, and 300 K) can be seen below in Figure 100.
As seen in the figure above, there appears to be a general dependence upon temperature such that for increasing temperature, the reverse bias current increases as well. The reverse bias current at 50 K and 100 K is essentially the same; however the reverse bias current for other temperatures are much more easily distinguishable. Furthermore, since the reverse bias current tends toward the saturation current, which is a function of $T^2$, the reverse current should be a function of temperature as well.

In order to compare the reverse current and the saturation current as a function of time, they were plotted together below in Figure 101, along with the Cernox RTD temperature vs. time.
As seen in the figure above, the saturation current and reverse current both have a negative linear trend during the gamma-only cryogenic irradiation portion of the experiment and both have an increase in current during the beginning of the heating portion of the experiment, and then a downward trend between ~16.5 and 17.5 hours. The only obvious difference in trend is the linear increase in current for the reverse current vs. the flat region for the saturation current from ~17.5 to 22 hours. The fact that both currents are on the same order of magnitude and have fairly similar trends provides some reassurance that the fit value for the saturation current is reasonable. Also, inlaid into the figure above is the average forward bias $I_s$ fit value and the average measured reverse current at each temperature step during the heating portion of the experiment, plotted vs.
temperature. Observing the trend in the average values, shows that there may be some trapped charge release as a function of temperature during the heating portion of the experiment.

As previously described, the uncorrected ideality factor (n’) was also determined for the fit of Equation 21. It has previously been discussed that the ideality factor has been shown to decrease as a function of increasing temperature through the cryogenic temperature ranges, and shown to often be higher than 2 even at room temperature for GaN based HEMTs (indicating tunneling or effects other than thermionic emission). However, the calculated fit values for the uncorrected ideality factor (n’), for the research completed herein, are significantly higher than the values previously presented and discussed. This is due to the unknown resistances, $R_{HEMT}$, and the resulting uncorrected voltage drop ($V_{HEMT}$). However, despite the vastly different values for the ideality factor, there are noticeable important trends as a function of radiation and as a function of temperature that can be investigated further. The fit for the uncorrected ideality factor (n’) and Cernox RTD measured temperature for the duration of the gamma-only cryogenic irradiation experiment can be seen below in Figure 102, plotted vs. time.
As seen in the figure above, there were two distinct time ranges with very different behavior during the experiment. First, the cryogenic gamma-only irradiation portion of the experiment with the changing gamma dose rate shows an effect on the ideality factor during the irradiation from 0.1 hours to ~14.5 hours. In order to examine this portion of the experiment in greater detail, the data for 0-14.5 hours was plotted with the gamma dose rate vs. time and can be seen below in Figure 103. Furthermore, in order to examine the change in the uncorrected ideality factor as a function of temperature during the heating portion of the experiment (no gamma radiation present), the uncorrected ideality factor was plotted vs. time for the heating portion of the experiment, from 14.5-22 hours below in Figure 104.
As seen in the figure above, when the data was first collected, the uncorrected ideality factor was on the range of ~650 while the CRIF experimental volume (and GaN HEMTs) were at 4.2 K, but before being in the presence of gamma-only radiation. After the first few minutes, the CRIF was moved into place beside the reactor and the ideality factor dropped immediately to ~350. This precipitous drop appears to be a near instantaneous effect of the gamma radiation dose. As the gamma dose rate decreases to a negligible value at just ~4 hours, the ideality factor increases to steady state, also at ~4 hours. After 4 hours, the gamma dose rate remains negligible and the uncorrected ideality factor remains constant at about the same value as the initial measurement, before the presence of the radiation. Inlaid into the figure is a plot of the uncorrected ideality factor.
vs. the gamma dose rate. The dependence of the uncorrected ideality factor vs. the gamma dose rate appears to be linear. Therefore, the shape of the curves, in both plots in the figure, indicate that the uncorrected ideality factor is a function of gamma dose rate at cryogenic temperatures. For operation in a gamma-only field at cryogenic temperatures, the uncorrected ideality factor decreases, resulting in a higher operating current for the diode, since a smaller ideality factor in Equation 21 results in a larger argument of the exponential. This means that gamma-only irradiation under cryogenic temperatures seems to cause a change in the uncorrected ideality factor that improves the operation of the GaN HEMTs, while simultaneously causing a change in the saturation current (as previously discussed) that is harmful to the operation of the GaN HEMTs.

![GaN Transistor 1 Ideality Factor vs. Time](image)

Figure 104: Plot of Uncorrected Ideality Factor (n’) and Cernox RTD Temperature vs. Time for the Duration of the Gamma-Only Cryogenic Irradiation GaN Transistor Experiments
As seen in the figure above, there is a very large change in the uncorrected ideality factor as a function of temperature. In some of the previously discussed papers on the temperature dependence of the ideality factor in GaN HEMTs as a function of temperature, the data appeared to fit a negative exponential as a function of temperature, such that as the temperature approached zero, the ideality factor was increasing exponentially. That type of behavior appears in the figure above as well, but the change below 50 K is very large. The plot range is zoomed in further to see the higher temperature effects on the uncorrected ideality factor, which can be seen below in Figure 105.

Figure 105: Plot of Uncorrected Ideality Factor (n’) and Cernox RTD Temperature vs. Time for the Duration of the Gamma-Only Cryogenic Irradiation GaN Transistor Experiments
In the higher temperature region of the heating portion of the experiment, the exponentially decreasing behavior of the uncorrected ideality factor as a function of temperature is again evident. As the temperature increases to 300 K, the uncorrected ideality factor reaches a minimum value (~7) which is larger than the previously reported values from other studies, but of the same order of magnitude. Taken together, the cryogenic irradiation experiments indicate that while the diodes continued to function throughout the experiment, regardless of the presence of the gamma radiation and regardless of the temperature, there are, nonetheless, noticeable effects in the operation of the GaN HEMTs. Specifically, the gamma radiation at cryogenic temperatures improves the ideality factor of the GaN HEMTs, while decreasing the saturation current. These competing effects must be studied more closely in a constant dose gamma-only cryogenic irradiation experiment, for multiple dose rates, to fully understand these effects and come to a conclusion about the dose rate under which these devices may fail. However, for dose rates and total accumulated dose comparable to that of these experiments, the GaN gate to source Schottky diode behavior has been demonstrated to function successfully as a HEMT gate. Finally, temperature has a noticeable impact on the saturation current of the GaN HEMTs and a huge impact on the ideality factor of the HEMTs. The fact that the ideality factor increases exponentially as the temperature decreases indicates that the GaN HEMTs do not behave according to thermionic emission theory at cryogenic temperatures, despite the fact that the gate still turns on, increasing the current, in the forward bias direction, allowing for operation of the GaN HEMT gate in this temperature range.
7.6. Reactor-On Cryogenic Irradiation Experimental Results

During the reactor-on cryogenic irradiation experiments, the CRIF was cooled with LN2 and subsequently with LHe via the previously described experimental procedure. The purpose of these cryogenic irradiation experiments was to understand the combined effects of low temperatures and a mixed radiation field and to determine whether or not greater levels of damage were present than in analogous room temperature experiments.

First, the data acquisition systems were started and data was collected without the presence of liquid cryogen or radiation. Then, the CRIF Main Dewar was filled with LN2 and all CRIF structures and materials under test were precooled overnight to 77 K. The next morning, the CRIF Main Dewar was emptied and refilled with LHe to achieve ~4.2 K in all of the CRIF structural materials and materials under test. Finally, the CRIF resting on the steel plates at the bottom of the 10” Dry Tube, was moved into place beside the reactor core and the reactor was brought up to 15 kW power. At this point, the reactor was continuously operated at steady state at 15 kW for 5 hours and 7 minutes before the reactor was shut down. Once the control rods were fully inserted into the OSURR core, the CRIF and 10” Dry Tube were moved away from the OSURR core and data was continually taken for ~one more hour before the heating portion of the experiment began. The CRIF experimental volume was heated back up to room temperature. The data acquisition systems continued to acquire date during this heating portion of the experiments and for a subsequent 10 days. The temperature measured by the Cernox

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RTDs can be seen below in Figure 106 and Figure 107 (Zoomed-In Plot of Figure 106), plotted along with the reactor power level, as a function of time.

![Cernox RTD Temperature and Reactor Power Level vs. Time](image)

**Figure 106:** Plot of Cernox RTD Measured Temperature and OSURR Power Level vs. Time Inside the CRIF Experimental Volume During the Reactor-on Cryogenic Irradiation Experiments
As is seen above, the Cernox RTD temperature increased slightly as soon as the reactor was turned on, due to radiation-induced (mostly gamma-induced) heating of the structural materials inside the CRIF experimental volume. However, the maximum temperature achieved was only ~9 K, which was a ~5 K increase above the base LHe starting point of 4 K.

7.6.1. **Reactor-On Cryogenic Irradiation OBR Results**

The reactor-on cryogenic irradiation experiments using the OBR followed the previously described procedures. In this case the experiment was designed to understand the functionality of the OBR spectral shift sensing feature within the extreme
environment of mixed field irradiation at cryogenic temperatures. Data was taken approximately every minute using the Luna OBR. The data collected was then processed for spectral shift, like in the cryogenic materials characterization experiment and the gamma-only cryogenic irradiation experiment. Again, the single-mode silica optical fiber length range of 16 m to 20 m was investigated and reprocessed. Also, the average reflected light amplitude of the optical fiber for a 15 cm section (17.8 m – 17.95 m) within the experimental volume of the CRIF was again examined for the duration of the experiment. The spectral shift and the average reflected amplitude for data within the experimental volume of the CRIF are considered below. Plots of the OBR reprocessing spectral shift data at three optical fiber lengths inside the CRIF experimental volume, corresponding to 17.85 m, 17.9 m and 17.95 m, and the Cernox RTD temperature profile of the experiment plotted vs. time can be seen below in Figure 108. The same spectral shift data can be seen again below in Figure 109, plotted along with the reactor power level of the experiment vs. time.
Figure 108: Plot of OBR Spectral Shift and Reactor Power Level vs. Time for Multiple Fiber Lengths (7.85 m, 17.9 m, & 17.95 m) During the Reactor-On Cryogenic Irradiation OBR Experiment
As seen in the figure, the OBR spectral shift measurement is very flat throughout the duration of the irradiation period of the experiment. There is a slight difference in the measured spectral shift of the OBR for the 17.85 m point compared to the other two points, indicating a slightly lower temperature in the region. However this difference is quite small and all three measurements remain consistently flat throughout the irradiation period. This indicates that the OBR measured a roughly constant spectral shift, which corresponds to a nearly constant temperature profile throughout this period. Furthermore, the radiation did not cause a significant enough degradation in the reflected optical signal to cause a failure of the OBR when reprocessing for spectral shift.
There appears to be noise throughout the duration of the experiment, and although not during the irradiation period, there are multiple times when the OBR does lose functionality (ability to measure a reasonable spectral shift). First, the signal is extremely noisy from ~17.5 hours to ~19 hours, which corresponds to the cryostat being cooled with LHe, lifted to the top of the reactor pool, lowered into the 10” Dry Tube, and moved beside the reactor core. This part of the experiment involved moving and straining the lead-in optical fibers and caused the OBR to lose functionality during the period. Second, the signal was extremely noisy for a few minutes after the irradiation period (at ~25 hours), when the CRIF and 10” Dry Tube were moved away from the reactor core. Third, the OBR lost functionality at ~27 hours, which corresponded to the CRIF being lifted back to the reactor pooltop for the LHe refill. Finally, the noise in the measurement at ~37 hours and ~41 hours is unexplained. The OBR change in the spectral shift during the heating portion of the experiment lags the Cernox RTD temperature measurement, demonstrating that the time constant for the thermal transfer from the heating element to the mounting platforms was shorter than to the optical fibers.

The average amplitude of the reflected signal for the same 15 cm length of optical fiber, from 17.8 m to 17.95 m, as the cryogenic materials characterization experiment and the gamma-only cryogenic irradiation experiment, inside the experimental volume of the CRIF was examined. The light amplitude reflected from each point was averaged to produce an average reflected optical amplitude over the region. This average reflected optical amplitude vs. time can be seen plotted below along with the reactor power level vs. time, in Figure 110. The average reflected amplitude was also plotted along with the
OBR spectral shift vs. time for the same 15 cm section of fiber and can be seen below in Figure 111.

Figure 110: Plot of Average Backscatter Amplitude and Reactor Power Level vs. Time for a 15 cm Section (17.8 m – 17.95 m) of Fiber within the Experimental Volume of the CRIF During the Reactor-On Cryogenic Irradiation OBR Experiment
As seen in the figures above, the reactor operation period does cause a decrease in the average reflected amplitude from the optical fiber in the experimental volume of the CRIF, on the order of ~1.5 dB which is relatively high. The reactor irradiation at cryogenic temperatures did not cause the spectral shift measurement to fail. However, the results of the figure above indicate that if irradiated for long enough at cryogenic temperatures at 15 kW there may eventually be a failure of the spectral shift sensing of the OBR in a single-mode silica optical fiber using 1550 nm light as the reflected signal decreases with mixed field radiation dose. This loss of average reflected amplitude (in dB) appears to be decreasing linearly during the irradiation period. Because the dose rate is constant at a steady state reactor operational power, the degradation in the average
reflected optical amplitude (in dB) is a linear function of the total dose received. This indicates that the OBR could be used in a cryogenic mixed irradiation field for a total dose comparable to that experienced in this experiment, but would likely eventually fail. This suggests that further work should be done to determine the failure dose for the OBR spectral shift sensing capability using a single-mode silica optical fiber.

Interestingly, after the irradiation period, the average reflected amplitude remained in the range of ~-125.75 dB to -126 dB while the CRIF experimental volume remained cold. However, at the commencement of the heating experiment, the average reflected amplitude began to rise. Although there is some variation in the average reflected amplitude signal during the heating portion of the experiment, once the spectral shift returned to a value commensurate with room temperature, the average reflected amplitude returned to the starting value for the experiment of ~ -124.5 dB. This indicates that the radiation damage was “locked-in” to the optical fiber, while the experimental volume remained at cryogenic temperatures. However, the heating back to room temperature was enough to allow for the radiation-induced defects to anneal. This means that the defects are probably the result of atoms being removed from their original locations within the silica structure. This is most likely caused by neutron-induced dislocations from neutron inelastic or elastic scattering, resulting in PKA formation causing defect chains within the material. The low temperature annealing appears to provide enough thermal energy for many of these atoms to find their local low energy states, reconstituting molecular bonds, mending the local amorphous silica structure. If this experiment had been completed in a cryogenic irradiation facility without in situ
measurement capabilities, the experimenters would conclude that there was no observable radiation-induced damage for an irradiation at or near 4.2 K. This clearly would be a false result. Therefore the unique capabilities of this cryogenic irradiation facility, allowing for in situ measurements to be made throughout a cryogenic irradiation period and during a low temperature heating/annealing period, are important to understanding these effects.

7.6.2. Reactor-On Cryogenic Irradiation Optical Fiber Transmission Results

The reactor-on cryogenic irradiation optical transmission experiment followed the experimental procedures previously described. The optical transmission system again recorded experimental data throughout the duration of the experiment and the added attenuation was calculated across a broad spectral range, 500 nm to 2000 nm. The experimental data for this experiment can be found below in Figure 112, plotted as added attenuation vs. wavelength for multiple times during the irradiation period of the experiment.
In the figure above, the times chosen were all during the 5 hour and 7 minute irradiation period of the experiment. The reactor power was at steady state at 15 kW during this irradiation period, therefore, the dose rate was considered to be constant for gamma radiation and the flux was considered to be constant for the neutron radiation. This means that each time point represents a higher accumulated dose as a function of time and the increase in accumulated dose is linear with time. As seen in the figure above, there is very little added attenuation throughout the irradiation period across all wavelengths between 1000 nm and 2000 nm. However, the wavelengths between 500 nm and 1000 nm show an increase in added attenuation that increases as the wavelength decreases between 1000 nm and 500 nm. The increase in added attenuation in dB/m in
the low wavelength region appears to be nearly linear with time and therefore a linear increase as a function of either accumulated gamma dose, neutron equivalent damage dose, or both. These wavelengths were investigated further as a function of time. Below in Figure 113 and Figure 114 is a plot of added attenuation vs. time for multiple wavelengths: 500 nm, 600 nm, 700 nm, 800 nm, & 900 nm plotted with the reactor power level and with the Cernox RTD measured temperature, respectively.

Figure 113: Plot of Added Attenuation and Reactor Power Level vs. Time for Multiple Wavelengths: 500 nm, 600 nm, 700 nm, 800 nm, & 900 nm Light During the Reactor-on Irradiation Optical Attenuation Experiment
Figure 114: Plot of Added Attenuation and Cernox RTD Measured Temperature vs. Time for 500 nm, 600 nm, 700 nm, 800 nm, & 900 nm Light During the Reactor-on Irradiation Optical Attenuation Experiment

As seen in the figures above, there is a significant increase in added attenuation during the irradiation period. At each plotted wavelength, the increase appears to be linear during the irradiation period; however the slope of each wavelength is different, with lower wavelengths having a greater positive slope. Furthermore, there is an increase immediately when the reactor reaches 15 kW for each wavelength. In the gamma-only experiments, the added attenuation was negative in the presence of gamma irradiation and appeared to decrease the optical attenuation as a function of total gamma radiation dose. In this case, the steady state mixed radiation field (major components being neutron and gamma irradiation, but with other types present at lower levels) at cryogenic
temperatures appears to increase the added attenuation as a function of mixed field total radiation dose.

In order to distinguish further between the effects of the different types of radiation, it is informative to observe the section of the figure from immediately after the reactor shutdown to the right side of the plot. In this region we can see that there is a nearly immediate decrease in added attenuation, when the reactor is shut down. All of the wavelengths decreased in value upon reactor shutdown. The added attenuation for 500 nm light decreased to ~1 dB/m and the added attenuation at other wavelengths decreased to lower levels. This decrease began instantly upon shutdown, but appears to follow an exponential decrease toward a steady state value as the time increase to ~27 hours. At this point, the cryostat was moved and refilled with LHe. There was a noticeable increase immediately at ~27 hours causing all of the examined wavelengths to reach steady state at ~2 dB/m. This increase was likely because of the jostling of the optical leads and the CRIF while moving and refilling the CRIF Main Dewar with LHe. Then, we see the previous levels of added attenuation reached after the beginning of the heating portion of the experiment.

After the exponential decrease, near 27 hours, and once the lower attenuation state was reached after the heating portion of the experiment began, it is obvious that at wavelengths close to 500 nm there is still some added attenuation, on the order of ~1 dB/m. This would indicate permanent, or “locked-in” damage. This is likely from the creation of new defects. These defects are most likely caused by neutron damage within the optical fiber. Interestingly, even as time increases toward the right-hand side of the
plot, there is not a noticeable change in the added attenuation at these wavelengths. This suggests that the damage did not anneal during the heating portion of the experiment, nor after being left at room temperatures for an extended period of time.

In order to fully understand this behavior, a longer irradiation period or higher reactor power level, with more neutron induced defects generated for a larger overall neutron fluence, is likely necessary.

Other wavelengths were also examined in greater detail for these reactor-on cryogenic irradiation optical attenuation experiments. Below in Figure 115 and Figure 116 are the plots for added attenuation vs. time for multiple wavelengths: 1000nm, 1100 nm, 1200 nm, 1300 nm, and 1400 nm.

Figure 115: Plot of Added Attenuation and Reactor Power Level vs. Time for 1000 nm, 1100 nm, 1200 nm, 1300 nm, & 1400 nm Light During the Reactor-on Irradiation Optical Attenuation Experiment
As seen in the figures above there is a slight increase in added attenuation during the reactor irradiation portion of the experiment for 1000 nm, 1100 nm, and 1200 nm, but no observable change for 1300 nm or 1400 nm. The increase in this wavelength region from 1000 nm to 1200 nm could be due to increased defects in these wavelength regions, or could be a low level tail from the lower wavelength defects that were previously discussed. Here at all five wavelengths, there is an increase when the cryostat was moved and refilled with LHe. Again, this added attenuation is not due to the generation of new defects, but likely due to strain on the lead-in and lead-out wires during this moving and re-filling process, and the measured values return back to nearly 0 dB/m after the beginning of the heating portion of the experiment.
Again 1550 nm is a wavelength of particular importance and was examined more thoroughly for the duration of the experiment. Below in Figure 117 and Figure 118 are plots for the added attenuation for 1550 nm light vs. time, for the duration of the experiment, plotted along with the reactor power level and with the Cernox RTD measured temperature, respectively.

**Figure 117: Plot of Added Attenuation and Reactor Power Level vs. Time for 1550 nm Light During the Reactor-on Cryogenic Irradiation Optical Attenuation Experiment**
In both of the plots, there is very little added attenuation (<0.1 dB/m) of 1550 nm light throughout the duration of the experiment, including all cooling, heating, and irradiation portions of the experiment. This indicates that silica optical fiber does not have defects created during cryogenic irradiation that are optically active at 1550 nm. Furthermore, at least for radiation dose rate and dose levels comparable to those seen in these experiments, 1550 nm light in single-mode (demonstrated above in the reactor-on cryogenic irradiation OBR experiments) and multi-mode silica is an effective communication medium that will survive the extreme combined conditions of cryogenic irradiation in a mixed field. However, it should be noted that the single-mode silica fiber demonstrated noticeable changes in average reflected amplitude for 1550 nm light,
whereas the optical transmission experiment measured no noticeable change in added attenuation for 1550 nm light. Therefore, although the single-mode silica still worked with the OBR as a method for deducing the spectral shift, there was a noticeable change in the reflected amplitude, which could cause failure at higher total dose. The multi-mode fiber indicates no such failure mode as a function of total dose.

