

Simulation and utilization of irradiation facilities

by

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Abstract

Simulations were created and utilized for different irradiation facilities to examine the effects that neutron and x-ray radiation has on Caco-2 and HepG2 cell cultures. Once outside Earth's geomagnetic field, the radiation environment becomes more harsh, causing there to be greater risk to the astronauts. One of the major risks of interplanetary space travel is space radiation-induced carcinogenesis. With increased duration of the mission, the risk to the astronauts increases. This increased risk of carcinogenesis causes the maximum duration of a mission to be limited. The radiation field that impinges upon the astronauts is complex and is made up of a variety of radiation types. The complex field of space radiation needs a terrestrial experimental source for comparative studies. The radiation that was primarily examined in this work was neutron and x-rays. The neutron sources that were simulated are the KSU TRIGA Mark II Thermal Column and deuterium-tritium fusion neutrons. The x-ray sources were a 6 MV Varian LINAC and a RadSource RS1800 biological irradiator.

Accurate understanding of the dose to astronauts is vital to astronaut safety and the success of the mission, which leads to the need for accurate models and simulation. The nuclear reactor model, which was partially modeled in a previous work, was upgraded to include the thermal column. An MCNP FMESH4 tally was used to determine the simulated neutron flux across the irradiation section of the thermal column. The output was converted to neutrons per kilowatt using the k_{eff} and $\bar{\nu}$.

The neutron generator experiment room was modeled in previous work. The neutron generator had to be moved as the previous simulation had the source placed in a different location and the cell cultures were modeled. The cell culture dishes were modeled and located inside of the experiment room where they would be placed in a physical experiment. The MCNP F6 energy deposition tally was used to determine the dose rate from the neutron generators on the cells.

The RS1800 was previously modeled, but the source term needed to be changed to account for the different voltage and current settings used for the experiments. The voltage and current control the x-ray spectrum; in the original model the settings were 130 kV and 1 mA for the voltage and current, respectively. For this work, the voltage was increased to 160 kV and either 1 mA or 12.5 mA were used for the current depending on if the irradiation was chronic or acute. An MCNP F4 tally was used with an energy-dependent response function to convert the flux density into dose rate.

Experiments were conducted to examine the effects induced in the cells by different types of radiation. The doses to the cells that were irradiated were accurately characterized for x-ray and neutrons. The neutrons came from a deuterium-tritium fusion neutron generator with energies of 14.1 MeV and a dose rate of approximately 60 mGy h⁻¹. The x-rays came from a RS1800 biological irradiator and a 6 MV LINAC; the dose rates of these machines varied and are discussed in the section with each experiment. In the neutron experiments, the dose rate was originally incorrectly found to be 5 mGy h⁻¹. The target dose in the neutron experiments was 40-80 mGy, which would have taken 48-106 min rather than the 8-16 hours used in the experiment. The increased dose to the cells led to high cell death and very little usable data after the experiment. The x-ray doses ranged from 0.5 Gy up to 16 Gy in some experiments. Multiple cell assays were used in the quantification of the radiation damage including cell viability, reactive oxygen species (ROS), and double-strand break (DSB). Cell viability assays examine the survivability of cells post exposure. ROS assays examine the reactive oxygen species created by the cell in response to the radiation. The DSB assay stains the double-strand breaks caused by damage to the DNA making them quantifiable. The assays all utilize immunostaining to generate the fluorescence that is seen in the confocal images. These images were analyzed to get the data. After irradiation of the cells and the different cell assays were performed, there was a dose dependent response in the cell death using a live/dead assay. There was no change seen in the cell viability using a MTT assay because of the cell density. There was little to no ROS generated in any of the experiments, since Caco-2 and HepG2 are epithelial cell lines. There was a dose dependent response to the DSB generated after x-ray exposure to acute exposure. There were significantly fewer DSB

generated after chronic exposure to x-rays, as expected, due to the smaller dose received at one time. In between fractions, the 24 hours of repair time allows for the cell to repair some of the DSBs.

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Dr. Jing Ding also assisted in performing the cell culturing and assays.

Dedication

This work is dedicated to my wife, parents and grandparents who supported and encouraged me throughout this entire process.

Chapter 1

Introduction

1.1 Space Radiation Environment

Crewed interplanetary space missions are currently anticipated in the future. One major plan is a mission to Mars, which has a considerable increase in the mission duration relative to an ISS mission. The increase in duration leads to more factors that will affect the crew, including isolation, partial gravity, and the radiation environment. Earth's atmosphere and magnetic field shield space radiation; once outside the realm of this protection, the radiation environment becomes more harsh². The radiation environment is comprised primarily of highly-energetic, heavy charged particles (HZE) from Galactic Cosmic Rays (GCRs) and Solar Particle Events (SPEs), which results in an increased risk of exposure-induced carcinogenesis. Space radiation-induced carcinogenesis is a major risk, with a Mars mission having up to 4% increased risk of cancer from one estimate^{3;4}. The risk to an individual is also dependent on biological factors such as age and sex. For example, an older male has a lower risk than a younger female exposed to the same dose. The risk of radiation induced cancer is lower for older people and males^{3;5}.

GCRs are high energy, fully-ionized atomic nuclei ranging from hydrogen up to trace amounts of plutonium. SPEs occur when charged particles are accelerated by solar activity to high velocities. These HZE interact in the spacecraft shielding material creating a secondary

field of broad Linear Energy Transfer (LET) spectrum that includes contributions from heavy ions, neutrons, pions, muons, electrons and other particles in the spacecraft incident on the crew⁶. On less shielded configurations, such as on the ISS compared to a Mars base configuration, the contribution to the dose from secondary neutrons is estimated to be 30%⁷. The dose contribution from secondary neutrons on a Mars base, which would be much more shielded, could be up to 50%⁷. This leads to the need for accurate knowledge of the dose to cell samples from space radiation, and the effects of the different types of space radiation on the target. Since the secondary neutron dose is estimated to be a major contributor to astronaut total dose, neutrons are of interest for space radiation protection.

The neutron interaction that is most common is scatter. Neutron scatter is split into two categories: elastic and inelastic scatter. In elastic scatter, the neutron collides with the target and the total energy and total momentum is left unchanged. Elastic scattering is sometimes compared to billiard balls colliding. Inelastic scatter involves some of the neutron energy being transferred to the target nucleus leaving it in an excited state, which then decays to the ground state by emitting gamma rays. Since neutron scattering is the most common type of interaction that occurs, the equation to calculate the maximum energy loss per elastic scatter is shown in Eq. 1.1. The equation shows that with a lower Z for the target nucleus, the higher the energy loss per interaction. Using hydrogen as the target nucleus, this leads to a maximum energy loss of 100% and an average energy loss of 50%.

$$\frac{E'}{E} = \frac{A^2 + 1 + 2A\cos(\theta)}{(1 + A)^2} \quad (1.1)$$

1.2 Radiobiology

The large amount of energy that can be deposited through hydrogen scattering leads to major cell damage in the crew as hydrogen is a large portion of the human body. Since neutrons are high-Linear Energy Transfer (LET) radiation, they cause different cell damage than photons, a low-LET radiation⁸. Low-LET radiation causes many scattered simpler damage sites to cells compared to the complex damage caused by higher LET radiation⁹. One damaging

effect caused by radiation is the DNA Double-Strand Break (DSB). This is caused when radiation interacts with the DNA in the nucleus of the cell, depositing energy and breaking both strands of the double helix. DSBs are more complicated and more difficult to repair than Single-Strand Breaks (SSBs), which occur when only one strand of the double helix is broken. DSB are commonly accepted as the most biologically significant lesion caused by radiation^{4;10;11}. One unrepaired DSB can cause permanent growth arrest and cell death¹². SSBs are easier to repair as the cells have the unbroken strand to use as a guide for how to repair the break. DSBs, though, do not have that unbroken strand guiding the cell on how to repair the break, leading to other pathways being activated to repair the broken double helix.

Two commonly examined methods of DSB repair are through 53BP1 and γ -H2AX. Both of these appear rapidly upon the DSB generation; within 15 minutes they can be seen via immunostaining¹³. Through studies conducted by other researchers, it has been found that the peak number of DSBs can be seen 30 minutes after irradiation with a time dependent decrease in number until background is reached¹⁴⁻¹⁶. γ -H2AX is a phosphorylated histone that recognizes DNA damage, recruiting ataxia teleangiectasia mutated (ATM) to stop the progression of the cell cycle and to activate the DNA repair proteins¹⁷. P53-binding protein 1 (53BP1) acts as a DSB signaling protein, beginning the repair pathways¹². Neutron interactions cause single large, complex DNA damage sites whereas lower-LET radiation such as photons cause many, simpler, damage sites. Fig. 1.1 contains Caco-2 cells irradiated with 3 Gy of x-rays examining the γ -H2AX repair mechanism. Since the sites are larger and more complex from neutron irradiation, the repair would take longer and be more difficult to complete when compared to more simple damage. DNA damage can lead to misrepair, then cancer or even cell death. DSBs are constantly being produced in metabolically-active cells, somewhere in the range of 10-50 DSBs per cell per day, depending on cell cycle and tissue type¹⁸.

Cell death is also vitally important to understand in relation to radiation dose, as losing cells causes other health issues to arise. The dependence on dose and cell viability is important to examine. There are several different methods to assess cell viability; a cou-

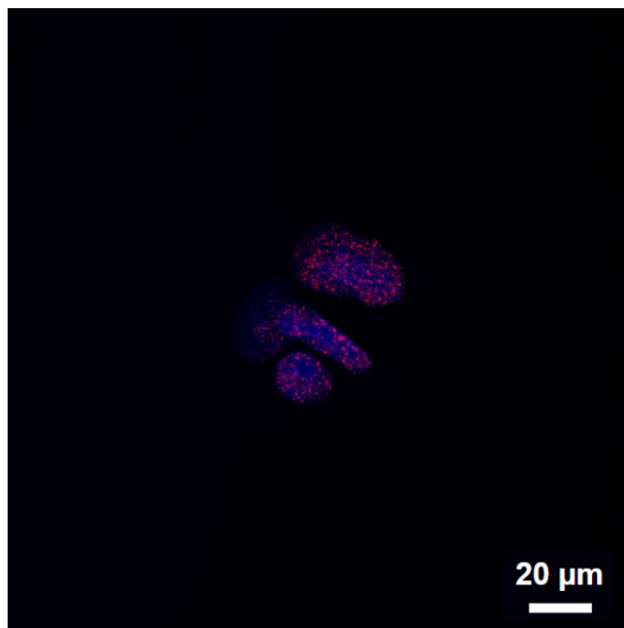


Figure 1.1: *Caco-2 cells irradiated with 3 Gy x-ray examining γ -H2AX DSB. The blue color is DAPI which stains the cell nucleus and the red dots are the DSBs*

ple are Live/Dead (L/D) assay and MTT assay. L/D assays utilizes EthD-1, which is a high-affinity nucleic acid stain. This stain is weakly fluorescent until bound with DNA and then it emits red fluorescence. As cells die, the boundaries between the nuclei and the rest of the cell begins to break down, which allows the dye to stain the DNA. In healthy cells, the stain cannot reach the DNA. For staining of live cells, Calcein AM is used, which is a cell-permeant dye. It is non-fluorescent compound that once it passes through the cell membrane it is converted to green or blue fluorescent Calcein by the cell. The conversions allows for the confocal images to be taken. The combination of these two dyes allows for the counting of live and dead cells. Based on previous studies, there is expected to be a dose dependent response to viability¹⁹⁻²¹. The other viability assay used is the MTT assay, which is a measure of cellular metabolic activity. This assay is based on the reduction of a yellow tetrazolium salt to a purple formazan crystal by metabolically active cells. The viable cells reduce the MTT to formazan. After the MTT has been reduced, the formazan crystal are dissolved using a solubilization solution and the absorption is measured using a mutliwell spectrophotometer. The darker the final solution, the greater number of viable metabolically active cells there are. A study was conducted to determine when best to begin

the MTT assay and to determine whether there is a dependency on the plating cell density for the MTT assay with exposure to radiation²⁰. In that study, it was found that there is a dependence on the cell plating density for the MTT assay. Up to 100 Gy, the authors saw very little change in the viability of the cells at higher cell plating density, but when the cell density was reduced, there was a dose dependent decrease in the viability²⁰. This shows that if too many cells are present, the MTT assay is not an effective viability assay. A different study showed that after radiation, there was an increase in mitochondrial biogenesis, which results in increased mitochondrial mass, enhancing formazan formation, despite the decrease in cell number. The increase in mitochondrial mass could explain the constant MTT results over different dose values with a high cell count²².

Another aftereffect of radiation exposure is the creation of Reactive Oxygen Species (ROS). ROS are normally byproduct of oxygen metabolism, so they are present in normal healthy cells. ROS have roles in signaling as well as maintaining homeostasis. When cells are exposed to radiation, ROS can be generated as a cellular response to the radiation damage, leading to additional damage. ROS target lipids, which results in lipid peroxidation and cell membrane damage. DNA damage can also occur because of ROS, leading to cell mutation or cell death. The ROS generation in epithelial cells is lesser than that of endothelial cells based on a reference that irradiated Caco-2 epithelial cells lining a channel with Human Umbilical Vein Endothelial Cells (HUVECs) in the coculture²³. Getting an understanding of the ROS generated based on the dose received is critical to being able to mitigate the damage from ROS.

The two cell types used in this work were Caco-2, an immortalized cell line of human colorectal adenocarcinoma cells, and HepG2, an immortalized liver cell line of hepatocellular carcinoma. Fig. 1.2 and 1.3 show bright field images of the specific cells used. Both of these cell lines are epithelial and have similar doubling times (39 and 44 hours for Caco-2 and HepG2, respectively). Three different cell culture plates were examined in the dose rate simulations while only one was used in the actual radiation experiments. Fig. 2.4, and 2.5 show the cell dishes used in the simulation while Fig. ?? shows the dishes that were used in the irradiation experiments. The cells cultured in the 14 mm dishes and the 2D culture

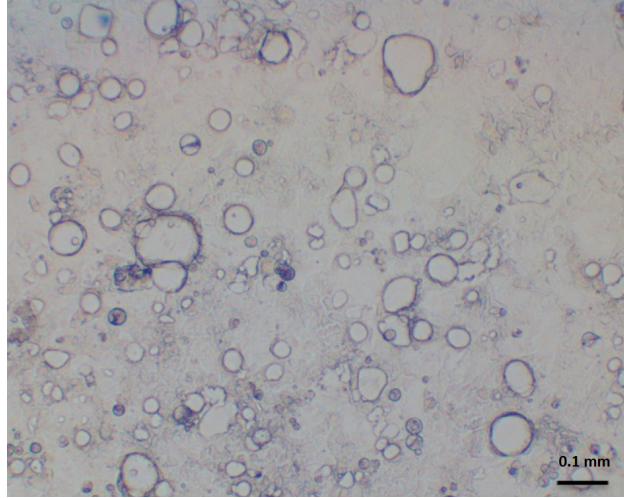


Figure 1.2: *Image of Caco-2 cells, 3 days after seeding onto the cell dish with no irradiation.*

plate create a monolayers at the bottom of the well. The 3D cell culture pate uses a Printed Circuit Board (PCB), dielectrophoresis, and electrowetting to automate culturing^{24–28}. The process of digital microfluidic chips will be discussed more in the conclusion. The cells were purchased from ATCC, and the procedures for initial seeding, subculturing/passaging, and care were followed from the specific cell line product sheets. Cell media was exchanged every other day till confluence was reached and then the cells were passaged. The cell cultures for experiments were either seeded 8 days before irradiation or 1 day before irradiation. These different culture times before irradiation were chosen to examine the different effects cell number has on the assays.

Carcinogenesis is a major limiting factor for space exploration due to the harsher radiation environment that is always present, which is why additional shielding and mitigation techniques are needed. The mitigation techniques can either be medical countermeasures or better shielding methods during exposure. These will prolong the allowable duration of exploratory missions while keeping the astronauts safe. To ensure astronaut safety, two different types of radiation for the cell exposure to be analyzed. The KSU Veterinary Medicine linear accelerator (LINAC) and a RadSource RS 1800 biological irradiator were used for the x-ray sources. ThermoFisher B322 and P385 neutron generators were used as neutron sources. Two different types of radiation are needed to create Relative Biological Effective-

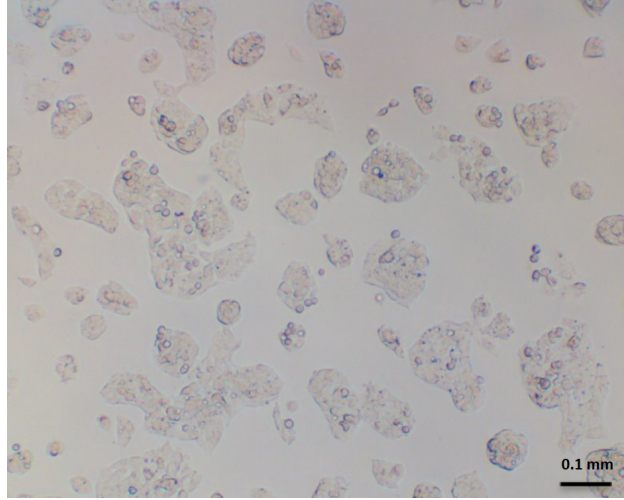


Figure 1.3: *Image of HepG2 cells, 3 days after seeding onto the cell dish with no irradiation.*

ness (RBE) values. RBE values are a ratio of doses from two different radiation types to cause the same biological effect with Eq. 1.2 shown below. For example, high energy photons cause significantly less cell damage than high energy neutrons along the track length, which leads to more complex damage and a higher RBE for the neutrons. Most studies list RBE values related to photon dose as the comparison. Space radiation neutrons are primarily fast with energies greater than 100 MeV and an RBE of at least 20^{5;29}. The end goal of the exposures is to create RBE values for different biological endpoints including DSB, ROS, and cell viability for neutron and x-ray doses.

$$RBE = \frac{Dose_{xray}}{Dose_{neutron}} \quad (1.2)$$

1.3 Neutron Exposure Facilities

One of the main focuses of this study was simulating neutron exposure, as the secondary neutron field to astronauts is a major contributor to the dose. Different sources of neutrons currently exist, including neutron generators utilizing fusion, nuclear reactors utilizing fission, and radioactive decay sources like ²⁵²Cf.

One of the two neutron generators used in the experiments is shown in Fig. 3.3. This

generator has a 4 inch diameter, aluminum housing and utilized Deuterium-Tritium (DT) fusion to generate neutrons. DT neutron generators were chosen as the source of neutrons as most space radiation neutron dose is delivered by neutrons with energies greater than 100 MeV. DT fusion neutrons have the greatest possible energy outside of large scale accelerator facilities and they are convenient, controllable radiation sources³⁰. Previous studies have demonstrated the ability to simulate the high-LET portion of GCR spectra using DT fusion neutrons, providing a ground based space radiation simulator^{14;29;31}. The premise for DT neutron generators is either the deuterium or the tritium is accelerated and caused to collide with the other nucleus. The voltage and current that cause the acceleration can be adjusted to control the reaction and control the output. The high energy of the accelerated particle is enough to cause the fusion to occur, with the specific reaction shown in Eq. 1.3^{32;33}. The DT fusion reaction has 3 different outcomes that can be produced, as shown in the equation.

$$D+T \longrightarrow {}^5\text{He}^* = \begin{cases} \xrightarrow{\approx 1} n(14.1\text{MeV}) + \alpha(3.5\text{MeV}) \\ \xrightarrow{\approx 4 \times 10^{-5}} \begin{cases} {}^5\text{He} + \gamma_0(16.75\text{MeV}) \\ {}^5\text{He} + \gamma_1(\approx 13.5\text{MeV}) \end{cases} \end{cases} \quad (1.3)$$

The interaction between deuterium and tritium causes the creation of a ${}^5\text{He}$ which rapidly undergoes one of the three decays shown in the equation. The most probable decay is shown in the top pathway where it decays releasing a 14.1 MeV neutron and a 3.5 MeV alpha particle, this occur almost 100% of the time. Approximately 0.004% of the time, the excited particle decays by gamma emission of either a 16.75 MeV or 13.5 MeV photon. Neutron generators can be used in a wide variety of applications, including oil well logging, activation analysis of many different materials such as meteoric, biological, and geological activation^{34–38}. Neutron generators can also be used to expose cells causing damage.

Nuclear reactors can be used in some of the same ways that neutron generators are, for example, in neutron activation analysis and exposing target material with given doses. Kansas

State University has a TRIGA Mark II nuclear reactor facility that is used in academic, education, and research purposes. The facility has several experimental facilities including: the In-core/In-pool irradiation locations, two radial beam ports, a fast radial beam port, a tangential beam port, thermalizing column, and thermal column. This study focused mainly on the thermal column as the flux density can be selectively modified using different materials to approximate a space radiation field. The modified flux can then be used as a space radiation environment simulator for ground based irradiation experiments.

Colorado State University created a facility that utilizes a ^{252}Cf neutron source for long duration low dose rate exposures³⁹. The ^{252}Cf source emits alpha particles and has a small chance to undergo spontaneous fission. Approximately 20% of the dose is from photons, while the rest is neutrons, with a total dose rate of 1 mGy d^{-1} ³⁹. This facility can be used to expose animals to low dose rate to approximate what astronauts receive while in space. These types of facilities are very useful for studying the effects space-like radiation environments have on specimens^{39–41}.

1.4 Modeling and Simulation

The ability to simulate radiation transport is essential to accurate understanding of the dose to a sample. Numerous studies have been conducted that use different radiation transport codes. One of the most general and widely used radiation transport codes is Monte Carlo N-Particle (MCNP) Transport⁴². MCNP is a multi-use, with a wide array of possible simulation types. A large number of particle types can be simulated, including neutrons, photon, electrons, heavy charged particles, and many others. The wide array of source particles lends to the general nature of the transport code in that numerous different types of problems can be solved. Particles are transported through defined geometries utilizing pseudo-random numbers to propagate the particles and simulate the different reaction types. There is a wide variety of geometry types built into MCNP as macrobodies, for example, right parallelepiped and right circular cylinders. There are also simple shapes defined in MCNP, such as planes, spheres, and cylinders, to be use in creating more complex geometry. Meshes can be used to

import more complex CAD models from other software. Structured meshes that come from the PARTISN discrete ordinates codes and unstructured meshes created from Abaqus/CAE can both be embedded in the geometry. The work conducted in this study utilized the unstructured meshes from Abaqus CAE for some of the simulated geometry.

The combination of the wide array of source particles, geometries, and materials makes MCNP applicable to many different simulation types. MCNP has numerous tallies for quantification of the desired value including surface current and flux, volume flux, particle heating, and many more. The tally types allow for many different simulation outputs and the ability to modify the tallies creates further adjustability.

Previous studies have modeled the DT experiment facility, the RS1800 biological irradiator, and part of the KSU nuclear reactor facility^{43–46}. The DT experiment facility was designed to enable bulk-material irradiation experiments to simulate oil-well logging. The bulk-material used in the irradiations was either sand or water to approximate the materials in oil-logging scenarios. The use of neutron generators in the oil-logging industries is intended to replace highly radioactive sources, such as AmBe or ^{137}Cs , with controllable machine sources^{47;48}. The neutron generators in the previously conducted studies and this work have all been modeled as mono-energetic, isotropic, point sources of 14.1 MeV neutrons. The interior design of the neutron generator is unknown.

The Rad Source RS1800 biological irradiator advertised for cell and tissue biological research is able to deliver high dose rates fully shielded in a compact machine. The irradiation chamber offers four different shelves for adjustable distance between source and target. The RS1800 uses a Comet MCR-225/26 X-ray tube which has a pure tungsten target and anode angle of 30° . SpekCalc was used to simulate the source spectrum at 130 kV and 1 mA including a 2 mm beryllium layer to filter low energy photons^{49–51}. The previous simulation was created for the better overall dose estimate to electronics to prevent electronic failures due to radiation damage^{43;52}. The work discussed in this paper used a higher voltage of 160 kV and the new source spectrum was generated using SpekCalc to account for the increase.

Extensive work has previously gone into the model and simulating the NorthEast Beam-Port (NEBP) of the KSU TRIGA II nuclear reactor^{44;45}. Accurate understanding of the

neutron output is vital to deliver desired doses as well as ensure the safety of the operators. The first of the two major previous works focused on the neutron flux characterization of the beamport and the second demonstrated the ability to simulate a biological irradiation chamber in the NEBP. The neutron flux characterization work utilized a previously created model of the TRIGA Mark II reactor which contained the fuel elements, central thimble, grid plates, and graphite reflector⁴⁵. The northeast beamport was added to the model which consisted of two, six-foot, cylindrical segments with diameters of 6 in and 8 in. A lead shadow shield is located at the junction of the two segments to reduce the gamma component of the outward particles. The NEBP was mostly cylinders and planes which made the model straightforward to create. The nuclear reactor is surrounded by a concrete structural region that was simply modeled a cylinder with the assumption that the complex geometry a high distance would have minimal effect on the neutron flux. The MCNP simulation originally was setup as a KCODE problem which through simulation was converted to a SDEF source. This was done so the simulation would be compatible with the code ADVANTG used in variance reduction and the generation of weight windows. The use of MCNP's built-in Watt spectrum and a spatial distribution determined from the KCODE simulation was used to create the SDEF source card. Once the source card was created, flux tallies as functions of energy, position, and angle were created to analyze the neutron flux of the NEBP which is compared to experimental results from Bonner sphere spectroscopy and gold foil tube experiments.