Finally, the highest wavelengths were also examined in further detail for the duration of the experiment. Seen below in Figure 119 and Figure 120 are the plots for added attenuation vs. time along with the reactor power level and the Cernox RTD temperature, respectively, for five wavelengths: 1600 nm, 1700 nm, 1800 nm, 1900 nm, and 2000 nm.

Figure 119: Plot of Added Attenuation and Reactor Power Level vs. Time for Multiple Wavelengths for 1600 nm, 1700 nm, 1800 nm, 1900 nm, & 2000 nm Light During the Reactor-on Irradiation Optical Attenuation Experiment
As seen in both figures, there is a slight increase to ~0.75 dB/m and subsequent decrease back to 0 dB/m during the LHe cooling portion of the experiment. Furthermore, similar behavior to the other wavelengths is seen during the moving and LHe refill portion of the experiment. Here there is an increase at all five wavelengths, which decreases back to 0 dB/m after the beginning of the heating portion of the experiment. At these higher wavelengths, there is no change in added attenuation during the cryogenic irradiation portion of the experiment, which indicates that there is no change in optical transmission as a function of the mixed field radiation dose rate or total dose. Therefore, these higher wavelengths, similar to the 1550 nm, may be functional for communicating optical signals under the combined extreme conditions of cryogenic irradiation.
During these reactor-on cryogenic irradiation experiments optical transmission experiments, the multi-mode silica optical fibers were subjected to a mixed radiation field at or near 4.2 K for a total gamma dose of 791.0 krad (in tissue) and a total radiation displacement damage dose of 54.3 krad(Si). The optical fibers demonstrated stable operation with negligible added attenuation at higher wavelengths and specifically at or near 1550 nm. However there was significant added attenuation at wavelengths <1000 nm, increasing as the wavelength decreased toward 500 nm. This behavior could have a tail that causes low levels of optical attenuation towards higher wavelengths and at higher dose rates or higher total dose could potentially be detrimental to the functionality of sending optical signals at higher wavelengths. This added attenuation at lower wavelengths is likely due to breaking bonds within the silica structure leading to SiO and OH formations that are optically active within the lower wavelengths regions.

7.6.3. **Reactor-On Cryogenic Irradiation Transistor Results**

The reactor-on cryogenic irradiation GaN transistor experiment followed the experimental procedures previously described. The NI PXI integrated electronics measurement system again recorded experimental data throughout the duration of the experiment. As in the gamma-only cryogenic irradiation experiment, the NI PXI system was wired to the gate and source and the current was measured for an applied voltage over the range of -4 V to +3 V. However, in this experiment, 20 data points were taken across the applied voltage range, instead of the fewer 10. Typical I-V curves for multiple times (corresponding to increased total radiation displacement dose) during the
irradiation portion of the reactor-on cryogenic irradiation GaN experiment can be seen below in Figure 121.

![I-V Curve for GaN Transistor 1](image)

**Figure 121:** Plot of Current vs. Voltage for Multiple Times (and Multiple Total Accumulated Dose Levels) During the Irradiation Portion of the Reactor-on Cryogenic Irradiation GaN Transistor Experiment

The I-V curves for the many data points during this experiment were fit to Equation 21, using the same procedure previously described for the data processing in the gamma-only cryogenic irradiation experiment, to find the saturation current, \( I_s \) and the uncorrected ideality factor, \( n' \). The fit values for the saturation current throughout the duration of the experiment can be found below, in Figure 122, plotted with the Cernox RTD temperature vs. time.
As seen in the figure above, the saturation current begins in the first few minutes at low values ~5E-8 A at room temperature and then increases quickly during the LN2 cooling portion of the experiment to a period of roughly steady operation at ~ 3E-7 A during the steady state LN2 period. Next, the current drops precipitously during the LHe cooling down period of the experiment back to ~1E-7 A. Then, during the reactor-on cryogenic irradiation portion of the experiment, the saturation current increases linearly back to ~3E-7 A. Finally, when the heating portion of the experiment begins, there is a sharp increase in the saturation current up to 1E-6 A, and then a slow decrease during the heating portion of the experiment. Finally, the decrease continues until a roughly steady state period is reached after ~40 hours, at nearly the same average value for the saturation
current as found in the beginning of the experiment (also at room temperature). This roughly steady state portion from ~40 hours until the end of the experiment at ~240 hours shows a seemingly sinusoidal increase and decrease centered around an average value of ~5E-8 A. This noise may be cyclical noise that is carried on the power supply outlets available at the reactor pooltop.

In order to investigate the irradiation period of the experiment in further detail, the same data was plotted in the same way, but with an expanded time scale for only the time range near the irradiation portion of the experiment. This data was plotted along with the reactor power vs. time in Figure 123, and plotted with the Cernox RTD temperature vs. time in Figure 124.

![GaN Transistor 1 Saturation Current and Reactor Power Level vs. Time](image)

**Figure 123: Zoomed-In Plot of the Saturation Current and Reactor Power Level vs. Time During the Irradiation Portion of the Reactor-on Cryogenic Irradiation GaN Transistor Experiment**
As seen in the two plots above, there is linear increase in the saturation current during the irradiation period. This linear increase was similar to the effects seen in the gamma-only cryogenic irradiation experiment, despite the fact that the dose rate was constant in this experiment and included neutrons, instead of gamma-only radiation that was decreasing exponentially in dose rate. Interestingly, also similar to the gamma-only experiments, upon the commencement of heating the experimental volume, there was a sharp increase in saturation current during the heating period until about 27.5 hours, corresponding to a temperature of ~ 75 K. This again may indicate the release of trapped charge as the thermal energy of the GaN HEMTs was increased. Then, again like the gamma-only
experiments, as the temperature was continually increased, the saturation current again decreased toward a steady state value.

In order to better quantify the increase in saturation current vs. time during the irradiation portion of the reactor-on cryogenic irradiation experiment, the calculated saturation was fit for a straight line and the slope was determined. This saturation current data will be used to compare the effects of cryogenic mixed field irradiation to the same mixed field radiation dose rate and total dose for room temperature irradiations in section 7.7.3. The linear fit for the saturation current vs. time for the irradiation portion of the reactor-on cryogenic irradiation experiment can be seen below in Figure 125.

![Figure 125: Linear Fit for the Saturation Current vs. Time During the Irradiation Portion of the Reactor-on Cryogenic Irradiation GaN Transistor Experiment](image)
Finally, the heating portion of the curve was plotted along with the Cernox RTD Temperature as a function of time and can be seen below in Figure 126.

![GaN Transistor 1 Saturation Current vs. Time](image_url)

**Figure 126: Zoomed-In Plot of the Saturation Current and Cernox RTD Measured Temperature vs. Time During the Heating Portion of the Reactor-on Cryogenic Irradiation GaN Transistor Experiment**

As seen in the figure above, the saturation current continues to decrease throughout the heating portion of the experiment until reaching steady state when the temperature reached ~250 K, at ~27 hours. For all times after ~27 hours, the saturation current was roughly steady at ~1E-7 A. These results again confirmed the value of such a facility. Had the transistor I-V curves not been taken in situ during the cooling portion of the experiment, during the cryogenic irradiation portion of the experiment, and during the heating portion of the experiment, many of the effects of cryogenic irradiation and low temperature annealing in these GaN HEMTs would have been lost.
In order to further understand the results of the $I_s$ fits, they were plotted along with the average measured current in the reverse bias direction below in Figure 127, along with the measured Cernox RTD temperature for the duration of the cryogenic irradiation and heating portions of the experiment.

![GaN Transistor 1 Saturation Current and Reverse Current vs. Time](image)

**Figure 127: Zoomed-In Plot of the Saturation Current, Reverse Bias Current, and Cernox RTD Measured Temperature vs. Time During the Cryogenic Irradiation and Heating Portions of the Reactor-on Cryogenic Irradiation GaN Transistor Experiment**

In the figure above, the measured current in the reverse bias direction is again higher than the fit values for the saturation current made in the forward bias direction, similar to the results of the gamma-only cryogenic irradiation experiment. Here we see that the general trend in the two currents is the same, there is an increase that begins upon the startup of the reactor to 15 kW. Both currents increase in a linear manner during the reactor
irradiation portion of the experiment. The fit saturation current then demonstrates behavior similar to trapped charge release at the beginning of the heating portion of the experiment (similar to the gamma-only cryogenic irradiation experiment), whereas the measured reverse current does not. Then, during the heating portion of the experiment, after ~28 hours (corresponding to ~ 75 K), both currents decrease with time. It appears that the current is affected by the cryogenic irradiation and that all of these effects are annealed out of the GaN HEMTs as the temperature is increased back to room temperature.

Similar plots were also made for the uncorrected ideality factor, n’. Below in Figure 128, the uncorrected ideality factor fits for each data set taken throughout the duration of the reactor-on cryogenic irradiation experiments is plotted along with the Cernox RTD temperature vs. time.

![GaN Transistor 1 Ideality Factor vs. Time](image)

**Figure 128**: Plot of Uncorrected Ideality Factor and Cernox RTD Measured Temperature vs. Time for the Duration of the Reactor-on Cryogenic Irradiation GaN Transistor Experiment
As seen in the figure above, the uncorrected ideality factor depends strongly upon the temperature. The ideality factors at 4 K (n’ = 650) and at room temperatures (n’ = 6.5) are similar to those from the gamma-only cryogenic irradiation experiments. In the figure the uncorrected ideality factor increases linearly during the cryogenic irradiation portion of the experiment. In order to investigate this linear increase further, the same uncorrected ideality factor data was plotted again but only for a time range near the cryogenic irradiation period of the experiment. This plot can be seen below in Figure 129 for the uncorrected ideality factor plotted with the Cernox RTD measured temperature vs. time, for a limited time range. The same data for the uncorrected ideality factor was plotted below again with the reactor power vs. time for the same time range, in Figure 130.
Figure 129: Zoomed-In Plot of Uncorrected Ideality Factor and Cernox RTD Measured Temperature vs. Time During the Irradiation Portion of the Reactor-on Cryogenic Irradiation GaN Transistor Experiment
In the figures above, the effects, on the uncorrected ideality factor, of temperature and cryogenic irradiation are again evident. As the temperature decreases to 4 K, there is a corresponding increase in the uncorrected ideality factor to ~650. Then, as the reactor was powered up to 15 kW, at ~19.4 hours, there is a corresponding slight increase in temperature to ~6 K, due to gamma heating, and a decrease in the uncorrected ideality factor to ~380. During the irradiation period, the temperature remains flat at ~6 K and the uncorrected ideality factor increases, seemingly linearly, to ~450. After the reactor was shut down and the CRIF was moved away, the uncorrected ideality factor increased again, but this time it went to a higher value, of ~680. The linear increase during the irradiation period and the resulting higher value of ~680 in uncorrected ideality factor
appears to be a total irradiation dose effect. Again, since the dose rate was constant at steady state reactor power, a linear change corresponds to a total dose effect. In this case, it appears that neutron induced defects may cause an overall increase in uncorrected ideality factor that remained after the CRIF was no longer in the radiation field. Next, the quick jump in temperature and corresponding dip in uncorrected ideality factor is evident at ~22 hours. This corresponded to the experimenters moving and refilling the CRIF with LHe. Therefore, this is likely an effect of jostling the lead-in and lead-out wires or possible transient temperature effects during the refill process. The ideality factor then stabilizes at a higher level again between ~22 and 22.5 hours. Finally, the heating portion of the experiment begins again and the uncorrected ideality factor drops back down precipitously.

In order to more fully understand the linear increase in the uncorrected ideality factor during the irradiation period, the uncorrected ideality factor data, during this time period, was fit to a line. This fit was done in the same manner as the previously described fit for the saturation current. Again, this fit will be used for comparison to the fit for the room temperature mixed field irradiation experiment of the same dose rate and total dose, in section 7.7.3. The plot of the fit for the uncorrected ideality factor as a function of time can be seen below in Figure 131.
In the figure above, we see that there is an increase in the linear fit for the uncorrected ideality factor from 380 to ~445 for a total neutron displacement dose equivalent in silicon of 54.3 krad(Si), during the 5 hour and 7 minutes irradiation at 6 K and at 15 kW reactor power.

Finally, the same ideality factor data was plotted again below with the Cernox RTD temperature vs. time, but for only the heating period of the experiment, in Figure 132.
In the figure above, the ideality factor again appears to have an negative exponential dependence with temperature, such that as the temperature increases from 4 K to 300 K, the ideality factor decreases exponentially. As seen before in the gamma-only cryogenic irradiation experiments, the uncorrected ideality factor decreases back to roughly the same initial value as observed before the cryogenic irradiation. This means that for the dose rates and total dose experienced in this experiment, the GaN HEMTs seem to recover the gate-to-source Schottky diode uncorrected ideality factor during low temperature annealing between 4 K and room temperature. The damage in this case is not “locked-in” and the mobility of defects is high enough as the temperature increases back to room temperature to anneal the material. This again demonstrates the valuable nature
of the CRIF as a research facility, since these cryogenic irradiation and low temperature annealing effects would not be observable without in situ measurement capabilities. The radiation induced defects at cryogenic temperatures are noticeable and could become catastrophic to the functionality of the GaN HEMTs if the total dose was increased while cryogenic temperatures were maintained. This could be particularly problematic in a space mission with a significantly higher total dose. However, for dose levels comparable to those in this experiment, the combined effects of cryogenic irradiation, although they cause a noticeable change in the uncorrected ideality factor, do not cause a failure of the gate-to-source diode action of the GaN HEMTs.

7.7. **Reactor-On Room Temperature Irradiation Experimental Results**

During the room temperature reactor irradiation experiments, there was no cryogen inside the CRIF. The purpose of this final experiment was to determine whether or not the radiation induced damage, seen in the reactor-on cryogenic experiments was greater than for analogous experiments completed at room temperature. The experiment was intended to replicate the same reactor irradiation period at the same reactor power level as the reactor-on cryogenic irradiation experiment. Therefore, in the room temperature experiments, the CRIF, still inside the 10” Dry Tube, had all of the materials still mounted in the same locations as in previous experiments and connected to the same data measurement and acquisition experiments. The CRIF experimental volume was still under vacuum conditions, with a small amount of inserted helium gas, during these experiments as well.
First, the data acquisition systems were started and data was collected without the presence of liquid cryogen or radiation. During the first ~one hour of the experiments, the CRIF, resting on the steel plates at the bottom of the 10” Dry Tube was moved into place beside the reactor core and the reactor was again brought up to 15 kW power. At this point, the reactor was continuously operated at steady state at 15 kW for 5 hours and 7 minutes before the reactor was shut down. Once the control rods were fully inserted into the OSURR core, the CRIF and 10” Dry Tube were moved away from the OSURR core and data was continually taken for ~one more hour. During all of these experiments, the temperature was still monitored by the Cernox RTDs and recorded by the Lakeshore 335 Temperature Controller. The temperature was monitored so that heating within the experimental volume could be monitored. Although there was no cryogen inside the CRIF, room temperature was not precisely maintained. Without a cold bath, the inner experimental volume underwent a slow increase in temperature during the reactor irradiation portion of the experiment, from ~295 K to ~301 K. The temperature measured by the Cernox RTDs can be seen below in Figure 133, plotted along with the reactor power level, as a function of time.
As is seen above, the Cernox RTD temperature increased as soon as the reactor was turned on, due to radiation-induced (mostly gamma-induced) heating of the structural materials inside the CRIF experimental volume. However, the maximum temperature achieved was only ~6 K higher than the room temperature starting point. For the sake of these experiments, this limited amount of radiation induced heating is negligible, and the experiments will be considered performed at constant room temperature.

7.7.1 Reactor-On Room Temperature Irradiation OBR Results

The reactor-on room temperature irradiation experiments using the OBR followed the previously described procedures. In this case an “apples to apples” comparison was
desired to understand the functionality of the OBR spectral shift sensing feature with single-mode silica optical fiber for the same radiation period and at the same reactor power as the reactor-on cryogenic irradiation OBR experiment. Data was taken approximately every minute using the Luna OBR. The data collected was then processed for spectral shift, like in the cryogenic materials characterization experiments. Again, the silica single-mode optical fiber length range of 16 m to 20 m was investigated and reprocessed. Also, the average reflected light amplitude of the optical fiber for a 15 cm section (17.8 m – 17.95 m) within the experimental volume of the CRIF was again examined for the duration of the experiment. The spectral shift and the average reflected amplitude for data within the experimental volume of the CRIF are considered below. Plots of the OBR reprocessing spectral shift data at three optical fiber lengths inside the CRIF experimental volume, corresponding to 17.85 m, 17.9 m and 17.95 m, and the Cernox RTD temperature profile of the experiment plotted vs. time can be seen below in Figure 134. The same spectral shift data can be seen again below in Figure 135, plotted along with the reactor power level of the experiment vs. time.
Figure 134: Plot of OBR Spectral Shift and Cernox RTD Temperature vs. Time for Multiple Fiber Lengths (17.85 m, 17.9 m, & 17.95 m) Within the Experimental Volume of the CRIF During the Room Temperature Reactor Irradiation OBR Experiments
As seen in the figure above, the spectral shift follows the increase in temperature due to gamma heating. There appears to be noise throughout the duration of the experiment, but there are only two times when the OBR appears to lose functionality (ability to measure a reasonable spectral shift). First, the signal is extremely noisy on the left hand side of the figure, which corresponds to the beginning of the experiment when the CRIF was being set in place at the bottom of the 10” Dry Tube and the CRIF inside of the 10” Dry Tube was being moved beside the reactor core. Second, the signal is extremely noisy a few minutes after the irradiation period, when the CRIF and 10” Dry
Tube were moved away from the reactor core. These noisy measurements are likely due to strain on the lead-in optical fibers.

Again, the average amplitude of the reflected signal for the same 15 cm length of optical fiber, from 17.8 m to 17.95 m, as the cryogenic materials characterization experiment, gamma-only cryogenic irradiation experiment, and the reactor-on cryogenic irradiation experiment, inside the experimental volume of the CRIF was examined. The light amplitude reflected from each point was averaged to produce an average reflected optical amplitude over the region. This average reflected optical amplitude vs. time can be seen plotted below along with the reactor power level vs. time, in Figure 136.

![Average Backscatter Amplitude and Reactor Power Level vs. Time](image)

**Figure 136:** Plot of Average Backscatter Amplitude and Reactor Power Level vs. Time for a 15 cm Section of Fiber (17.8 m – 17.95 m) Inside the Experimental Volume of the CRIF During the Room Temperature Reactor Irradiation OBR Experiment
As seen in the figure above, the reactor operation period does cause a decrease in the average reflected amplitude from the optical fiber in the experimental volume of the CRIF. However, this decrease is only on the order of ~0.25 dB which is still quite low. As discussed previously, the reactor irradiation at room temperature did not cause the spectral shift measurement to fail. However, the results of the figure above indicate that if irradiated for long enough at room temperatures at 15 kW or during a room temperature irradiation at higher reactor powers (higher damage dose levels) there may eventually be a failure of the spectral shift sensing of the OBR in a single-mode silica optical fiber using 1550 nm light as the reflected signal decreases with mixed field radiation dose. Furthermore, these results demonstrate a much lower degradation in the average reflected amplitude than the reactor-on cryogenic irradiation experiments for the same reactor power and irradiation duration (same total radiation dose). The average reflected amplitude decrease is actually a rather convoluted measurement, since the attenuation in the optical signal could happen as the light travels down the optical fiber on its way to the 15 cm length under consideration or after reflection, on the way back to the OBR. Additionally, more light could simply pass through the irradiated region, if scattering centers, that are optically active for 1550 nm light were destroyed via cryogenic irradiation. The effects of cryogenic irradiation were much more pronounced than the effects of room temperature irradiation in the mixed field of the OSURR, resulting in a 1.5 dB decrease compared to a 0.25 dB decrease in reflected amplitude.
7.7.2. Reactor-On Room Temperature Irradiation Optical Fiber Transmission

Results

The room temperature reactor-on optical transmission radiation experiments followed the experimental procedures previously described. The optical transmission system again recorded experimental data throughout the duration of the experiment and the added attenuation was calculated across a broad spectral range, 500 nm to 2000 nm. The experimental data for this experiment can be found below in Figure 137, plotted as added attenuation vs. wavelength for multiple times during the irradiation period of the experiment.

![Figure 137: Plot of Added Attenuation and vs. Wavelength for Multiple Times During the Room Temperature Reactor Irradiation Optical Attenuation Experiment](image)

Added Attenuation vs. Wavelength for Multiple Times

- Att vs Wavelength at 1 hrs
- Att vs Wavelength at 2 hrs
- Att vs Wavelength at 3 hrs
- Att vs Wavelength at 4 hrs
- Att vs Wavelength at 5 hrs
Overall, the maximum change in added attenuation across the measured wavelength region was extremely small (less than +/-1 dB/m at almost all wavelengths).