The second of the works mentioned focused on model improvements to the NEBP exit, core control rods, updated libraries, and flux density spectrum created using an algorithm to minimize differences between the new and simulated experimental Bonner sphere measurements⁴⁴. The original NEBP model was divided into two models; the reactor out to the edge of the beamport and the exterior, as it would result in inefficient performance when ran together. The cross section libraries were updated from ENDF B-VII to ENDF B-VIII. Improvements were made to the model geometry including to some of the control rods. Results obtained in the previous work were used with updated source and response functions to incorporate the experimental data into a better simulation. The final steps of

the work with updating the NEBP looked at simulating the dose to biological samples in a cell culture flask. The cell culture flask was simulated rotating and translating to determine the uniformity in the absorbed dose.

The creation of the simulations is vital for the accurate understanding of the dose received and the physics going on. The ability to run simulations before and during experiments to understand and hypothesize the outcome is vital. Once the MCNP scripts are created, they can be selectively modified to be used in numerous other experiments and desired outcomes than what they were originally designed. The nuclear reactor model is one example, where it is slowly being built upon from the previously created northeast beam port model.

Chapter 2

Modeling and Simulation

2.1 Thermal Column

A previous work modeled the KSU reactor, including the core and northeast beam port⁴⁴. Shown in Fig. 2.1 is a top down view of the nuclear reactor model showing the core configuration and the northeast beam port done previously.

Further improvements to the model must be made, as the eventual end goal is to have a complete working model of the entire KSU nuclear reactor. Using the reactor blueprints to get the required measurements, the thermal column model can be created. The next step in upgrading the reactor model is adding the thermal column. As mentioned in Chapter 1, the flux in the thermal column could be modified to approximate the LET spectrum impinging on astronauts. The thermal column was designed using planes and cylinders. Shown in

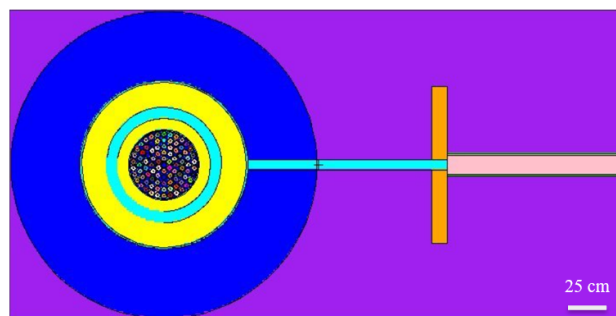


Figure 2.1: *Top down view of previously modeled KSU northeast beam port*

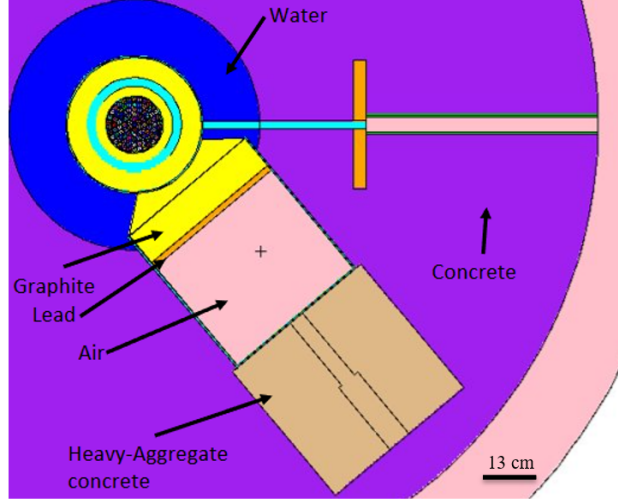


Figure 2.2: Top view of the KSU TRIGA II thermal column model. The thermal column contains the 32,000 lb concrete door, air section where irradiations are conducted, lead curtain to control the photon flux, and the graphite section that leads to the core.

Fig. 2.2 is a top down view of the added thermal column to the existing model.

The thermal column model includes the door, which is roughly 32,000 lb of concrete and a boron-lined aluminum box with air filling the space. Shown in Fig. 2.2 is a labeled top-down view of the model with the brown representing the thermal column door and pink shows the air where the irradiations will be conducted. A lead curtain separates the graphite and core from the graphite bricks and irradiation area. $S(\alpha, \beta)$ cards were used for a number of materials to specify the thermal neutron scattering treatment. The tables that were included are: h-h2o.40t, grph30.40t, f3-56.40t, al-27.40t, h-poly.40t, h-zrh.40t, and zr-zrh.40t. These set the isotopes of the specific materials to be treated as in the thermal regime if the data tables exist. Tables that are included impact the materials of hydrogen in water, graphite, iron, aluminum, polyethylene, zirconium and hydrogen in zirconium hydride. Uniform importances for photons and neutrons were used out to the graveyard where all particles were killed. The air section of the model is where the tally will be taken. The neutron flux was tallied using the FMESH4 track-length tally over a 3D mesh tally and modified to output the flux per kilowatt rather than per source neutron. The tally had a 3D mesh with 15 points each in the x, y, and z directions totaling 3375 data points.

2.2 Neutron Generator

2.2.1 Simulated Neutron Dose

The neutron generators were simulated as point sources located 5.08 and 7.62 cm away from the center of the cell cultures. These distances were chosen because the neutron generators had diameters of 2 in and 4 in with the target placed 1 in away from the outside of the neutron generator. They were modeled as point sources since no information is known about the interior of the neutron generator. The neutron generator exterior shell is made of aluminum so it was excluded as the probability of neutron interaction is relatively low and can be ignored. A simulation was created to characterize the dose to the cells from the neutrons. In a previous work, the neutron experiment room had been modeled in MCNP⁴⁶. This model was used to simulate the neutron generator to determine if there was a significant room return on the dose. Fig. 2.3 shows the simulated room geometry and the location of the neutron generator and cells. The bulk irradiation tank in the simulation was not used in this experiment.

The walls, floor, and ceiling are modeled as concrete by using rectangular parallelepiped and circular cylinders. There were three different culture plates used in this work. Shown in Fig. 2.4, 2.5, and the Cellvis 35 mm cell dish (Cellvis, D35-20-1.5-N) are the three cell culture plates. The first two were used in the simulation of the dose rate so that in the future more complex cell cultures and organoid models could be used in radiation experiments; however, these were not used in the actual radiation exposures covered in this work. The third dish type was used in all of the radiation exposures covered in this work.

The model shown in Fig. 2.4 was created in Solidworks. Abaqus CAE was used to convert the CAD file into a MCNP mesh that could be imported into the room geometry. Ultimately, this model will be used to create 3D hydrogel cell cultures to more accurately imitate actual cells. These 3D cell cultures would better represent in-vivo environment. The 3D model was created using 302 macrobodies in MCNP as the same conversion method using CAD model and Abaqus was attempted. However, due to an error that kept causing the simulation to

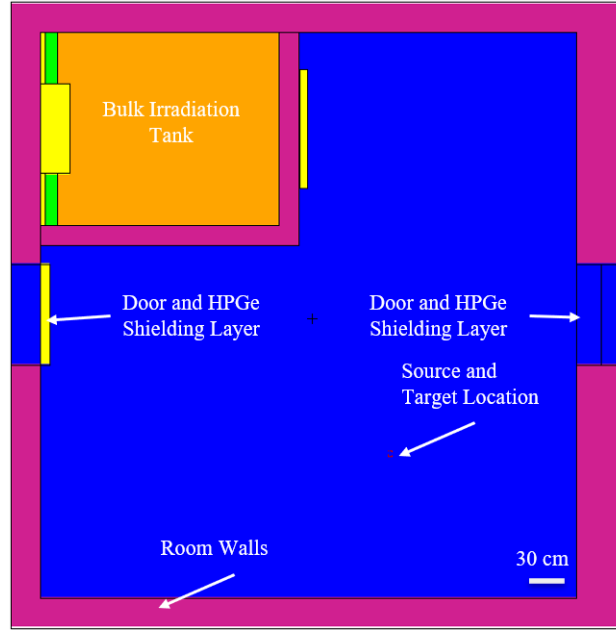


Figure 2.3: *MCNP6.2 simulated room geometry for neutron generator experiments. Room includes a bulk irradiation tank that was not used in this work. Geometry was created using rectangular parallelepiped and circular cylinders. Materials used in the simulation are shown in Appendix A.*

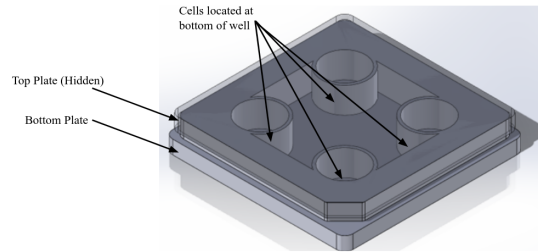


Figure 2.4: *Modeled 2D cell culture plate commonly used in 2D monolayer cell culturing.*

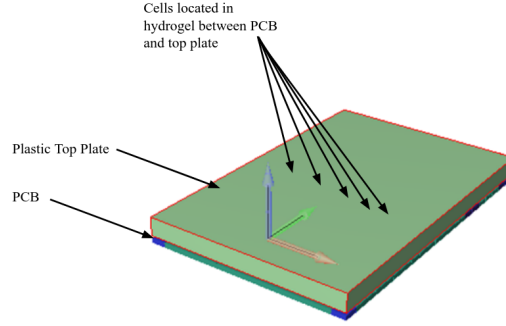


Figure 2.5: *Simplified digital microfluidic cell culture chip model used in organoid and 3D cell culturing.*

fail, the geometry was created using simplified method of macrobodies. In the simulation, the center of cells was located 5.08 cm from the center axis of the neutron source for the B322 and 7.62 cm for the P385 generators.

For the transport of the particles, default photon and neutron physics settings were used other than the “coilf” parameter. The “coilf” parameter was set to 4.0, which simulates light-ion recoils making one ion from elastic scatter and Neutron Capture Ion Algorithm (NCIA). Uniform importance of one was set for all geometry out to the graveyard, where all particles are killed. The target volumes for the tallies were the cell layers, which are marked in the figures. The cell volumes were 0.8 cm^3 and 0.0045 cm^3 for the 2D and 3D cell cultures, respectively. All cell cultures were modeled as right circular cylinders at the bottom of the well locations. An F6 energy deposition tally was used to determine the dose per source particle to the cells. This tally uses heating numbers from nuclear data tables to find estimates of the energy deposited per unit track length during transport. When no tabular data is available the energy deposition is calculated at the time of the nuclear interaction. The units returned from this tally are megaelectronvolt per gram per source particle, which were converted to gray per source particle. The output after this conversion would just be multiplied by the experimental source strength determined from the foil activation experiments to determine the dose rate of the neutron generator. Shown in Table 2.1 are the dose results of the simulations; combining these values with the results of the foil activation analysis will give the dose rates needed to determine length of irradiation

Table 2.1: *Output values of the F6 tally in MCNP6.2 for the two different simulated plates*

Plate	F6 Value [MeV g ⁻¹ Source Particle ⁻¹]	Error [%]
2D Plate	0.00103	0.67
3D PCB	0.00105	1.3

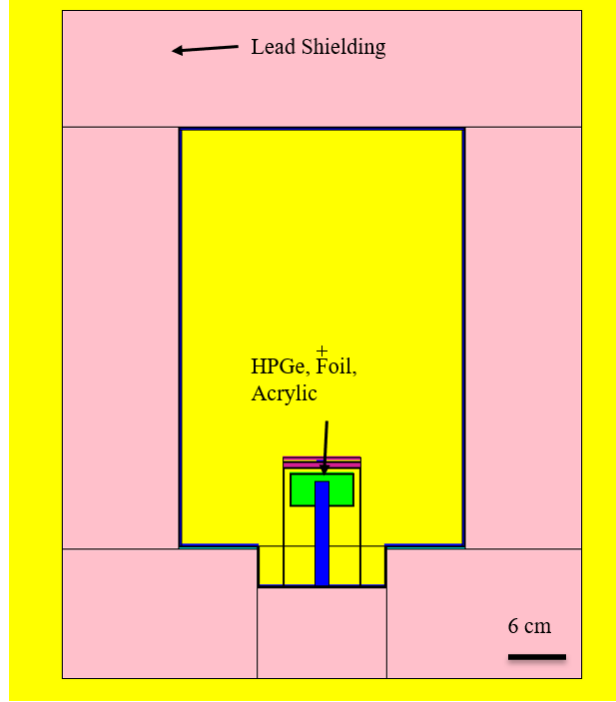


Figure 2.6: *Simulated geometry of HPGe detector used in the determination of the detection efficiency. Simulation included HPGe detector, detector housing, lead shield, acrylic sheets, and activated copper foil. MCNP material card is shown in Appendix B.*

to reach target dose to the cells.

2.2.2 HPGe Detector Simulation

Shown in Fig. 2.7 is the model geometry with the foil, acrylic and HPGe labeled. The source of particles was simulated as positrons uniformly being emitted from the copper foil with energies sampled from the previously shown energy distribution. Photon and electron physics were turned on; positrons are included in the electron physics. Positrons are transported until they annihilate giving off two 511 keV photons, which are then transported until they either hit the boundary of the problem and are killed, interact and stop, or interact in the detector volume and are tallied. An F8 energy distribution of pulses created in a cell tally

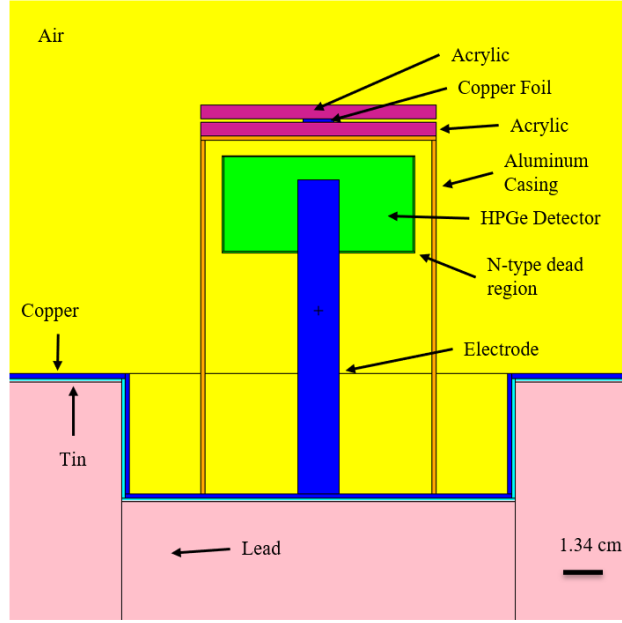


Figure 2.7: *Zoomed in image of the simulated HPGe detector of the copper foil and acrylic sheet. Copper foil is sandwiched between acrylic sheets, which act as positron absorbers, to help control the range of the positrons.*

was used to simulate the pulse height distribution of the actual experiment to determine the detector efficiency. The output of this tally is an energy dependent pulse height distribution per source particle. The energy bin containing the 511 keV peak will output the number of pulses deposited in the detection volume per source particle which is the efficiency that is needed. Once the efficiency is found and the peak counts have been determined in the 511 keV peak, the neutron source strength can be calculated which is needed to determine the dose rate of the generator.

2.3 X-ray Generators

In a previous work the x-ray generator, shown in Fig. 2.8 was modeled and the spatial characteristics were established⁴³. The MCNP script of that model was updated with the higher settings that were used in this work. The previous work had the voltage and current set at 130 kV and 1 mA, while this work had the settings at 160 kV and 12.5 mA. These higher settings mean that the greatest energy of the x-rays is now 160 keV and the total



Figure 2.8: *RadSource RS 1800 biological irradiator used as a source of x-rays.*

number of x-rays is also higher, as the current and voltage both control the number of the x-rays. The RS 1800 has different filtration in the generator to shield some low energy x-rays that are produced. These filtration layers are 2 mm of beryllium, 0.0254 cm of zinc, and 0.127 cm of aluminum. The beryllium layer was included in the source simulation in SpekCalc, while the zinc and aluminum layers were modeled in MCNP. The MCNP material card is shown in Appendix C. The MCNP model utilizes the FMESH4 tally and an energy-dependent response function to simulate the ion chamber as if it was moving across the shelf to get an estimate of the dose rate to that location. The simulated dose distribution from the 30° emission angle is shown in Fig. 2.9. The error bars are smaller than the plot points.

Shown in Fig. 2.10, is the x-ray output for the RS 1800 generated using SpekCalc^{49–51}.

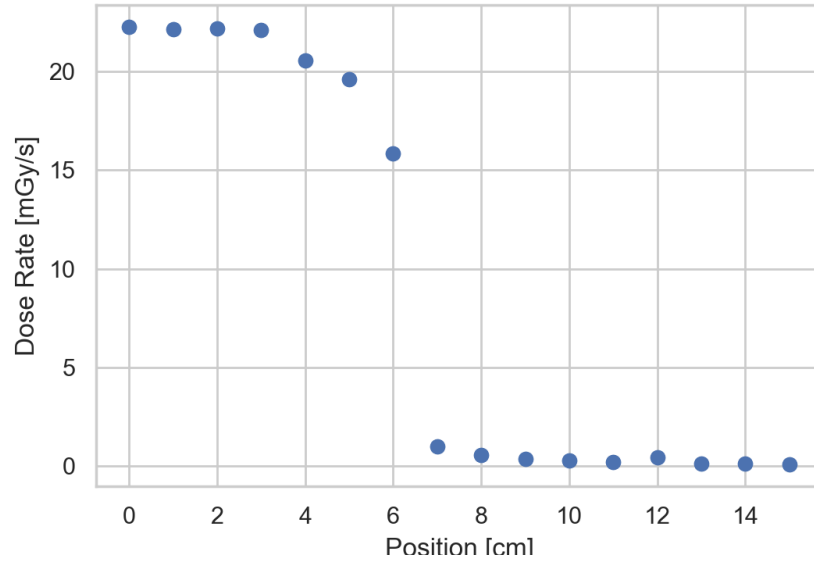


Figure 2.9: *The dose distribution across shelf 1 of the RS1800 x-ray generator. Symmetry is assumed across the center point and the cell dishes that were irradiated were centered approximately 2 cm away from the center.*

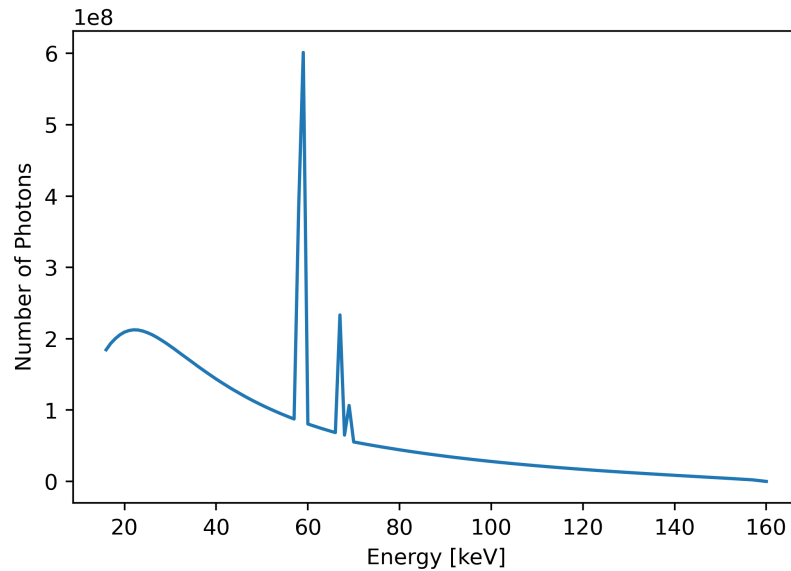


Figure 2.10: *SpekCalc simulated photon output given a voltage of 160 kV and current of 12.5 mA. 2 mm beryllium filtration layer and 30° emission angle included in the SpekCalc software*

Chapter 3

Experiments

3.1 Neutron Generator Characterization

To understand the dose that the neutron generator can output, the neutron output must be characterized. Utilizing the Texas Convention Method (TCM), the neutron output can be determined^{53;54}. The TCM uses the $^{63}\text{Cu}(n,2n)^{62}\text{Cu}$ reaction which has an energy threshold of around 11 MeV, meaning that any neutron below the 11 MeV will not be able to cause this reaction. This product decays through positron emission. The positron will eventually slow down and annihilate with an electron giving off two 511 keV photons which can be measured. There is a one to one ratio of positrons emitted to neutrons absorbed. So, using Eq. 3.1, one can calculate the flux density from the neutron generator after irradiating a copper foil with a known mass, and for a known duration.

$$\phi = \frac{P_k A \lambda}{N_A m \sigma \epsilon (1 - e^{-\lambda t_1}) e^{-\lambda t_2} (1 - e^{-\lambda t_3})} \quad (3.1)$$

Table 3.2 shows the parameters found and used in the calculation of the neutron flux. λ is the decay constant, N_A is Avagadro's number, A is the atomic mass number of copper, m is the mass of the copper foil, σ is the activation cross section, a_i is the isotopic abundance, I_γ is the γ -ray intensity of the 511 keV peak, η is the detection efficiency, and ϵ is the overall efficiency which multiplies η , I_γ , and a_i together. The detection efficiency, η , will

be acquired from simulating the pulse height spectrum per source particle in MCNP 6.2 from the activated copper foil. The source particles in the simulation are the positrons being emitted from the copper foil. Since the output is a pulse height spectrum per source particle, the I_γ must be divided by two. This must be done as the I_γ is the γ -ray intensity of the 511 keV peak but since the detection efficiency is per positron emission it bypasses the two annihilation photons and tracks the one positron. The distance from the neutron source inside the generator, which was assumed to be down the center axis of the generator, to the center of the copper foil for each different neutron generator is d_{B322} and d_{P385} with the peak counts of the 511 keV peak of the experiment shown as P_k .

The copper foil chosen is approximately 10 mm×10 mm×1 mm, weighing 0.98 g. This weigh is important as it determines the total activation possible or the saturation value of the activation experiment. During irradiation, the neutrons are interacting in the copper foil, scattering and being absorbed. Saturation occurs when the entire copper foil is activated, so with more mass the total saturation activity is higher. While the irradiation is happening and the foil is activating, the already activated copper is decaying via the previously mentioned reaction. For the $^{63}\text{Cu}(n,2n)^{62}\text{Cu}$ reaction, there is a point of irradiation where a secondary reaction start to cause a significant influence on the counts. This happens due to the half life of the secondary product being much longer than the half life of the product of interest. So, the experiments that were conducted had irradiations of 30 min, shorter than the duration where secondary reactions would start to cause additional error in the measuring but still long enough that saturation was close to being achieved. In Fig. 3.1 and 3.2, the calculated number density of copper as the irradiation would be happening with each different neutron generator. The vertical lines on the plot are the different phases of the foil activation experiment that was conducted and will be discussed in a later section.

The foil activation experiment was designed so that the copper foil could be irradiated while keeping all personnel safe. The same general procedure was used for both neutron generators. Before the irradiations were conducted, the building and surrounding area had to be secured so that the public did not receive any unnecessary and unsafe dose. Wooden stakes and rope were placed around the area that has been previously designated as unsafe

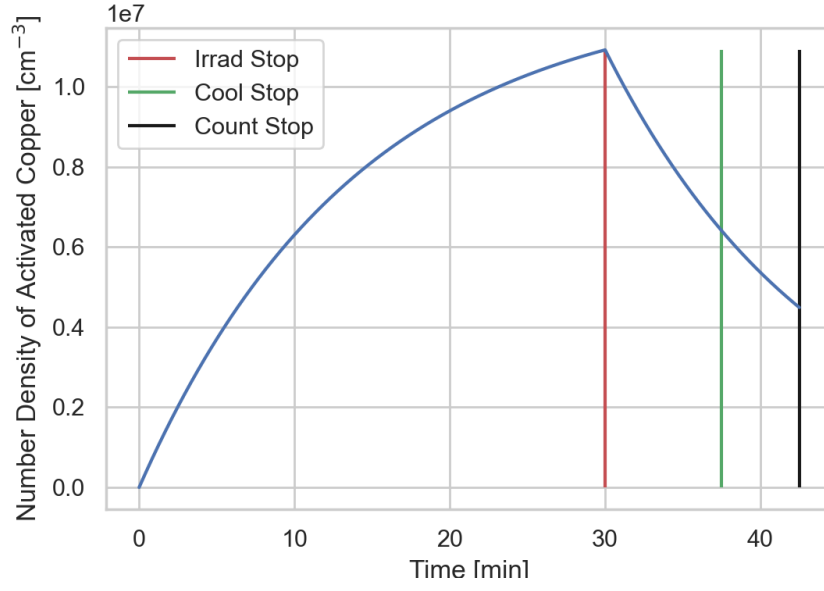


Figure 3.1: *Calculated number density of activated copper for the B322 DT neutron generator foil experiment.*

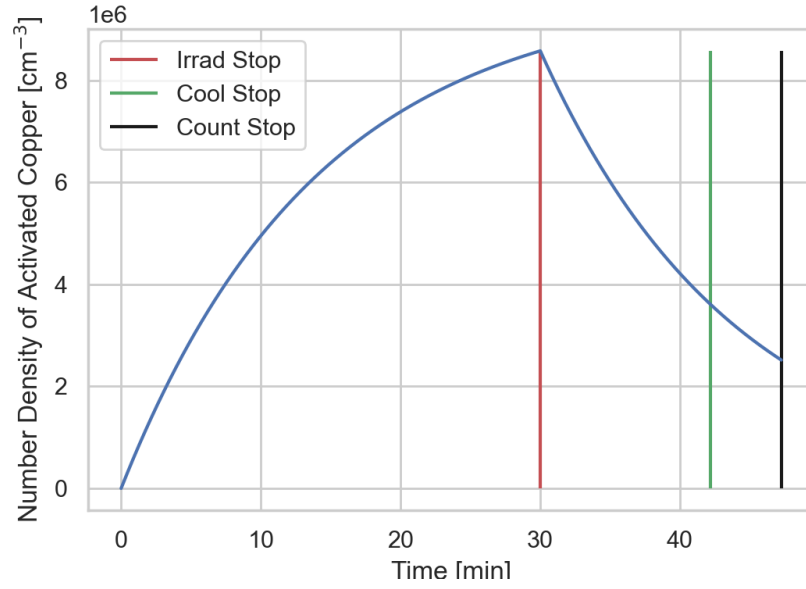


Figure 3.2: *Calculated number density of activated copper for the P385 DT neutron generator foil experiment.*

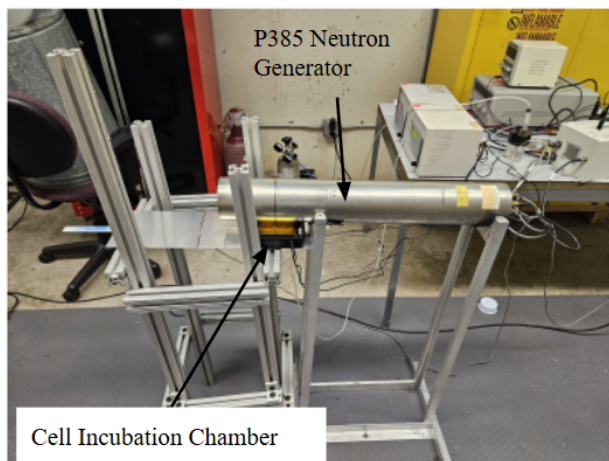


Figure 3.3: *ThermoFisher P385 DT Neutron Generator on aluminum stand with aluminum sample holder and cell culture chamber.*



Figure 3.4: *Exterior of King Hall Annex set up for irradiation*

for general public around the building. Fig. 3.4 shows the exterior of King Hall Annex and the area that public access was denied. The threshold for what was designated as not for general public was 2 mR/h. The dose rate at the rope boundary was far below this threshold. Signs were placed on all doorways leading to the inside of the building to designate a no entry point. During generator operation, flashing hazard lights were on in the hallways and door interlocks were in place so if someone attempted to enter the experiment room everything would turn off.

Once the area was secure so that no public could gain access, the experiment room setup began, with the copper foil being placed on the sample holder 5.08 cm away from

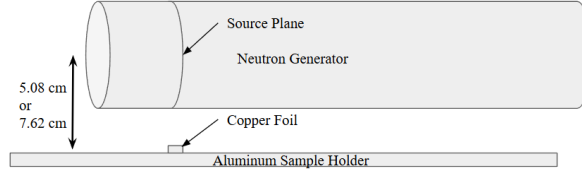


Figure 3.5: *Schematic showing the copper foil placed on sample holder to conduct neutron activation experiment*

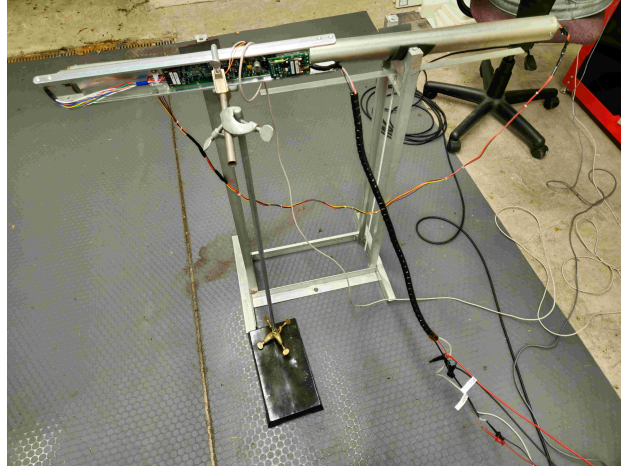


Figure 3.6: *B322 neutron generator on aluminum stand with control PCB.*

the source point for the ThermoFisher B322 neutron generator. Fig. 3.5 demonstrates the placement of the copper foil for both neutron generators as they are different sizes, with the ThermoFisher B322 neutron generator having a diameter of 2 in and the ThermoFisher P385 neutron generator having a diameter of 4 in. This changes the distance from the center of the generator to the foil by 2.54 cm.

The neutron generators are controlled using a computer down the hall from the experiment room. Shown in Fig. 3.6, is the B322 neutron generator sitting on the aluminum stand with the control PCB next to it, placed in the experiment room where irradiations were conducted. The generator stand and sample holder are made out of aluminum to minimize the effect on the neutron flux from the additional material, as more material leads to more interactions of the particles. Aluminum was chosen due to its smaller cross section for neutron interaction.

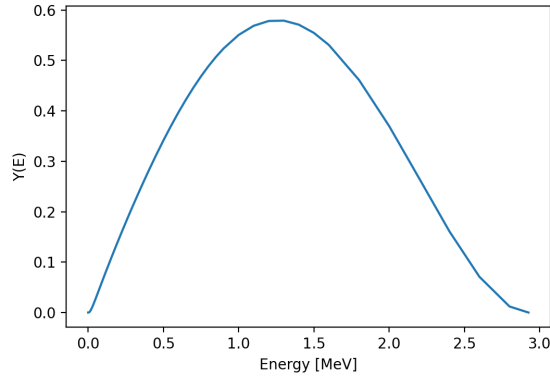


Figure 3.7: *Probability Density Function (PDF) for the positron emission spectrum for activated copper 62 using RadToolbox¹. The PDF was the source term in the HPGe MCNP simulation.*

Once the foil and neutron generator were setup, all personnel exited the experiment room and made sure the doors were closed. Two people stood outside near the edge of the rope boundary to ensure no one crossed it while the experiment was being conducted. Foil activation experiments were conducted with both neutron generators as they have different maximum settings. The settings that control the neutron output are the current and high voltage. For the B322, the maximum current and voltage are 70 μA and 95 kV. The P385 has maximum settings of 70 μA and 130 kV. Both foil experiments were conducted at these maximum settings for 30 min. Once the 30 minute irradiation was complete, the generator and surrounding material had to be left alone for a short duration. This time allowed the dose rate to fall below the 2 mR/h, which was measured using an ion chamber. After the exposure rate was below the threshold, tweezers were used to knock the activated copper foil into a lead pig for transportation. The lead pig and foil were transferred to the Ward Hall Radioactive Sample Handling facility to utilize the High Purity Germanium (HPGe) detector to measure the 511 keV gamma rays from the positron annihilations. The setup of the HPGe detector is shown in Fig. 2.6 and 2.7, with the foil, acrylic, and HPGe detector labeled. The acrylic was placed on the top and bottom of the activated foil to act as a positron absorber. The positrons are emitted with a spectrum of energies shown in Fig. 3.7 and each energy has a corresponding range it will travel before annihilating. In air, these

Table 3.1: *Time values for the copper foil activation analysis*

Time	Value [min]
t_1	30
$t_{2,B322}$	7.5
$t_{2,P385}$	11.183
$t_{3,B322}$	5
$t_{3,P385}$	5.06

Table 3.2: *Parameters for the TCM equation*

Parameter	Value	Units	Error [%]
A	62.9	[g]	N/A
λ	1.184873×10^{-3}	$[s^{-1}]$	0.021
N_A	6.022×10^{23}		N/A
m	0.98	[g]	
σ	0.460271	[b]	4.25
a_i	0.6917		N/A
I_γ	1.9566		N/A
η	0.0907462		0.001
d_{B322}	5.08	[cm]	N/A
d_{P385}	7.62	[cm]	N/A
$P_{k,B322}$	12869	[cts]	0.88
$P_{k,P385}$	7332	[cts]	1.2

ranges are longer, as there is less energy deposited so the acrylic is placed on top and bottom of the foil to shorten the range that the positrons are able to travel to increase the detection efficiency. To find the detection efficiency, an MCNP simulation was created that modeled the HPGe detector discussed in Section 2.2.2.

3.1.1 Dose Rate

After the activation experiment was performed and all of the needed values to determine the dose rate and neutron source strength were found and Eq. 3.1 was used to determine the neutron flux density. Table 3.3 shows the experimental neutron flux density and neutron output for both neutron generators. The values were then used with the simulated neutron dose to determine the neutron generator dose rate.

For the B322, the neutron source strength can be derived by multiplying the neutron flux density by $4\pi(5.08\text{cm})^2$ and for the P385 would be multiplying the flux density by

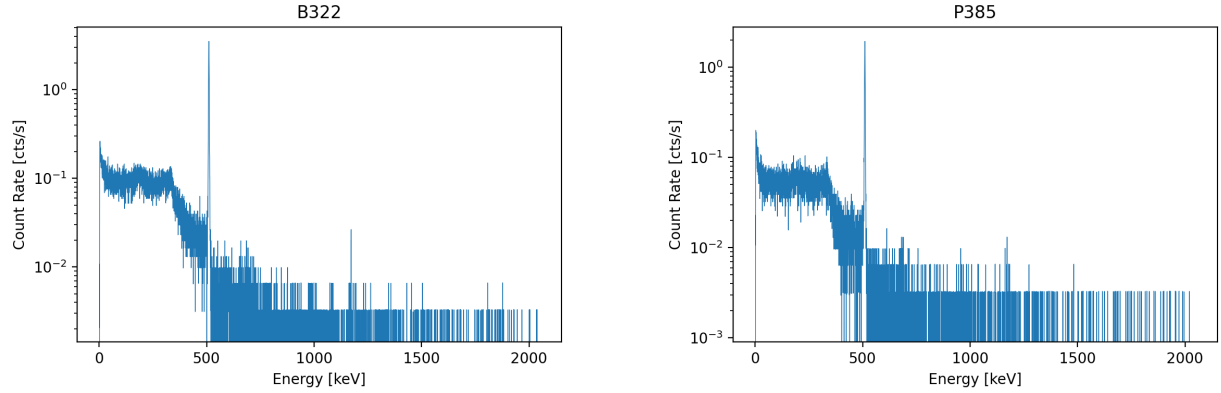


Figure 3.8: Background subtracted neutron activation analysis plots for B322 and P385 DT neutron generators after irradiation of copper foil.

Table 3.3: Experimental neutron output of B322 and P385 neutron generators

Generator	Distance [cm]	Neutron Yield [n s^{-1}]	Neutron Flux [$\text{n cm}^{-2}\text{s}^{-1}$]
B322	5.08	1.2×10^8	3.7×10^5
P385	7.62	2.3×10^8	2.9×10^5

$4\pi(7.62\text{cm})^2$ to change flux into neutrons per second. These values are shown in Table. 3.3. Multiplying the neutron source strength by the simulated dose per source particle returns the dose rate per second to the cells. The values were converted to per hour and the dose rate from the neutron generators to the different cell cultures is shown in Table 3.4. The total irradiation time needed to achieve the target dose to the cells can be determined using the calculated dose rates. The cell dish dose rate was assumed to be the same as the plate dose rate.

Table 3.4: Dose rate from each neutron generator examined to each cell configuration

Generator	Cell Plate	Dose Rate [mGy hr^{-1}]	Error [%]
B322	Plate	71-72	4.3
	PCB	69-73	4.3
P385	Plate	60-62	4.4
	PCB	57-62	4.4

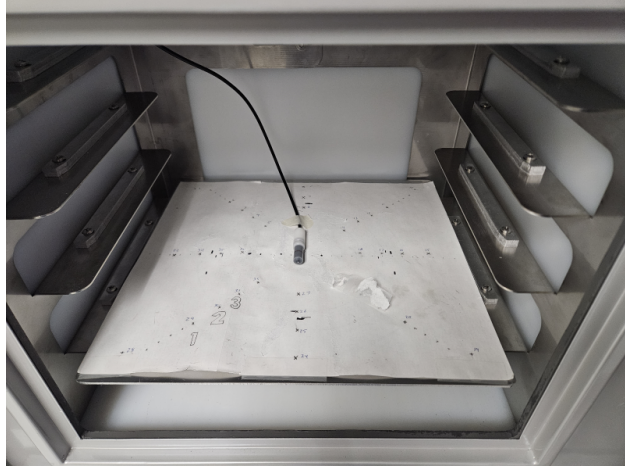


Figure 3.9: *RadCal 10X6-0.6 ion chamber sitting in the center of shelf 1 of the RadSource RS1800.*

3.2 X-ray Source Characterization

LINACs operate by accelerating electrons through a wave guide at specific times during an oscillating radio frequency. The electrons then collide with a heavy metal target, typically tungsten, causing bremsstrahlung x-rays or characteristic x-rays. A collimator then shapes the beam which reaches the target. The RS 1800 x-ray generator works in a similar way to the LINAC. Electrons are accelerated and collide with a target also typically tungsten. The major difference is the acceleration method that is used. X-ray generators use a cathode and an anode, which have set voltages and currents running through them which dictate the output of the generator. There is a linear relationship between the current and the x-ray output while the voltage has a squared relationship with the output. The voltage also sets the maximum energy of the x-rays, for example, if the voltage of the x-ray generator is set at 160 kV. Then the highest possible x-ray energy would be 160 kV. MCNP6.2 was used to simulate the x-ray generator and the associated dose rate. This was done while also using a 10X6-0.6 high dose rate Radcal ion chamber to measure the dose rate. The ion chamber was placed in the center of shelf 1 in the RS 1800, shown in Fig. 3.9.

The x-ray generator was also used to expose the ion chamber to measure the dose rate at the higher settings. The software Accu-gold was used to connect to the ion chamber and read out the measurements as they were being conducted. Fig. 3.11 shows the GUI that is

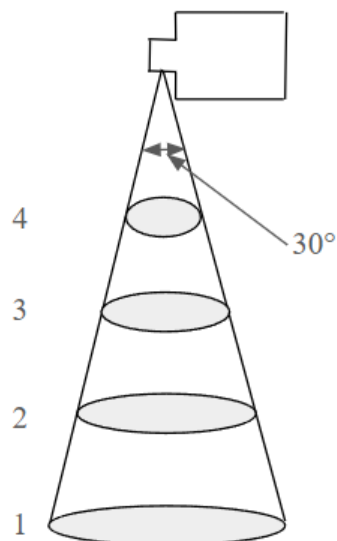


Figure 3.10: Schematic showing the emission angle of the RS 1800 source

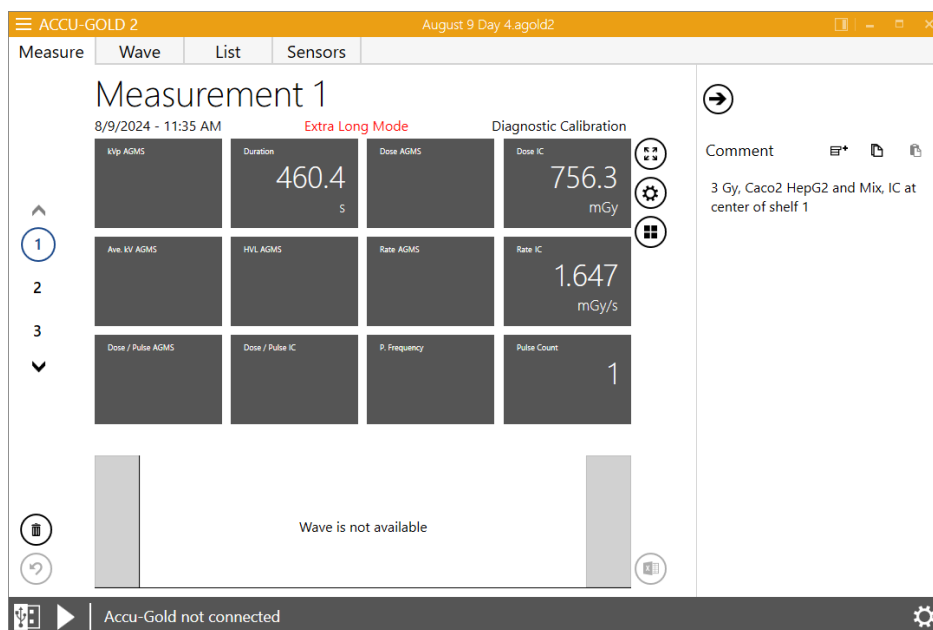


Figure 3.11: Main page on the Accu-Gold software showing the dose rate, total dose and time of experiment.

	Start Time	Duration	kVp AGMS	Dose AGMS	Dose IC	Ave. kV AGMS	HVL AGMS	Rate AGMS	Rate IC	Dose / Pulse AGMS	Dose / F IC
1	8/9/2024 11:35:05 AM	460.4 s			756.3 mGy				1.647 mGy/s		
2	8/9/2024 11:46:03 AM	228.0 s			374.9 mGy				1.644 mGy/s		
3	8/9/2024 11:51:24 AM	74.02 s			121.6 mGy				1.643 mGy/s		

Figure 3.12: Table page of Accu-Gold where you can export all the data to an Excel spreadsheet for ease of analysis.

used to read out the dose measurements from the software. The units of dose can be changed between gray and roentgen. Once the dose to the ion chamber is above the threshold the ion chamber and software begin automatically reading out the dose rate, keeping track of the time of irradiation, total dose, dose rate. Once the exposure stops, the software saves the values, and if a new exposure starts, it splits it into another tab and begins again. These values can all be exported to an Excel sheet to create ease of data analysis, shown in Fig. 3.12. The ion chamber measurements were used to scale the source in the MCNP simulation to confirm the simulation was using the correct output.

The LINAC from Kansas State University College of Veterinary Medicine was operated by their staff and the calculations were done by them. The cells were irradiated using a 2 cm bolus, which is a tissue like material. To confirm the dose is going to the treatment location, a bolus is placed over top of the target.

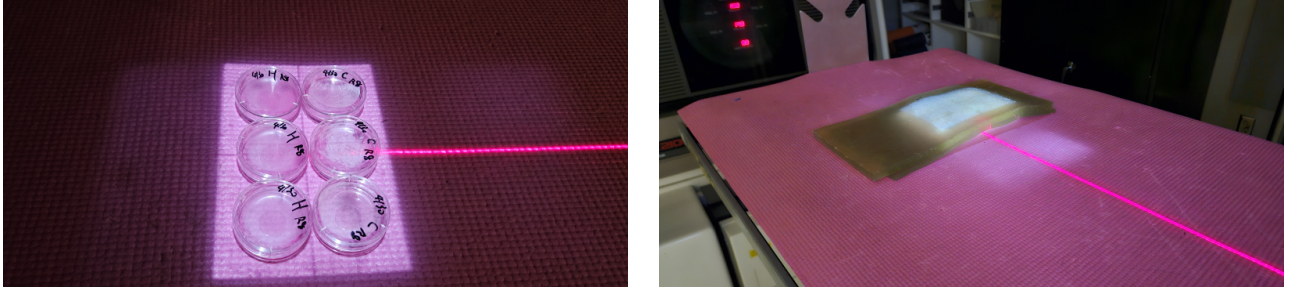


Figure 3.13: *LINAC experimental setup, left image showing the cell dishes and irradiation field. Right image showing the 2 cm bolus placement.*

3.2.1 Ion Chamber Measurements

To keep the cells at the controlled environment, the dose rate had to be kept high so the exposure time was short. The dose rate to be used is vital in determining the length of exposure. The cell environment needed to be controlled to ensure that the cells grow correctly. The irradiations needed to be kept short so the settings on the RS 1800 were set to the highest value to determine what maximum dose rate could be achieved. The settings that were used are 160 kV and 12.5 mA with the ion chamber located at the center of the first shelf. The generator was turned on to measure the dose rate at the settings and locations. At these settings and location, the ion chamber read a dose rate of 22.25 mGy s^{-1} . This setting was used for all but one of the cell irradiations. The other cell irradiation that did not use these settings was conducted to expose the cells to a more chronic x-ray dose. So, a lower dose rate was used and the total dose was fractionated over multiple days to achieve. The same ion chamber location was used with it placed at the center of shelf 1. The voltage was kept at the same value of 160 kV but the current was reduced down to 1 mA. By making this reduction the dose rate dropped from the 22.25 mGy s^{-1} to 1.65 mGy s^{-1} , which made the exposure take roughly 13 times longer.

3.3 Neutron Cell Irradiations

For the neutron cell irradiation, the target dose is 40-80 mGy. This means that the total irradiation time is 48-53 minutes for the 40 mGy samples and 96-106 minutes for the 80 mGy.

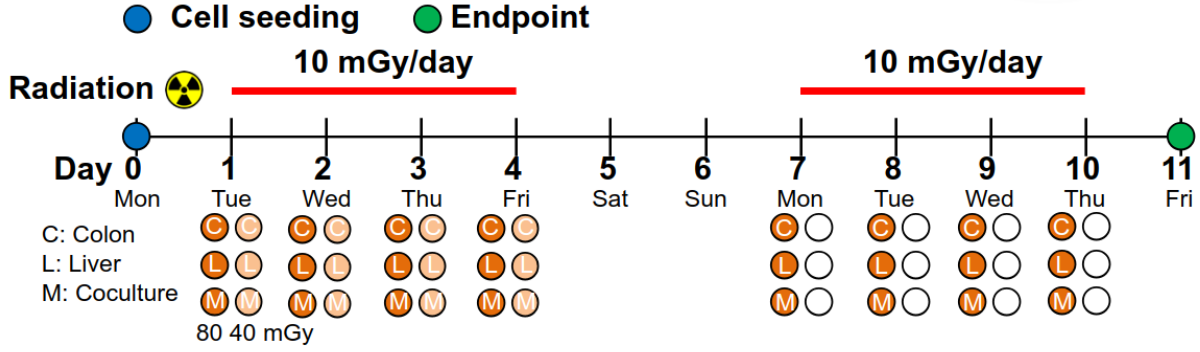


Figure 3.14: *Fractionated neutron dose exposure plan.*

All cell irradiations were performed with the ThermoFisher P385 neutron generator which has a higher output than the ThermoFisher B322. Before the experiments were conducted there was an error in the neutron dose simulation that caused the dose rate to the cells to be approximately 5 mGy h^{-1} rather than the more accurate 60 mGy h^{-1} that the P385 actually outputs. The error led the exposure time to neutron irradiation to be significantly longer and the cells getting a much higher dose than desired. The neutron irradiation exposure was fractionated due to the incorrectly assumed low dose rate. Six different cell cultures were irradiated in the neutron exposures; 40 mGy Caco-2, 80 mGy Caco-2, 40 mGy HepG2, 80 mGy HepG2, 40 mGy coculture of Caco-2 and HepG2, and 80 mGy coculture of Caco-2 and HepG2. The irradiations were separated into 4 exposures for the 40 mGy and 8 exposures for the 80 mGy cells. The plan and time frame for the exposures are shown in Fig. 3.14 where the 40 mGy cell are exposed for one week and the 80 mGy cell are exposed for two weeks, two hours each day.