Unfortunately, during these experiments, the black spectrometer was acquiring so much light, that it was saturated. The data acquisition system allows the user to decrease the integration time (also known as the light collection period), which is usually a valid way to ensure that the full peak shape of the light source in the measurement range is acquired. However, in this case, even with very short integration times, the peak was still cutoff in the range of ~560 nm to 895 nm. Although radiation is expected to increase the attenuation through the optical fiber, the room temperature reactor-on optical transmission experiment did not induce enough optical attenuation to cause a noticeable change in the measured signal. At all times during the experiment, the black spectrometer was saturated in this range, and therefore there was no discernable change in this wavelength range (560 nm to 895 nm). This lost data range can be seen in the figure above as the flat region between 560 nm and 895 nm with breaks in the measured data.

At all of the other wavelengths, the measured added attenuation was very limited, indicating very limited radiation induced or activated defects throughout the measured optical range. The saturation issues that were previously discussed make it impossible to definitively say that there was no change in added attenuation in the range of 560 nm to 895 nm. However, at all other points within the plot, the added attenuation is very limited. The only portion of the figure that shows any trend with time, during the irradiation period is in the very low wavelength region of ~500 nm - ~540 nm. This data can be seen in greater detail in Figure 138 below, where the added attenuation is plotted
along with the reactor power level vs. time for multiple wavelengths from 500 nm to 540 nm.

![Figure 138: Plot of Added Attenuation and Cernox RTD Temperature vs. Time for 1550 nm During the Gamma-Only Irradiation Optical Attenuation Experiment](image)

As seen in the figure above, there is an immediate increase in the added attenuation, to ~ 0.5 dB/m in the 500 nm, 510 nm, and 520 nm optical signal. Although this signal is very small, it was observed across all three of these low wavelengths and an immediate jump with reactor power indicates a dose rate effect. Likely this indicates that there are defects that are optically active in this range and the gamma dose rate of 154.6 krad/hr at 15 kW is enough to populate these defects. Then, there is a gradual increase in the added attenuation across the 500 nm to 540 nm optical signals. After ~ 4.5 hours, the highest wavelength, 540 nm, optical signal also increases in optical attenuation. In the 500 nm, 510 nm, and 520 nm optical signals, the added attenuation appears to increase linearly,
which for the constant gamma and neutron dose rates in the experiment would indicate a
cumulative dose effect from the gamma irradiation and/or neutron irradiation. As
discussed previously, the work by David Hawn indicated that neutron induced defects
build up over time within a multi-mode silica optical fiber. These are directly
proportional to the reactor power, since the neutron flux scales linearly with reactor
power. In this case, the data indicates that at a steady state reactor power, the neutrons
cause a linear buildup of defects that are optically active for optical signals near 500 nm.
Unfortunately, the 520 nm, 530 nm, and 540 nm optical signals demonstrate a seemingly
sinusoidal noise behavior. This noise may be due to cyclical noise carried over the
electrical power lines in the OSU NRL building or due to other variations in the
transmission measurement system. These measured optical signals still demonstrate an
increase with radiation dose, but it is not as obviously linear as for the lower two
wavelengths. In all cases, the added attenuation dropped immediately after the reactor
was shut down. After shutdown, the neutron flux decreases in the first few seconds to
~0.001 of the steady state neutron flux and then falls of exponentially following six
exponential decay groups. The gamma dose falls off exponentially during this period as
well. The data shows a nearly immediate decrease in added attenuation upon reactor
shutdown, but not to the original added attenuation values of zero. Instead it appears that
the added attenuation floor has increased permanently due to neutron irradiation-induced
defects. The immediate drop is likely due to quick decrease in the gamma irradiation dose
and the depopulation of optically active defects at ~500 nm. As previously discussed,
these low wavelength optically active defects could come from many sources. When the
reactor was shut down and the gamma dose rate dropped exponentially, the optical fiber recovers a lower added attenuation signal. However, they do not return to the original added attenuation level and do not appear to decrease toward that original level (added attenuation = zero) following the exponential decay of the reactor shut down field. Instead they appear to maintain a constant level at ~0.3 dB/m, which would indicate that there are new long-term stable defects caused by the neutron irradiation. This new constant level for post-irradiation added attenuation is much lower than that observed in the reactor-on cryogenic irradiation experiment (~1 dB/m). Similar to the discussion for the differences between the two reactor irradiation experiments with the OBR, it is therefore obvious that cryogenic mixed field reactor irradiation causes more defects in the low wavelength region near 500 nm than room temperature mixed field reactor irradiation for the same total dose. Moreover, the cryogenic irradiations cause a greater number of defects to be generated and “locked-in” than comparable room temp irradiation. In the cryogenic irradiation experiment, the added attenuation decreased again to a lower steady state value, still slightly above the original scan value, (i.e. greater than 0 dB/m, around 0.5 dB/m) during the heating portion of the experiment. This is again important because it signifies that there is low temperature annealing happening between 4.2 K and room temperature. Therefore, the CRIF is a particularly useful and unique facility because it can measure the added attenuation in an optical fiber in situ during the irradiation period and post-irradiation, during the heating portion of the experiment. Without such capability, the experimenters may assume that the defects generated during
the cryogenic irradiation were commensurate with the defects observed after the fiber was warmed back to room temperature.

Despite the indication of neutron induced damage for defects that are optically active at very low wavelengths near 500 nm, the overall attenuation across the measured wavelength range is very limited. Again, 1550 nm light was examined in further detail due to its relevance to the telecommunications industry and because of its relevance to the OBR experiments. The added attenuation for a 1550 nm optical signal can be seen below in Figure 139 plotted as a function of time, along with the reactor power level for the duration of the experiment.

![Figure 139: Plot of Added Attenuation and Cernox RTD Temperature vs. Time for 1550 nm Light](image)

As expected in the figure above, the added attenuation is nearly flat for duration of the experiment for the 1550 nm optical signal. There is very little change in the signal and
there is no obvious added attenuation of 1550 nm light due to reactor irradiation at room
temperature. This indicates that the optical fiber would likely survive similar levels of
radiation dose for much longer periods of time and that multi-mode silica optical fibers
would be useful as a communication medium in mixed radiation fields. This is not
surprising since the 1550 nm optical signals demonstrated negligible added attenuation in
all of the previous experiments in this dissertation. However, again the difference
between the results from the single-mode silica OBR experiment and the multi-mode
optical attenuation experiment for the same irradiation conditions should be noted.
Specifically, the OBR, which is a more sensitive measurement system did indicate a
change in the average reflected amplitude of the 1550 nm optical signal, whereas the
optical attenuation system recorded no noticeable change in the added attenuation.

Taken together, the results of this room temperature irradiation experiment show
that the overall added attenuation at room temperature appears to be significantly less
than for the same irradiation period and similar dose rates at cryogenic temperatures.
However, due to the saturation of part of the black spectrometer spectral range, we cannot
draw definitive conclusions about the added attenuation in the wavelength region of 560
nm to 895 nm. There is a slight change in added attenuation in the very low wavelength
regions near 500 nm; however the increased optical attenuation is still very low and on
the order of the noise range for other optical wavelengths. Finally, 1550 nm light shows
great promise as a wavelength with no obvious radiation defect-induced or radiation
populated scattering center.
7.7.3. **Reactor-On Room Temperature Irradiation Transistor Results**

The reactor-on room temperature irradiation GaN transistor experiment followed the experimental procedures previously described. The NI PXI integrated electronics measurement system again recorded experimental data throughout the duration of the experiment. As in the reactor-on cryogenic irradiation experiment, the NI PXI system wired to the gate and source and the current was measured for an applied voltage across the range of -4 V to +3 V, collecting 20 data points across the applied voltage range. Typical I-V curves for multiple times, corresponding to: before irradiation (10 minutes), during irradiation for increased total radiation displacement dose (2, 4, & 6 hours), and post-irradiation (6 hours and 10 minutes) during the GaN experiment can be seen below in Figure 140.

![I-V Curve for GaN Transistor 1](image)

**Figure 140:** Plot of Current vs. Voltage for Multiple Times (and Multiple Total Accumulated Dose Levels) During the Irradiation Portion of the Reactor-on Room Temperature Irradiation GaN Transistor Experiment
In the figure above, there is a noticeable change in diode behavior in GaN HEMTs under forward bias as a function of radiation. The diode seems to turn on more strongly as a function of time, and therefore of radiation dose, measuring a slightly higher current for a given voltage.

In order to investigate the forward bias behavior of the diode the data was again fit to the modified diode equation (Equation 21) to find fits for the saturation current and the uncorrected ideality factor. The fit values for the saturation current throughout the duration of the experiment can be found below, in Figure 141, plotted with the Cernox RTD temperature vs. time.

![GaN Transistor 2 Saturation Current vs. Time](image)

**Figure 141**: Plot of Saturation Current and Cernox RTD Measured Temperature vs. Time for the Duration of the Reactor-on Room Temperature Irradiation GaN Transistor Experiment
Although the entire experiment was considered to be at room temperature, it is obvious that there was an increase in temperature from ~295 K to ~301 K during the experiment due to gamma heating, because the diode could not be kept at room temperature without a cold source. As seen in the figure above, the saturation current begins in the first few minutes at low values of ~1E-8 A, and then increases during the reactor-on cryogenic irradiation portion of the experiment to an average saturation current of ~3E-8 A and then remains steady for the last ~1 hour of the experiment after being removed from the radiation field. This seemingly linear increase was similar to the effects seen in the reactor-on cryogenic irradiation experiment.

In order to better quantify the increase in saturation current vs. time during the irradiation portion of the reactor-on cryogenic irradiation experiment, the calculated saturation current was fit for a straight line and the slope was determined. The linear fit for the saturation current vs. time for the irradiation portion of the reactor-on cryogenic irradiation experiment can be seen below in Figure 142.
Similar plots were also made for the uncorrected ideality factor, $n'$. Below in Figure 143, the fit value for the uncorrected ideality factor ($n'$) for each data set taken throughout the duration of the reactor-on cryogenic irradiation experiments is plotted along with the Cernox RTD temperature vs. time.
As seen in the figure above, the uncorrected ideality factor also increases slightly from the beginning of the irradiation period to the end of the irradiation period. The fit values for the uncorrected ideality factor show quite a bit of noise, which may be due to the noise limitations of the measurement system.

In order to more fully understand the increase in the uncorrected ideality factor during the irradiation period, the uncorrected ideality factor data, during this time period, was fit to a line. This fit was done in the same manner as the previously described fit for
the saturation current. The plot of the fit for the uncorrected ideality factor as a function of time can be seen below in Figure 144.

![GaN Transistor 2 Ideality Factor vs. Time](image)

**Figure 144: Linear Fit for the Uncorrected Ideality Factor vs. Time During the Irradiation Portion of the Reactor-on Cryogenic Irradiation GaN Transistor Experiment**

In the figure above, we see that there is an increase in the linear fit for the uncorrected ideality factor from ~ 5.6 to ~ 5.8 for a total neutron displacement dose equivalent in silicon of 54.3 krad(Si), during the 5 hour and 7 minutes irradiation at room temperature and at 15 kW reactor power. Interestingly, the fit values for the uncorrected ideality factor during the beginning of this experiment were the lowest values calculated across all three irradiation experiments (5.6 instead of 6.5 in the gamma-only and reactor-on
cryogenic irradiation experiments). Even with the increase in the figure above, the uncorrected ideality factor is less than previously calculated values at room temperature.

For both the saturation current and the uncorrected ideality factor, there were changes observed as a function of the mixed field radiation dose. However, in both cases, the effects were more limited than the effects for cryogenic irradiation at the same dose levels. Specifically, the saturation current was increased by 7.5E-8 A for the cryogenic reactor-on irradiation and by 1.8E-8 A for the room temperature reactor-on irradiation. Analogously, the uncorrected ideality factor increased by 65 for the cryogenic reactor-on irradiation and by 0.2 for the room temperature reactor-on irradiation. As was seen in the previously discussed data for the reactor-on cryogenic irradiation experiment, the uncorrected ideality factor is exponentially related to the temperature of the measurement. Therefore, it is difficult to compare the change in the diode uncorrected ideality factor fits as a function of radiation dose. However, we can compare the values more directly by examining the change in uncorrected ideality factor as a percentage of the un-irradiated uncorrected ideality factor. In this case, if we take the differences previously discussed (65 and 0.2 respectively) and divide them by the un-irradiated values for the uncorrected ideality factor (380 and 5.6 respectively), the percent change for the reactor-on cryogenic irradiation experiments was 17.1% and the percent change for the reactor-on room temperature was 3.57%. This further demonstrates the higher level of effects seen in the cryogenic irradiation GaN HEMT experiment vs. the room temperature irradiation GaN HEMT experiment. These results further illustrate the value
of the CRIF and the in situ measurement capabilities, when trying to understand the effects of cryogenic irradiation and low temperature annealing.
Chapter 8: Conclusions and Future Work

The CRIF has been designed and tested for temperature control to above room temperature from a base temperature of 4.2 K using LHe as a cryogen. Additionally, the CRIF has been tested and demonstrated to support similar experiments from 77 K to above room temperature using LN2 as a cryogen. The Empty 10” Dry Tube and the CRIF were simulated using MCNP6. The results estimate that the reactor can operate for up to 6.66 hours at a reactor power of 15 kW and a total neutron fast flux of $4.05 \times 10^{10}$ neutrons/(cm$^2$-s) in the experimental volume of the CRIF, before total LHe boil-off occurs. The LHe filled CRIF was operated for 5 hours and 7 minutes during a cryogenic irradiation experiment with the OSURR operating at steady state power of 15 kW. It was estimated that 30% to 40% of the LHe remained after the irradiation period, indicating that the CRIF could operate for a longer period of time than the successful 5 hour and 7 minute operation and likely longer than the conservatively estimated (using the MCNP6 model results) irradiation period of 6.66 hours. Additionally the increase in operational temperature in the experimental volume of the CRIF was to a maximum of ~ 6 K, allowing for continuous operation at very low temperatures near the boiling temperature of LHe (4.2 K).

The MCNP6 results were compared to the experimental results of another graduate student who completed foil activation experiments to confirm the neutron energy flux profile in the empty 10” Dry Tube. Additionally, the MCNP6 empty 10” Dry
Tube simulation results of the neutron total flux axial profile and the gamma field were compared to the results from axial activation experiments and a gamma dose measurement made with a magnesium walled ion chamber. The neutron energy flux in the experimental volume of the CRIF was converted to radiation displacement dose rate in silicon for easier comparison to other experiments completed in electronic materials.

Finally, the CRIF was used for four sets of experiments. The CRIF supported cryogenic materials characterization experiments for OBR supported single-mode silica optical fibers, multi-mode silica optical fiber transmission, and GaN HEMT Schottky diode behavior across the gate and source contacts.

**Experiments at Cryogenic Temperatures Without Radiation**

During the experiments made at cryogenic temperatures without radiation, the OBR measured a steady state spectral shift during the portions of the experiment with steady state temperature. It measured a time dependent spectral shift during the cooling down and heating periods of the experiments that indicates operability down to cryogenic temperatures. Additionally, there was no observable change in the average reflected amplitude of the optical signal as a function of temperature in the fiber section held within the experimental volume of the CRIF. There was also no observable change in the optical transmission through the range of temperatures measured (4 K to 300 K).

The GaN HEMTs were first thermal shock tested by dipping them directly into LN2 and/or LHe without any precooling to confirm that the devices, the packaging, and the mounts could survive thermal cycling quickly to 77 K and/or 4 K from room temperature. After they were demonstrated to survive the thermal shock tests, the devices
were tested, along with the previously described optical fibers. There was an observable change in the reverse current of the GaN HEMTs, but the forward bias I-V measurements did not contain enough data points to fit the modified diode equation.

**Gamma-Only Cryogenic Irradiation Experiments**

The same materials and data acquisition systems were then used to complete gamma-only cryogenic irradiation experiments in the reactor shutdown field, which was an exponentially decreasing gamma-only dose rate source. During these experiments, the OBR continued to consistently measure the same spectral shift in the experimental volume, corresponding to cryogenic temperatures, despite the presence of the gamma-only radiation. The OBR also measured negligible change in average reflected optical amplitude for the fiber section within the experimental volume of the CRIF. The optical transmission measurement system measured no change in the higher wavelength regions, especially around 1550 nm. However, it measured an improvement in the optical transmission at lower wavelengths between, 500 nm and 1000 nm, appearing to be a function of radiation dose rate and/or total accumulated dose. This improvement was up to a maximum of ~17.5 dB/m (near 500 nm) in negative added attenuation (positive optical transmission). This behavior may be linked to ionization of optically active defects within this region. The change in the optical fiber attenuation in this low wavelength region then remained constant after the CRIF experimental volume was heated back to room temperature, suggesting that this improvement may be permanent.

Finally, the GaN HEMTs were analyzed by fitting the I-V curves to the modified Schottky diode equation for the saturation current and the uncorrected ideality factor for
each set of data throughout the duration of the experiments. The saturation current
decreased linearly during the cryogenic irradiation portion of the experiment from about
7.5E-7 A to about 2.5E-7 A, and then increased briefly during the beginning of the
heating portion of the experiment, before returning to a steady state value of ~2.5E-7 A.
This may indicate trapped charge building up during the irradiation period and being
released after warming from 4 K to the temperature range near 75 K. The uncorrected
ideality factor demonstrated a strong dependence upon temperature and appeared to fit a
negative exponential dependence, such that as the temperature increased from 4 K to 300
K, the uncorrected ideality factor decreased exponentially. The uncorrected ideality factor
also demonstrated a dependence on the gamma dose rate, showing a decrease in the
presence of the gamma-only radiation and then a slow asymptotic increase back to the
original uncorrected ideality factor value (measured at 4 K before placing the CRIF in the
gamma-only reactor shutdown field) as the gamma-only radiation decreased to a
negligible value.

**Reactor-On Cryogenic Irradiation Experiments**

The same materials and data acquisition systems were then used to complete
reactor-on cryogenic irradiation experiments, which were conducted at steady state
operation at 15 kW for a displacement dose rate in silicon (equivalency) of 2.95 rad(Si)/s,
operating at CRIF experimental volume temperatures between 4 and 7 K. During these
experiments, the OBR continued to consistently measure the same spectral shift in the
experimental volume, corresponding to cryogenic temperatures, despite the mixed field
reactor irradiation. The OBR did measure a noticeable change in average reflected optical
amplitude (~ 1.5 dB decrease) for the fiber section within the experimental volume of the CRIF during the cryogenic irradiation period. The optical transmission measurement system again measured a negligible change in the higher wavelength regions, especially around 1550 nm. However, it measured an increase in the optical attenuation (~ 17.5 dB/m increase in optical attenuation maximum at ~500 nm) as a function of mixed field radiation total accumulated dose at lower wavelengths between 500 nm and 1000 nm. The change in the optical fiber attenuation in this low wavelength region decreased rapidly after the CRIF was removed from the radiation field, and decreased further during the beginning of the heating portion of the experiment. However, the optical attenuation in this lower wavelength region remained steady and at a higher value than before the experiment, suggesting that some of the optical attenuation is permanent and due to newly accumulated defects from the cryogenic irradiation. Overall the behavior of the lower wavelength region throughout the duration of the experiment is likely due to some combination of the generation of new defects, due to neutron-induced displacements, and activation/deactivation of optical defects due to gamma radiation ionization.

Finally, the GaN HEMTs were analyzed by fitting the I-V curves to the modified Schottky diode equation for the saturation current and the uncorrected ideality factor for each set of data throughout the duration of the experiments. The saturation current increased during the cryogenic irradiation portion of the experiment and then further increased briefly during the beginning of the heating portion of the experiment, before returning to a steady state value, similar to the gamma-only cryogenic irradiation experiments. The uncorrected ideality factor demonstrated a strong negative exponential
dependence upon temperature again. The uncorrected ideality factor also demonstrated a dependence on the total reactor mixed-field accumulated radiation dose, showing a linear increase during the cryogenic irradiation period. The effects of the reactor-on cryogenic irradiation seemed to go away as the temperature was increased back to 300 K, indicating that the effects were not permanent in the GaN HEMTs for this radiation dose.

**Reactor-On Room Temperature Experiments**

Finally, the same materials and data acquisition systems were used to complete reactor-on room temperature irradiation experiments, which were conducted at steady state operation at 15 kW for a displacement dose rate in silicon (equivalency) of 2.95 rad(Si)/s, operating at or near room temperature (minimum temperature of 294 K and maximum temperature of 301 K). During these experiments, the OBR measured a slight decrease in the spectral shift in the optical fiber within the experimental volume, corresponding to the slight increase in temperature within the CRIF experimental volume during mixed field reactor irradiation. The measurement of spectral shift again demonstrated no sign of failure, despite the presence of the mixed-field reactor irradiation at room temperature. The OBR did measure a noticeable change in average reflected optical amplitude (~ 0.25 dB decrease) for the fiber section within the experimental volume of the CRIF during the cryogenic irradiation period. This decrease in average reflected amplitude was less than that observed for the same total mixed field radiation dose (same reactor power of 15kW, irradiation period, and mixed field radiation dose rate) for the analogous experiment conducted at cryogenic temperatures. The optical transmission measurement system again measured a negligible change in the higher
wavelength regions, especially around 1550 nm. However, it measured an increase in the optical attenuation (~ 17.5 dB/m increase in optical attenuation maximum at ~500 nm) as a function of mixed field radiation total accumulated dose at lower wavelengths between 500 nm and 1000 nm. The change in the optical fiber attenuation in this low wavelength region decreased rapidly after the CRIF was removed from the radiation field. During this experiment, some of the lower wavelength region was unfortunately saturated in the black spectrometer, showing no change in optical signal throughout the experiment. However, the optical attenuation in the very low wavelength region near 500 nm demonstrated an added optical attenuation as a function of mixed field total accumulated radiation dose at a much lower level (~ 1 dB/m), than the analogous reactor-on cryogenic irradiation experiment.