Due to the exposure times of the experiment being two hours per day, the cell dishes must be kept inside of an incubator to keep them at a constant 37°C and 5% CO_2 concentration so there are no growth problems. Fig. 3.15 show the incubator that housed the cells during the two hour irradiation. The incubation chamber is made of black anodized aluminum alloy which will have some activation to the metal. The interior of the incubation chamber has enough space for the six cell dishes that were irradiated. Fig. 3.16 show the cell dish placement inside the incubation chamber before the chamber was placed underneath the

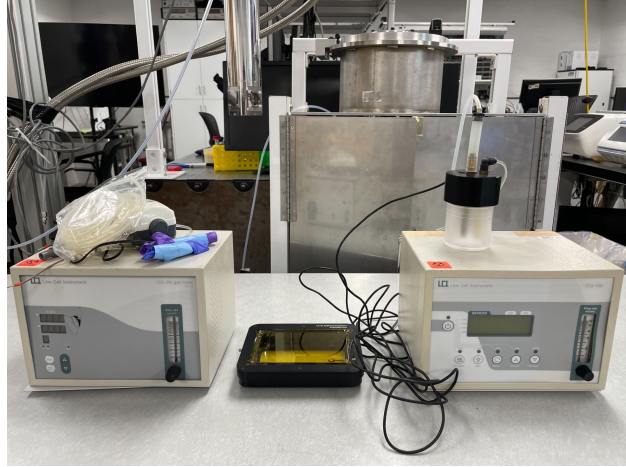


Figure 3.15: *Cell incubator that housed the cells during neutron irradiation. Incubator maintained a temperature of 37°C , relative humidity of 85%, and CO_2 concentration of 5%.*

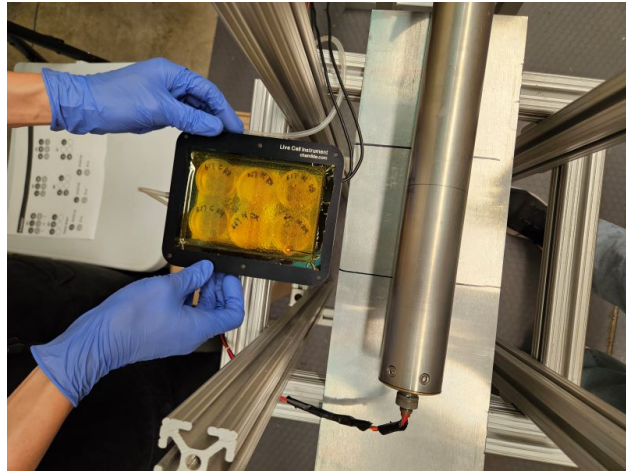


Figure 3.16: *Cell dishes placed inside the incubation chamber before irradiation begun.*

neutron generator. After everything else was setup for the exposure, the incubation chamber was placed with the source plane of the neutron generator down the center of the cells shown in Fig. 3.17. The cells were irradiated following the previously shown experiment plan and DSB and ROS assays were performed on the cells.

3.3.1 Neutron Generator Activation

Another experiment was performed where the neutron generator was operated at the maximum settings for one hour to evaluate the cell incubation chamber, sample holder and gen-

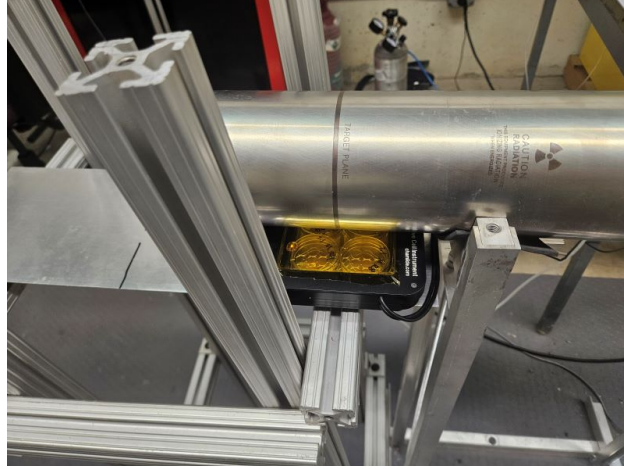


Figure 3.17: *Incubator placement containing the cells centered underneath the neutron generator*

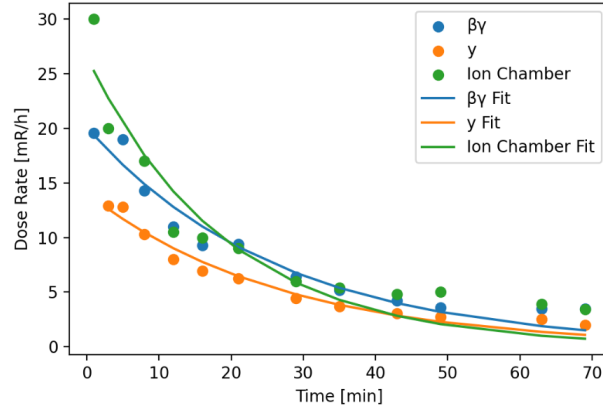


Figure 3.18: *Dose rate values plotted against time after irradiation with fitted curves.*

erator housing activation after irradiation. The neutron generator was operated at 130 kV and 70 μ A for 1 hour where the generator was then turned off and periodic measurements were taken with an ion chamber and a high range frisker. The high range frisker had a beta shield that covered the detector portion so that way measurements could be taken counting gamma rays with and without beta rays. From the fitted curves applied to the data the half-lives of decay were calculated based on the different measurement types.

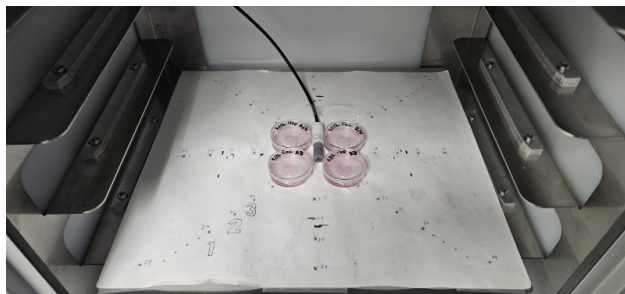


Figure 3.19: *Cell dish placement centered on shelf 1 during x-ray irradiation.*

3.4 X-ray Cell Irradiations

The same type of cell dishes that were used in the neutron irradiation were used in the x-ray irradiation. The cell dishes were placed around the ion chamber which was still centered on the first shelf, an example of the configuration is shown in Fig. 3.19.

Shown in Fig. 2.9, is the dose distribution across the shelf. As can be seen, it is relatively constant close to the center of the plate out to a radius of approximately 6 cm. Since the cell dishes are kept close to the center of the shelf the dose to each dish is assumed to be constant. The dishes were taken out of the incubator and brought to the x-ray generator, including the control cells. The cells that were to be irradiated are placed around the ion chamber while the rest of the cells are left in the transfer box but kept in the experiment so the environmental conditions are as close to the same for all samples. The generator voltage was kept constant for all irradiations at 160 kV but the current was changed to allow for lower dose rate exposures. The two values of the current were 1 mA and 12.5 mA with corresponding dose rates of 1.65 mGy s^{-1} and 22.25 mGy s^{-1} . The current chosen for each irradiation will be shown with the corresponding results.

Chapter 4

Results

4.1 MCNP Simulation

Models of the different radiation sources were successfully created and simulated. The nuclear reactor thermal column was successfully modeled and the neutron flux across the irradiation section was tallied, which can be seen in Fig. 4.1. The plot shows one plane of the FMESH4 tally, with 15 data points in the x, y, and z directions for the mesh, after being converted from neutrons per square centimeter to neutrons per kilowatt. The simulated air volume in the thermal column ranged from -67.675 to 51.705 cm and one of the central slices was shown. The spatial neutron flux result was as expected, with a significantly higher flux on the reactor core side of the thermal column than the door side. The photon flux across the same irradiation area of the thermal column is shown in Fig. 4.2. The spatial photon flux has a significant decrease due to the lead curtain that is on the core side of the thermal column. The slightly increased photon flux on towards the edges is assumed to be from photon streaming around the lead curtain. The energy distribution of neutrons and photons was taken across the irradiation area of the thermal column and is shown in Fig. 4.3 with expected results. There is a two order of magnitude difference in the number of thermal neutrons compared to the rest of the neutron spectrum, which confirms that the thermal column simulation is correctly modeled. The neutron generators and x-ray generators were

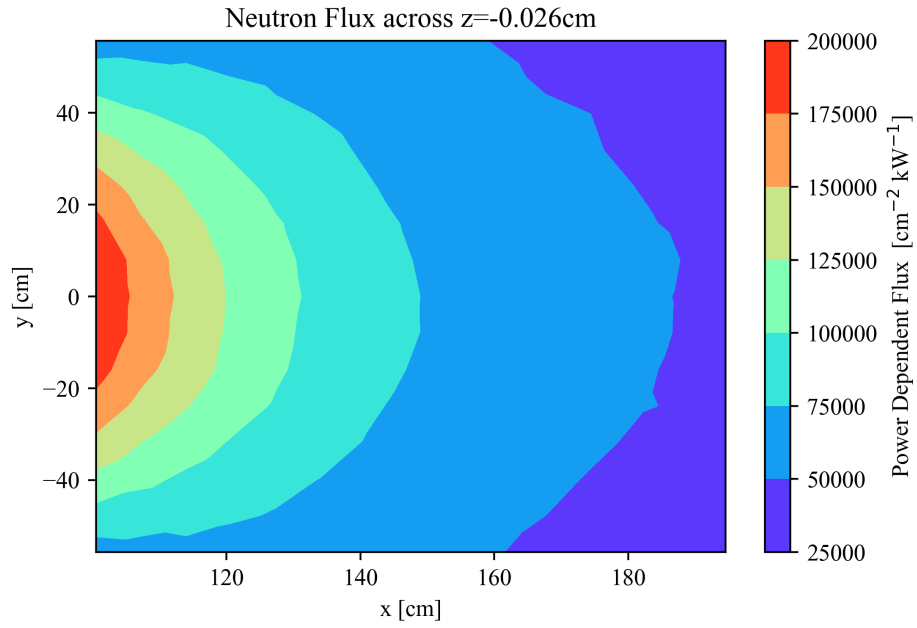


Figure 4.1: Power dependent thermal column neutron flux across the -0.026 cm plane tallied using the FMESH₄.

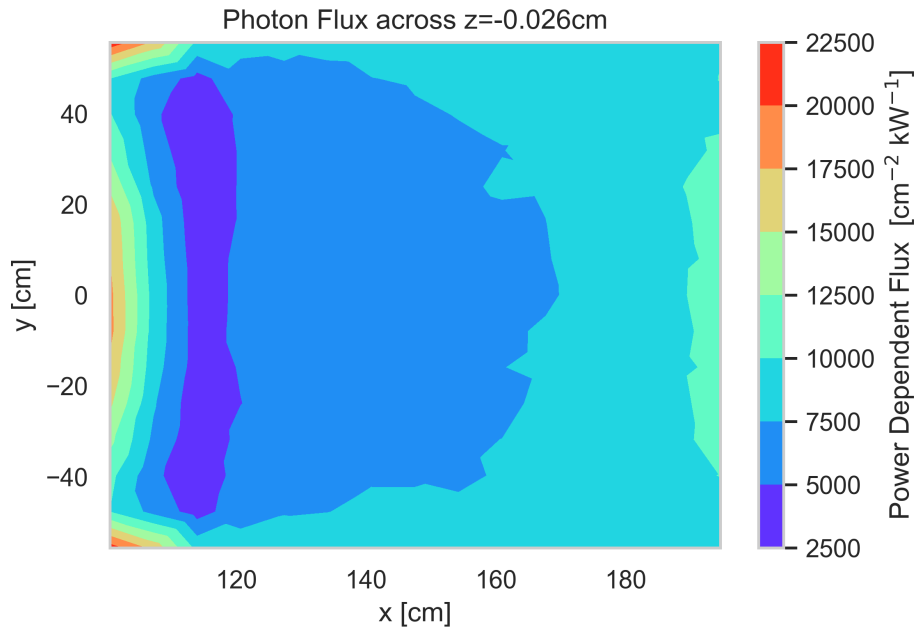


Figure 4.2: Power dependent photon flux across the -0.026 cm plane tallied using the FMESH₄.

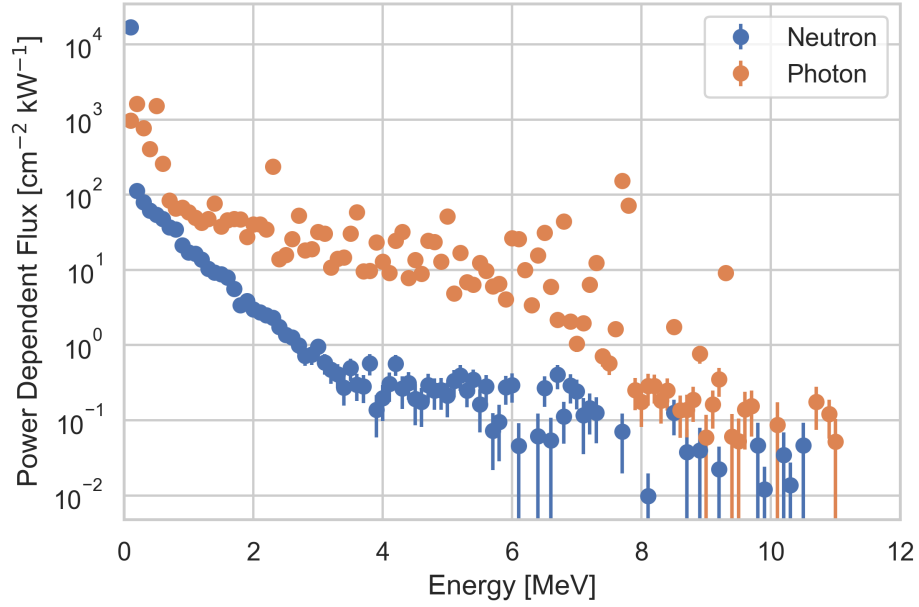


Figure 4.3: *Thermal column energy dependent neutron and photon flux*

Table 4.1: *X-ray and neutron generator settings an dose rates*

Device	Voltage	Current	Dose Rate
P385	130 kV	70 μ A	$\approx$ 60 mGy/hr
RS1800	160 kV	12.5 mA	22.25 mGy/s
	160 kV	1.0 mA	1.65 mGy/s

modeled and used to accurately determine the dose rate the cells received in the exposure experiments conducted.

4.2 Cell Assays

In chapter 3, the neutron generator and x-ray generator were characterized for the use in cell irradiation experiments. Accurate knowledge of the dose rates were obtained and shown in Table 4.1 for the x-ray generator and neutron generator. The neutron generator dose rate is located 7.62cm away from the center of the generator. The x-ray dose rates are at the center of shelf 1.

4.2.1 Neutron Cell Experiments

As was previously stated in section 3.3, there was an error in the dose estimate that was not found until after the cell exposures were conducted so the cell received a much greater dose than desired. The target dose for the cells were 40 mGy and 80 mGy and the incorrect estimate of the dose rate was 5 mGy h^{-1} . The cells were irradiated for 8 and 16 hours receiving actual doses of 480 mGy and 960 mGy. Fig. 4.4 shows images of the cells after neutron irradiation. The cells were seeded onto the dishes 24 hours before the first irradiation. The cells were irradiated for 2 hours each day for four days, where after the first week of irradiation half of the samples were taken to be analyzed. The other half of the samples were left in the incubator until the next set of irradiation were to begin. The cell media was exchanged every other day to allow for proper cell growth. The same 4 day irradiation was performed the second week on the other half of the cells. The γ -H2AX assay was started 30 minutes after irradiation ended for both sets of cells. Immunofluorescence staining procedure from reference⁵⁵ was used for all experiments.

The number of cells in the irradiated image is assumed to be from loss of cell life due to the high dose the cells received. The target dose for neutron irradiation was 40-80 mGy which from the original dose rate calculation of 5 mGy h^{-1} the calculated exposure time was 8 and 16 hours. After the exposure was conducted, the actual dose rate was calculated to be 60 mGy h^{-1} leading to a total dose to the cell cultures of 480 and 960 mGy. That means the cells received approximately twelve times the dose than desired. Due to the much higher dose, the cells likely were killed and when the media exchange happened every other day, the dead cells were removed with spent media. The neutron irradiated cells showed very little ROS in the 960 mGy sample and none in the 480 mGy.

Utilizing ImageJ Fiji for the analysis of the DSB that can be seen in the irradiated samples the number of DSBs per cell were counted and plotted using a strip plot in python. In ImageJ when analyzing the cells, the "Size (pixel²)" parameter was set to 10,000-infinity for Caco-2 and 5,000-infinity for HepG2 to account for the different sized nuclei. The prominence setting for analyzing the DSB was kept at 20 for all pictures to avoid biasing.

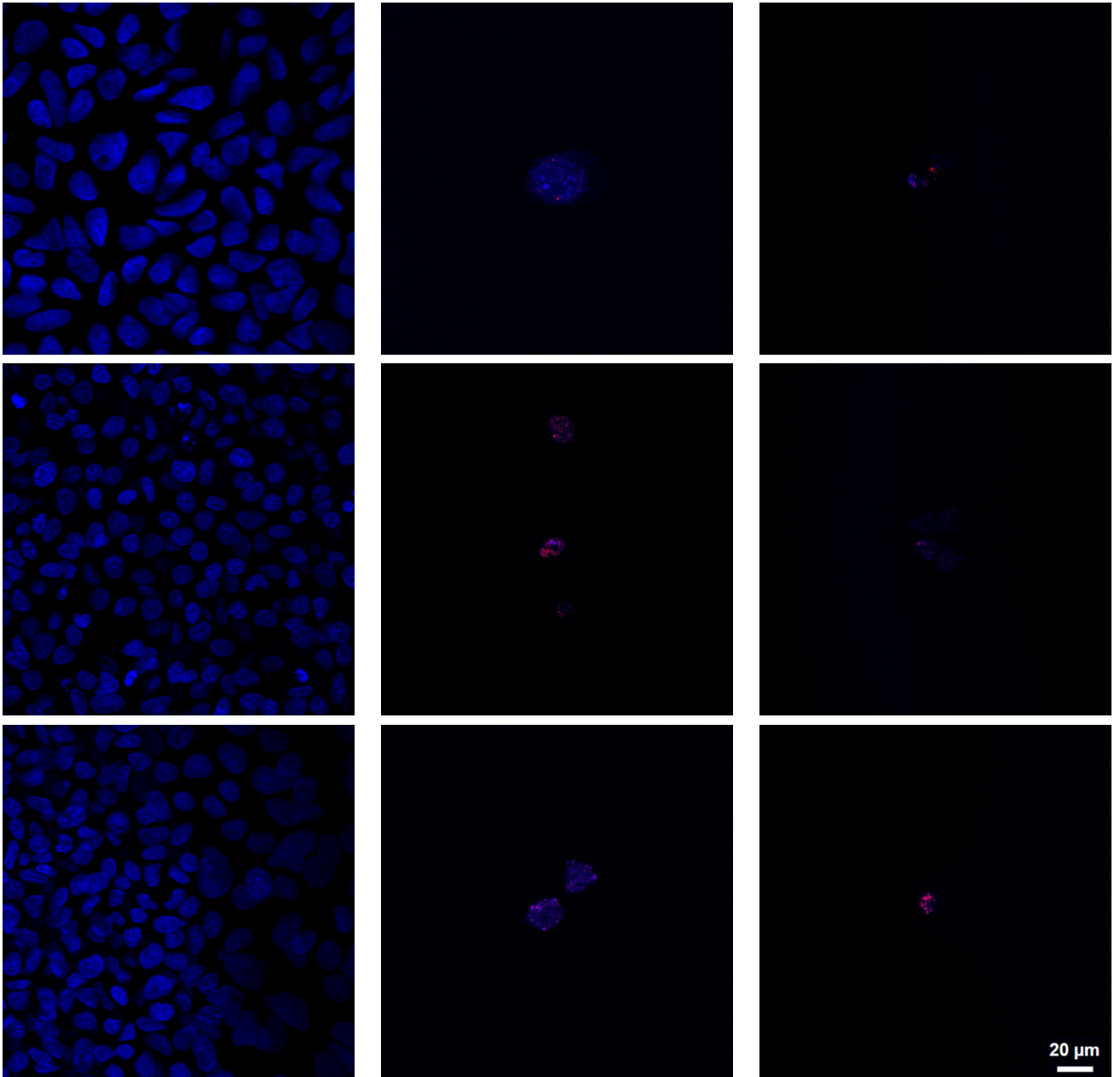


Figure 4.4: *DAPI (stains the cell nucleus blue) and γ -H2AX (stains the DSB red) stained images of Caco-2 in first row and HepG2 in seconds row and a mix of Caco-2 and HepG2 cells in the third row. Cells were exposed to 0 mGy, 480 mGy, and 960 mGy from left to right*

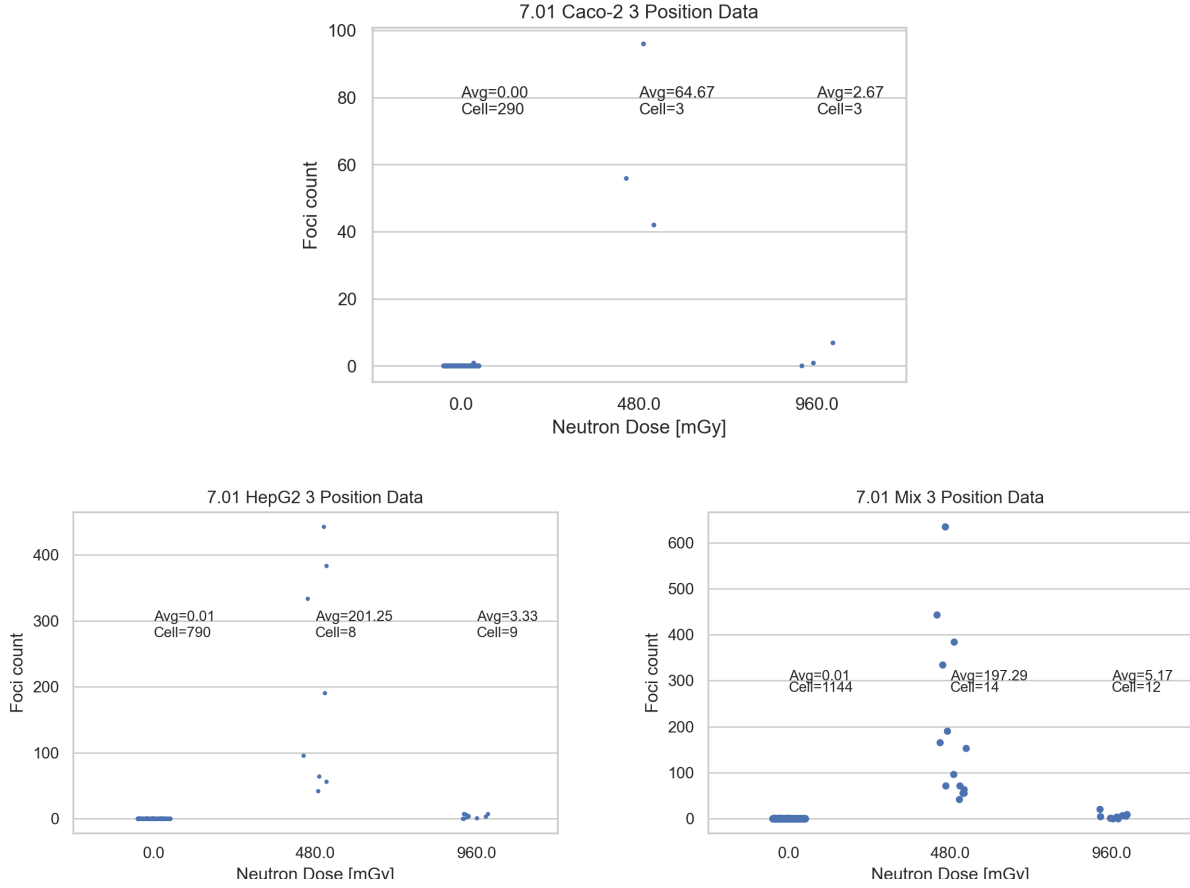


Figure 4.5: *Strip plots of the neutron irradiated samples*

Fig. 4.5 show the DSB data for the limited neutron irradiation available, while there is an increase in DSB after exposure at 480 mGy. The dose was too high to truly quantify the DSB creation based on dose received.

4.2.2 X-ray Cell Experiments

The procedure for the cell culturing was the same for the x-ray experiments as for the neutron exposure. For the DNA DSB experiments that will be presented, the cells were seeded 24 hours before exposure. For the other experiments, the specific details will be listed along with the experiment.

Table 4.2: *DNA DSB experiment time points and exposure type.*

Experiment	Culture before treatment [hr]	Irradiate	Assay [min]
7.16.2024	24	Acute	30
7.31.2024	24	Acute	30
8.05.2024	24	Chronic	30

DSB

Three different x-ray irradiation experiments will be presented here. All three of the experiments used the same time points shown in Table. 4.2. The cells were seeded 24 hours before irradiation.

The different between the acute exposures and the chronic exposures is the number of exposures. For the 2 acute experiments, all of the dose was delivered at one time. The settings of the x-ray generator for the acute exposures were 160 kV and 12.5 mA which led to a dose rate of 22.25 mGy s^{-1} . The chronic experiments were irradiated at much lower dose rate so the exposure time was longer and closer to what astronauts receive in space. The settings of the x-ray generator for the exposures were 160 kV and 1 mA so the dose rate was 1.65 mGy s^{-1} . This different in dose rate led to the irradiation time being approximately 13.5 times longer. The total dose was also fractionated and split between four days, irradiating the cells to 25% of the total dose each day, then performing the assay 30 minutes after the final exposure.