The GaN HEMTs were again analyzed by fitting the I-V curves to the modified Schottky diode equation for the saturation current and the uncorrected ideality factor for each set of data throughout the duration of the experiments. The saturation current increased during the irradiation portion of the experiment, before returning to a steady state value, similar to the reactor-on cryogenic irradiation experiments. However, in this experiment, the increase in the saturation current was less than the increase in the analogous reactor-on cryogenic irradiation experiment. The uncorrected ideality factor also demonstrated a dependence on the total reactor mixed-field accumulated radiation dose, showing a linear increase during the irradiation period. In this case, the increase in the uncorrected ideality factor was much less than for the analogous reactor-on cryogenic
irradiation experiment in absolute terms and as a percentage change from the value calculated before the irradiation period.

In all of the experiments completed during the reactor-on cryogenic irradiation experiments and the reactor-on room temperature experiments, the cryogenic irradiations demonstrated a stronger dependence on the radiation dose rate or the radiation total accumulated dose. In some of the cryogenic experiments, the effects appeared to be “locked-in,” even after the low temperature annealing portion of the experiment. However, in other experiments the effects disappeared after the low temperature annealing. Taken together, the effects of cryogenic mixed field irradiation warrant further study. Some of the observed effects in optical (silica single-mode and multi-mode optical fiber) and electronic materials (GaN HEMTs) indicate that failure of the operation of a device could occur at either higher dose rates or higher total accumulated mixed-field radiation dose for experiments conducted at or near 4.2 K. These effects may be relevant for future space missions. The CRIF has unique capabilities that allow for the types of in situ measurements made herein. These in situ measurements are necessary, when trying to understand the combined effects of the harsh environments of low temperatures and high radiation dose and the effects of low temperature annealing.
Appendix A: MCNP6 code for empty 10" Dry Tube Simulations

The following code is an input deck for the MCNP6 SSW run, completed for the results presented herein. The code includes the model of the OSURR and the empty 10" Dry Tube. This is the first step of two, in which the radiation tracks generated from the OSURR core are transported to the 10" Dry Tube and recorded as they cross a surface of the 10" Dry Tube, using the Surface Source Write (SSW) mode of MCNP6.

Subsequently, a second run has been completed, using the generated output file for the SSW run as an input for the Surface Source Read simulation, which reads the recorded radiation tracks and uses them as a source for transporting the radiation into the 10" Dry Tube. In order to complete the second step, the SSW run must first be completed. Then the input deck, seen below, has to be changed to run in SSR mode. Instructions on this process can be found in the MCNP manual. Further, the detector tallies are not commented out in this code. They can be commented out to reduce the time required to complete the SSW run, but they must be used in the subsequent SSR run to simulate the radiation flux and energy deposition in the axial air detectors.
OSURR core model - 6/1/15

- model has CIF, PIF and AIF
- added 10" dry tube - 2/27/14 comment out, or remove if not in use
- Can't use both 7" and 10" tubes in code, because you can't use both in the reactor pool
- * Note: If the core cells are changed, make sure to update cell cards, transformation cards, and ksrc card****.

Cell cards

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- 012 0 032 -035 -043 imp:n=1 imp:p=1 $ Cell A5 - AIF ID
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- 018 3 -1.00 011 -012 022 -023 032 -035 044 imp:n=1 imp:p=1 $ - Water - AIF
- 013 0 011 -012 023 -024 032 -035 fill=1 (013) imp:n=1 imp:p=1 $ Cell A4 - fuel
- 014 0 011 -012 024 -025 032 -035 fill=1 (014) imp:n=1 imp:p=1 $ Cell A3 - fuel
- 015 0 011 -012 025 -026 032 -035 fill=1 (015) imp:n=1 imp:p=1 $ Cell A2 - fuel
- 016 3 -1.00 011 -012 026 -027 032 -035 imp:n=1 imp:p=1 $ Cell A1 - water

2nd column of core

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<td>015 -016 021 -022 032 -035 046 fill=1 (058) imp:n=1 imp:p=1</td>
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</table>

310
$ Core grid plate

$ BP1 plug

$ Rest of Beam Port 1

$ BP2 plug

$ Rest of Beam Port 2

10" Dry Tube Cells

10in Al Dry Tube Walls

10in Al Dry Tube Wall for SSW SSR (Lower Segment)

10in Al Dry Tube Wall for SSW SSR (Middle Segment)

10in Al Dry Tube Wall for SSW SSR (Upper Segment)

10in Al Dry Tube Bottom

10in Al Dry Tube Flange Connection

Water above 10in Al Dry Tube Flange Connection

Water below 10in Al Dry Tube Flange Connection

Steel Plates at Bottom of 10in Dry Tube

Steel Plates at Bottom of 10in Dry Tube for SSW SSR

Air above Cryostat for Empty Dry Tube

Air above Cryostat (Gap between Main Dewar and Top) for SSW SSR

Al Inside of Hard Flux Box Walls

Gaseous N2 Inside of Hard Flux Box

No 10in dry tube

South Reflector

West Reflector

Water below South Reflector
074 3 -1.00 010 060 027 -028 031 -032 imp:n=1 imp:p=1 $ Water below West Reflector
081 3 -1.00 010 -017 020 -028 030 -031 056 imp:n=1 imp:p=1 $ Water below core
082 3 -1.00 010 -017 020 -028 035 -036 042 044 046 056 imp:n=1 imp:p=1 $ Water above core
083 0 035 -036 -042 imp:n=1 imp:p=1 $ CIF void above core
084 0 035 -036 -044 imp:n=1 imp:p=1 $ AIF void above core
085 0 035 -036 -046 imp:n=1 imp:p=1 $ PIF void above core
086 3 -1.00 016 -017 020 -028 031 -035 -060 052 056 imp:n=1 imp:p=1 $ Water N of core
087 3 -1.00 011 -016 020 -021 031 -035 056 1300 imp:n=1 imp:p=1 $ Water E of core
088 3 -1.00 010 -011 020 -022 031 -035 -060 imp:n=1 imp:p=1 $ Water SE of core
091 5 -3.35 017 -018 020 -028 030 -036 051 052 imp:n=1 imp:p=1 $ Concrete wall
095 0 (-010:018:-020:028:-030:036) -099 imp:n=1 imp:p=1 $ Interior void
099 0 099 imp:n=0 imp:p=0 $ Exterior void

c Universe 1 cells - fuel cell

c 101 2 -2.70 101 -102 111 -129 131 -132 u=1 imp:n=1 imp:p=1 $ Left side plate
102 2 -2.70 103 -104 111 -129 131 -132 u=1 imp:n=1 imp:p=1 $ Right side plate
103 0 102 -103 111 -112 131 -132 u=1 fill=6 (103) imp:n=1 imp:p=1 $ Plate 1 - dummy
104 0 102 -103 112 -113 131 -132 u=1 fill=5 (104) imp:n=1 imp:p=1 $ Plate 2 - fuel
105 0 102 -103 113 -114 131 -132 u=1 fill=5 (105) imp:n=1 imp:p=1 $ Plate 3 - fuel
106 0 102 -103 114 -115 131 -132 u=1 fill=5 (106) imp:n=1 imp:p=1 $ Plate 4 - fuel
107 0 102 -103 115 -116 131 -132 u=1 fill=5 (107) imp:n=1 imp:p=1 $ Plate 5 - fuel
108 0 102 -103 116 -117 131 -132 u=1 fill=5 (108) imp:n=1 imp:p=1 $ Plate 6 - fuel

312
109 0 fuel 102 -103 117 -118 131 -132 u=1 fill=5 (109) imp:n=1 imp:p=1 $ Plate 7 -
110 0 fuel 102 -103 118 -119 131 -132 u=1 fill=5 (110) imp:n=1 imp:p=1 $ Plate 8 -
111 0 fuel 102 -103 119 -120 131 -132 u=1 fill=5 (111) imp:n=1 imp:p=1 $ Plate 9 -
112 0 fuel 102 -103 120 -121 131 -132 u=1 fill=5 (112) imp:n=1 imp:p=1 $ Plate 10 -
113 0 fuel 102 -103 121 -122 131 -132 u=1 fill=5 (113) imp:n=1 imp:p=1 $ Plate 11 -
114 0 fuel 102 -103 122 -123 131 -132 u=1 fill=5 (114) imp:n=1 imp:p=1 $ Plate 12 -
115 0 fuel 102 -103 123 -124 131 -132 u=1 fill=5 (115) imp:n=1 imp:p=1 $ Plate 13 -
116 0 fuel 102 -103 124 -125 131 -132 u=1 fill=5 (116) imp:n=1 imp:p=1 $ Plate 14 -
117 0 fuel 102 -103 125 -126 131 -132 u=1 fill=5 (117) imp:n=1 imp:p=1 $ Plate 15 -
118 0 fuel 102 -103 126 -127 131 -132 u=1 fill=5 (118) imp:n=1 imp:p=1 $ Plate 16 -
119 0 fuel 102 -103 127 -128 131 -132 u=1 fill=5 (119) imp:n=1 imp:p=1 $ Plate 17 -
120 0 dummy 102 -103 128 -129 131 -132 u=1 fill=6 (120) imp:n=1 imp:p=1 $ Plate 18-
dummy 121 3 -1.00 (-101:104::111:129:131:132) -141 u=1 imp:n=1 imp:p=1 $ Water

c Universe 2 - Control cell with shim safety rod at position 1
c
201 2 -2.70 101 -102 111 -129 131 -132 u=2 imp:n=1 imp:p=1 $ Left side
plate 202 2 -2.70 103 -104 111 -129 131 -132 u=2 imp:n=1 imp:p=1 $ Right side
plate 203 0 fuel 102 -103 111 -212 131 -132 u=2 fill=5 (203) imp:n=1 imp:p=1 $ Plate 1 -
204 0 fuel 102 -103 212 -213 131 -132 u=2 fill=5 (204) imp:n=1 imp:p=1 $ Plate 2 -
205 0 fuel 102 -103 213 -214 131 -132 u=2 fill=5 (205) imp:n=1 imp:p=1 $ Plate 3 -
206 0 fuel 102 -103 214 -215 131 -132 u=2 fill=5 (206) imp:n=1 imp:p=1 $ Plate 4 -
207 0 fuel 102 -103 215 -216 131 -132 u=2 fill=5 (207) imp:n=1 imp:p=1 $ Plate 5 -
208 0 fuel 102 -103 216 -217 131 -132 u=2 fill=6 (208) imp:n=1 imp:p=1 $ Plate 6 -

313
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<th>Plate</th>
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<th>Material</th>
<th>Imp</th>
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<td>100 -103 219 -220 131 -132</td>
<td>u=2 fill=5 (210)</td>
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<td>9</td>
<td>100 -103 220 -221 131 -132</td>
<td>u=2 fill=5 (211)</td>
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<td>10</td>
<td>100 -103 221 -222 131 -132</td>
<td>u=2 fill=5 (212)</td>
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<td>3 -1.00 -242 -268</td>
<td>250 -132</td>
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<td>7 -8.60 -260 -230</td>
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<td>7 -8.60 230 -231 241 -242 262 266 250 -132</td>
<td>u=2 imp:n=1 imp:p=1</td>
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<td>242</td>
<td>7 -8.60 231 -232 240 -243</td>
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<td>u=2 imp:n=1 imp:p=1 $ Water S of rod</td>
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<td>252</td>
<td>3 -1.00 237 -103 240 -243 250 -132 261</td>
<td>u=2 imp:n=1 imp:p=1 $ Water N of rod</td>
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<td>3 -1.00 102 -103 217 -240 250 -132</td>
<td>u=2 imp:n=1 imp:p=1 $ Water E of rod</td>
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<td>u=2 imp:n=1 imp:p=1 $ Water below rod</td>
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<td>2 -2.70 101 -102 111 -129 131 -132</td>
<td>u=4 imp:n=1 imp:p=1 $ Left side plate</td>
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<td>2 -2.70 103 -104 111 -129 131 -132</td>
<td>u=4 imp:n=1 imp:p=1 $ Right side plate</td>
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<td>403</td>
<td>0 102 -103 111 -212 131 -132</td>
<td>u=4 fill=5 (203) imp:n=1 imp:p=1 $ Plate 1 - fuel</td>
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<td>404</td>
<td>0 102 -103 212 -213 131 -132</td>
<td>u=4 fill=5 (204) imp:n=1 imp:p=1 $ Plate 2 - fuel</td>
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<td>405</td>
<td>0 102 -103 213 -214 131 -132</td>
<td>u=4 fill=5 (205) imp:n=1 imp:p=1 $ Plate 3 - fuel</td>
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<td>406</td>
<td>0 102 -103 214 -215 131 -132</td>
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<td>0 102 -103 215 -216 131 -132</td>
<td>u=4 fill=5 (207) imp:n=1 imp:p=1 $ Plate 5 - fuel</td>
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315
dummy 408  0         102 -103 216 -217 131 -132  u=4 fill=6 (208) imp:n=1 imp:p=1  $ Plate  6 -
dummy 409  0         102 -103 218 -219 131 -132  u=4 fill=6 (209) imp:n=1 imp:p=1  $ Plate  7 -

g 410  0         102 -103 219 -220 131 -132  u=4 fill=5 (210) imp:n=1 imp:p=1  $ Plate  8 -

g 411  0         102 -103 220 -221 131 -132  u=4 fill=5 (211) imp:n=1 imp:p=1  $ Plate  9 -

g 412  0         102 -103 221 -222 131 -132  u=4 fill=5 (212) imp:n=1 imp:p=1  $ Plate 10 -

g 413  0         102 -103 222 -223 131 -132  u=4 fill=5 (213) imp:n=1 imp:p=1  $ Plate 11 -

g 414  0         102 -103 223 -129 131 -132  u=4 fill=5 (214) imp:n=1 imp:p=1  $ Plate 12 -
g 415  3 -1.00  (-101:104:-111:129:-131:132) -141  u=4 imp:n=1 imp:p=1  $ Water c
c Universe 4 - Regulating rod
c
320  8 -8.60 -280 281 -270  276 -132  u=4 imp:n=1 imp:p=1  $ S piece of reg rod
321  8 -8.60 270 -271 272 -273 276 -132  u=4 imp:n=1 imp:p=1  $ W piece of reg rod
322  8 -8.60 270 -271 274 -275 276 -132  u=4 imp:n=1 imp:p=1  $ E piece of reg rod
323  8 -8.60 282 -283 271  276 -132  u=4 imp:n=1 imp:p=1  $ N piece of reg rod
c
330 3 -1.00 102 -103 275 -218 276 -132  u=4 imp:n=1 imp:p=1  $ Water W of rod
331 3 -1.00 102 -270 272 -275 276 -132  280  u=4 imp:n=1 imp:p=1  $ Water S of rod
332 3 -1.00 271 -103 272 -275 276 -132  283  u=4 imp:n=1 imp:p=1  $ Water N of rod
333 3 -1.00 102 -103 217 -272 276 -132  u=4 imp:n=1 imp:p=1  $ Water E of rod
334 3 -1.00 102 -103 217 -218 131 -276  u=4 imp:n=1 imp:p=1  $ Water below rod
c
340 3 -1.00 -281 -270 276 -132  u=4 imp:n=1 imp:p=1  $ Water inside rod
341 3 -1.00 270 -271 273 -274 276 -132  u=4 imp:n=1 imp:p=1
342 3 -1.00 271 -282 276 -132  u=4 imp:n=1 imp:p=1
c c Universe 5 - Fuel plate
c
501 2 -2.70 301-302 311-314 321-322 u=5 imp:n=1 imp:p=1 $ Al left of fuel
502 2 -2.70 302-303 311-312 321-322 u=5 imp:n=1 imp:p=1 $ Al above fuel
503 1 -5.221 302-303 312-313 321-322 u=5 imp:n=1 imp:p=1 $ Fuel
504 2 -2.70 302-303 313-314 321-322 u=5 imp:n=1 imp:p=1 $ Al below fuel
505 2 -2.70 303-304 311-314 321-322 u=5 imp:n=1 imp:p=1 $ Al right of fuel
506 3 -1.00 (-301:304:-311:314:-321:322) -141 u=5 imp:n=1 imp:p=1 $ Water
c
601 2 -2.70 301-304 311-314 321-322 u=6 imp:n=1 imp:p=1 $ Aluminum plate
c
602 3 -1.00 (-301:304:-311:314:-321:322) -141 u=6 imp:n=1 imp:p=1 $ Water
c
c Universe 6 - Dummy plate
c
700 2 -2.70 101-102 111-129 131-132 u=11 imp:n=1 imp:p=1 $ Left side plate
701 2 -2.70 103-104 111-129 131-132 u=11 imp:n=1 imp:p=1 $ Right side plate
702 0 dummy 102-103 111-112 131-132 u=11 fill=6 (103) imp:n=1 imp:p=1 $ Plate 1 -
dummy
703 0 dummy 102-103 112-113 131-132 u=11 fill=6 (104) imp:n=1 imp:p=1 $ Plate 2 -
dummy
704 0 fuel 102-103 113-114 131-132 u=11 fill=5 (105) imp:n=1 imp:p=1 $ Plate 3 -
dummy
705 0 dummy 102-103 114-115 131-132 u=11 fill=6 (106) imp:n=1 imp:p=1 $ Plate 4 -
dummy
706 0 dummy 102-103 115-116 131-132 u=11 fill=6 (107) imp:n=1 imp:p=1 $ Plate 5 -
dummy
707 0 dummy 102-103 116-117 131-132 u=11 fill=6 (108) imp:n=1 imp:p=1 $ Plate 6 -
dummy
708 0 fuel 102-103 117-118 131-132 u=11 fill=5 (109) imp:n=1 imp:p=1 $ Plate 7 -
dummy
709 0 dummy 102-103 118-119 131-132 u=11 fill=6 (110) imp:n=1 imp:p=1 $ Plate 8 -
dummy
710 0 dummy 102-103 119-120 131-132 u=11 fill=6 (111) imp:n=1 imp:p=1 $ Plate 9 -
dummy
711 0 - dummy 102-103 120-121 131-132 u=11 fill=6 (112) imp:n=1 imp:p=1 $ Plate 10 -
712 0 - dummy
713 0 - fuel
714 0 - dummy
715 0 - dummy
716 0 - dummy
717 0 - fuel
718 0 - dummy
719 0 - dummy
dummy
720 -1.00 (-101:104::111:129::131:132) -141 u=11 imp=n=1 imp=p=1 $ Water
721 2 -2.70 101 -102 111 -129 131 -132 u=12 imp=n=1 imp=p=1 $ Left side
plate
722 2 -2.70 103 -104 111 -129 131 -132 u=12 imp=n=1 imp=p=1 $ Right side
plate
723 0 dummy
724 0 dummy
725 0 fuel
726 0 dummy
727 0 dummy
dummy
728 0 fuel
729 0 dummy
730 0 fuel
731 0 dummy
732 0 - dummy
102 -103 121 -122 131 -132 u=11 fill=6 (113) imp=n=1 imp=p=1 $ Plate 11
102 -103 122 -123 131 -132 u=11 fill=5 (114) imp=n=1 imp=p=1 $ Plate 12
102 -103 123 -124 131 -132 u=11 fill=6 (115) imp=n=1 imp=p=1 $ Plate 13
102 -103 124 -125 131 -132 u=11 fill=6 (116) imp=n=1 imp=p=1 $ Plate 14
102 -103 125 -126 131 -132 u=11 fill=6 (117) imp=n=1 imp=p=1 $ Plate 15
102 -103 126 -127 131 -132 u=11 fill=5 (118) imp=n=1 imp=p=1 $ Plate 16
102 -103 127 -128 131 -132 u=11 fill=6 (119) imp=n=1 imp=p=1 $ Plate 17
102 -103 128 -129 131 -132 u=11 fill=6 (120) imp=n=1 imp=p=1 $ Plate 18-

318
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<th>Plate</th>
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</tr>
<tr>
<td>27</td>
<td>102 -103 119 -120 131 -132 u=13 fill=6 (111) imp:n=1 imp:p=1 $ Plate 9 -</td>
</tr>
<tr>
<td>28</td>
<td>102 -103 120 -121 131 -132 u=13 fill=6 (112) imp:n=1 imp:p=1 $ Plate 10</td>
</tr>
</tbody>
</table>
754 0 fuel
755 0 dummy
756 0 fuel
757 0 dummy
758 0 fuel
759 0 dummy
760 0 fuel
dummy
762 3 -1.00 (-101:104:-111:129:-131:132) -141 u=13 imp:n=1 imp:p=1 Water