For the 07.16.2024 experiment, Caco-2, HepG2, and a mix of the two were irradiated with 1.5 and 3.0 Gy and starting the assay 30 minutes after exposure. The strip plots of the ImageJ data analyzed counting the number of DSB per cell nuclei is shown in Fig. 4.6. The 7.31.2024 experiment was the same as the 07.16.2024 experiment with an added 0.5 Gy exposure. Some of the images analyzed using ImageJ showing the dose dependence of DSB generation is shown in Fig. 4.7 with the strip plot data analysis in Fig. 4.8. Fig. 4.9 show histogram plots of the DSB generated from the 7.31 experiment. Due to the higher cell number in the HepG2 cell cultures, there are more data points and a distribution can start to be seen in the higher dose. The 08.05.2024 experiment was the chronic exposure experiment where the dose was fractionated into a quarter of the dose being delivered on

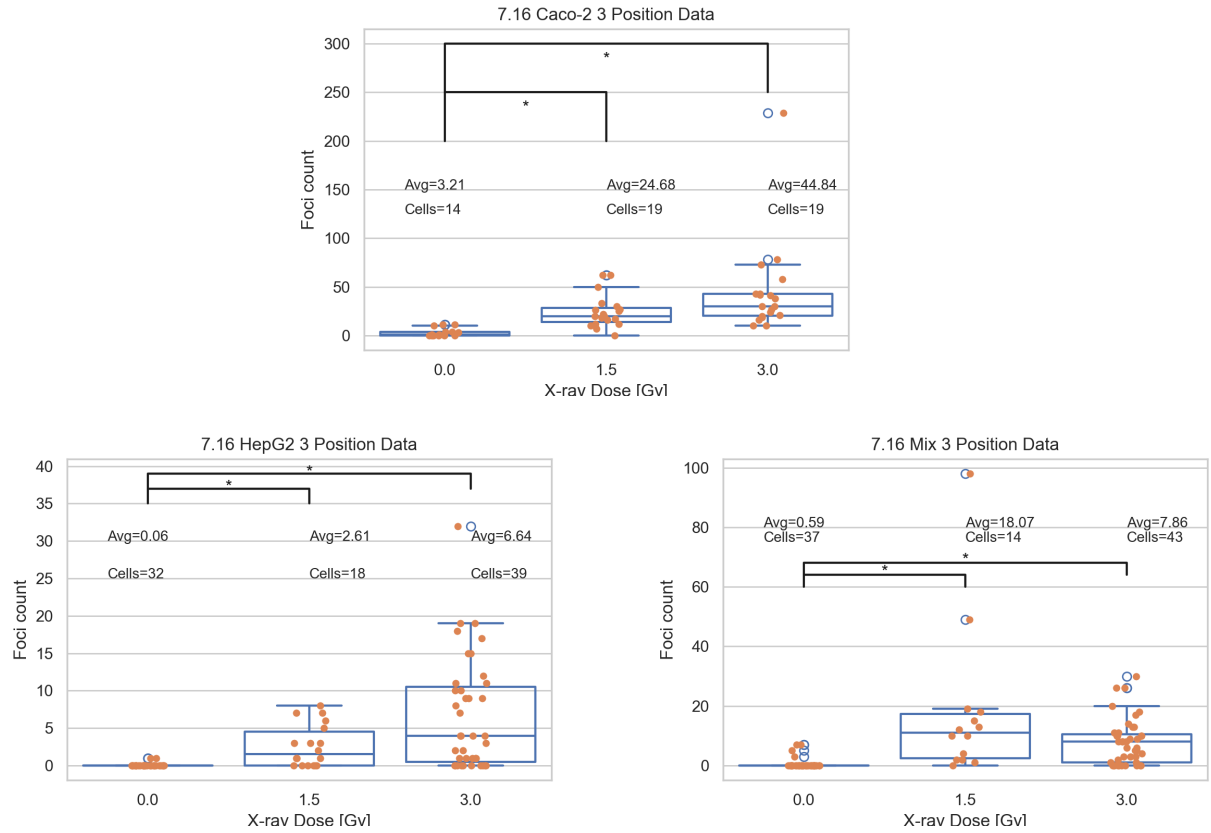


Figure 4.6: *Caco-2*, *HepG2*, and coculture strip plots of DSB per cell nuclei potted showing a dose dependence on the DSB generation. * P value<0.01. Orange DSB data points with a box plot on top. The center line of the box is the median value of the dataset, the edges of the box are the lower and upper quartile value, the value where the horizontal lines stop are the upper and lower values of data sets, and the circles above are outlier values.

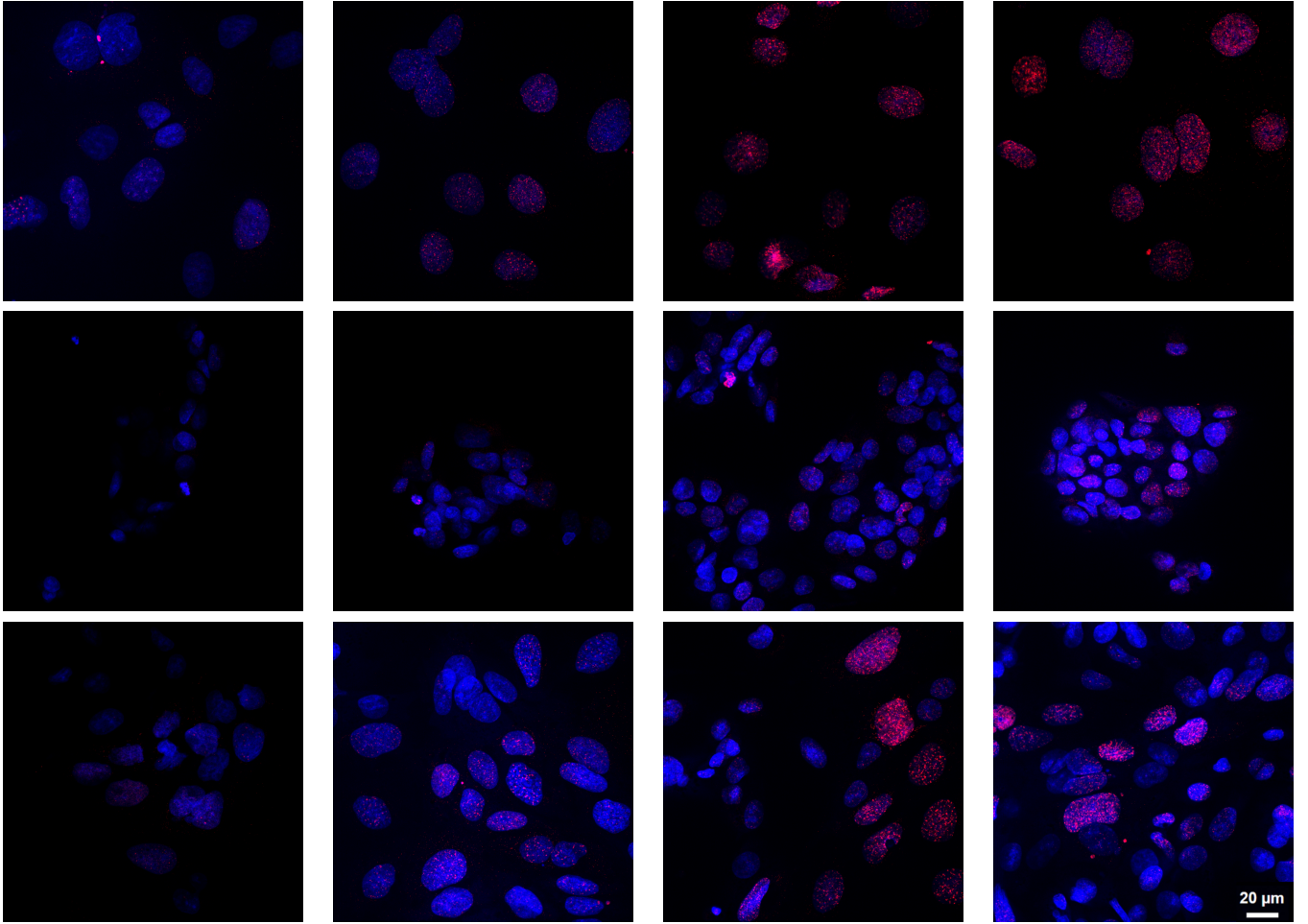


Figure 4.7: DAPI (stains the cell nucleus blue) and γ -H2AX (stains the DSB red) stained images of Caco-2 in first row and HepG2 in seconds row and a mix of Caco-2 and HepG2 cells in the third row. Cells were exposed to 0 Gy, 0.5 Gy, 1.5 Gy, and 3.0 Gy from left to right.

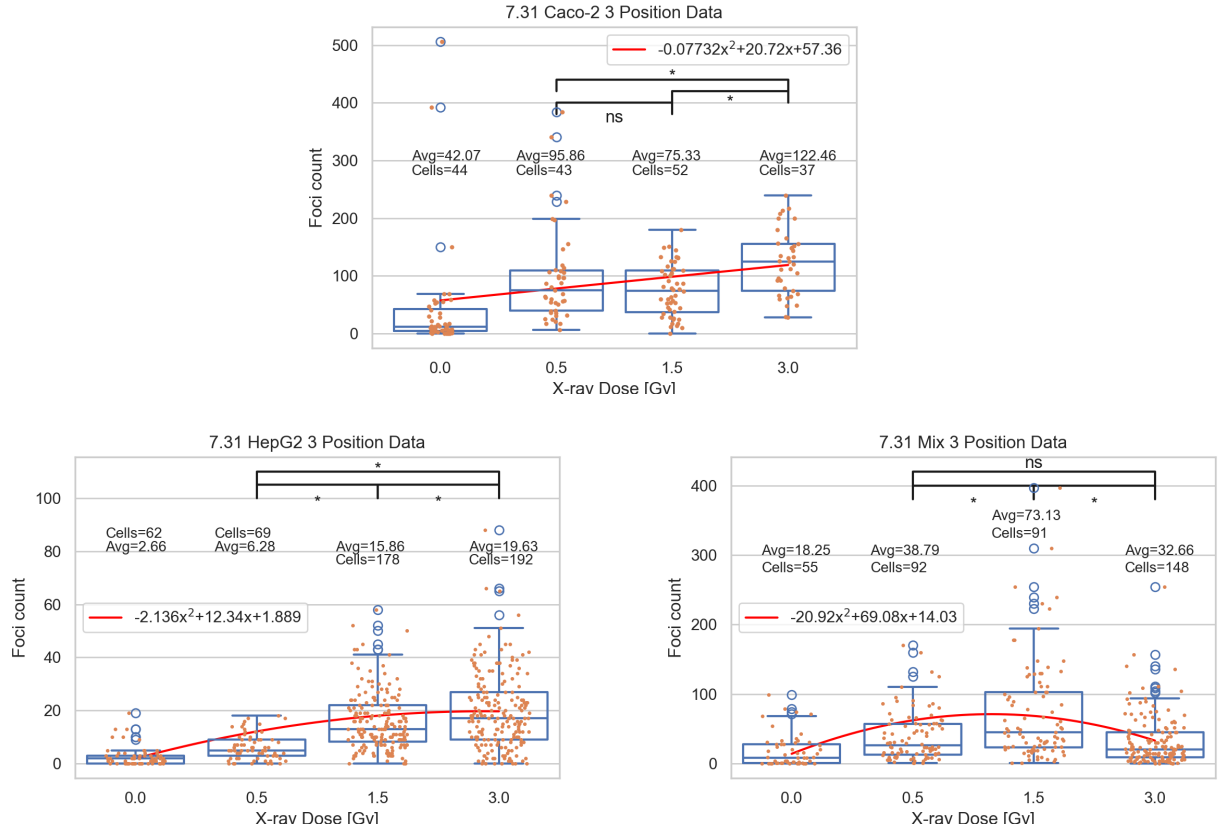


Figure 4.8: *Caco-2*, *HepG2*, and coculture strip plots of DSB per cell nuclei potted showing a dose dependence on the DSB generation. * P value < 0.05 . ns is not significant. Orange DSB data points with a box plot on top. The center line of the box is the median value of the dataset, the edges of the box are the lower and upper quartile value, the value where the horizontal lines stop are the upper and lower values of data sets, and the circles above are outlier values.

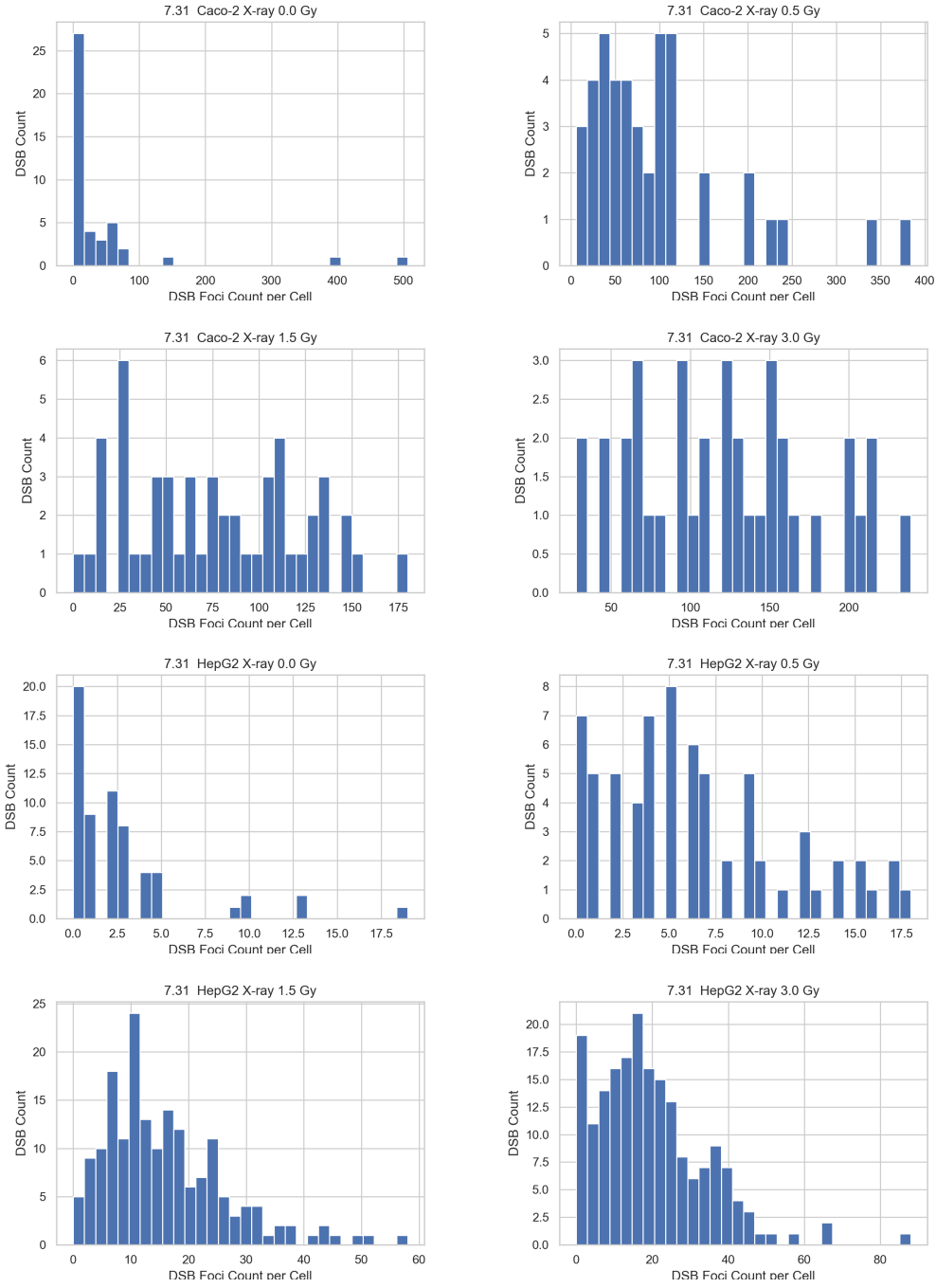


Figure 4.9: Histogram of the DSB foci count for the 7.31 x-ray experiment Caco-2 and HepG2 Data sets. Due to the HepG2 having a higher cell number a distribution can start to be seen in the higher dose.

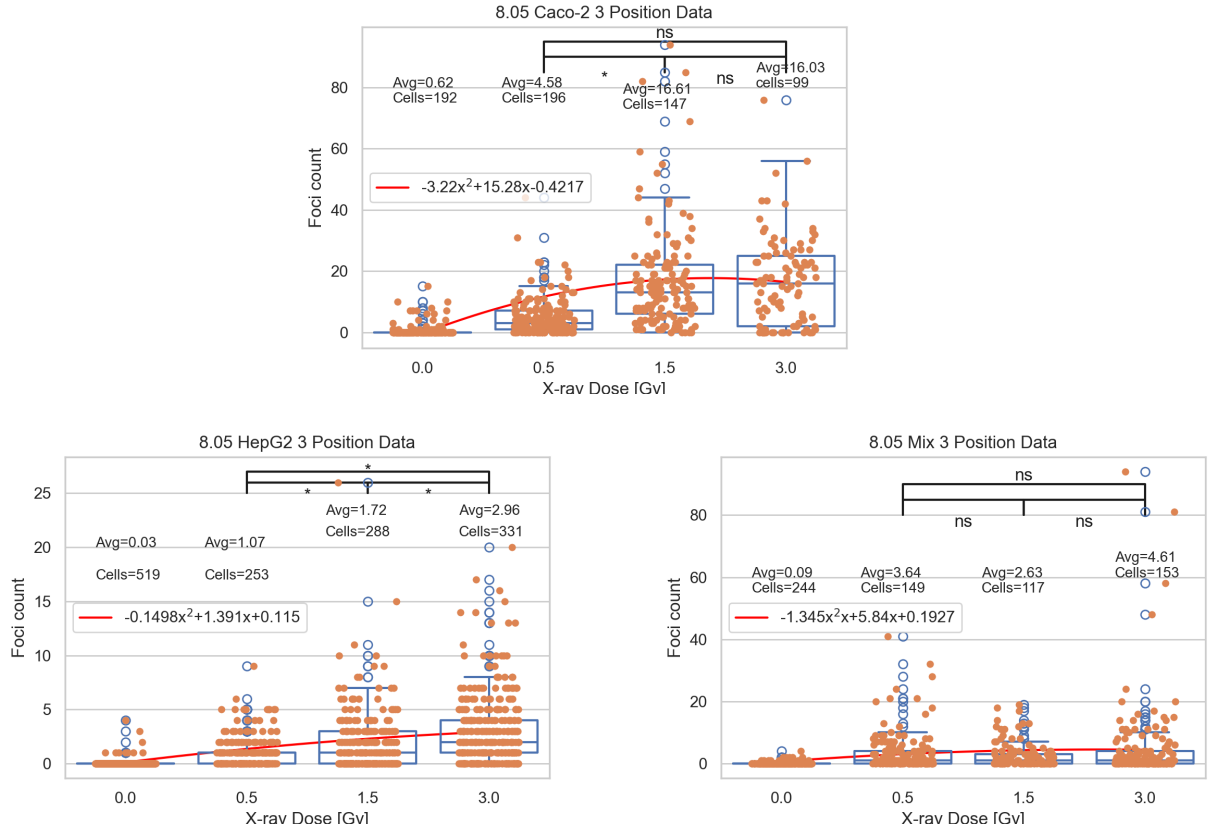


Figure 4.10: DNA DSB data from chronic x-ray exposure to Caco-2, HepG2, and coculture of the two cell types. * P value < 0.01 . ns is not significant. Orange DSB data points with a box plot on top. The center line of the box is the median value of the dataset, the edges of the box are the lower and upper quartile value, the value where the horizontal lines stop are the upper and lower values of data sets, and the circles above are outlier values.

each of four days. The cells were seeded 24 hours before the first exposure was conducted and the assay was started 30 minutes after the final exposure was done. The total DSBs were expected to be lower as there is 24 hours of repair time in between each exposure which can be seen in the results in Fig. 4.10.

The LINAC exposures were conducted using the 6 MV LINAC at KSU Vet Med. Shown in Fig. 4.11 is the DSB generated for Caco-2 and HepG2 cells irradiated with 4 and 8 Gy. The dataset label BC is for a set of cells that were left in the incubator during the entire process from seeding up until the assay was started. That was done to test if the temperature and environment shift from being taken out of the incubator had any effect on the DSBs generated. The data for the 7.31 and 8.05 was fitted to a linear quadratic equation which

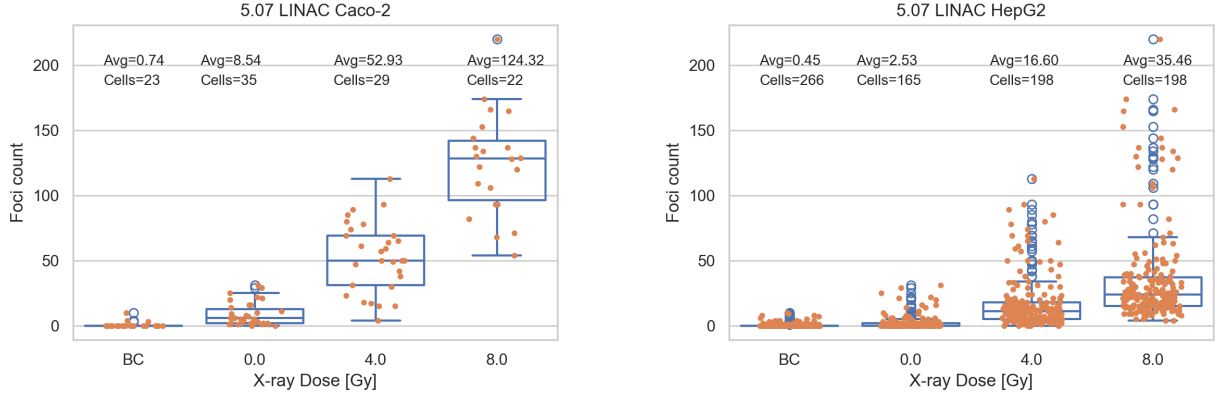


Figure 4.11: 5.07.2024 LINAC exposure of 4 and 8 Gy

shown in the legends of the plots if the corresponding equation and a comparison between the combined linear quadratic equations is shown in Fig. 4.12. The Caco-2 cells had more DSB generated as expected, due to Caco-2 cells being more radiosensitive than HepG2 cells. The linear quadratic equation had associated error with each of the parameters and through error propagation, the error in the number of DSB generated at a given energy equation is shown in Eq. 4.1. The variance and covariance parameters for the equation are given in Table. 4.3.

$$\text{var}(DSB(D)) = D^4\text{var}(a) + D^2\text{var}(b) + \text{var}(c) + 2D^3\text{Cov}(a, b) + 2D^2\text{Cov}(a, c) + 2D\text{Cov}(b, c) \quad (4.1)$$

All of the results showed a dose dependent nature to the amount of DSBs, to better visualize this all of the data was put on a plot in Fig. 4.13 for the x-ray data. There was no significant difference in the DSB generated for the LINAC control vs the BC that was left in the incubator so the transfer did not cause any additional DSBs.

ROS

Experiments were performed multiple different times irradiating Caco-2 and HepG2 with different doses of x-rays to determine the dependency of dose on ROS generation. However, through the irradiations there were no significant difference in ROS generation between 0 Gy up to 16 Gy, shown in Fig. 4.14 for Caco-2 and HepG2.

Table 4.3: Variance and covariance values for the linear quadratic fit using the DSB data and Eq. 4.1 with D being the x-ray dose. Orange DSB data points with a box plot on top. The center line of the box is the median value of the dataset, the edges of the box are the lower and upper quartile value, the value where the horizontal lines stop are the upper and lower values of data sets, and the circles above are outlier values.

Experiment	7.31			8.05		
	Caco-2	HepG2	Mix	Caco-2	HepG2	Mix
Var(a)	33.0	0.27	7.27	0.208	0.0037	0.0908
Var(b)	324.	3.21	82.4	1.922	0.035	0.865
Var(c)	99.8	1.54	28.1	0.464	0.0075	0.171
Cov(a,b)	-99.2	-0.90	-23.9	-0.604	-0.0109	-0.272
Cov(b,c)	-128.	-1.77	-37.2	-0.654	-0.0097	-0.237
Cov(a,c)	32.3	0.422	9.38	0.171	0.00244	0.061

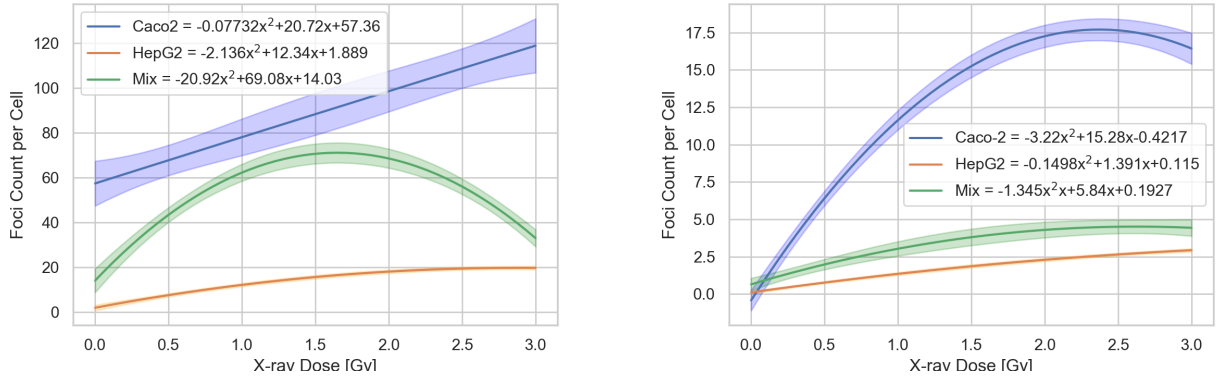


Figure 4.12: Linear quadratic fit for 7.31 DSB experiment (left) and 8.05 DSB experiment (right). Both sets of fits show a relative dose dependent increase in DSB generated up to a point where it starts to decrease.