Plate 11

Plate 12

Plate 13

Plate 14

Plate 15

Plate 16

Plate 17

Plate 18

Universe 14 cells - OPH-004

Plate 1

Plate 2

Plate 3

Plate 4

Plate 5

Plate 6

Plate 7

Plate 8

Plate 9

Plate 10

Plate 11

Plate 12

Plate 13

Plate 14

Plate 15

Plate 16

Plate 17

Plate 18

Plate 1

Plate 2

Plate 3

Plate 4

Plate 5

Plate 6

Plate 7

Plate 8

Plate 9

Plate 10

320
Plate 11

Fuel dummy

Plate 12

Fuel

Plate 13

Fuel

Plate 14

Fuel dummy

Plate 15

Fuel

Plate 16

Fuel dummy

Plate 17

Fuel

Plate 18

Fuel

Water c

Air filling Dry Tube Experimental Section Universe 15
c

Air Detectors for Empty Dry Tube****

Air Detector 1

Air Detector 2

Air Detector 3

Air Detector 4

Air Detector 5

Air Detector 6

Air Detector 7

Air Detector 8

Air Detector 9

Air Detector 10

Air Detector 11

Air Detector 12

Air Detector 13

Air Detector 14

Air Detector 15

$ Air Outside of Cylinder Cell in Test Universe 15

c

$ Water c

3001 32 -0.00121 1203 -1210 -054 #2011 #2012 #2013 #2014 #2015 #2016 #2017 & #2018 #2019 #2020 #2021 #2022 & #2023 #2024 #2025 #2026 #2027 #2028 #2029 #2030 #2031 #2032 #2033 #2034 & #2035 #2036 #2037 #2038 #2039 #2040 #2041 #2042 #2043 #2044 #2045 #2046 & #2047 #2048 #2049 #2050 #2051 #2052 #2053 #2054 #2055 #2056 #2057 #2058 & #2059 #2060 #2061 #2062 #2063 #2064 #2065 #2066 #2067 #2068 #2069 #2070 & #2071 imp:n=1 imp:p=1 $ Air Outside of Cylinder Cell in Test Universe 15
c

****Air Detectors for Empty Dry Tube****

Air Detector 1

Air Detector 2

Air Detector 3

Air Detector 4

Air Detector 5

Air Detector 6

Air Detector 7

Air Detector 8

Air Detector 9

Air Detector 10

Air Detector 11

Air Detector 12

Air Detector 13

Air Detector 14

Air Detector 15

321
2026 32 -0.00121 -1398 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 16
2027 32 -0.00121 -1399 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 17
2028 32 -0.00121 -1400 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 18
2029 32 -0.00121 -1401 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 19
2030 32 -0.00121 -1402 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 20
2031 32 -0.00121 -1403 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 21
2032 32 -0.00121 -1404 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 22
2033 32 -0.00121 -1405 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 23
2034 32 -0.00121 -1406 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 24
2035 32 -0.00121 -1407 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 25
2036 32 -0.00121 -1408 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 26
2037 32 -0.00121 -1409 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 27
2038 32 -0.00121 -1410 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 28
2039 32 -0.00121 -1411 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 29
2040 32 -0.00121 -1412 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 30
2041 32 -0.00121 -1413 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 31
2042 32 -0.00121 -1414 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 32
2043 32 -0.00121 -1415 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 33
2044 32 -0.00121 -1416 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 34
2045 32 -0.00121 -1417 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 35
2046 32 -0.00121 -1418 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 36
2047 32 -0.00121 -1419 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 37
2048 32 -0.00121 -1420 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 38
2049 32 -0.00121 -1421 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 39
2050 32 -0.00121 -1422 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 40
2051 32 -0.00121 -1423 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 41
2052 32 -0.00121 -1424 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 42
2053 32 -0.00121 -1425 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 43
2054 32 -0.00121 -1426 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 44
2055 32 -0.00121 -1427 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 45
2056 32 -0.00121 -1428 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 46
2057 32 -0.00121 -1429 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 47
2058 32 -0.00121 -1430 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 48
2059 32 -0.00121 -1431 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 49
2060 32 -0.00121 -1432 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 50
2061 32 -0.00121 -1433 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 51
2062 32 -0.00121 -1434 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 52
2063 32 -0.00121 -1435 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 53
2064 32 -0.00121 -1436 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 54
2065 32 -0.00121 -1437 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 55
2066 32 -0.00121 -1438 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 56
2067 32 -0.00121 -1439 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 57
2068 32 -0.00121 -1440 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 58
2069 32 -0.00121 -1441 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 59
2070 32 -0.00121 -1442 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 60
2071 32 -0.00121 -1443 imp:n=1 imp:p=1 vol=0.125 $ Air Detector 61

c

**********************************************************************
************* Surface cards ********************************************
**********************************************************************

010  px  -56.515 $ South end of pool
011  px  -19.075 $ South end of core
012  px  -11.445 $ Divide core columns A & B
013  px  -3.815 $ Divide core columns B & C
014  px   3.815 $ Divide core columns C & D
015  px   11.445 $ Divide core columns D & E
016  px   19.075 $ North end of core
017  px   56.520 $ North end of pool
018  px   224.000 $ North end of concrete wall
009  px   39.075 $ North end of graphite plug

020  py  -266.700 $ East wall
021  py  -22.890 $ East end of core
022  py  -15.260 $ Divide core rows 6 & 5
023  py   -7.630 $ Divide core rows 5 & 4
024  py    0.000 $ Divide core rows 4 & 3
025  py    7.630 $ Divide core rows 3 & 2
026  py   15.260 $ Divide core rows 2 & 1
027  py   22.890 $ West end of core
028  py   55.880 $ West wall

030  pz  -106.680 $ Pool floor
031  pz   -43.280 $ Bottom of grid plate
032  pz   -30.480 $ Core bottom
033  pz     0.000 $ Center of core
035  pz    30.480 $ Core top
036  pz   200.00 $ Pool top

041  c/z   0.0  3.8 1.7780 $ CIF tube ID
042  c/z   0.0  3.8 1.9050 $ CIF tube OD


045  c/z   15.26  -19.079 3.1750 $ PIF tube ID
046  c/z   15.26  -19.079 3.8100 $ PIF tube OD

323
c
051  c/x  0.0  8.0 8.0                      $ Beam port 1
c
052  gq  0.25 0.75 1 0.866 0 0 -9.5375 -16.5194 30.48 262.6931
   $ Beam port 2
c 053  c/y  22.885 26.670 5.08               $ Rabbit tube *** Not in use
c
054  c/z  0 -44.49 12.065                $ 10in tube ID r=4.75"
5004 c/z  0 -44.49 12.065001             $ 10in tube ID for SSW SSR
055  c/z  0 -44.49 12.700                $ 10in tube OD r=5"
056  c/z  0 -44.49 15.875                $ 10in tube connection flanges raidii (with 2.5in flange)
c
   $ Reflector plane for West and south
c
099  so  500                                $ Big sphere
c
c  Surfaces for universe 1 - fuel cell
c
101  px  -3.810                       $ South edge of south side plate
102  px  -3.330                       $ North edge of south side plate
103  px   3.330                       $ South edge of north side plate
104  px   3.810                       $ North edge of north side plate
c
111  py  -3.810                       $ West edge of side plates
112  py  -3.384                       $ West edge of 2nd plate cell
113  py  -2.961                       $ West edge of 3rd plate cell
114  py  -2.538                       $ West edge of 4th plate cell
115  py  -2.115                       $ West edge of 5th plate cell
116  py  -1.692                       $ West edge of 6th plate cell
117  py  -1.269                       $ West edge of 7th plate cell
118  py  -0.846                       $ West edge of 8th plate cell
119  py  -0.423                       $ West edge of 9th plate cell
120  py   0.000                       $ West edge of 10th plate cell
121  py  0.423                        $ West edge of 11th plate cell
122  py   0.846                       $ West edge of 12th plate cell
123  py  1.269                        $ West edge of 13th plate cell
124  py  1.692                        $ West edge of 14th plate cell
125  py  2.115                        $ West edge of 15th plate cell
126  py  2.538                        $ West edge of 16th plate cell
127  py  2.961                        $ West edge of 17th plate cell
128  py  3.384                        $ West edge of 18th plate cell
129 py 3.810 $ Top of side plates
131 pz -30.481 $ Bottom of fuel cell
132 pz 30.481 $ Top of fuel cell
141 so 35 $ Water surrounding fuel cell
Surfaces for universe 2,3,4 - control cells
  o X-planes and Z-planes same as in universe 1
  o Bottom and top of side plates same as in universe 1
  o Surrounding water cell same as universe 1
212 py -3.415 $ West edge of 2nd plate cell
213 py -3.028 $ West edge of 3rd plate cell
214 py -2.641 $ West edge of 4th plate cell
215 py -2.254 $ West edge of 5th plate cell
216 py -1.867 $ West edge of 6th plate cell
217 py -1.480 $ West edge of 7th plate cell
218 py 1.480 $ West edge of control rod cell
219 py 1.867 $ West edge of 8th plate cell
220 py 2.254 $ West edge of 9th plate cell
221 py 2.641 $ West edge of 10th plate cell
222 py 3.028 $ West edge of 11th plate cell
223 py 3.415 $ West edge of 12th plate cell
Surfaces for shim safety control rods
230 px -1.9844 $ For defining grooves in rod
231 px -1.3494 $ For defining grooves in rod
232 px -0.8731 $ For defining grooves in rod
233 px -0.2381 $ For defining grooves in rod
234 px 0.2381 $ For defining grooves in rod
235 px 0.8731 $ For defining grooves in rod
236 px 1.3494 $ For defining grooves in rod
237 px 1.9844 $ For defining grooves in rod
240 py -1.0795 $ East edge of rod
241 py -0.8750 $ For defining grooves in rod
242 py 0.8750 $ For defining grooves in rod
243 py 1.0795 $ West edge of rod
250 pz 0.0 $ Bottom of rod (Rod height)
Surfaces for regulating rod

Surfaces for universes 5 and 6 - fuel plates and dummy plates

Surrounding water cell same as universe 1
**Dry Tube Planar Surfaces**

- **1201**: pz -106.680 $ Bottom of dry tube outer wall **(Already covered by Pool Floor (030))
- **1202**: pz -104.775 $ Bottom of dry tube inner wall
- **1203**: pz -38.100 $ Top of Steel Plates
- **5003**: pz -38.10001 $ Top of Steel Plates for SSW SSR
- **1204**: pz 74.930 $ Dry Tube - Bottom of flange connection 1
- **1205**: pz 78.74 $ Dry Tube - Top of flange connection 1

**Dry Tube Hard Flux Nitrogen Gas Box Outside**

- **1300**: BOX -10.16 -36.87 -15.24 0 0 0 0 30.48 0 13.97 0

**Dry Tube Hard Flux Nitrogen Gas Box Inside**

- **1301**: BOX -9.8425 -36.5525 -15.24 19.685 0 0 0 0 30.1625 0 13.335 0

**Air Detectors**

- **1383**: BOX -0.25 -44.74 -35.81 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 1
- **1384**: BOX -0.25 -44.74 -33.27 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 2
- **1385**: BOX -0.25 -44.74 -30.73 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 3
- **1386**: BOX -0.25 -44.74 -28.19 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 4
- **1387**: BOX -0.25 -44.74 -25.65 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 5
- **1388**: BOX -0.25 -44.74 -23.11 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 6
- **1389**: BOX -0.25 -44.74 -20.57 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 7
- **1390**: BOX -0.25 -44.74 -18.03 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 8
- **1391**: BOX -0.25 -44.74 -15.49 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 9
- **1392**: BOX -0.25 -44.74 -12.95 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 10
- **1393**: BOX -0.25 -44.74 -10.41 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 11
- **1394**: BOX -0.25 -44.74 -7.87 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 12
- **1395**: BOX -0.25 -44.74 -5.33 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 13
- **1396**: BOX -0.25 -44.74 -2.79 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 14
- **1397**: BOX -0.25 -44.74 -0.25 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 15
- **1398**: BOX -0.25 -44.74 2.29 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 16
- **1399**: BOX -0.25 -44.74 4.83 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 17
- **1400**: BOX -0.25 -44.74 7.37 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 18
- **1401**: BOX -0.25 -44.74 9.91 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 19
- **1402**: BOX -0.25 -44.74 12.45 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 20
- **1403**: BOX -0.25 -44.74 14.99 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 21
- **1404**: BOX -0.25 -44.74 17.53 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 22
- **1405**: BOX -0.25 -44.74 20.07 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 23
- **1406**: BOX -0.25 -44.74 22.61 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 24
- **1407**: BOX -0.25 -44.74 25.15 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 25
- **1408**: BOX -0.25 -44.74 27.69 0.5 0 0 0 0.5 0 0 0 0.5 $ Air Detector 26
mode n p e
kcode 50000 1.000 10 1220 $ 5 days
c
c Specify one point in each region of fissile material
Transformation cards

Transformation from fuel cell (or control cell) coordinate system to reactor coordinate system.

```
tr011 -15.260 -19.075 0.000 0 -1 0 1 0 0 0 0 1 1 $ Cell A6
tr013 -15.260 -3.815 0.000 0 -1 0 1 0 0 0 0 1 1 $ Cell A4
tr014 -15.260 3.815 0.000 0 -1 0 1 0 0 0 0 1 1 $ Cell A3
tr015 -15.260 11.445 0.000 0 -1 0 1 0 0 0 0 1 1 $ Cell A2
tr022 -7.630 -11.445 0.000 0 -1 0 1 0 0 0 0 1 1 $ Cell B5
tr023 -7.630 -3.815 0.000 0 -1 0 1 0 0 0 0 1 1 $ Cell B4
tr024 -7.630 3.815 0.000 0 -1 0 1 0 0 0 0 1 1 $ Cell B3
tr025 -7.630 11.445 0.000 0 -1 0 1 0 0 0 0 1 1 $ Cell B2
tr026 -7.630 19.075 0.000 0 -1 0 1 0 0 0 0 1 1 $ Cell B1
tr032 0.000 -11.445 0.000 0 -1 0 1 0 0 0 0 1 1 $ Cell C5
tr033 0.000 -3.815 0.000 0 -1 0 1 0 0 0 0 1 1 $ Cell C4
tr035 0.000 11.445 0.000 0 -1 0 1 0 0 0 0 1 1 $ Cell C2
tr036 0.000 19.075 0.000 0 -1 0 1 0 0 0 0 1 1 $ Cell C1
tr041 7.630 -19.075 0.000 0 -1 0 1 0 0 0 0 1 1 $ Cell D6
tr042 7.630 -11.445 0.000 0 -1 0 1 0 0 0 0 1 1 $ Cell D5
tr043 7.630 -3.815 0.000 0 -1 0 1 0 0 0 0 1 1 $ Cell D4
tr044 7.630 3.815 0.000 0 -1 0 1 0 0 0 0 1 1 $ Cell D3
tr045 7.630 11.445 0.000 0 -1 0 1 0 0 0 0 1 1 $ Cell D2
tr046 7.630 19.075 0.000 0 -1 0 1 0 0 0 0 1 1 $ Cell D1
tr052 15.260 -11.445 0.000 0 -1 0 1 0 0 0 0 1 1 $ Cell E5
tr053 15.260 -3.815 0.000 0 -1 0 1 0 0 0 0 1 1 $ Cell E4
tr054 15.260 3.815 0.000 0 -1 0 1 0 0 0 0 1 1 $ Cell E3
tr055 15.260 11.445 0.000 0 -1 0 1 0 0 0 0 1 1 $ Cell E2
```

Transformation from fuel plate (or dummy plate) coordinate system to fuel cell coordinate system.

```
tr103 0.000 -3.5955 0.000 1 0 0 0 1 0 0 0 1 1
tr104 0.000 -3.1725 0.000 1 0 0 0 1 0 0 0 1 1
```
c Transformation from fuel plate (or dummy plate) coordinate system to
control cell coordinate system.
c
tr203  0.000 -3.6085  0.000  1  0  0  0  1  0  0  0  1  1
tr204  0.000 -3.2215  0.000  1  0  0  0  1  0  0  0  1  1
tr205  0.000 -2.8345  0.000  1  0  0  0  1  0  0  0  1  1
tr206  0.000 -2.4475  0.000  1  0  0  0  1  0  0  0  1  1
tr207  0.000 -2.0605  0.000  1  0  0  0  1  0  0  0  1  1
tr208  0.000 -1.6735  0.000  1  0  0  0  1  0  0  0  1  1
tr209  0.000  1.6735  0.000  1  0  0  0  1  0  0  0  1  1
tr210  0.000  2.0605  0.000  1  0  0  0  1  0  0  0  1  1
tr211  0.000  2.4475  0.000  1  0  0  0  1  0  0  0  1  1
tr212  0.000  2.8345  0.000  1  0  0  0  1  0  0  0  1  1
tr213  0.000  3.2215  0.000  1  0  0  0  1  0  0  0  1  1
tr214  0.000  3.6085  0.000  1  0  0  0  1  0  0  0  1  1

c Transformation from the cryostat experiment coordinate system to
the full core coordinate system (universe 10)
c
t400  0 -44.49  6.350  1  0  0  0  1  0  0  0  1  1

c surface source write

c ssw  -5004(6001)  5003(6005) -5010(6007) SYM=0  $ 10in Dry Tube

c
nonu  $for use with ssw/ssr card in some cases

c
**Empty 10 inch Dry Tube Air Detector Tallies**

fc4 Fluence averaged over Air Detector cells per NPS

  2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 &
  2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 &
  2047 2048 2049 2050 2051 2052 2053 2054 2055 2056 2057 2058 &
  2059 2060 2061 2062 2063 2064 2065 2066 2067 2068 2069 2070 2071

fc14 Fluence averaged over Air Detector cells per NPS

  2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 &
  2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 &
  2047 2048 2049 2050 2051 2052 2053 2054 2055 2056 2057 2058 &
  2059 2060 2061 2062 2063 2064 2065 2066 2067 2068 2069 2070 2071

fc24 Fluence averaged over Air Detector cells per NPS

  2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 &
  2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 &
  2047 2048 2049 2050 2051 2052 2053 2054 2055 2056 2057 2058 &
  2059 2060 2061 2062 2063 2064 2065 2066 2067 2068 2069 2070 2071

e4 1-9 298LOG 2+1 $tally bins

fc444 Displacement damage tally

  2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 &
  2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 &
  2047 2048 2049 2050 2051 2052 2053 2054 2055 2056 2057 2058 &
  2059 2060 2061 2062 2063 2064 2065 2066 2067 2068 2069 2070 2071

fm444 1e-24 14 444

c
fc16 Total neutron energy deposition

  2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 &
  2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 &
  2047 2048 2049 2050 2051 2052 2053 2054 2055 2056 2057 2058 &
  2059 2060 2061 2062 2063 2064 2065 2066 2067 2068 2069 2070 2071

fc26 Total photon energy deposition

  2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 &
  2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 &
  2047 2048 2049 2050 2051 2052 2053 2054 2055 2056 2057 2058 &
  2059 2060 2061 2062 2063 2064 2065 2066 2067 2068 2069 2070 2071

fc36 Total electron energy deposition

+fc6 Total collision heating
  2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 &
  2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 &
  2047 2048 2049 2050 2051 2052 2053 2054 2055 2056 2057 2058 &
  2059 2060 2061 2062 2063 2064 2065 2066 2067 2068 2069 2070 2071

+fc6 Material compositions ****

***** Material compositions *****

c Material #1 - Fuel :
c
m1  92235.70c 0.0365 $from OSU docs
    92238.70c 0.1479
    13027.70c 0.1229
    14000.60c 0.6927

c Material #2 - Aluminum : 2.70 g/cc

c m2  13027.70c 1.000

mt2  al27.12t

c Material #3 - Water : 1.00 g/cc

c m3  01001.70c 0.667  08016.70c 0.333

mt3  lwtr.60t

c Material #4 - Graphite : 1.70 g/cc

c m4  06000.70c 1.000

mt4  grph.60t

c Material #5 - Barytes Concrete : 3.35 g/cc ***

c m5  01001.70c 0.110  08016.70c 0.600  20000.62c 0.040
    16032.70c 0.100  19000.62c 0.040  56138.70c 0.110

c Material #7 - Shim Safety Boron Stainless Steel

c mt7  26000.55c -0.715  24000.50c -0.185  28000.50c -0.085
    05010.70c -0.015
<table>
<thead>
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c

Material #21 - Super Insulation 2.528 g/cc

c

Material #23 - $ Heating Element (Manganin Wire) 8.7194 g/cc estimate from constituents

c

Material #22 29063.70c 5.60832E-01
<table>
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<tr>
<th>Material #24 - Silica (Silicon Dioxide)</th>
<th>2.648 g/cc</th>
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<tr>
<td>m24</td>
<td>3.07403E-01</td>
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<td>14029.70c</td>
<td>1.55651E-02</td>
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<td>1.03323E-02</td>
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<tr>
<td>8017.70c</td>
<td>2.53346E-04</td>
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| Material #25 - Nitrogen Liquid Density = 0.807 g/cc, Gaseous Density here = 0.00173 g/cc |
|---------------------------------------|------------|
| m25                                  | 0.99634    |
| 7014.70c                             | 0.99634    |
| 7015.70c                             | 0.00366    |

<table>
<thead>
<tr>
<th>Material #26 - GaAs 5.3176 g/cc</th>
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<tr>
<td>m26</td>
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<tr>
<td>31069.70c</td>
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<tr>
<th>Material #27 - Copper for Duroid Board 8.96 g/cc</th>
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<table>
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<tr>
<th>Material #28 - Common Plastic (Pure Polyethylene, specifically low-density polyethylene (estimate (C2H4)3H2)) (Wikipedia: density = 0.91-0.94 g/cc) 0.925 g/cc</th>
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<tr>
<td>m28</td>
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<td>6012.50d</td>
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<tr>
<td>6013.42c</td>
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<tr>
<th>Material #30 - GaAs Device Package Leads, Copper with Silver and Tin Plating 8.7939 g/cc</th>
</tr>
</thead>
<tbody>
<tr>
<td>m29</td>
</tr>
<tr>
<td>6012.50d</td>
</tr>
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<td>1001.70c</td>
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<tr>
<th>Material #30 - GaAs Device Package Leads, Copper with Silver and Tin Plating 8.7939 g/cc</th>
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<tr>
<td>m29</td>
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<td>1001.70c</td>
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<td>1002.70c</td>
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</table>
Material #31 - Duroid Board Homogenized Material calculated density 3.1353 g/cc

Material #32 - Air density 0.00121 g/cc

Material #33 - MS-800 Device Wiring 8.50 g/cc
24052.70c 1.79601E-01
24053.70c 2.03653E-02
24054.70c 5.06935E-03
13027.70c 5.16340E-02
29063.70c 1.51646E-02
29065.70c 6.75908E-03

c
Material #34 - Liquid Helium 0.125 g/cc

c
m34 2003.70c 1.37E-06
2004.70c 0.99999863

c
Material #35 - Carbon Steel Plates 7.82 g/cc

c
m35 6000 -0.005
26000 -0.995

c
print
prdmp 2j 1 2
Appendix B: MCNP6 code for the CRIF in the 10" Dry Tube Simulations

The following code is an input deck for the MCNP6 SSW run, completed for the results presented herein. The code includes the model of the OSURR, the 10" Dry Tube, and the CRIF inside of the 10" Dry Tube. This is the first step of two, in which the radiation tracks generated from the OSURR core are transported to the 10" Dry Tube and recorded as they cross a surface of the 10" Dry Tube, using the Surface Source Write (SSW) mode of MCNP6. Subsequently, a second run has been completed, using the generated output file for the SSW run as an input for the Surface Source Read simulation, which reads the recorded radiation tracks and uses them as a source for transporting the radiation into the 10" Dry Tube. In order to complete the second step, the SSW run must first be completed. Then the input deck, seen below, has to be changed to run in SSR mode.

Instructions on this process can be found in the MCNP manual. In this case, the detector tallies have been commented out. They must be used in the subsequent SSR run to simulate the radiation flux and energy deposition in the axial air detectors. Finally, in the below code, only the sections that were added or edited to complete the run, and differ from the code in Appendix A, were included. This was meant to not repeat code and save space within this document. Therefore, these sections must be added into or replace sections of the code from Appendix A.
c***********************************************************************
c**************************** Cell cards **********************************
c***********************************************************************
c ****10" Dry Tube Cells****
c
2000 2 -2.70  5004 -055  1202 -036 imp:n=1 imp:p=1 $ 10in Al Dry Tube Walls
6000 2 -2.70  054 -5004  1202 -5003 imp:n=1 imp:p=1 $ 10in Al Dry Tube Wall for SSW SSR (Lower Segment)
6001 2 -2.70  054 -5004  5003 -5010 imp:n=1 imp:p=1 $ 10in Al Dry Tube Wall for SSW SSR (Middle Segment)
6002 2 -2.70  054 -5004  5010 -036 imp:n=1 imp:p=1 $ 10in Al Dry Tube Wall for SSW SSR (Upper Segment)
2001 2 -2.70  -055  030 -1202 imp:n=1 imp:p=1 $ 10in Al Dry Tube Bottom
2002 2 -2.70  055 -056  1204 -1205 imp:n=1 imp:p=1 $ 10in Al Dry Tube Flange Connection
2003 3 -1.00  055 -056 -036  1205 imp:n=1 imp:p=1 $ Water above 10in Dry Tube Flange Connection
2004 3 -1.00  055 -056  030 -1204 1300 imp:n=1 imp:p=1 $ Water below 10in Al Dry Tube Flange Connection
2005 35 -7.82 -54 -5003  1202 imp:n=1 imp:p=1 $ Steel Plates at Bottom of 10in Dry Tube
6005 35 -7.82 -54 -1203  5003 imp:n=1 imp:p=1 $ Steel Plates at Bottom of 10in Dry Tube for SSW SSR
2006 0 1203 -1210 -054 fill=10 (400) imp:n=1 imp:p=1 $ 10in Dry Tube Cryostat and Aluminum Stand Universe section
2007 32 -0.00121 -054  5010 -036 1000 #2011 #2012 #2013 #2014 #2016 &
    imp:n=1 imp:p=1 $ Air above Cryostat
6007 32 -0.00121 -054  1210 -5010 imp:n=1 imp:p=1 $ Air above Cryostat (Gap between Main Dewar and Top) for SSW SSR
2008 2 -2.70 -1300  1301 055 imp:n=1 imp:p=1 $ Al Inside of Hard Flux Box Walls
2009 25 -0.00173 -1301 055 054 imp:n=1 imp:p=1 $ Gaseous N2 Inside of Hard Flux Box
2010 3 -1.00  030 -036 -055 imp:n=1 imp:p=1 $ No 10in dry tube

 ****Vacuum Tube Cells****
c
2011 2 -2.70  1000 -1001  1206 -036 imp:n=1 imp:p=1 $ Vacuum Transfer Tube
2012 2 -2.70  1000 -1001 -1206  1207 imp:n=1 imp:p=1 $ Vacuum Transfer Tube Flange Top Connector
2013 2 -2.70 1000 -1002 -1207 1208 imp:n=1 imp:p=1 $ Vacuum Transfer Tube Flange Neck
2014 2 -2.70 1000 -1003 -1208 1209 imp:n=1 imp:p=1 $ Vacuum Transfer Tube Flange Bottom Connector
2015 0 -1000 -036 5010 imp:n=1 imp:p=1 $ Vacuum Void inside of Transfer Tube
2016 20 -1.80 1000 -1004 -1209 5010 imp:n=1 imp:p=1 $ Cryostat G10 Top
071 4 -1.70 010 -011 060 -027 032 -035 imp:n=1 imp:p=1 $ South Reflector
072 4 -1.70 010 060 027 -028 032 -035 imp:n=1 imp:p=1 $ West Reflector
073 3 -1.00 010 -011 060 -027 031 -032 imp:n=1 imp:p=1 $ Water below South Reflector
074 3 -1.00 010 060 027 -028 031 -032 imp:n=1 imp:p=1 $ Water below West Reflector
081 3 -1.00 010 -017 020 -028 030 -031 056 imp:n=1 imp:p=1 $ Water below core
082 3 -1.00 010 -017 020 -028 035 -036 042 044 046 056 imp:n=1 imp:p=1 $ Water above core
083 0 035 -036 -042 imp:n=1 imp:p=1 $ CIF void above core
084 0 035 -036 -044 imp:n=1 imp:p=1 $ AIF void above core
085 0 035 -036 -046 imp:n=1 imp:p=1 $ PIF void above core
086 3 -1.00 016 -017 020 -028 031 -035 -060 051 052 056 imp:n=1 imp:p=1 $ Water N of core
087 3 -1.00 016 -017 020 -021 031 -035 056 1300 imp:n=1 imp:p=1 $ Water E of core
088 3 -1.00 010 -011 020 -022 031 -035 -060 imp:n=1 imp:p=1 $ Water SE of core
091 5 -3.35 017 -018 020 -028 030 -036 051 052 imp:n=1 imp:p=1 $ Concrete wall
095 0 (-010:018:-020:028:-030:036) -099 imp:n=1 imp:p=1 $ Interior void
099 0 099 imp:n=0 imp:p=0 $ Exterior void

***** Universe 10 Cells: 10" Dry Tube and Cryostat Cells *****

Universe 10 cells - Cryostat in 10" tube
c Trying to match most cells to relevant surfaces (i.e. use 2000 number system for related 1000 surface numbers)

c ****5.5" Aluminum Stand between top of Steel Plates and bottom of Cryostat****
2017 18 -2.70 -1267 1268 -1114 u=10 imp:n=1 imp:p=1 $ Top of 5.5" Aluminum Stand
2018 32 -0.00121 -1268 1269 -1114 #2325 #2326 #2327 #2328 &
   u=10 imp:n=1 imp:p=1 $ Air between Aluminum Stand Top and Bottom
2019 18 -2.70 -1269 -1114 u=10 imp:n=1 imp:p=1 $ Bottom of 5.5" Aluminum Stand
2325 18 -2.70 -1110 -1268 1269 u=10 imp:n=1 imp:p=1 $ Aluminum Post 1 of 5.5" Aluminum Stand
2326 18 -2.70 -1111 -1268 1269 u=10 imp:n=1 imp:p=1 $ Aluminum Post 2 of 5.5" Aluminum Stand
2327 18 -2.70 -1112 -1268 1269 u=10 imp:n=1 imp:p=1 $ Aluminum Post 3 of 5.5" Aluminum Stand
2328 18 -2.70 -1113 -1268 1269 u=10 imp:n=1 imp:p=1 $ Aluminum Post 4 of 5.5" Aluminum Stand
2329 32 -0.00121 1114 -1267 u=10 imp:n=1 imp:p=1 $ Air gap between 5.5" Aluminum Stand and 10" Dry Tube Inner Wall

c ****Main Dewar Cells****
2020 32 -0.00121 1005 1267 u=10 imp:n=1 imp:p=1 $ Air between outer wall of cryostat and inner wall of dry tube
2021 18 -2.70 -1005 1006 1267 u=10 imp:n=1 imp:p=1 $ Al6061 Outer Wall of Main Dewar Side
2022 18 -2.70 -1006 1008 1211 u=10 imp:n=1 imp:p=1 $ Al6061 Outer Wall of Main Dewar Top
2023 18 -2.70 -1006 -1266 1267 u=10 imp:n=1 imp:p=1 $ Al6061 Outer Wall of Main Dewar Bottom
2024 0 -1006 1007 1265 -1211 u=10 imp:n=1 imp:p=1 $ Vacuum on Inside of Wall of Main Dewar Side
2025 21 -2.528 -1007 1008 1265 -1211 u=10 imp:n=1 imp:p=1 $ Superinsulation Wrap in Inside of Wall of Main Dewar Side
2026 20 -1.80 -1008 1009 1264 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ G10 Inner Wall of Main Dewar Side
2027 0 1266 -1265 -1006 u=10 imp:n=1 imp:p=1 $ Vacuum on Inside of Wall of Main Dewar Bottom
2028 20 -1.80 -1008 -1264 1265 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ G10 Inner Wall of Main Dewar Bottom

c ****Outer Canister and Inner Cryostat Structural Support Cells****

c
$ Volume of Liquid Nitrogen
2030 34 -0.125 -1009 1223 1018 #2031 #2032 #2036 #2037 #2038 #2039 #2040 &
    #2041 #2042 #2043 #2044 #2045 &
    vol=12704.48 u=10 imp:n=1 imp:p=1 tmp1=6.635e-009 $ Volume of Liquid Nitrogen
2031 20 -1.80 -1018 1019 1228 u=10 imp:n=1 imp:p=1 tmp1=6.635e-009 $ Cryostat central vacuum G10 tube/structural support
2032 0 -1019 1038 1230 1100 1101 1102 &
    1103 1104 1105 1106 1107 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Cryostat central vacuum G10 tube/structural support inside void **should change material to homogenize with wires
2033 25 -0.807 -1009 1028 -1223 1225 u=10 imp:n=1 imp:p=1 tmp1=6.635e-009 $ Liquid Nitrogen in bottom of cryostat around outer canister top
2033 34 -0.125 -1009 1028 -1223 1225 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Liquid Helium in bottom of cryostat around outer canister top
2034 25 -0.807 -1009 1010 -1225 1263 #2048 &
    u=10 imp:n=1 imp:p=1 tmp1=6.635e-009 $ Liquid Nitrogen in bottom of cryostat around outer canister wall
2034 34 -0.125 -1009 1010 -1225 1263 #2048 &
    u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Liquid Helium in bottom of cryostat around outer canister wall
2035 25 -0.807 -1009 -1263 1264 u=10 imp:n=1 imp:p=1 tmp1=6.635e-009 $ Liquid Nitrogen in bottom of cryostat below outer canister
2035 34 -0.125 -1009 -1263 1264 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Liquid Helium in bottom of cryostat below outer canister
2036 20 -1.80 -1020 1021 1221 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Cryostat off-axis filler G10 tube/structural support
2037 20 -1.80 -1022 1023 1220 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Cryostat off-axis straw G10 tube/structural support
2038 18 -2.70 -1024 1018 -1212 1213 #2036 #2037 &
    u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Reflective Aluminum Structural Support Ring #1
2039 18 -2.70 -1024 1018 -1214 1215 #2036 #2037 &
    u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Reflective Aluminum Structural Support Ring #2
2040 18 -2.70 -1024 1018 -1216 1217 #2036 #2037 &
    u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Reflective Aluminum Structural Support Ring #3
2041 18 -2.70 -1024 1018 -1218 1219 #2036 #2037 &
    u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Reflective Aluminum Structural Support Ring #4
**Structural support plane connector 1**

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<th>Z</th>
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<th>U</th>
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<td>-1.80</td>
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**Structural support plane connector 2**

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<td>imp:n=1 imp:p=1 tmp1=3.619e-010</td>
</tr>
</tbody>
</table>

$ Cryostat outer canister top Al connection to central G10 vacuum tube

$ Cryostat outer canister top bolt rings

$ Cryostat outer canister top

$ Cryostat outer canister top walls

$ Cryostat outer canister connection flange

$ Cryostat outer canister walls

$ Cryostat outer canister bottom

$ Inner Canister Top Flange

$ Inner Canister Thread

$ Inner Canister Walls
Inner Canister Bottom

Vacuum inside inner canister

Superinsulation

Wire Peg #1

Wire Peg #2

Wire Peg #3

Al Connector between inner canister top and weird mounting block

Weird Mounting Block

Aluminum Mounting Block Box

Plastic Side Mounting Support Box 1 for Plastic Pin Box

Plastic Side Mounting Support Box 2 for Plastic Pin Box

Plastic Pin Box (approximated as box)

Lower Mounting Al 1/4-20 Threaded Rod for Platforms (only measured to top of first platform)

Al Hexagonal 1/4-20 Nut 1

Mounting Platform 1
c ****GaN/GaAs Devices and Mounts****
c
2090  31 -1.43  -1319 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Duroid Board 1
2092  28 -0.925  -1383  1384  1385 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ GaAs Device Plastic Packaging 1
2093  30 -8.7939  -1384  #2094 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ GaAs Device Sn/Cu Leads 1
2094  26 -5.3176  -1385 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ GaAs Device 1
2104  31 -1.43  -1320  1319  1321 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Duroid Board 2
2106  28 -0.925  -1386  1387  1388 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ GaAs Device Plastic Packaging 2
2107  30 -8.7939  -1387  #2108 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ GaAs Device Sn/Cu Leads 2
2108  26 -5.3176  -1388 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ GaAs Device 2
2118  31 -1.43  -1321 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Duroid Board 3
2120  28 -0.925  -1389  1390  1391 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ GaAs Device Plastic Packaging 3
2121  30 -8.7939  -1390  #2122 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ GaAs Device Sn/Cu Leads 3
2122  26 -5.3176  -1391 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ GaAs Device 3
<table>
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<td>$ Duroid Board 4</td>
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<tr>
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<td>u=10 imp:n=1 imp:p=1 tmp1=3.619e-010</td>
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<tr>
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<td>30 -8.7939 -1393 #2136</td>
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<td>$ GaAs Device Sn/Cu Leads 4</td>
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<tr>
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<td>u=10 imp:n=1 imp:p=1 tmp1=3.619e-010</td>
<td>$ GaAs Device 4</td>
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<td>31 -1.43 -1323</td>
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<td>u=10 imp:n=1 imp:p=1 tmp1=3.619e-010</td>
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<td>28 -0.925 -1398 1399 1400</td>
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<td>u=10 imp:n=1 imp:p=1 tmp1=3.619e-010</td>
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<td>2164</td>
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<td>2176</td>
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2286 31 -1.43 -1333 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Duroid Board 15
2288 28 -0.925 -1425 1426 1427 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ GaAs Device Plastic Packaging 15
2289 30 -8.7939 -1426 #2290 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ GaAs Device Sn/Cu Leads 15
2290 26 -5.3176 -1427 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ GaAs Device 15
2300 31 -1.43 -1334 1331 1333 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Duroid Board 16
2302 28 -0.925 -1428 1429 1430 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ GaAs Device Plastic Packaging 16
2303 30 -8.7939 -1429 #2304 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ GaAs Device Sn/Cu Leads 16
2304 26 -5.3176 -1430 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ GaAs Device 16

Manganin Wire

2320 23 -8.7194 1014 -1043 -1290 1291 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Manganin Wire 1 Analogous Cylinder
2321 23 -8.7194 1014 -1043 -1292 1293 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Manganin Wire 1 Analogous Cylinder
2322 23 -8.7194 1014 -1043 -1294 1295 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Manganin Wire 1 Analogous Cylinder
2323 23 -8.7194 1014 -1043 -1296 1297 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Manganin Wire 1 Analogous Cylinder
2324 23 -8.7194 1014 -1043 -1298 1299 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Manganin Wire 1 Analogous Cylinder

**** Fiber Tubes and Fibers ****

2400 18 -2.70 1039 -1040 -1233 1271 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Left Fiber Tube
2401 18 -2.70 1041 -1042 -1233 1271 1307 u=10 imp:n=1 imp:p=1 & tmp1=3.619e-010 $ Right Fiber Tube
2402 0 -1039 1090 1091 1092 1093 -1233 1271 & u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Void in Left Fiber Tube
2403 0 -1041 1094 1095 1096 1097 -1233 1271 1307 & u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Void in Right Fiber Tube

Fiber 1

2421 24 -2.648 -1090 1272 -1440 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Fiber 1: 1st Section: Vertical Section of Silica Single-Mode Fiber in Experimental Volume

348
1: 1st Section: Vertical Section of Silica Single-Mode Fiber in Experimental Volume
2: 1st Section: Vertical Section of Silica FBG Fiber in Experimental Volume
3: 1st Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
4: 1st Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
5: 1st Section: Vertical Section of Silica FBG Fiber in Vacuum Tube
6: 1st Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
7: 1st Section: Vertical Section of Silica Single-Mode Fiber in Experimental Volume
8: 1st Section: Vertical Section of Silica FBG Fiber in Vacuum Tube

1: 2nd Section: Vertical Section of Silica Single-Mode Fiber in Experimental Volume
2: 2nd Section: Vertical Section of Silica FBG Fiber in Experimental Volume
3: 2nd Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
4: 2nd Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
5: 2nd Section: Vertical Section of Silica FBG Fiber in Vacuum Tube
6: 2nd Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
7: 2nd Section: Vertical Section of Silica Single-Mode Fiber in Experimental Volume
8: 2nd Section: Vertical Section of Silica FBG Fiber in Vacuum Tube

1: 3rd Section: Vertical Section of Silica Single-Mode Fiber in Experimental Volume
2: 3rd Section: Vertical Section of Silica FBG Fiber in Experimental Volume
3: 3rd Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
4: 3rd Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
5: 3rd Section: Vertical Section of Silica FBG Fiber in Vacuum Tube
6: 3rd Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
7: 3rd Section: Vertical Section of Silica Single-Mode Fiber in Experimental Volume
8: 3rd Section: Vertical Section of Silica FBG Fiber in Vacuum Tube

1: 4th Section: Vertical Section of Silica Single-Mode Fiber in Experimental Volume
2: 4th Section: Vertical Section of Silica FBG Fiber in Experimental Volume
3: 4th Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
4: 4th Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
5: 4th Section: Vertical Section of Silica FBG Fiber in Vacuum Tube
6: 4th Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
7: 4th Section: Vertical Section of Silica Single-Mode Fiber in Experimental Volume
8: 4th Section: Vertical Section of Silica FBG Fiber in Vacuum Tube

1: 5th Section: Vertical Section of Silica Single-Mode Fiber in Experimental Volume
2: 5th Section: Vertical Section of Silica FBG Fiber in Experimental Volume
3: 5th Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
4: 5th Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
5: 5th Section: Vertical Section of Silica FBG Fiber in Vacuum Tube
6: 5th Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
7: 5th Section: Vertical Section of Silica Single-Mode Fiber in Experimental Volume
8: 5th Section: Vertical Section of Silica FBG Fiber in Vacuum Tube

1: 6th Section: Vertical Section of Silica Single-Mode Fiber in Experimental Volume
2: 6th Section: Vertical Section of Silica FBG Fiber in Experimental Volume
3: 6th Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
4: 6th Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
5: 6th Section: Vertical Section of Silica FBG Fiber in Vacuum Tube
6: 6th Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
7: 6th Section: Vertical Section of Silica Single-Mode Fiber in Experimental Volume
8: 6th Section: Vertical Section of Silica FBG Fiber in Vacuum Tube

1: 7th Section: Vertical Section of Silica Single-Mode Fiber in Experimental Volume
2: 7th Section: Vertical Section of Silica FBG Fiber in Experimental Volume
3: 7th Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
4: 7th Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
5: 7th Section: Vertical Section of Silica FBG Fiber in Vacuum Tube
6: 7th Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
7: 7th Section: Vertical Section of Silica Single-Mode Fiber in Experimental Volume
8: 7th Section: Vertical Section of Silica FBG Fiber in Vacuum Tube