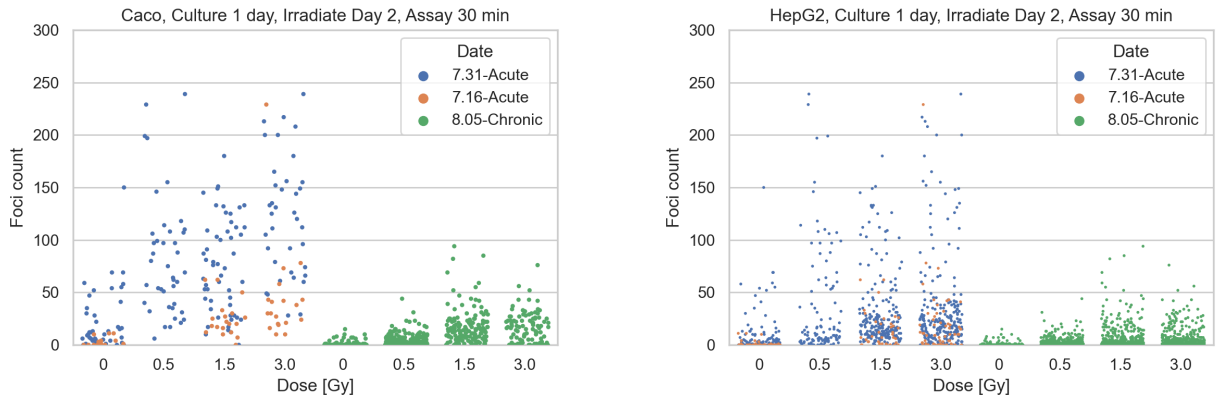


Figure 4.13: X-ray data plotted together to better visualize the comparison of the different experiments.

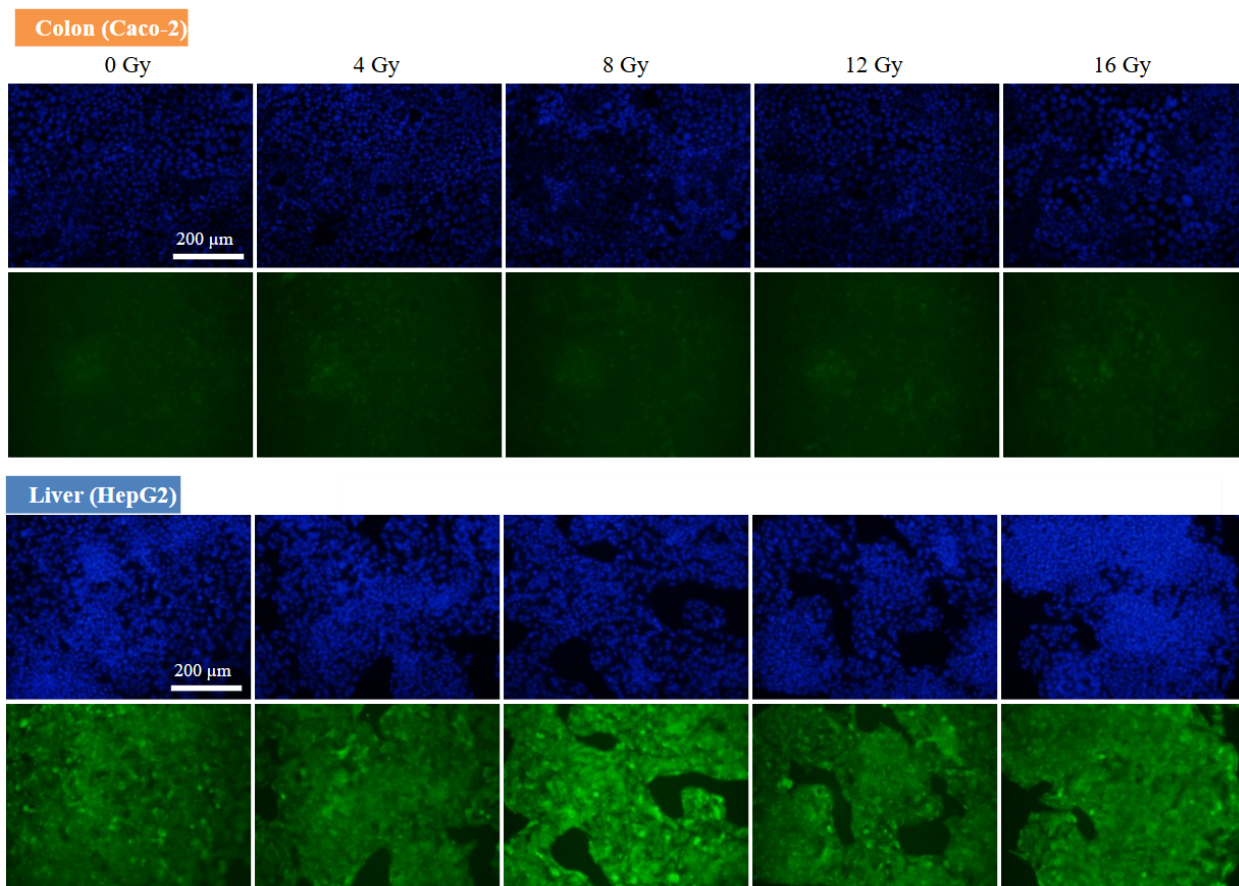


Figure 4.14: *Caco-2 and HepG2 images of DAPI(blue) and ROS (green) irradiated cells up to 16 Gy with no significant difference in ROS between doses.*

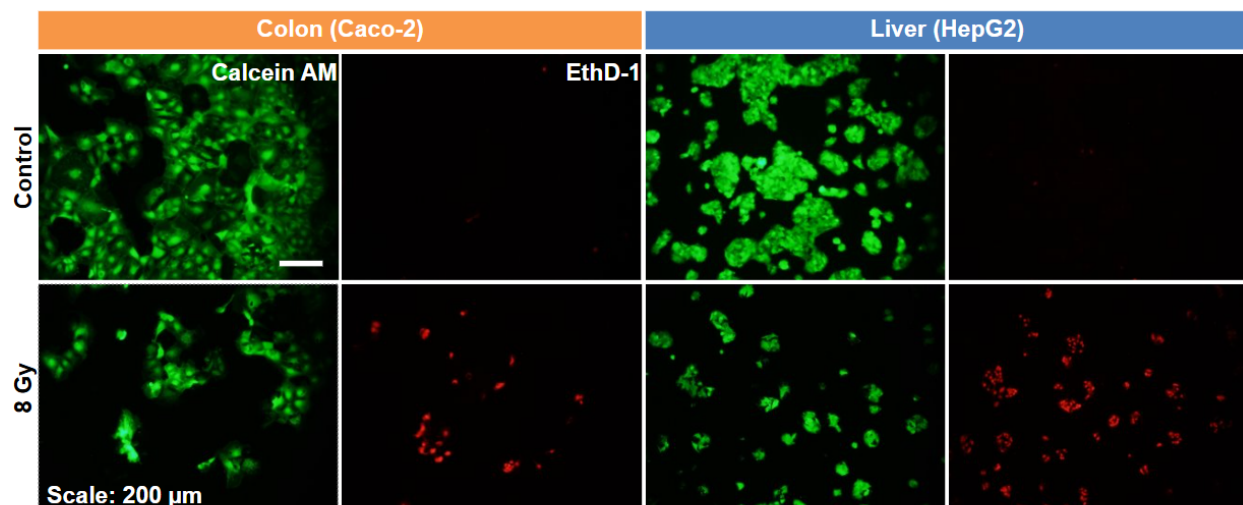


Figure 4.15: *L/D assay after 3 days culturing and 8 Gy of irradiation.*

Cell Viability

Cell viability was analyzed using two different assays; live/dead (L/D) and MTT. The assays were gone into more detail in the introductory section. However, to give a brief overview the L/D assay uses Calcein AM to stain live cells and EthD-1 to stain the DNA that is released when cells are dead. Live cells are then fluorescent green and the dead cells are fluorescent red. DAPI which stains the nuclei of cells blue can also be used to visualize cells in L/D assays. The MTT assay is a colorimetric assay that assessed metabolic activity, that metabolically active cell convert tetrazolium dye MTT into insoluble formazan, which gives the MTT assay its purple color.

Shown in Fig. 4.15 is the L/D assay that was performed. The cells were cultured for 3 days before irradiation; on day 3 they were irradiated with 8 Gy of x-ray. The cell staining was begun immediately upon completion of exposure. The expected result of very few dead cell in the control sample while significantly more in the irradiated cells.

The MTT assay was performed multiple times on different irradiation experiments, changing the assay time point to examine if the time after exposure had any effect on the viability. Table 4.4 shows the different assay start times that were examined.

The MTT assays all showed very little change in cell viability at any time point. This

Table 4.4: *MTT assay details for x-ray experiments*

Experiment	Culture Time [Days]	Assay Start [Hr]
3.26.2024	8	3
4.03.2024	8	24
4.23.2024	8	48

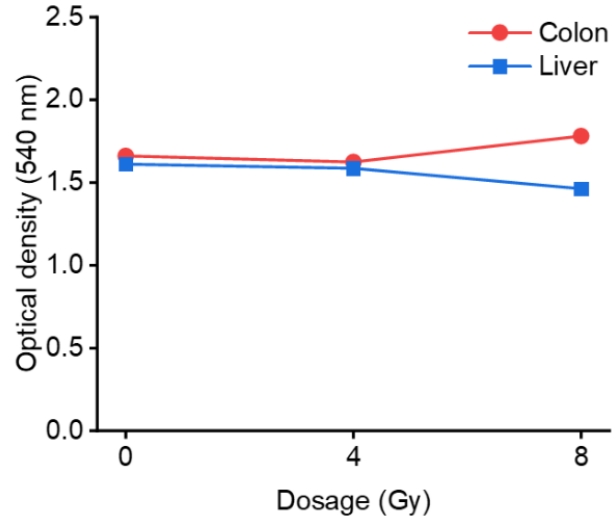


Figure 4.16: *3.26.2024 experiment starting assay 3 hours after exposure*

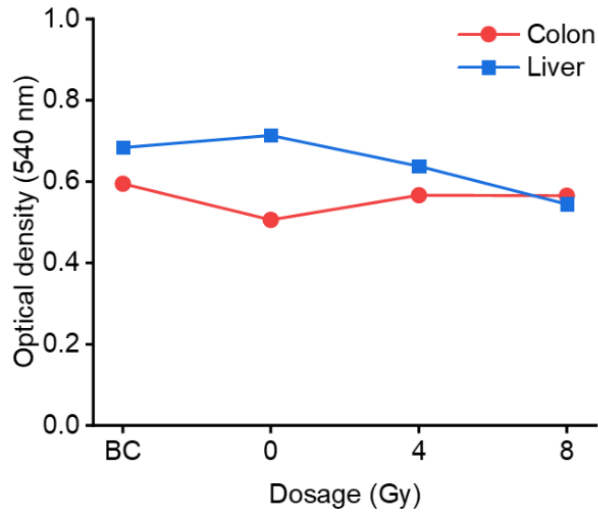


Figure 4.17: *4.03.2024 experiment starting 24 hours after exposure*

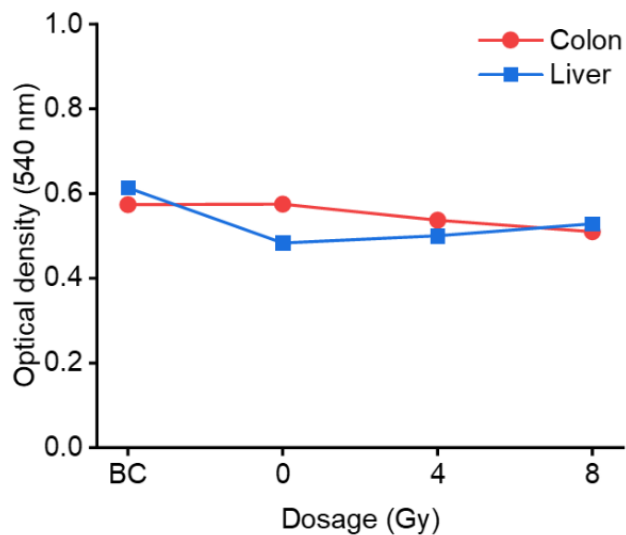


Figure 4.18: *4.23.2024 experiment starting assay 48 hours after exposure*

is assumed to be due to the number of cell analyzed during the assay. Discussed in the introduction, another study found that there is a correlation between the cell density and the outcome of the MTT assay as in that paper the irradiated cells up to 100 Gy and the MTT assay was unchanged. During these exposures the cells had been cultured for 8 days, with a doubling time of approximately 39 and 44 hours for Caco-2 and HepG2 respectively. There were large numbers of cells in the assay which could be the reason very little change in viability was seen.

Chapter 5

Conclusion

5.0.1 MCNP Simulations

The thermal column was successfully implemented in the NEBP model. Spatial and energy dependent flux tallies were created for the neutron and photon flux to confirm the model was working as intended. The results of the tallies show the thermal neutron flux is significantly higher than the rest of the spectrum and that the lead curtain is controlling the photon flux. The model can now be used in designing physical experiments utilizing the mixed field. The RS1800 source term was successfully updated with the increase in voltage and current settings to account for the higher dose rate. The updated simulation was used in the design of the cell exposures to determine the time frames that were achievable.

The dose rate from the neutron generator was successfully modeled after the error was found due to the significant cell killing. The cause of the error is that in MCNP the default neutron physics has light-ion recoil off so protons from neutron and hydrogen elastic scattering were not simulated^{56;57}. The absence of the proton leads to drastically decreased energy deposition when using the F6 energy deposition tally which leads to an incorrect final dose. The fix for this issue is utilizing the coilf parameter in the neutron physics, when coilf is set to 4 it simulates one light-ion from elastic scattering and utilizes the Neutron Capture Ion Algorithm for neutron capture. Fixing this parameter changed the simulated dose rate of the P385 DT neutron generator from 5 mGy h⁻¹ to approximately 60 mGy h⁻¹.

5.0.2 Neutron Experiment

Due to the error in the initial dose calculation, there was very little usable data in the final results due to the increased dose that the cells received and the prolonged exposure. It was shown that there was significant cell death after irradiation of 480 mGy and 960 mGy with some DSB being able to be seen when γ -H2AX staining was performed. Based on references, the neutron survival fraction of certain cell types for 1 Gy of fast neutron exposure is approximately 50%^{58;59}. Since the dose was fractionated between four days, there are other factors affecting the survival fraction. While the activation of the neutron generator aluminum exterior was measured after an exposure was completed, the activation dose rate of the incubation chamber and neutron generator while the experiments were conducted is unknown. The additional dose rate from the activated neutron generator, and activated incubation chamber combined with the multi-day exposure where the cell media was exchanged led to loss of cells.

5.0.3 X-ray Experiments

Multiple experiments were performed utilizing x-rays examining different assays including viability, ROS, and DSB. Shown in Fig. 4.15 is an image of the L/D assay showing that there is cell death after irradiation which this result is expected. The MTT assays that were performed showed no significant change in viability at different doses. Based on reference papers that were found and discussed in the introduction, the near constant MTT results are attributed to the cell density in the cultures. From the reference²⁰, it was demonstrated that with higher cell plating densities the dose to the cell could be up to 100 Gy and the MTT results would still be the same. When the cell plating density was lower, there was a dose dependent decrease in the MTT result. The reference²² demonstrated that there is an increase in mitochondrial mass after irradiation which increases formazan formation. Formazan is the main target for analyzing in MTT assays, which from the increased formazan formation it decreases the effect the radiation has in respect to the MTT assay. These two effects are assumed to be the cause of the near constant MTT assay. The cell doubling time

for Caco-2 and HepG2 being 39 and 44 hours, respectively, means that roughly four doubling times went by before the irradiation was conducted. This means that there was a significant number of cells during irradiation. A way to determine if the high cell count is the cause, is to decrease the plating density or decreasing the culture time before the irradiation, so the cell count is lower for the assay.

Fig. 4.14 shows the results of one of the ROS assays that were performed which showed no significant difference between the range of doses. Caco-2 and HepG2 are both epithelial cell lines and that is one possible reason behind the near constant ROS. From reference²³, they compared a number of different assays including ROS on a DMF cell culture that contained both epithelial Caco-2 cells and endothelial HUVEC cells. Their results shows that there were significantly more ROS generated in the HUVEC cells than in the Caco-2 and when the coculture was analyzed it seemed that the endothelial cells were more reactive to the x-rays.

The DSB assays were performed several times utilizing x-rays from an RS1800 biological irradiator as well as a 6 MV LINAC. The DSB generated showed a dose dependency, as dose increased so did the number of DSBs. This agreed with the references that were found that also demonstrated a dose dependent response^{10;13}. In the 7.31 HepG2 experiment, a poison distribution can start to be seen in the higher doses. Additional Caco-2 cells would be needed to see if a poison distribution appears as well. Linear quadratic fits were created for an acute and a chronic x-ray exposure. The linear quadratic fit showed a linear dose dependent DSB generation of Caco-2 for the acute exposure, while in all the other cell cultures there was a decline after 1.5 Gy. The decline could be attributed to the more radioresistant nature of the HepG2 when compared to Caco-2 or the cells being saturated and not being able to repair anymore DSB. The LINAC exposure assay was begun 1 hour after irradiation so the number of DSBs had already started to decrease, however, it still had significant DSBs.

5.0.4 Future Work

More experiments ideally would have been performed to get better statistical results and to better understand the result that radiation plays in cell damage. Due to the constant value in the MTT results, the viability was not really examined. Experiment could be performed where the cell plating density is adjusted to analyze at what cell density the MTT assay is usable. Once the optimal cell plating density is found, the dose effect on MTT results can be examined. Additional ROS experiments need to be performed to confirm that no ROS is generated in epithelial Caco-2 and HepG2 cells. DSB experiments could be performed to further investigate the dose dependent response and further improve the functions that were derived for the DSBs given an x-ray dose. The assay start time could also be examined to confirm the reference material that the peak number of DSBs occur 30 min after exposure with a time dependent study. A time dependent study could also be used to determine the repair time given different initial doses.

Since the neutron dose rate has been corrected and the actual dose rate is known, all neutron experiments would be performed again to get data for the target doses of 40-80 mGy. Further work can be made with the neutron generator simulations to more accurately model the experiments, such as modeling the neutron generator and sample holder more accurately. Neutron exposures would be performed looking at all the assays discussed. The thermal column of the nuclear reactor will be used for the mixed-field irradiation of cells examining at the same assays. The reactor model can still be improved to add additional beamports and the thermalizing column to have a complete reactor model.

The final major difference to future experiments would be utilizing digital microfluidic chips in the cell culturing instead of the 2D monolayer cell cultures that were irradiated. These DMF chips have been previously demonstrated to form in-vivo-like microtissues and organoids that imitate human cell functions^{60;61}. They utilize dielectrophoresis and electrowetting in the culturing process to automate organoid culturing after cells are seeded into hydrogels²⁴⁻²⁸. Using these DMF chips could better represent human cell models than traditional monolayer cell cultures.

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Appendix A

Neutron Generator MCNP Material Composition

Room 207 - Neutron Dose

c

c -----

c --- CELL CARDS -----

c -----

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1005 63 -1.4806 -605 IMP:P,N=1

1006 63 -1.4806 -606 IMP:P,N=1

1007 63 -1.4806 -607 IMP:P,N=1

1008 63 -1.4806 -608 IMP:P,N=1

1009 63 -1.4806 -609 IMP:P,N=1

1010 63 -1.4806 -610 IMP:P,N=1

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1013 63 -1.4806 -613 IMP:P,N=1
1014 63 -1.4806 -614 IMP:P,N=1
1015 63 -1.4806 -615 IMP:P,N=1
1016 63 -1.4806 -616 IMP:P,N=1
1017 63 -1.4806 -617 IMP:P,N=1
1018 63 -1.4806 -618 IMP:P,N=1
1019 63 -1.4806 -619 IMP:P,N=1
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1021 63 -1.4806 -621 IMP:P,N=1
1022 62 -1.385 -622 IMP:P,N=1
1023 64 -1.5761 -623 IMP:P,N=1
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1080 66 -1.7673 -680 IMP:P,N=1
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1097 66 -1.7673 -697 IMP:P,N=1

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1105 63 -1.4806 -705 IMP:P,N=1
1106 65 -1.6717 -706 IMP:P,N=1
1107 68 -1.9585 -707 IMP:P,N=1
1108 67 -1.8629 -708 IMP:P,N=1
1109 65 -1.6717 -709 IMP:P,N=1
1110 67 -1.8629 -710 IMP:P,N=1
1111 67 -1.8629 -711 IMP:P,N=1
1112 67 -1.8629 -712 IMP:P,N=1
1113 66 -1.7673 -713 IMP:P,N=1
1114 66 -1.7673 -714 IMP:P,N=1
1115 65 -1.6717 -715 IMP:P,N=1
1116 65 -1.6717 -716 IMP:P,N=1
1117 65 -1.6717 -717 IMP:P,N=1
1118 66 -1.7673 -718 IMP:P,N=1
1119 66 -1.7673 -719 IMP:P,N=1
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1121 67 -1.8629 -721 IMP:P,N=1
1122 65 -1.6717 -722 IMP:P,N=1
1123 68 -1.9585 -723 IMP:P,N=1
1124 65 -1.6717 -724 IMP:P,N=1
1125 63 -1.4806 -725 IMP:P,N=1
1126 63 -1.4806 -726 IMP:P,N=1

1127 65 -1.6717 -727 IMP:P,N=1
1128 68 -1.9585 -728 IMP:P,N=1
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1133 66 -1.7673 -733 IMP:P,N=1
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1144 68 -1.9585 -744 IMP:P,N=1
1145 65 -1.6717 -745 IMP:P,N=1
1146 63 -1.4806 -746 IMP:P,N=1
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1148 65 -1.6717 -748 IMP:P,N=1
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1159 65 -1.6717 -759 IMP:P,N=1
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1162 66 -1.7673 -762 IMP:P,N=1
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1165 67 -1.8629 -765 IMP:P,N=1
1166 65 -1.6717 -766 IMP:P,N=1
1167 63 -1.4806 -767 IMP:P,N=1
1168 63 -1.4806 -768 IMP:P,N=1
1169 65 -1.6717 -769 IMP:P,N=1
1170 68 -1.9585 -770 IMP:P,N=1
1171 67 -1.8629 -771 IMP:P,N=1
1172 66 -1.7673 -772 IMP:P,N=1
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1177 66 -1.7673 -777 IMP:P,N=1
1178 65 -1.6717 -778 IMP:P,N=1
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1194 67 -1.8629 -794 IMP:P,N=1
1195 67 -1.8629 -795 IMP:P,N=1
1196 67 -1.8629 -796 IMP:P,N=1
1197 67 -1.8629 -797 IMP:P,N=1
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1199 65 -1.6717 -799 IMP:P,N=1
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1202 66 -1.7673 -802 IMP:P,N=1
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1204 67 -1.8629 -804 IMP:P,N=1
1205 67 -1.8629 -805 IMP:P,N=1
1206 65 -1.6717 -806 IMP:P,N=1
1207 68 -1.9585 -807 IMP:P,N=1
1208 65 -1.6717 -808 IMP:P,N=1
1209 63 -1.4806 -809 IMP:P,N=1
1210 63 -1.4806 -810 IMP:P,N=1
1211 65 -1.6717 -811 IMP:P,N=1
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1215 66 -1.7673 -815 IMP:P,N=1
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1219 66 -1.7673 -819 IMP:P,N=1
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1223 67 -1.8629 -823 IMP:P,N=1
1224 67 -1.8629 -824 IMP:P,N=1
1225 67 -1.8629 -825 IMP:P,N=1
1226 67 -1.8629 -826 IMP:P,N=1
1227 65 -1.6717 -827 IMP:P,N=1
1228 68 -1.9585 -828 IMP:P,N=1
1229 65 -1.6717 -829 IMP:P,N=1
1230 63 -1.4806 -830 IMP:P,N=1
1231 63 -1.4806 -831 IMP:P,N=1
1232 65 -1.6717 -832 IMP:P,N=1
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1254 64 -1.5761 -854 IMP:P,N=1
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1256 64 -1.5761 -856 IMP:P,N=1
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1266 64 -1.5761 -866 IMP:P,N=1
1267 64 -1.5761 -867 IMP:P,N=1
1268 64 -1.5761 -868 IMP:P,N=1
1269 63 -1.4806 -869 IMP:P,N=1
1270 63 -1.4806 -870 IMP:P,N=1
1271 64 -1.5761 -871 IMP:P,N=1