1: 8th Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
2: 8th Section: Vertical Section of Silica FBG Fiber in Experimental Volume
3: 8th Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
4: 8th Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
5: 8th Section: Vertical Section of Silica FBG Fiber in Vacuum Tube
6: 8th Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
7: 8th Section: Vertical Section of Silica Single-Mode Fiber in Experimental Volume
8: 8th Section: Vertical Section of Silica FBG Fiber in Vacuum Tube
2450 24 -2.648  -1101 -1448 1447 u=10 imp:n=1 imp:p=1  tmp1=3.619e-010  $ Fiber
2: 5th Section: Vertical Section of Silica FBG Fiber in Vacuum Tube
2451 24 -2.648  -1101 -1449 1448 u=10 imp:n=1 imp:p=1  tmp1=3.619e-010  $ Fiber
2: 6th Section: Vertical Section of Silica FBG Fiber in Vacuum Tube
2452 24 -2.648  -1101 -1450 1449 u=10 imp:n=1 imp:p=1  tmp1=3.619e-010  $ Fiber
2: 7th Section: Vertical Section of Silica FBG Fiber in Vacuum Tube
2453 24 -2.648  -1101  1450 u=10 imp:n=1 imp:p=1  tmp1=3.619e-010  $ Fiber
2: 8th Section: Vertical Section of Silica FBG Fiber in Vacuum Tube

2461 24 -2.648  -1092 1272 -1440 u=10 imp:n=1 imp:p=1  tmp1=3.619e-010  $ Fiber
3: 1st Section: Vertical Section of Silica Multi-Mode Fiber in Experimental Volume
2462 24 -2.648  -1092 1440 -1441 u=10 imp:n=1 imp:p=1  tmp1=3.619e-010  $ Fiber
3: 2nd Section: Vertical Section of Silica Multi-Mode Fiber in Experimental Volume
2463 24 -2.648  -1092 1441 -1442 u=10 imp:n=1 imp:p=1  tmp1=3.619e-010  $ Fiber
3: 3rd Section: Vertical Section of Silica Multi-Mode Fiber in Experimental Volume
2464 24 -2.648  -1092 1442 -1443 u=10 imp:n=1 imp:p=1  tmp1=3.619e-010  $ Fiber
3: 4th Section: Vertical Section of Silica Multi-Mode Fiber in Experimental Volume
2465 24 -2.648  -1092 1443 -1232 u=10 imp:n=1 imp:p=1  tmp1=3.619e-010  $ Fiber
3: 5th Section: Vertical Section of Silica Multi-Mode Fiber in Experimental Volume
2466 24 -2.648  -1102 -1444 1230 u=10 imp:n=1 imp:p=1  tmp1=3.619e-010  $ Fiber
3: 1st Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube
2467 24 -2.648  -1102 -1445 1440 u=10 imp:n=1 imp:p=1  tmp1=3.619e-010  $ Fiber
3: 2nd Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube
2468 24 -2.648  -1102 -1446 1445 u=10 imp:n=1 imp:p=1  tmp1=3.619e-010  $ Fiber
3: 3rd Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube
2469 24 -2.648  -1102 -1447 1446 u=10 imp:n=1 imp:p=1  tmp1=3.619e-010  $ Fiber
3: 4th Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube
2470 24 -2.648  -1102 -1448 1447 u=10 imp:n=1 imp:p=1  tmp1=3.619e-010  $ Fiber
3: 5th Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube
2471 24 -2.648  -1102 -1449 1448 u=10 imp:n=1 imp:p=1  tmp1=3.619e-010  $ Fiber
3: 6th Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube
2472 24 -2.648  -1102 -1450 1449 u=10 imp:n=1 imp:p=1  tmp1=3.619e-010  $ Fiber
3: 7th Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube
2473 24 -2.648  -1102  1450 u=10 imp:n=1 imp:p=1  tmp1=3.619e-010  $ Fiber
3: 8th Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube

2481 14  -3.980  -1093 1272 -1440 u=10 imp:n=1 imp:p=1  tmp1=3.619e-010  $ Fiber
4: 1st Section: Vertical Section of Sapphire Multi-Mode Fiber in Experimental Volume
2482 14  -3.980  -1093 1440 -1441 u=10 imp:n=1 imp:p=1  tmp1=3.619e-010  $ Fiber
4: 2nd Section: Vertical Section of Sapphire Multi-Mode Fiber in Experimental Volume
2483 14  -3.980  -1093 1441 -1442 u=10 imp:n=1 imp:p=1  tmp1=3.619e-010  $ Fiber
4: 3rd Section: Vertical Section of Sapphire Multi-Mode Fiber in Experimental Volume
2484 14  -3.980  -1093 1442 -1443 u=10 imp:n=1 imp:p=1  tmp1=3.619e-010  $ Fiber
4: 4th Section: Vertical Section of Sapphire Multi-Mode Fiber in Experimental Volume
4: 5th Section: Vertical Section of Sapphire Multi-Mode Fiber in Experimental Volume
2486 24 -2.648 -1103 -1444 1230 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Fiber
4: 1st Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube Spliced to Sapphire
2487 24 -2.648 -1103 -1445 1444 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Fiber
4: 2nd Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube Spliced to Sapphire
2488 24 -2.648 -1103 -1446 1445 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Fiber
4: 3rd Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube Spliced to Sapphire
2489 24 -2.648 -1103 -1447 1446 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Fiber
4: 4th Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube Spliced to Sapphire
2490 24 -2.648 -1103 -1448 1447 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Fiber
4: 5th Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube Spliced to Sapphire
2491 24 -2.648 -1103 -1449 1448 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Fiber
4: 6th Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube Spliced to Sapphire
2492 24 -2.648 -1103 -1450 1449 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Fiber
4: 7th Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube Spliced to Sapphire
2493 24 -2.648 -1103 -1450 1450 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Fiber 4:
8th Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube Spliced to Sapphire
2501 24 -2.648 -1094 1272 -1440 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Fiber
5: 1st Section: Vertical Section of Silica Single-Mode Fiber in Experimental Volume
2502 24 -2.648 -1094 1440 -1441 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Fiber
5: 2nd Section: Vertical Section of Silica Single-Mode Fiber in Experimental Volume
2503 24 -2.648 -1094 1441 -1442 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Fiber
5: 3rd Section: Vertical Section of Silica Single-Mode Fiber in Experimental Volume
2504 24 -2.648 -1094 1442 -1443 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Fiber
5: 4th Section: Vertical Section of Silica Single-Mode Fiber in Experimental Volume
2505 24 -2.648 -1094 1443 -1232 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Fiber
5: 5th Section: Vertical Section of Silica Single-Mode Fiber in Experimental Volume
2506 24 -2.648 -1104 -1444 1230 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Fiber
5: 1st Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
2507 24 -2.648 -1104 -1445 1444 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Fiber
5: 2nd Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
2508 24 -2.648 -1104 -1446 1445 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010 $ Fiber
5: 3rd Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube
5: 4th Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube

5: 5th Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube

5: 6th Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube

5: 7th Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube

5: 8th Section: Vertical Section of Silica Single-Mode Fiber in Vacuum Tube

6: 1st Section: Vertical Section of Silica FBG Fiber in Experimental Volume

6: 2nd Section: Vertical Section of Silica FBG Fiber in Experimental Volume

6: 3rd Section: Vertical Section of Silica FBG Fiber in Experimental Volume

6: 4th Section: Vertical Section of Silica FBG Fiber in Experimental Volume

6: 5th Section: Vertical Section of Silica FBG Fiber in Experimental Volume

6: 6th Section: Vertical Section of Silica FBG Fiber in Experimental Volume

6: 7th Section: Vertical Section of Silica FBG Fiber in Experimental Volume

6: 8th Section: Vertical Section of Silica FBG Fiber in Experimental Volume

7: 1st Section: Vertical Section of Silica Multi-Mode Fiber in Experimental Volume

7: 2nd Section: Vertical Section of Silica Multi-Mode Fiber in Experimental Volume

7: 3rd Section: Vertical Section of Silica Multi-Mode Fiber in Experimental Volume
Fiber 7: 4th Section: Vertical Section of Silica Multi-Mode Fiber in Experimental Volume
2544 24 -2.648  -1096 1442 -1443 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
7: 4th Section: Vertical Section of Silica Multi-Mode Fiber in Experimental Volume
2545 24 -2.648  -1096 1443 -1232 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
7: 5th Section: Vertical Section of Silica Multi-Mode Fiber in Experimental Volume
2546 24 -2.648  -1106 -1444 1230 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
7: 1st Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube
2547 24 -2.648  -1106 -1445 1444 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
7: 2nd Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube
2548 24 -2.648  -1106 -1446 1445 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
7: 3rd Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube
2549 24 -2.648  -1106 -1447 1446 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
7: 4th Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube
2550 24 -2.648  -1106 -1448 1447 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
7: 5th Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube
2551 24 -2.648  -1106 -1449 1448 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
7: 6th Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube
2552 24 -2.648  -1106 -1450 1449 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
7: 7th Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube
2553 24 -2.648  -1106 -1450 1450 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
7: 8th Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube
2554 24 -2.648  -1106 -1451 1451 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
8: 1st Section: Vertical Section of Sapphire Multi-Mode Fiber in Experimental Volume
2555 14 -3.980  -1097 1272 -1440 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
8: 1st Section: Vertical Section of Sapphire Multi-Mode Fiber in Experimental Volume
2556 14 -3.980  -1097 1440 -1441 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
8: 2nd Section: Vertical Section of Sapphire Multi-Mode Fiber in Experimental Volume
2557 14 -3.980  -1097 1441 -1442 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
8: 3rd Section: Vertical Section of Sapphire Multi-Mode Fiber in Experimental Volume
2558 14 -3.980  -1097 1442 -1443 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
8: 4th Section: Vertical Section of Sapphire Multi-Mode Fiber in Experimental Volume
2559 14 -3.980  -1097 1443 -1232 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
8: 5th Section: Vertical Section of Sapphire Multi-Mode Fiber in Experimental Volume
2560 24 -2.648  -1107 -1444 1230 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
8: 1st Section: Vertical Section of Sapphire Multi-Mode Fiber in Vacuum Tube Spliced to Sapphire
2561 14 -3.980  -1097 1272 -1440 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
8: 1st Section: Vertical Section of Sapphire Multi-Mode Fiber in Vacuum Tube Spliced to Sapphire
2562 14 -3.980  -1097 1440 -1441 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
8: 2nd Section: Vertical Section of Sapphire Multi-Mode Fiber in Vacuum Tube Spliced to Sapphire
2563 14 -3.980  -1097 1441 -1442 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
8: 3rd Section: Vertical Section of Sapphire Multi-Mode Fiber in Vacuum Tube Spliced to Sapphire
2564 14 -3.980  -1097 1442 -1443 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
8: 4th Section: Vertical Section of Sapphire Multi-Mode Fiber in Vacuum Tube Spliced to Sapphire
2565 14 -3.980  -1097 1443 -1232 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
8: 5th Section: Vertical Section of Sapphire Multi-Mode Fiber in Vacuum Tube Spliced to Sapphire
2566 24 -2.648  -1107 -1444 1230 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
8: 1st Section: Vertical Section of Sapphire Multi-Mode Fiber in Vacuum Tube Spliced to Sapphire
2567 24 -2.648  -1107 -1445 1444 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
8: 2nd Section: Vertical Section of Sapphire Multi-Mode Fiber in Vacuum Tube Spliced to Sapphire
2568 24 -2.648  -1107 -1446 1445 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
8: 3rd Section: Vertical Section of Sapphire Multi-Mode Fiber in Vacuum Tube Spliced to Sapphire
2569 24 -2.648  -1107 -1447 1446 u=10 imp:n=1 imp:p=1 tmp1=3.619e-010  $ Fiber
8: 4th Section: Vertical Section of Sapphire Multi-Mode Fiber in Vacuum Tube Spliced to Sapphire
8: 5th Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube Spliced to Sapphire
8: 6th Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube Spliced to Sapphire
8: 7th Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube Spliced to Sapphire
8: 8th Section: Vertical Section of Silica Multi-Mode Fiber in Vacuum Tube Spliced to Sapphire

**Fibers 9&10**

9: Horizontal Section of Sapphire Multi-Mode Fiber

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**Surface cards**

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$ Cryostat central vacuum tube above cryostat
$ Cryostat Main Dewar Top KF-25 flange top wide ring outside, and width of transfer tube
$ Cryostat Main Dewar Top KF-25 flange narrow neck outside
$ Cryostat Main Dewar Top bottom of KF-25 mating flange top outer radius
$ Cryostat Main Dewar Top

$ Outer cylinder surface for air between cryostat outer surface and dry tube inner surface *** Not in use
$ Cryostat Main Dewar outer wall outside
$ Cryostat Main Dewar outer wall inside
1041  c/z  2.76225  0 0.10875  $ Right Fiber Tube IR
1042  c/z  2.76225  0 0.15875  $ Right Fiber Tube OR
1043  cz  3.5587  $ Manganin Heating Wire Analogous Cylinder Outer Radius (IR = Superinsulation)
1090  c/z  -2.76925 0.007 0.00625  $ Fiber 1: Silica Single-Mode Off-the-shelf Fiber
1091  c/z  -2.75525 0.007 0.00625  $ Fiber 2: Silica Single-Mode FBG Fiber
1092  c/z  -2.75525 -0.007 0.005  $ Fiber 3: Silica Multi-Mode Fiber
1093  c/z  -2.76925 -0.007 0.006  $ Fiber 4: Sapphire Multi-Mode Fiber
1094  c/z  2.76925 0.007 0.00625  $ Fiber 5: Silica Single-Mode Off-the-shelf Fiber
1095  c/z  2.75525 0.007 0.00625  $ Fiber 6: Silica Single-Mode FBG Fiber
1096  c/z  2.75525 -0.007 0.005  $ Fiber 7: Silica Multi-Mode Fiber
1097  c/z  2.76925 -0.007 0.006  $ Fiber 8: Sapphire Multi-Mode Fiber
1098  c/x -0.007 -11.49375 0.00625  $ Fiber 9: Horizontal Section of Silica Multi-Mode Fiber
1099  c/x  0.007 -11.49375 0.00625  $ Fiber 10: Horizontal Section of Sapphire Multi-Mode Fiber
1100  c/z  0.15559 0.021 0.00625  $ Fiber 1: Silica Single-Mode Off-the-shelf Fiber
1101  c/z  0.15559 0.007 0.00625  $ Fiber 2: Silica Single-Mode FBG Fiber
1102  c/z  0.15559 -0.007 0.006  $ Fiber 3: Silica Multi-Mode Fiber
1103  c/z  0.15559 -0.021 0.005  $ Fiber 4: Sapphire Multi-Mode Fiber
1104  c/z -0.15559 0.021 0.00625  $ Fiber 5: Silica Single-Mode Off-the-shelf Fiber
1105  c/z -0.15559 0.007 0.00625  $ Fiber 6: Silica Single-Mode FBG Fiber
1106  c/z -0.15559 -0.007 0.006  $ Fiber 7: Silica Multi-Mode Fiber
1107  c/z -0.15559 -0.021 0.005  $ Fiber 8: Sapphire Multi-Mode Fiber
1110  c/z  0 9.5758 0.9525  $ 5.5" Aluminum Stand Post 1 for supporting Cryostat
1111  c/z  0 -9.5758 0.9525  $ 5.5" Aluminum Stand Post 2 for supporting Cryostat
1112  c/z -9.5758 0 0.9525  $ 5.5" Aluminum Stand Post 3 for supporting Cryostat
1113  c/z  9.5758 0 0.9525  $ 5.5" Aluminum Stand Post 4 for supporting Cryostat
1114  cz  11.7475  $ 5.5" Aluminum Stand Top and Bottom Outer Radius
356

****Dry Tube Planar Surfaces****

1201  pz  -106.680  $ Bottom of dry tube outer wall **(Already covered by Pool Floor (030))
1202  pz  -104.775  $ Bottom of dry tube inner wall
1203  pz  -38.100  $ Top of Steel Plates
5003  pz  -38.100001  $ Top of Steel Plates for SSW SSR
1204  pz  74.930  $ Dry Tube - Bottom of flange connection 1
1205  pz  78.74  $ Dry Tube - Top of flange connection 1

****Cryostat Planar Surfaces****
<table>
<thead>
<tr>
<th>Page</th>
<th>Value</th>
<th>Measurement</th>
</tr>
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<tbody>
<tr>
<td>1206</td>
<td>134.643</td>
<td>Top of flange connection</td>
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<tr>
<td>1207</td>
<td>134.275</td>
<td>Top piece of flange connection underside</td>
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<tr>
<td>1208</td>
<td>130.175</td>
<td>Bottom piece of flange connection underside</td>
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<tr>
<td>1209</td>
<td>129.540</td>
<td>Top of Main Dewar Top</td>
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<tr>
<td>1210</td>
<td>128.270</td>
<td>Top of Main Dewar outside wall</td>
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<tr>
<td>1211</td>
<td>120.015</td>
<td>Top of Main Dewar inside wall</td>
</tr>
<tr>
<td>1212</td>
<td>115.761</td>
<td>Reflective Aluminum Structural Support Ring #1 Top</td>
</tr>
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<td>115.443</td>
<td>Reflective Aluminum Structural Support Ring #1 Bottom</td>
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<td>108.966</td>
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<td>Reflective Aluminum Structural Support Ring #4 Bottom</td>
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<td>Bottom of Straw</td>
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<td>Top of Outer Canister Connecting Joint to vacuum tube</td>
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<td>1222</td>
<td>11.43</td>
<td>Top of Outer Canister Mounting Rings</td>
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<tr>
<td>1223</td>
<td>10.389</td>
<td>Bottom of Outer Canister Mounting Rings or Top of Outer Canister Top outside</td>
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<tr>
<td>1224</td>
<td>10.071</td>
<td>Bottom of Outer Canister Mounting Rings or Top of Outer Canister Top inside</td>
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<tr>
<td>1225</td>
<td>7.153</td>
<td>Bottom of Outer Canister Mounting Top or Top of Outer Canister Flange</td>
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<td>1226</td>
<td>5.883</td>
<td>Bottom of Outer Canister Mounting Canister Flange</td>
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<tr>
<td>1228</td>
<td>4.575</td>
<td>Inner Canister G10 Mounting Joint Top</td>
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<td>1229</td>
<td>4.397</td>
<td>Top of Wire Wrapped around Inner Canister G10 Mounting Joint</td>
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<td>Bottom of Inner Canister Top Threaded Joint</td>
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<td>0.985</td>
<td>Wire Mounting Pegs</td>
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<td>Top of Weird Wire Mounting Block</td>
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<td>Bottom of Metal Center Mounting Block</td>
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<td>1242</td>
<td>-7.576</td>
<td>Top of 1st Metal Device Mounting Platform</td>
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<td>1243</td>
<td>-7.8935</td>
<td>Bottom of 1st Metal Device Mounting Platform</td>
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<td>Top of 2nd Metal Device Mounting Platform</td>
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<td>Bottom of 3rd Metal Device Mounting Platform</td>
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<td>Top of 4th Metal Device Mounting Platform</td>
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<td>Bottom of Al 1/4-20 Center Mounting Rod</td>
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<td>1260</td>
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<td>Part</td>
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<tr>
<td>1261</td>
<td>pz -11.872 $</td>
<td>Bottom of Inner Canister Outer Wall</td>
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<td>1262</td>
<td>pz -13.167 $</td>
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<td>pz -13.802 $</td>
<td>Bottom of Outer Canister Outer Wall</td>
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<td>1264</td>
<td>pz -14.9225 $</td>
<td>Inner wall of main Dewar bottom inside</td>
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<td>1265</td>
<td>pz -15.240 $</td>
<td>Inner wall of main Dewar bottom outside</td>
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<tr>
<td>1266</td>
<td>pz -30.1625 $</td>
<td>Outer wall of main Dewar bottom inside</td>
</tr>
<tr>
<td>1267</td>
<td>pz -30.480001 $</td>
<td>Outer wall of main Dewar bottom outside</td>
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<tr>
<td>1268</td>
<td>pz -31.75 $ 5.5&quot; Aluminum Spacer Cryostat Mounting Stand, Bottom of Top</td>
<td></td>
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<tr>
<td>1269</td>
<td>pz -43.18 $ 5.5&quot; Aluminum Spacer Cryostat Mounting Stand, Top of Bottom</td>
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<tr>
<td>1270</td>
<td>pz 0.62500 $</td>
<td>Manganin Wire: 1st Analogous Cylinder Top</td>
</tr>
<tr>
<td>1271</td>
<td>pz 0.60913 $</td>
<td>Manganin Wire: 1st Analogous Cylinder Bottom</td>
</tr>
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<td>1272</td>
<td>pz -1.79087 $</td>
<td>Manganin Wire: 2nd Analogous Cylinder Top</td>
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<td>1273</td>
<td>pz -1.80673 $</td>
<td>Manganin Wire: 2nd Analogous Cylinder Bottom</td>
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<td>pz -4.20673 $</td>
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<td>pz -6.62260 $</td>
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<td>1277</td>
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<td>1278</td>
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<td>Manganin Wire: 5th Analogous Cylinder Top</td>
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<td>1279</td>
<td>pz -9.05433 $</td>
<td>Manganin Wire: 5th Analogous Cylinder Bottom</td>
</tr>
<tr>
<td>1280</td>
<td>BOX -10.16 -36.87 -15.24</td>
<td>Dry Tube Hard Flux Nitrogen Gas Box Outside</td>
</tr>
<tr>
<td>1282</td>
<td>BOX 1.2750 0.0000 32.4480 0.1703 0.0150 0.0000 -0.4800 5.4480 &amp; 0.0000 0.0000 0.0000 -8.9789</td>
<td>G10 Structural support plane connector 1</td>
</tr>
<tr>
<td>1283</td>
<td>BOX -1.2750 0.0000 32.4480 -0.1703 0.0150 0.0000 0.4800 5.4480 &amp; 0.0000 0.0000 0.0000 -9.2200</td>
<td>G10 Structural support plane connector 2</td>
</tr>
<tr>
<td>1284</td>
<td>BOX 0.9092 0.20503 -1.039 -1.1142 -1.1142 0 -0.70417 0.70417 &amp; 0 0 0 -5.197</td>
<td>Aluminum Mounting Block Box</td>
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<tr>
<td>1285</td>
<td>BOX 2.1708 0.72361 -2.774 -0.12726 -0.12726 0 -1.4472 1.4472 &amp; 0 0 0 -2.832</td>
<td>Plastic Side Mounting Support Box 1 for Plastic Pin Box</td>
</tr>
<tr>
<td>1286</td>
<td>BOX -0.59635 -2.0436 -2.774 -0.12726 -0.12726 0 -1.4472 1.4472 &amp; 0 0 0 -2.832</td>
<td>Plastic Side Mounting Support Box 2 for Plastic Pin Box</td>
</tr>
</tbody>
</table>
c Plastic Pin Box (approximated as box)
1307 BOX  2.775 -0.13504 -2.421 -2.6399 0 -0.7975 0.7975 0 0 0 & 
-3.627
c Al Hexagonal 1/4-20 Nut 1
1314 RHP 0.00000 0.00000 -11.00000 0.00000 0.00000 0.53850 &
  0.39097 0.39097 0.00000
c Al Hexagonal 1/4-20 Nut 2
1315 RHP 0.00000 0.00000 -10.14400 0.00000 0.00000 0.53850 &
  0.39097 0.39097 0.00000
c Al Hexagonal 1/4-20 Nut 3
1316 RHP 0.00000 0.00000 -9.28800 0.00000 0.00000 0.53850 &
  0.39097 0.39097 0.00000
c Al Hexagonal 1/4-20 Nut 4
1317 RHP 0.00000 0.00000 -8.43200 0.00000 0.00000 0.53850 &
  0.39097 0.39097 0.00000
c Al Hexagonal 1/4-20 Nut 5
1318 RHP 0.00000 0.00000 -7.57600 0.00000 0.00000 0.53850 &
  0.39097 0.39097 0.00000
c ** Surfaces for GaN/GaAs Device Experiments (universe 9) **
c c * Duroid Board Dialectric Substrates *
c c Duroid Board 1
1319 BOX -0.074235 1.2761 -7.576 1.3504 -1.3504 0 1.3504 1.3504 &
  0 0 0 0.0062
c Duroid Board 2
1320 BOX  1.2761 0.074235 -7.576 -1.3504 -1.3504 0 1.3504 -1.3504 &
  0 0 0 0.0062
c Duroid Board 3
1321 BOX  0.074235 -1.2761 -7.576 -1.3504 1.3504 0 -1.3504 -1.3504 &
  0 0 0 0.0062
c Duroid Board 4
1322 BOX -1.2761 -0.074235 -7.576 1.3504 1.3504 0 -1.3504 1.3504 &
  0 0 0 0.0062
c Duroid Board 5
1323 BOX -0.074235 1.2761 -8.432 1.3504 -1.3504 0 1.3504 1.3504 &
  0 0 0 0.0062
c Duroid Board 6
c Duroid Board 7
1325  BOX  0.074235 -1.2761 -8.432 -1.3504 1.3504 0 -1.3504 -1.3504 &
       0 0 0 0.0062