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 1273 62 -1.385 -873 IMP:P,N=1
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 1276 63 -1.4806 -876 IMP:P,N=1
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 1282 63 -1.4806 -882 IMP:P,N=1
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 1284 63 -1.4806 -884 IMP:P,N=1
 1285 63 -1.4806 -885 IMP:P,N=1
 1286 63 -1.4806 -886 IMP:P,N=1
 1287 64 -1.5761 -887 IMP:P,N=1
 1288 64 -1.5761 -888 IMP:P,N=1
 1289 63 -1.4806 -889 IMP:P,N=1
 1290 63 -1.4806 -890 IMP:P,N=1
 1291 63 -1.4806 -891 IMP:P,N=1
 1292 64 -1.5761 -892 IMP:P,N=1
 1293 62 -1.385 -893 IMP:P,N=1
 2 6 -0.998207 -100 IMP:P,N=1
 3 6 -0.998207 -200 IMP:P,N=1
 4 6 -0.998207 -300 IMP:P,N=1
 5 6 -0.998207 -400 IMP:P,N=1
 6 6 -0.998207 -500 IMP:P,N=1
 600 51 -1.86 501 -502 509 -510 511 -512 100 200 300 400 500 IMP:P,N=1 \$ FC40 layer
 601 50 -1.06 501 -502 -509 510 -511 512 505 -506 507 -508 IMP:P,N=1 \$ Poly outside

```

c of FC40
602 50 -1.06 502 -503 505 -506 507 -508 IMP:P,N=1 $ Poly layer on top of cells
c --- BEE chamber
105 2 -0.0012 -40 114 118 116 113 120 122 515 #2 #3 #4 #5 #6 #50 #51 TRCL=1
c imp:n,p=1 $ room air
106 1 -2.35 40 -41 101 102 103 110 111 112 113 114 TRCL=1 imp:n,p=1 $ room walls
107 1 -2.35 -116 115 118 TRCL=1 imp:n,p=1 $ BEE walls
108 6 -0.998207 -115 113 118 #129 #130 #131 #132 TRCL=1 imp:n,p=1 $ inside BEE
109 5 -2.7 -118 117 TRCL=1 imp:n,p=1
c borehole pipe
110 2 -0.0012 -117 TRCL=1 imp:n,p=1 $ inside borehole
99 0 41 -99 101 102 103 104 105 106 121 120 100 200 300 400 500 TRCL=1
imp:n,p=1 $ void
c --- doors and door shields
120 2 -0.0012 -112 TRCL=1 imp:n,p=1 $ inner door void
121 2 -0.0012 -110 TRCL=1 imp:n,p=1 $ outer door void
122 2 -0.0012 -111 TRCL=1 imp:n,p=1 $ outer door plug
123 3 -1.00 -113 119 118 TRCL=1 imp:n,p=1 $ inner wall shield (12 in)
124 3 -1.00 -119 118 TRCL=1 imp:n,p=1 $ inside borehole shield (11 in)
125 3 -1.00 -114 TRCL=1 imp:n,p=1 $ inner door shield (4 in)
126 3 -1.00 -120 TRCL=1 imp:n,p=1 $ outer door shield (3 in)
127 0 -121 TRCL=1 imp:n,p=1 $ top wall shield (5 in)
128 3 -1.00 -122 118 TRCL=1 imp:n,p=1 $ borehole wall shielding (3 in)
129 3 -1.00 -123 TRCL=1 imp:n,p=1 $ in-tank shielding
c (2 in Borated poly)
130 4 -0.95 -124 TRCL=1 imp:n,p=1 $ in-tank shielding (5 in Poly)
131 3 -1.00 -125 TRCL=1 imp:n,p=1 $ in-tank shielding
c (2 in Borated poly)
132 4 -0.95 -126 TRCL=1 imp:n,p=1 $ in-tank shielding (5 in Poly)

```

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c --- roof voids and shields

31  2  -0.0012    -101    TRCL=1  imp:n,p=1      $ roof space 1
32  2  -0.0012    -102    TRCL=1  imp:n,p=1      $ roof space 2
33  2  -0.0012    -103    TRCL=1  imp:n,p=1      $ roof space 3
34  3   -1.00     -104    TRCL=1  imp:n,p=1      $ skylight shield 1
35  3   -1.00     -105    TRCL=1  imp:n,p=1      $ skylight shield 2
36  3   -1.00     -106    TRCL=1  imp:n,p=1      $ skylight shield 3

c --- borehole pipe shielding cover

50  3 -1.00 ((-70 71 84 -79):(-72 73 80 -83):(74 -75 80 84):(76 -77 -79 -83)
      :(-81 72 75):(-85 75 -71):(78 -71 -76):(82 72 -76)) 60 -61 TRCL=1 imp:n,p=1
51  3 -1.00  -71 72 75 -76 81 85 -78 -82 62 -61 TRCL=1  imp:n,p=1

c --- outside environment

100  0      99      TRCL=1      imp:n,p=0      $ graveyard

c -----
c --- SURFACE CARDS -----
c -----

600 RPP -1.970000E+00 -1.684286E+00 -7.110000E-01 -4.252857E-01 -4.283400E-01 -3.350000E-01
601 RPP -1.970000E+00 -1.684286E+00 -4.252857E-01 -1.395714E-01 -4.283400E-01 -3.350000E-01
602 RPP -1.970000E+00 -1.684286E+00 -1.395714E-01 1.461429E-01 -4.283400E-01 -3.350000E-01
603 RPP -1.970000E+00 -1.684286E+00 1.461429E-01 4.318571E-01 -4.283400E-01 -3.350000E-01
604 RPP -1.970000E+00 -1.684286E+00 4.318571E-01 7.175714E-01 -4.283400E-01 -3.350000E-01
605 RPP -1.970000E+00 -1.684286E+00 7.175714E-01 1.003286E+00 -4.283400E-01 -3.350000E-01
606 RPP -1.970000E+00 -1.684286E+00 1.003286E+00 1.289000E+00 -4.283400E-01 -3.350000E-01
607 RPP -1.970000E+00 -1.684286E+00 1.289000E+00 1.574714E+00 -4.283400E-01 -3.350000E-01
608 RPP -1.970000E+00 -1.684286E+00 1.574714E+00 1.860429E+00 -4.283400E-01 -3.350000E-01
609 RPP -1.970000E+00 -1.684286E+00 1.860429E+00 2.146143E+00 -4.283400E-01 -3.350000E-01
610 RPP -1.970000E+00 -1.684286E+00 2.146143E+00 2.431857E+00 -4.283400E-01 -3.350000E-01
611 RPP -1.970000E+00 -1.684286E+00 2.431857E+00 2.717571E+00 -4.283400E-01 -3.350000E-01
612 RPP -1.970000E+00 -1.684286E+00 2.717571E+00 3.003286E+00 -4.283400E-01 -3.350000E-01
613 RPP -1.970000E+00 -1.684286E+00 3.003286E+00 3.289000E+00 -4.283400E-01 -3.350000E-01
614 RPP -1.970000E+00 -1.684286E+00 3.289000E+00 3.574714E+00 -4.283400E-01 -3.350000E-01
615 RPP -1.970000E+00 -1.684286E+00 3.574714E+00 3.860429E+00 -4.283400E-01 -3.350000E-01
616 RPP -1.970000E+00 -1.684286E+00 3.860429E+00 4.146143E+00 -4.283400E-01 -3.350000E-01
617 RPP -1.970000E+00 -1.684286E+00 4.146143E+00 4.431857E+00 -4.283400E-01 -3.350000E-01
618 RPP -1.970000E+00 -1.684286E+00 4.431857E+00 4.717571E+00 -4.283400E-01 -3.350000E-01
619 RPP -1.970000E+00 -1.684286E+00 4.717571E+00 5.003286E+00 -4.283400E-01 -3.350000E-01
620 RPP -1.970000E+00 -1.684286E+00 5.003286E+00 5.289000E+00 -4.283400E-01 -3.350000E-01
621 RPP -1.684286E+00 -1.398571E+00 -7.110000E-01 -4.252857E-01 -4.283400E-01 -3.350000E-01
622 RPP -1.684286E+00 -1.398571E+00 -4.252857E-01 -1.395714E-01 -4.283400E-01 -3.350000E-01

```

[illegible]

679 RPP -1.112857E+00 -3.271429E-01 3.860429E+00 4.146143E+00 -4.283400E-01 -3.350000E-01
680 RPP -1.112857E+00 -8.271429E-01 4.146143E+00 4.431857E+00 -4.283400E-01 -3.350000E-01
681 RPP -1.112857E+00 -8.271429E-01 4.431857E+00 4.717571E+00 -4.283400E-01 -3.350000E-01
682 RPP -1.112857E+00 -8.271429E-01 4.717571E+00 5.003286E+00 -4.283400E-01 -3.350000E-01
683 RPP -1.112857E+00 -8.271429E-01 5.003286E+00 5.289000E+00 -4.283400E-01 -3.350000E-01
684 RPP -8.271429E-01 -5.414286E-01 -7.110000E-01 -4.252857E-01 -4.283400E-01 -3.350000E-01
685 RPP -8.271429E-01 -5.414286E-01 -4.252857E-01 -1.395714E-01 -4.283400E-01 -3.350000E-01
686 RPP -8.271429E-01 -5.414286E-01 -1.395714E-01 1.461429E-01 -4.283400E-01 -3.350000E-01
687 RPP -8.271429E-01 -5.414286E-01 1.461429E-01 4.318571E-01 -4.283400E-01 -3.350000E-01
688 RPP -8.271429E-01 -5.414286E-01 4.318571E-01 7.175714E-01 -4.283400E-01 -3.350000E-01
689 RPP -8.271429E-01 -5.414286E-01 7.175714E-01 1.003286E+00 -4.283400E-01 -3.350000E-01
690 RPP -8.271429E-01 -5.414286E-01 1.003286E+00 1.289000E+00 -4.283400E-01 -3.350000E-01
691 RPP -8.271429E-01 -5.414286E-01 1.289000E+00 1.574714E+00 -4.283400E-01 -3.350000E-01
692 RPP -8.271429E-01 -5.414286E-01 1.574714E+00 1.860429E+00 -4.283400E-01 -3.350000E-01
693 RPP -8.271429E-01 -5.414286E-01 1.860429E+00 2.146143E+00 -4.283400E-01 -3.350000E-01
694 RPP -8.271429E-01 -5.414286E-01 2.146143E+00 2.431857E+00 -4.283400E-01 -3.350000E-01
695 RPP -8.271429E-01 -5.414286E-01 2.431857E+00 2.717571E+00 -4.283400E-01 -3.350000E-01
696 RPP -8.271429E-01 -5.414286E-01 2.717571E+00 3.003286E+00 -4.283400E-01 -3.350000E-01
697 RPP -8.271429E-01 -5.414286E-01 3.003286E+00 3.289000E+00 -4.283400E-01 -3.350000E-01
698 RPP -8.271429E-01 -5.414286E-01 3.289000E+00 3.574714E+00 -4.283400E-01 -3.350000E-01
699 RPP -8.271429E-01 -5.414286E-01 3.574714E+00 3.860429E+00 -4.283400E-01 -3.350000E-01
700 RPP -8.271429E-01 -5.414286E-01 3.860429E+00 4.146143E+00 -4.283400E-01 -3.350000E-01
701 RPP -8.271429E-01 -5.414286E-01 4.146143E+00 4.431857E+00 -4.283400E-01 -3.350000E-01
702 RPP -8.271429E-01 -5.414286E-01 4.431857E+00 4.717571E+00 -4.283400E-01 -3.350000E-01
703 RPP -8.271429E-01 -5.414286E-01 4.717571E+00 5.003286E+00 -4.283400E-01 -3.350000E-01
704 RPP -8.271429E-01 -5.414286E-01 5.003286E+00 5.289000E+00 -4.283400E-01 -3.350000E-01
705 RPP -5.414286E-01 -2.557143E-01 -7.110000E-01 -4.252857E-01 -4.283400E-01 -3.350000E-01
706 RPP -5.414286E-01 -2.557143E-01 -4.252857E-01 -1.395714E-01 -4.283400E-01 -3.350000E-01
707 RPP -5.414286E-01 -2.557143E-01 -1.395714E-01 1.461429E-01 -4.283400E-01 -3.350000E-01
708 RPP -5.414286E-01 -2.557143E-01 1.461429E-01 4.318571E-01 -4.283400E-01 -3.350000E-01
709 RPP -5.414286E-01 -2.557143E-01 4.318571E-01 7.175714E-01 -4.283400E-01 -3.350000E-01
710 RPP -5.414286E-01 -2.557143E-01 7.175714E-01 1.003286E+00 -4.283400E-01 -3.350000E-01
711 RPP -5.414286E-01 -2.557143E-01 1.003286E+00 1.289000E+00 -4.283400E-01 -3.350000E-01
712 RPP -5.414286E-01 -2.557143E-01 1.289000E+00 1.574714E+00 -4.283400E-01 -3.350000E-01
713 RPP -5.414286E-01 -2.557143E-01 1.574714E+00 1.860429E+00 -4.283400E-01 -3.350000E-01
714 RPP -5.414286E-01 -2.557143E-01 1.860429E+00 2.146143E+00 -4.283400E-01 -3.350000E-01
715 RPP -5.414286E-01 -2.557143E-01 2.146143E+00 2.431857E+00 -4.283400E-01 -3.350000E-01
716 RPP -5.414286E-01 -2.557143E-01 2.431857E+00 2.717571E+00 -4.283400E-01 -3.350000E-01
717 RPP -5.414286E-01 -2.557143E-01 2.717571E+00 3.003286E+00 -4.283400E-01 -3.350000E-01
718 RPP -5.414286E-01 -2.557143E-01 3.003286E+00 3.289000E+00 -4.283400E-01 -3.350000E-01
719 RPP -5.414286E-01 -2.557143E-01 3.289000E+00 3.574714E+00 -4.283400E-01 -3.350000E-01
720 RPP -5.414286E-01 -2.557143E-01 3.574714E+00 3.860429E+00 -4.283400E-01 -3.350000E-01
721 RPP -5.414286E-01 -2.557143E-01 3.860429E+00 4.146143E+00 -4.283400E-01 -3.350000E-01
722 RPP -5.414286E-01 -2.557143E-01 4.146143E+00 4.431857E+00 -4.283400E-01 -3.350000E-01
723 RPP -5.414286E-01 -2.557143E-01 4.431857E+00 4.717571E+00 -4.283400E-01 -3.350000E-01
724 RPP -5.414286E-01 -2.557143E-01 4.717571E+00 5.003286E+00 -4.283400E-01 -3.350000E-01
725 RPP -5.414286E-01 -2.557143E-01 5.003286E+00 5.289000E+00 -4.283400E-01 -3.350000E-01
726 RPP -2.557143E-01 3.000000E-02 -7.110000E-01 -4.252857E-01 -4.283400E-01 -3.350000E-01
727 RPP -2.557143

735	RPP	-2.557143E-01	0.000000E-02	1.860429E+00	2.146143E+00	-4.283400E-01	-3.350000E-01
736	RPP	-2.557143E-01	3.000000E-02	2.146143E+00	2.431857E+00	-4.283400E-01	-3.350000E-01
737	RPP	-2.557143E-01	3.000000E-02	2.431857E+00	2.717571E+00	-4.283400E-01	-3.350000E-01
738	RPP	-2.557143E-01	3.000000E-02	2.717571E+00	3.003286E+00	-4.283400E-01	-3.350000E-01
739	RPP	-2.557143E-01	3.000000E-02	3.003286E+00	3.289000E+00	-4.283400E-01	-3.350000E-01
740	RPP	-2.557143E-01	3.000000E-02	3.289000E+00	3.574714E+00	-4.283400E-01	-3.350000E-01
741	RPP	-2.557143E-01	3.000000E-02	3.574714E+00	3.860429E+00	-4.283400E-01	-3.350000E-01
742	RPP	-2.557143E-01	3.000000E-02	3.860429E+00	4.146143E+00	-4.283400E-01	-3.350000E-01
743	RPP	-2.557143E-01	3.000000E-02	4.146143E+00	4.431857E+00	-4.283400E-01	-3.350000E-01
744	RPP	-2.557143E-01	3.000000E-02	4.431857E+00	4.717571E+00	-4.283400E-01	-3.350000E-01
745	RPP	-2.557143E-01	3.000000E-02	4.717571E+00	5.003286E+00	-4.283400E-01	-3.350000E-01
746	RPP	-2.557143E-01	3.000000E-02	5.003286E+00	5.289000E+00	-4.283400E-01	-3.350000E-01
747	RPP	3.000000E-02	3.157143E-01	-7.110000E-01	-4.252857E-01	-4.283400E-01	-3.350000E-01
748	RPP	3.000000E-02	3.157143E-01	-4.252857E-01	-1.395714E-01	-4.283400E-01	-3.350000E-01
749	RPP	3.000000E-02	3.157143E-01	-1.395714E-01	1.461429E-01	-4.283400E-01	-3.350000E-01
750	RPP	3.000000E-02	3.157143E-01	1.461429E-01	4.318571E-01	-4.283400E-01	-3.350000E-01
751	RPP	3.000000E-02	3.157143E-01	4.318571E-01	7.175714E-01	-4.283400E-01	-3.350000E-01
752	RPP	3.000000E-02	3.157143E-01	7.175714E-01	1.003286E+00	-4.283400E-01	-3.350000E-01
753	RPP	3.000000E-02	3.157143E-01	1.003286E+00	1.289000E+00	-4.283400E-01	-3.350000E-01
754	RPP	3.000000E-02	3.157143E-01	1.289000E+00	1.574714E+00	-4.283400E-01	-3.350000E-01
755	RPP	3.000000E-02	3.157143E-01	1.574714E+00	1.860429E+00	-4.283400E-01	-3.350000E-01
756	RPP	3.000000E-02	3.157143E-01	1.860429E+00	2.146143E+00	-4.283400E-01	-3.350000E-01
757	RPP	3.000000E-02	3.157143E-01	2.146143E+00	2.431857E+00	-4.283400E-01	-3.350000E-01
758	RPP	3.000000E-02	3.157143E-01	2.431857E+00	2.717571E+00	-4.283400E-01	-3.350000E-01
759	RPP	3.000000E-02	3.157143E-01	2.717571E+00	3.003286E+00	-4.283400E-01	-3.350000E-01
760	RPP	3.000000E-02	3.157143E-01	3.003286E+00	3.289000E+00	-4.283400E-01	-3.350000E-01
761	RPP	3.000000E-02	3.157143E-01	3.289000E+00	3.574714E+00	-4.283400E-01	-3.350000E-01
762	RPP	3.000000E-02	3.157143E-01	3.574714E+00	3.860429E+00	-4.283400E-01	-3.350000E-01
763	RPP	3.000000E-02	3.157143E-01	3.860429E+00	4.146143E+00	-4.283400E-01	-3.350000E-01
764	RPP	3.000000E-02	3.157143E-01	4.146143E+00	4.431857E+00	-4.283400E-01	-3.350000E-01
765	RPP	3.000000E-02	3.157143E-01	4.431857E+00	4.717571E+00	-4.283400E-01	-3.350000E-01
766	RPP	3.000000E-02	3.157143E-01	4.717571E+00	5.003286E+00	-4.283400E-01	-3.350000E-01
767	RPP	3.000000E-02	3.157143E-01	5.003286E+00	5.289000E+00	-4.283400E-01	-3.350000E-01
768	RPP	3.157143E-01	6.014286E-01	-7.110000E-01	-4.252857E-01	-4.283400E-01	-3.350000E-01
769	RPP</						

791	RPP	6.014286E-01	8.871429E-01	-1.395714E-01	1.461429E-01	-4.283400E-01	-3.350000E-01
792	RPP	6.014286E-01	8.871429E-01	1.461429E-01	4.318571E-01	-4.283400E-01	-3.350000E-01
793	RPP	6.014286E-01	8.871429E-01	4.318571E-01	7.175714E-01	-4.283400E-01	-3.350000E-01
794	RPP	6.014286E-01	8.871429E-01	7.175714E-01	1.003286E+00	-4.283400E-01	-3.350000E-01
795	RPP	6.014286E-01	8.871429E-01	1.003286E+00	1.289000E+00	-4.283400E-01	-3.350000E-01
796	RPP	6.014286E-01	8.871429E-01	1.289000E+00	1.574714E+00	-4.283400E-01	-3.350000E-01
797	RPP	6.014286E-01	8.871429E-01	1.574714E+00	1.860429E+00	-4.283400E-01	-3.350000E-01
798	RPP	6.014286E-01	8.871429E-01	1.860429E+00	2.146143E+00	-4.283400E-01	-3.350000E-01
799	RPP	6.014286E-01	8.871429E-01	2.146143E+00	2.431857E+00	-4.283400E-01	-3.350000E-01
800	RPP	6.014286E-01	8.871429E-01	2.431857E+00	2.717571E+00	-4.283400E-01	-3.350000E-01
801	RPP	6.014286E-01	8.871429E-01	2.717571E+00	3.003286E+00	-4.283400E-01	-3.350000E-01
802	RPP	6.014286E-01	8.871429E-01	3.003286E+00	3.289000E+00	-4.283400E-01	-3.350000E-01
803	RPP	6.014286E-01	8.871429E-01	3.289000E+00	3.574714E+00	-4.283400E-01	-3.350000E-01
804	RPP	6.014286E-01	8.871429E-01	3.574714E+00	3.860429E+00	-4.283400E-01	-3.350000E-01
805	RPP	6.014286E-01	8.871429E-01	3.860429E+00	4.146143E+00	-4.283400E-01	-3.350000E-01
806	RPP	6.014286E-01	8.871429E-01	4.146143E+00	4.431857E+00	-4.283400E-01	-3.350000E-01
807	RPP	6.014286E-01	8.871429E-01	4.431857E+00	4.717571E+00	-4.283400E-01	-3.350000E-01
808	RPP	6.014286E-01	8.871429E-01	4.717571E+00	5.003286E+00	-4.283400E-01	-3.350000E-01
809	RPP	6.014286E-01	8.871429E-01	5.003286E+00	5.289000E+00	-4.283400E-01	-3.350000E-01
810	RPP	8.871429E-01	1.172857E+00	-7.110000E-01	-4.252857E-01	-4.283400E-01	-3.350000E-01
811	RPP	8.871429E-01	1.172857E+00	-4.252857E-01	-1.395714E-01	-4.283400E-01	-3.350000E-01
812	RPP	8.871429E-01	1.172857E+00	-1.395714E-01	1.461429E-01	-4.283400E-01	-3.350000E-01
813	RPP	8.871429E-01	1.172857E+00	1.461429E-01	4.318571E-01	-4.283400E-01	-3.350000E-01
814	RPP	8.871429E-01	1.172857E+00	4.318571E-01	7.175714E-01	-4.283400E-01	-3.350000E-01
815	RPP	8.871429E-01	1.172857E+00	7.175714E-01	1.003286E+00	-4.283400E-01	-3.350000E-01
816	RPP	8.871429E-01	1.172857E+00	1.003286E+00	1.289000E+00	-4.283400E-01	-3.350000E-01
817	RPP	8.871429E-01	1.172857E+00	1.289000E+00	1.574714E+00	-4.283400E-01	-3.350000E-01
818	RPP	8.871429E-01	1.172857E+00	1.574714E+00	1.860429E+00	-4.283400E-01	-3.350000E-01
819	RPP	8.871429E-01	1.172857E+00	1.860429E+00	2.146143E+00	-4.283400E-01	-3.350000E-01
820	RPP	8.871429E-01	1.172857E+00	2.146143E+00	2.431857E+00	-4.283400E-01	-3.350000E-01
821	RPP	8.871429E-01	1.172857E+00	2.431857E+00	2.717571E+00	-4.283400E-01	-3.350000E-01
822	RPP	8.871429E-01	1.172857E+00	2.717571E+00	3.003286E+00	-4.283400E-01	-3.350000E-01
823	RPP	8.871429E-01	1.172857E+00	3.003286E+00	3.289000E+00	-4.283400E-01	-3.350000E-01
824	RPP	8.871429E-01	1.172857E+00	3.289000E+00	3.574714E+00	-4.283400E-01	-3.350000E-01
825	RPP</						

847 RPP 1.172857E+00 1.458571E+00 3.860429E+00 4.146143E+00 -4.283400E-01 -3.350000E-01
848 RPP 1.172857E+00 1.458571E+00 4.146143E+00 4.431857E+00 -4.283400E-01 -3.350000E-01
849 RPP 1.172857E+00 1.458571E+00 4.431857E+00 4.717571E+00 -4.283400E-01 -3.350000E-01
850 RPP 1.172857E+00 1.458571E+00 4.717571E+00 5.003286E+00 -4.283400E-01 -3.350000E-01
851 RPP 1.172857E+00 1.458571E+00 5.003286E+00 5.289000E+00 -4.283400E-01 -3.350000E-01
852 RPP 1.458571E+00 1.744286E+00 -7.110000E-01 -4.252857E-01 -4.283400E-01 -3.350000E-01
853 RPP 1.458571E+00 1.744286E+00 -4.252857E-01 -1.395714E-01 -4.283400E-01 -3.350000E-01
854 RPP 1.458571E+00 1.744286E+00 -1.395714E-01 1.461429E-01 -4.283400E-01 -3.350000E-01
855 RPP 1.458571E+00 1.744286E+00 1.461429E-01 4.318571E-01 -4.283400E-01 -3.350000E-01
856 RPP 1.458571E+00 1.744286E+00 4.318571E-01 7.175714E-01 -4.283400E-01 -3.350000E-01
857 RPP 1.458571E+00 1.744286E+00 7.175714E-01 1.003286E+00 -4.283400E-01 -3.350000E-01
858 RPP 1.458571E+00 1.744286E+00 1.003286E+00 1.289000E+00 -4.283400E-01 -3.350000E-01
859 RPP 1.458571E+00 1.744286E+00 1.289000E+00 1.574714E+00 -4.283400E-01 -3.350000E-01
860 RPP 1.458571E+00 1.744286E+00 1.574714E+00 1.860429E+00 -4.283400E-01 -3.350000E-01
861 RPP 1.458571E+00 1.744286E+00 1.860429E+00 2.146143E+00 -4.283400E-01 -3.350000E-01
862 RPP 1.458571E+00 1.744286E+00 2.146143E+00 2.431857E+00 -4.283400E-01 -3.350000E-01
863 RPP 1.458571E+00 1.744286E+00 2.431857E+00 2.717571E+00 -4.283400E-01 -3.350000E-01
864 RPP 1.458571E+00 1.744286E+00 2.717571E+00 3.003286E+00 -4.283400E-01 -3.350000E-01
865 RPP 1.458571E+00 1.744286E+00 3.003286E+00 3.289000E+00 -4.283400E-01 -3.350000E-01
866 RPP 1.458571E+00 1.744286E+00 3.289000E+00 3.574714E+00 -4.283400E-01 -3.350000E-01
867 RPP 1.458571E+00 1.744286E+00 3.574714E+00 3.860429E+00 -4.283400E-01 -3.350000E-01
868 RPP 1.458571E+00 1.744286E+00 3.860429E+00 4.146143E+00 -4.283400E-01 -3.350000E-01
869 RPP 1.458571E+00 1.744286E+00 4.146143E+00 4.431857E+00 -4.283400E-01 -3.350000E-01
870 RPP 1.458571E+00 1.744286E+00 4.431857E+00 4.717571E+00 -4.283400E-01 -3.350000E-01
871 RPP 1.458571E+00 1.744286E+00 4.717571E+00 5.003286E+00 -4.283400E-01 -3.350000E-01
872 RPP 1.458571E+00 1.744286E+00 5.003286E+00 5.289000E+00 -4.283400E-01 -3.350000E-01
873 RPP 1.744286E+00 2.030000E+00 -7.110000E-01 -4.252857E-01 -4.283400E-01 -3.350000E-01
874 RPP 1.744286E+00 2.030000E+00 -4.252857E-01 -1.395714E-01 -4.283400E-01 -3.350000E-01
875 RPP 1.744286E+00 2.030000E+00 -1.395714E-01 1.461429E-01 -4.283400E-01 -3.350000E-01
876 RPP 1.744286E+00 2.030000E+00 1.461429E-01 4.318571E-01 -4.283400E-01 -3.350000E-01
877 RPP 1.744286E+00 2.030000E+00 4.318571E-01 7.175714E-01 -4.283400E-01 -3.350000E-01
878 RPP 1.744286E+00 2.030000E+00 7.175714E-01 1.003286E+00 -4.283400E-01 -3.350000E-01
879 RPP 1.744286E+00 2.030000E+00 1.003286E+00 1.289000E+00 -4.283400E-01 -3.350000E-01
880 RPP 1.744286E+00 2.030000E+00 1.289000E+00 1.574714E+00 -4.283400E-01 -3.350000E-01
881 RPP 1.744286E+00 2.030000E+00 1.574714E+00 1.860429E+00 -4.283400E-01 -3.350000E-01
882 RPP 1.744286E+00 2.030000E+00 1.860429E+00 2.146143E+00 -4.283400E-01 -3.350000E-01
883 RPP 1.744286E+00 2.030000E+00 2.146143E+00 2.431857E+00 -4.283400E-01 -3.350000E-01
884 RPP 1.744286E+00 2.030000E+00 2.431857E+00 2.717571E+00 -4.283400E-01 -3.350000E-01
885 RPP 1.744286E+00 2.030000E+00 2.717571E+00 3.003286E+00 -4.283400E-01 -3.350000E-01
886 RPP 1.744286E+00 2.030000E+00 3.003286E+00 3.289000E+00 -4.283400E-01 -3.350000E-01
887 RPP 1.744286E+00 2.030000E+00 3.289000E+00 3.574714E+00 -4.283400E-01 -3.350000E-01
888 RPP 1.744286E+00 2.030000E+00 3.574714E+00 3.860429E+00 -4.283400E-01 -3.350000E-01
889 RPP 1.744286E+00 2.030000E+00 3.860429E+00 4.146143E+00 -4.283400E-01 -3.350000E-01
890 RPP 1.744286E+00 2.030000E+00 4.146143E+00 4.431857E+00 -4.283400E-01 -3.350000E-01
891 RPP 1.744286E+00 2.030000E+00 4.431857E+00 4.717571E+00 -4.283400E-01 -3.350000E-01
892 RPP 1.744286E+00 2.030000E+00 4.717571E+00 5.003286E+00 -4.283400E-01 -3.350000E-01
893 RPP 1.744286E+00 2.030000E+00 5.003286E+00 5.289000E+00 -4.283400E-01 -3.350000E-01

100 RCC -1.2 1.5 -0.0744 0 0 0.0444 0.12 \$ hydrogel cells

200 RCC -0.6 1.5 -0.0744 0 0 0.0444 0.12

300 RCC 0 1.5 -0.0744 0 0 0.0444 0.12

400 RCC 0.6 1.5 -0.0744 0 0 0.0444 0.12

500 RCC 1.2 1.5 -0.0744 0 0 0.0444 0.12
 501 PZ -0.335 \$ Top Layer of PCB
 502 PZ -0.2906 \$ Top Layer of FC40/Cells
 503 PZ 0.0706 \$ Top Layer of Poly
 504 PZ 0.229 \$ Top Layer of Rim
 505 PX -1.97 \$ Left side of PCB
 506 PX 2.03 \$ Right Side of PCB
 507 PY -0.711 \$ Front side of PCB
 508 PY 5.289 \$ Back side of PCB
 509 PX -1.515 \$ Left Edge of FC40
 510 PX 1.575 \$ Right edge of FC40
 511 PY -0.241 \$ Front side of FC40
 512 PY 4.819 \$ Back side of FC40
 513 PZ -.42834 \$ Bottom Layer of the copper
 515 RPP -1.97 2.03 -0.711 5.289 -0.42834 -0.335
 c -- barriers
 40 RPP -152.40 396.24 -426.72 152.40 -114.30 193.04 \$ inside room
 41 RPP -182.88 441.96 -457.20 182.88 -175.26 223.52 \$ outside room
 c -- shielding cap
 60 PX 120.65
 61 PX 163.19
 62 PX 154.93
 70 PZ 6.35
 71 PZ -1.27
 72 PZ -24.13
 73 PZ -31.75
 74 PY 34.29

75 PY 41.91
76 PY 64.77
77 PY 72.39
78 P 0 1 1 57.42
79 P 0 1 1 68.19
80 P 0 1 1 12.98
81 P 0 1 1 23.76
82 P 0 1 -1 82.04
83 P 0 1 -1 92.82
84 P 0 1 -1 37.16
85 P 0 1 -1 49.76

c -- roof voids
101 RPP -152.40 396.24 30.48 152.40 193.04 223.52 \$ skylight void 1
102 RPP -152.40 396.24 -175.26 -53.34 193.04 223.52 \$ skylight void 2
103 RPP -152.40 396.24 -381.00 -259.08 193.04 223.52 \$ skylight void 3

c -- roof shields
104 RPP -167.64 411.48 15.24 167.64 223.52 238.76 \$ 6 in. poly over 1
105 RPP -167.64 411.48 -190.5 -38.1 223.52 238.76 \$ 6 in. poly over 2
106 RPP -167.64 411.48 -396.24 -243.84 223.52 238.76 \$ 6 in. poly over 3

c -- doors and door shields
110 RPP 421.64 441.96 -188.54 -85.72 -114.30 99.06 \$ outer door void
111 RPP 396.24 421.64 -188.54 -85.72 -114.30 99.06 \$ outer door plug
112 RPP -182.88 -152.40 -188.54 -85.72 -114.30 99.06 \$ inner door void
113 RPP -152.40 -121.92 7.62 99.06 -114.30 88.90 \$ inner wall shield (12 in.)
114 RPP -152.40 -142.24 -188.54 -85.72 -114.30 99.06 \$ inner door shield (4 in.)
120 RPP 441.96 449.58 -188.54 -85.72 -114.30 99.06 \$ outer door shield (3 in.)
121 RPP -35.56 86.36 182.88 195.58 -114.30 129.54 \$ top wall shield (5 in.)

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122 RPP 113.03 120.65 -7.62 114.3 -114.30 88.90 $ borehole wall shield (3 in.)
123 RPP -152.40 -147.32 99.06 152.40 -114.30 88.90
c in-tank shielding (left/Borated Poly)
124 RPP -147.32 -134.62 99.06 152.40 -114.30 88.90
c in-tank shielding (left/Poly)
125 RPP -152.40 -147.32 -45.72 7.62 -114.30 88.90
c in-tank shielding (right/Borated Poly)
126 RPP -147.32 -134.62 -45.72 7.62 -114.30 88.90
c in-tank shielding (right/Poly)
c -- enclosure walls
115 RPP -152.4 91.44 -45.72 152.4 -114.30 88.90 $ inside BEE walls
116 RPP -152.4 111.76 -66.04 152.4 -114.30 88.90 $ outside BEE walls
c -- borehole pipe
117 RCC -124.46 53.34 -12.7 264.16 0 0 10.16 $ inside borehole pie
118 RCC -124.46 53.34 -12.7 264.16 0 0 10.80 $ outside borehole pipe
119 RCC -152.4 53.34 -12.7 27.94 0 0 10.90 $ shielding inside
99 SO 1000 $ problem boundary

c -----
c --- DATA CARDS -----
c -----

Mode N P T H E D S T A #
SDEF par=n x=0 y=0 z=7.62 Erg=14.14
nps 2.5e7
phys:n j j j j j j 4
CUT:H j 0.1
CUT:D j 0.5