c Duroid Board 8
1326  BOX  -1.2761 -0.074235 -8.432 1.3504 1.3504 0 -1.3504 1.3504 &
       0 0 0 0.0062

c Duroid Board 9
1327  BOX  -0.074235 1.2761 -9.288 1.3504 -1.3504 0 1.3504 1.3504 &
       0 0 0 0.0062

c Duroid Board 10
1328  BOX  1.2761 0.074235 -9.288 -1.3504 1.3504 0 -1.3504 1.3504 &
       0 0 0 0.0062

c Duroid Board 11
1329  BOX  0.074235 -1.2761 -9.288 1.3504 1.3504 0 -1.3504 1.3504 &
       0 0 0 0.0062

c Duroid Board 12
1330  BOX  -1.2761 -0.074235 -9.288 1.3504 1.3504 0 1.3504 1.3504 &
       0 0 0 0.0062

c Duroid Board 13
1331  BOX  -0.074235 1.2761 -10.144 1.3504 -1.3504 0 1.3504 1.3504 &
       0 0 0 0.0062

c Duroid Board 14
1332  BOX  1.2761 0.074235 -10.144 -1.3504 1.3504 0 -1.3504 1.3504 &
       0 0 0 0.0062

c Duroid Board 15
1333  BOX  0.074235 -1.2761 -10.144 -1.3504 1.3504 0 1.3504 1.3504 &
       0 0 0 0.0062

c Duroid Board 16
1334  BOX  -1.2761 -0.074235 -10.144 1.3504 1.3504 0 -1.3504 1.3504 &
       0 0 0 0.0062

c * Device and Packaging Materials *

GaAs Device Plast
1383  BOX  0.90142 1.2266 -7.5698 0.32522 -0.32522 0 0.18382 0.18382 &
       0 0 0 0.16

GaAs Device Sn/Cu Leads 1
1384  BOX  0.97212 1.0994 -7.5698 0.12726 -0.12726 0 0.29694 0.29694 &
       0 0 0 0.04

GaAs Device 1
1385  BOX  0.93677 1.2266 -7.5448 0.28987 -0.28987 0 0.14847 0.14847 &
       0 0 0 0.11

GaAs Device Plastic Packaging 2
1386  BOX 1.2266 -0.90142 -7.5698 -0.32522 -0.32522 0 0.18382 -0.18382 &
       0 0 0 0.16
   c GaAs Device Sn/Cu Leads 2
1387  BOX 1.0994 -0.97212 -7.5698 0.29694 -0.29694 0 -0.12726 -0.12726 &
       0 0 0 0.04
   c GaAs Device 2
1388  BOX 1.2266 -0.93677 -7.5448 -0.28987 -0.28987 0 0.14847 -0.14847 &
       0 0 0 0.11
   c GaAs Device Plastic Packaging 3
1389  BOX -0.90142 -1.2266 -7.5698 -0.32522 0.32522 0 -0.18382 -0.18382 &
       0 0 0 0.16
   c GaAs Device Sn/Cu Leads 2
1390  BOX -0.97212 -1.0994 -7.5698 0.12726 0.12726 0 -0.29694 -0.29694 &
       0 0 0 0.04
   c GaAs Device 3
1391  BOX -0.93677 -1.2266 -7.5448 -0.28987 0.28987 0 -0.14847 -0.14847 &
       0 0 0 0.11
   c GaAs Device Plastic Packaging 4
1392  BOX -1.2266 0.90142 -7.5698 0.32522 0.32522 0 -0.18382 0.18382 &
       0 0 0 0.16
   c GaAs Device Sn/Cu Leads 4
1393  BOX -1.0994 0.97212 -7.5698 0.12726 0.12726 0 -0.29694 0.29694 &
       0 0 0 0.04
   c GaAs Device 4
1394  BOX -1.2266 0.93677 -7.5448 -0.28987 0.28987 0 -0.14847 0.14847 &
       0 0 0 0.11
   c GaAs Device Plastic Packaging 5
1395  BOX 0.90142 1.2266 -8.4258 0.32522 -0.32522 0 0.18382 0.18382 &
       0 0 0 0.16
   c GaAs Device Sn/Cu Leads 5
1396  BOX 0.97212 1.0994 -8.4258 0.12726 -0.12726 0 0.29694 0.29694 &
       0 0 0 0.04
   c GaAs Device 5
1397  BOX 0.93677 1.2266 -8.4008 0.28987 -0.28987 0 0.14847 0.14847 &
       0 0 0 0.11
   c GaAs Device Plastic Packaging 6
1398  BOX 1.2266 -0.90142 -8.4258 -0.32522 -0.32522 0 0.18382 -0.18382 &
       0 0 0 0.16
   c GaAs Device Sn/Cu Leads 6
1399  BOX 1.0994 -0.97212 -8.4258 0.29694 -0.29694 0 -0.12726 -0.12726 &
       0 0 0 0.04
   c GaAs Device 6
1400  BOX 1.2266 -0.93677 -8.4008 -0.28987 -0.28987 0 0.14847 -0.14847 &
       0 0 0 0.11

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c GaAs Device Plastic Packaging 12
1416 BOX -1.2266 0.90142 -9.2818 0.32522 0.32522 0 -0.18382 0.18382 &
0 0 0 0.16

c GaAs Device Sn/Cu Leads 12
1417 BOX -1.0994 0.97212 -9.2818 0.12726 0.12726 0 -0.29694 0.29694 &
0 0 0 0.04

c GaAs Device 12
1418 BOX -1.2266 0.93677 -9.2568 0.28987 0.28987 0 -0.14847 0.14847 &
0 0 0 0.11

c GaAs Device Plastic Packaging 13
1419 BOX 0.90142 1.2266 -10.1378 0.32522 -0.32522 0 0.18382 0.18382 &
0 0 0 0.16

c GaAs Device Sn/Cu Leads 13
1420 BOX 0.97212 1.0994 -10.1378 0.12726 -0.12726 0 0.29694 0.29694 &
0 0 0 0.04

c GaAs Device 13
1421 BOX 0.93677 1.2266 -10.1128 0.28987 -0.28987 0 0.14847 0.14847 &
0 0 0 0.11

c GaAs Device Plastic Packaging 14
1422 BOX 1.2266 -0.90142 -10.1378 -0.32522 -0.32522 0 0.18382 -0.18382 &
0 0 0 0.16

c GaAs Device Sn/Cu Leads 14
1423 BOX 1.0994 -0.97212 -10.1378 0.29694 -0.29694 0 -0.12726 -0.12726 &
0 0 0 0.04

c GaAs Device 14
1424 BOX 1.2266 -0.93677 -10.1128 -0.28987 -0.28987 0 0.14847 -0.14847 &
0 0 0 0.11

c GaAs Device Plastic Packaging 15
1425 BOX -0.90142 -1.2266 -10.1378 -0.32522 0.32522 0 -0.18382 -0.18382 &
0 0 0 0.16

c GaAs Device Sn/Cu Leads 15
1426 BOX -0.97212 -1.0994 -10.1378 -0.12726 0.12726 0 -0.29694 -0.29694 &
0 0 0 0.04

c GaAs Device 15
1427 BOX -0.93677 -1.2266 -10.1128 -0.28987 0.28987 0 -0.14847 -0.14847 &
0 0 0 0.11

c GaAs Device Plastic Packaging 16
1428 BOX -1.2266 0.90142 -10.1378 0.32522 0.32522 0 -0.18382 0.18382 &
0 0 0 0.16

c GaAs Device Sn/Cu Leads 16
1429 BOX -1.0994 0.97212 -10.1378 0.12726 0.12726 0 -0.29694 0.29694 &
0 0 0 0.04

c GaAs Device 16

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c

**** Fiber Planes ****

c 1271  pz  -11.250  $ Bottom of Fiber Tube
1272  pz  -11.500  $ Bottom of Vertical Fibers
1440  pz  -8.5  $ Fibers in Experimental Volume: Top of Fiber Sections 1
1441  pz  -5.5  $ Fibers in Experimental Volume: Top of Fiber Sections 2
1442  pz  -2.5  $ Fibers in Experimental Volume: Top of Fiber Sections 3
1443  pz  -0.5  $ Fibers in Experimental Volume: Top of Fiber Sections 4

c Top of Fiber Sections 5 is equal to the bottom of the threads on the inner canister top
1444  pz  8.343  $ Fibers in Vacuum Tube: Top of Fiber Sections 1
1445  pz  13.343  $ Fibers in Vacuum Tube: Top of Fiber Sections 2
1446  pz  23.343  $ Fibers in Vacuum Tube: Top of Fiber Sections 3
1447  pz  33.343  $ Fibers in Vacuum Tube: Top of Fiber Sections 4
1448  pz  43.343  $ Fibers in Vacuum Tube: Top of Fiber Sections 5
1449  pz  63.343  $ Fibers in Vacuum Tube: Top of Fiber Sections 6
1450  pz  83.343  $ Fibers in Vacuum Tube: Top of Fiber Sections 7

c Top of Fiber Sections 8 is equal to the top outer wall of the main Dewar
1460  px  -2.749  $ Left Side of Horizontal Section of Fibers
1461  px  2.749  $ Right Side of Horizontal Section of Fibers

***********************************************************************
***********************************************************************
**** Data cards ****
***********************************************************************

Transformation from the cryostat experiment coordinate system to
the full core coordinate system (universe 10)

tr400  0 -44.49 6.350 1 0 0 0 1 0 0 1 1

surface source write

ssw  -5004(6001) 5003(6005) -5010(6007) SYM=0 $ 10in Dry Tube

** Cryostat Experiment Tallies for use with SSR run**

fc4 Fluence averaged over GaAs device cells per NPS
f4:n 2094 2108 2122 2136 2150 2164 2178 2192 2206 2220 2234 2248 &
f 2262 2276 2290 2304 2421 2422 2423 2424 2425 2426 2427 2428 2429 2430 &
f 2431 2432 2433 2441 2442 2443 2444 2445 2446 2447 2448 2449 &
Fluence averaged over GaAs device cells per NPS.

Fluence averaged over GaAs device cells per NPS.

Displacement damage tally.

Tally bins.

Displacement damage tally.

Tally bins.
<table>
<thead>
<tr>
<th>Energy Deposition Type</th>
<th>Column Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron</td>
<td>2030-2031, 2033-2034, 2035-2036, 2044-2045, 2046-2047, 2048-2049, 2050-2054</td>
</tr>
<tr>
<td>Photon</td>
<td>2030-2031, 2033-2034, 2035-2036, 2044-2045, 2046-2047, 2048-2049, 2050-2054</td>
</tr>
</tbody>
</table>
Material compositions

Material #1 - Fuel:

m1  92235.70c  0.0365
    92238.70c  0.1479
    13027.70c  0.1229
    14000.60c  0.6927

Material #2 - Aluminum: 2.70 g/cc

m2  13027.70c  1.000
mt2  al27.12t

Material #3 - Water: 1.00 g/cc

m3  01001.70c  0.667
    08016.70c  0.333
mt3  lwtr.60t

Material #4 - Graphite: 1.70 g/cc

m4  06000.70c  1.000
mt4  grph.60t

Material #5 - Barytes Concrete: 3.35 g/cc

m5  01001.70c  0.110
    08016.70c  0.600
    20000.62c  0.040
16032.70c 0.100  19000.62c 0.040  56138.70c 0.110

Material #7 - Shim Safety Boron Stainless Steel
m7  26000.55c -0.715  24000.50c -0.185  28000.50c -0.085
    05010.70c -0.015

Material #8 - Reg Rod Stainless Steel
m8  26000.55c 0.699  24000.50c 0.185  28000.50c 0.085
    25055.70c 0.020  14000.60c 0.010  06000.70c 0.001

Material #14 - Sapphire 3.980 g/cc
m14  13027.70c  0.4
     8016.70c  0.6

Material #18 - Al-6061 plates
m18  22046.70c  7.04229E-05
     22047.70c  6.35086E-05
     22048.70c  0.000629282
     22049.70c  4.61803E-05
     22050.70c  4.4217E-05
     13027.70c  0.969190704
     24050.70c  7.96694E-05
     24052.70c  0.001536346
     24053.70c  0.000174209
     24054.70c  4.33644E-05
     26054.70c  0.000199574
     26056.70c  0.003132878
     26057.70c  7.23518E-05
     26058.70c  9.6287E-06
     29063.70c  0.001186026
     29065.70c  0.000528628
     12024.70c  0.010623374
     12025.70c  0.001344901
     12026.70c  0.001480736
     25055.70c  0.000743743
     14028.70c  0.007156238
     14029.70c  0.000362351
     14030.70c  0.000240533
     30000.70c  0.001041135
c Material #20 - G10 Plastic 1.8 g/cc

m20  08016.70c  6.38183E-01
     8017.70c  2.42602E-04
     14028.70c  2.21530E-01
     14029.70c  1.12170E-02
     14030.70c  7.44600E-03
     20040.70c  3.81397E-02
     20042.70c  2.54550E-04
     20043.70c  5.31133E-05
     20044.70c  8.20698E-04
     20046.70c  1.57373E-06
     20048.70c  7.35717E-05
     13027.70c  2.46388E-03
     12024.70c  1.08098E-02
     12025.70c  1.36850E-03
     12026.70c  1.50672E-03
     11023.70c  6.42821E-02
     16032.70c  1.52657E-03
     16033.70c  1.20493E-05
     16034.70c  6.76370E-05
     16036.70c  3.21316E-07

c Material #21 - Super Insulation 2.528 g/cc

m21  13027.70c  9.83409E-01
     14028.70c  6.16093E-05
     14029.70c  3.11954E-06
     14030.70c  2.07079E-06
     29063.70c  1.00625E-03
     29065.70c  4.48498E-04
     26054.70c  3.90444E-06
     26056.70c  6.12913E-05
     26057.70c  1.41548E-06
     26058.70c  1.88375E-07
     12024.70c  1.14910E-03
     12025.70c  1.45475E-04
     12026.70c  1.60168E-04
     25055.70c  2.96887E-05
     6012.50d  6.07910E-03
     6013.42c  6.57499E-05
     1001.70c  4.91532E-03
     1002.70c  5.65327E-07
     8016.70c  2.45701E-03
c Material #23 - Heating Element (Manganin Wire) 8.7194 g/cc estimate from constituents

m23 29063.70c 5.60832E-01
    29065.70c 2.49971E-01
    25055.70c 1.46891E-01
    28058.70c 2.88005E-02
    28060.70c 1.10938E-02
    28061.70c 4.82285E-04
    28062.70c 1.53739E-03
    28064.70c 3.91751E-04

c Material #24 - Silica (Silicon Dioxide) 2.648 g/cc

m24 14028.70c 3.07403E-01
    14029.70c 1.55651E-02
    14030.70c 1.03323E-02
    8016.70c 6.66447E-01
    8017.70c 2.53346E-04

c Material #25 - Nitrogen Liquid Density = 0.807 g/cc, Gaseous Density here = 0.00173 g/cc

m25 7014.70c 0.99634
    7015.70c 0.00366

c Material #26 - GaAs 5.3176 g/cc

m26 31069.70c 3.00540E-01
    31071.70c 1.99460E-01
    33075.70c 5.00000E-01

c Material #28 - Common Plastic (Pure Polyethylene, specifically low-density polyethylene (estimate (C2H4)3H2)) (Wikipedia: density = 0.91-0.94 g/cc) 0.925 g/cc

m28 6012.50d 1.48395E-01
    6013.42c 1.60500E-03
    1001.70c 8.49902E-01
    1002.70c 9.77500E-05

c Material #30 - GaAs Device Package Leads, Copper with Silver and Tin Plating 8.7939 g/cc
c
m30 29063.70c 6.06461E-01
   29065.70c 2.70308E-01
   47107.70c 3.34693E-02
   47109.70c 3.10946E-02
   50112.70c 5.69073E-04
   50114.70c 3.87204E-04
   50115.70c 1.99469E-04
   50116.70c 8.53022E-03
   50117.70c 4.50565E-03
   50118.70c 1.42092E-02
   50119.70c 5.03952E-03
   50120.70c 1.91138E-02
   50122.70c 2.71630E-03
   50124.70c 3.39684E-03

c c Material #31 - Duroid Board Homogenized Material calculated density 3.1353 g/cc
c
m31 14028.70c 7.21946E-02
   14029.70c 3.65552E-03
   14030.70c 2.42658E-03
   8016.70c 1.72569E-01
   8017.70c 6.56012E-05
   6012.50c 1.00612E-01
   6013.42c 1.08819E-03
   1001.70c 1.24880E-01
   1002.70c 1.43629E-05
   29063.70c 3.61409E-01
   29065.70c 1.61085E-01

c c Material #32 - Air density 0.00121 g/cc
c
m32 6000.70c 0.000151 $ C
   7014.70c 0.784437 $ N
   8016.70c 0.210750 $ O
   18000 0.004671 $ Ar

c c Material #33 - MS-800 Device Wiring 8.50 g/cc
c
m33 28058.70c 4.84772E-01
   28060.70c 1.86732E-01
   28061.70c 8.11786E-03
   28062.70c 2.58775E-02
   28064.70c 6.59398E-03

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Material #34 - Liquid Helium 0.125 g/cc

Material #35 - Carbon Steel Plates 7.82 g/cc
References

8 Weber et. al 1998
13 H. Govindarajan, "Atomic-Scale Modeling of the Effects of Irradiation on Silica Optical Fibers," The Ohio State University, Columbus, 2011.


34 T. Hanada, "Basic Properties of ZnO, GaN, and Related Materials,”