```

```

CUT:S j 0.5
CUT:T j 0.5
CUT:A j 0.5
CUT:# j 0.5
CUT:E j 0.001

c -----
c --- TRANSFORMATION -----
c -----

TR1 205.74 -280.67 -36.48 1 0 0 0 1 0 0 0 1 -1

c -----
c --- TALIIES -----
c -----

F6:N 2 3 4 5 6
+F16 2 3 4 5 6
F4:N 2 3 4 5 6

E4 1e-11 1e-10 1e-09 1e-08 1.e-07 1e-06 1e-05 0.0001 0.001 0.01
    0.1 1.0 10.0 14.1 15.0

FM4 2.1708E14

de4 1e-11 1e-10 1e-09 1e-08 1.e-07 1e-06 1e-05 0.0001 0.001 0.01
    0.1 1.0 10.0 14.1 15.0

df4      6.34318e-20 2.008410e-19 6.43019e-19 2.26904e-18 1.265787e-17
        1.134766e-16 1.120260e-15 1.11774e-14 1.1109745e-13 1.050839e-12
        7.044461e-12 2.760412e-11 5.86608e-11 6.53237E-11 6.80910e-11

c -----
c --- MATERIAL CARDS -----
c -----
c

```

```

c -----
c      Concrete, Oak Ridge (ORNL) (density = 2.30 g/cm^3)
c -----

m1      1001 -0.006187    $ H
        6000 -0.175193    $ C
        8016 -0.410184    $ O
        11023 -0.000271    $ Na
        12000 -0.032649    $ Mg
        13027 -0.010830    $ Al
        14000 -0.034479    $ Si
        19000 -0.001138    $ K
        20000 -0.321287    $ Ca
        26000 -0.007784    $ Fe

MT1      al27.22t

c

c -----
c      AIR: ANSI/ANS-6.4.3, Dry air;  density = 0.0012 g/cm^3
c -----

m2      7014 -.75519    $ N
        8016 -.23179    $ O
        6000 -.00014    $ C
        18000 -.01288    $ Ar

c

c -----
c      material: borated polyethylene d=1.00 g/cm^3  CH2 + 8 wt% B4C
c      B-11 5.029; B-10 1.234; C 80.595; H 13.143
c -----

```

```

m3      1001 -0.13143   $ H
        5010 -0.01234   $ B-10
        5011 -0.05029   $ B-11
        6000 -0.80594   $ C
MT3     poly.20t
c
c -----
c      material: polyethylene d=0.95 g/cm^3  CH2
c -----
m4      1001  2    $ O
        6000  1    $ C
MT4     poly.20t
c
c -----
c      material: aluminum 6061; density=2.7 g/cm^3
c -----
m5      12000 -0.01000   $ Mg
        13027 -0.97200   $ Al
        14000 -0.00600   $ Si
        22000 -0.00088   $ Ti
        24000 -0.00195   $ Cr
        25055 -0.00088   $ Mn
        26000 -0.00409   $ Fe
        29000 -0.00275   $ Cu
        30000 -0.00146   $ Zn
c -----
c  water; density = 0.998207 g/cm^3

```



```

c -----
m6      1001  2   $ H
        8016  1   $ 0
MT6     lwtr.20t
c
c -----
c Polystyrene
c Density = -1.060000
c Material Composition:
m50 1001 -0.077421
      6000 -0.922579
c FC40
c Density = 1.86
c Material Composition:
m51      6012.42c   -2.12E-01
          7014.60c   -2.34E-02
          7015.60c   -8.65E-05
          9019.60c   -7.65E-01
c Copper
c Density = -8.98
c Material Composition:
m52 29000 -1.0
c Polycarbonate
c Density = 1.2
c Material Composition:
m53      1001.60c   -5.55E-02
          1002.60c   -6.38E-06

```

	6012.42c	-7.56E-01
	8016.60c	-1.89E-01
c Board_0.05		
c Density = 1.2894		
c Material Composition:		
m61	1001.60c	-3.17E-02
	1002.60c	-3.65E-06
	5010.70c	-2.58E-03
	5011.70c	-1.04E-02
	6012.42c	-2.55E-01
	7014.60c	-1.31E-02
	7015.60c	-4.83E-05
	8016.60c	-3.34E-01
	9019.60c	-3.90E-03
	11023.60c	-4.15E-03
	12024.70c	-6.62E-03
	12025.70c	-8.38E-04
	12026.70c	-9.23E-04
	13027.60c	-3.82E-02
	14028.62c	-1.29E-01
	14029.62c	-6.57E-03
	14030.62c	-4.33E-03
	19039.70c	-1.40E-01
	19040.70c	-4.34E-03
	19041.70c	-5.44E-07
	20040.70c	-3.13E-04
	20042.70c	-7.31E-02

20043.70c	-4.88E-04
20044.70c	-1.02E-04
20046.70c	-1.57E-03
20048.70c	-3.02E-06
22046.70c	-1.41E-04
22047.70c	-2.18E-04
22048.70c	-1.96E-04
22049.70c	-1.94E-03
22050.70c	-1.43E-04
26054.60c	-1.37E-04
26056.62c	-1.14E-04
26057.60c	-1.80E-03
26058.60c	-4.15E-05
29000.50c	-5.52E-06

c Board_0.10

c Density = 1.385

c Material Composition:

m62	1001.60c	-2.95E-02
	1002.60c	-3.40E-06
	5010.70c	-2.40E-03
	5011.70c	-9.65E-03
	6012.42c	-2.37E-01
	7014.60c	-1.22E-02
	7015.60c	-4.49E-05
	8016.60c	-3.11E-01
	9019.60c	-2.60E-03
	11023.60c	-3.86E-03

12024.70c	-6.14E-03
12025.70c	-7.78E-04
12026.70c	-8.56E-04
13027.60c	-3.56E-02
14028.62c	-1.20E-01
14029.62c	-6.11E-03
14030.62c	-4.03E-03
19039.70c	-1.31E-01
19040.70c	-4.03E-03
19041.70c	-5.05E-07
20040.70c	-2.91E-04
20042.70c	-6.81E-02
20043.70c	-4.55E-04
20044.70c	-9.48E-05
20046.70c	-1.47E-03
20048.70c	-2.81E-06
22046.70c	-1.31E-04
22047.70c	-2.03E-04
22048.70c	-1.83E-04
22049.70c	-1.81E-03
22050.70c	-1.33E-04
26054.60c	-1.27E-04
26056.62c	-1.06E-04
26057.60c	-1.67E-03
26058.60c	-3.85E-05
29000.50c	-5.13E-06

c Board_0.15

c Density = 1.4806

c Material Composition:

m63	1001.60c	-2.76E-02
	1002.60c	-3.18E-06
	5010.70c	-2.24E-03
	5011.70c	-9.03E-03
	6012.42c	-2.22E-01
	7014.60c	-1.14E-02
	7015.60c	-4.20E-05
	8016.60c	-2.91E-01
	9019.60c	-3.40E-03
	11023.60c	-3.56E-03
	12024.70c	-5.76E-03
	12025.70c	-7.30E-04
	12026.70c	-8.03E-04
	13027.60c	-3.33E-02
	14028.62c	-1.13E-01
	14029.62c	-5.72E-03
	14030.62c	-3.77E-03
	19039.70c	-1.22E-01
	19040.70c	-3.72E-03
	19041.70c	-4.66E-07
	20040.70c	-2.68E-04
	20042.70c	-6.37E-02
	20043.70c	-4.25E-04
	20044.70c	-8.87E-05
	20046.70c	-1.37E-03

20048.70c	-2.63E-06
22046.70c	-1.23E-04
22047.70c	-1.93E-04
22048.70c	-1.74E-04
22049.70c	-1.72E-03
22050.70c	-1.26E-04
26054.60c	-1.21E-04
26056.62c	-9.81E-05
26057.60c	-1.54E-03
26058.60c	-3.56E-05
29000.50c	-4.73E-06

c Board_0.20

c Density = 1.5761

c Material Composition:

M64	1001	-2.595901E-02
	1002	-2.985630E-06
	5010	-2.107529E-03
	5011	-8.483071E-03
	6012	-2.063096E-01
	6013	-2.231389E-03
	7014	-1.068563E-02
	7015	-3.946837E-05
	8016	-2.723336E-01
	8017	-1.037389E-04
c	8018	-5.596439E-04
	9019	-3.200000E-03
	11023	-3.338390E-03

12024 -5.430310E-03
12025 -6.874680E-04
12026 -7.569023E-04
13027 -3.127930E-02
14028 -1.057976E-01
14029 -5.372146E-03
14030 -3.541358E-03
19039 -3.483824E-03
19040 -4.370746E-07
19041 -2.514187E-04
20040 -5.979156E-02
20042 -3.990586E-04
20043 -8.326570E-05
20044 -1.286609E-03
20046 -2.467132E-06
20048 -1.153384E-04
22046 -1.780070E-04
22047 -1.605299E-04
22048 -1.590627E-03
22049 -1.167294E-04
22050 -1.117668E-04
26054 -9.402793E-05
26056 -1.476037E-03
26057 -3.408814E-05
26058 -4.536506E-06
29063 -1.678064E-01
29065 -7.479358E-02

c Board_0.25

c Density = 1.6717

c Material Composition:

M65	1001	-2.447509E-02
	1002	-2.814958E-06
	5010	-1.983929E-03
	5011	-7.985561E-03
	6012	-1.945251E-01
	6013	-2.103930E-03
	7014	-1.006851E-02
	7015	-3.718898E-05
	8016	-2.567506E-01
	8017	-9.780288E-05
c	8018	-5.276208E-04
	9019	-3.000000E-03
	11023	-3.190020E-03
	12024	-5.096869E-03
	12025	-6.452550E-04
	12026	-7.104258E-04
	13027	-2.947980E-02
	14028	-9.976210E-02
	14029	-5.065677E-03
	14030	-3.339332E-03
	19039	-3.328988E-03
	19040	-4.176491E-07
	19041	-2.402446E-04
	20040	-5.639659E-02

20042 -3.764000E-04
 20043 -7.853787E-05
 20044 -1.213556E-03
 20046 -2.327048E-06
 20048 -1.087895E-04
 22046 -1.681177E-04
 22047 -1.516116E-04
 22048 -1.502259E-03
 22049 -1.102444E-04
 22050 -1.055575E-04
 26054 -8.585136E-05
 26056 -1.347683E-03
 26057 -3.112387E-05
 26058 -4.142016E-06
 29063 -1.977570E-01
 29065 -8.814297E-02

c Board_0.30

c Density = 1.7673

c Material Composition:

M66	1001.60c	-2.31E-02
	1002.60c	-2.66E-06
	5010.70c	-1.88E-03
	5011.70c	-7.56E-03
	6012.42c	-1.86E-01
	7014.60c	-9.52E-03
	7015.60c	-3.52E-05
	8016.60c	-2.43E-01

9019.60c	-2.80E-03
11023.60c	-3.04E-03
12024.70c	-4.81E-03
12025.70c	-6.09E-04
12026.70c	-6.71E-04
13027.60c	-2.79E-02
14028.62c	-9.44E-02
14029.62c	-4.79E-03
14030.62c	-3.16E-03
19039.70c	-1.02E-01
19040.70c	-3.17E-03
19041.70c	-3.98E-07
20040.70c	-2.29E-04
20042.70c	-5.33E-02
20043.70c	-3.56E-04
20044.70c	-7.43E-05
20046.70c	-1.15E-03
20048.70c	-2.20E-06
22046.70c	-1.03E-04
22047.70c	-1.58E-04
22048.70c	-1.43E-04
22049.70c	-1.41E-03
22050.70c	-1.04E-04
26054.60c	-9.93E-05
26056.62c	-8.18E-05
26057.60c	-1.28E-03
26058.60c	-2.96E-05

	29000.50c	-3.94E-06
--	-----------	-----------

c Board_0.35

c Density = 1.8629

c Material Composition:

M67	1001.60c	-2.20E-02
	1002.60c	-2.53E-06
	5010.70c	-1.78E-03
	5011.70c	-7.16E-03
	6012.42c	-1.76E-01
	7014.60c	-9.05E-03
	7015.60c	-3.34E-05
	8016.60c	-2.35E-01
	9019.60c	-2.70E-03
	11023.60c	-2.82E-03
	12024.70c	-9.34E-03
	12025.70c	-1.18E-03
	12026.70c	-1.30E-03
	13027.60c	-2.65E-02
	14028.62c	-8.95E-02
	14029.62c	-4.54E-03
	14030.62c	-3.00E-03
	19039.70c	-9.70E-02
	19040.70c	-2.94E-03
	19041.70c	-3.69E-07
	20040.70c	-2.12E-04
	20042.70c	-5.06E-02
	20043.70c	-3.38E-04

20044.70c	-7.05E-05
20046.70c	-1.09E-03
20048.70c	-2.09E-06
22046.70c	-9.77E-05
22047.70c	-1.53E-04
22048.70c	-1.38E-04
22049.70c	-1.37E-03
22050.70c	-1.01E-04
26054.60c	-9.62E-05
26056.62c	-7.77E-05
26057.60c	-1.22E-03
26058.60c	-2.82E-05
29000.50c	-3.75E-06

c Board_0.40

c Density = 1.9585

c Material Composition:

M68	1001.60c	-2.09E-02
	1002.60c	-2.40E-06
	5010.70c	-1.69E-03
	5011.70c	-6.82E-03
	6012.42c	-1.68E-01
	7014.60c	-8.60E-03
	7015.60c	-3.18E-05
	8016.60c	-2.24E-01
	9019.60c	-2.60E-03
	11023.60c	-2.74E-03
	12024.70c	-9.10E-03

12025.70c	-1.15E-03
12026.70c	-1.27E-03
13027.60c	-2.51E-02
14028.62c	-8.51E-02
14029.62c	-4.32E-03
14030.62c	-2.85E-03
19039.70c	-9.23E-02
19040.70c	-2.86E-03
19041.70c	-3.59E-07
20040.70c	-2.07E-04
20042.70c	-4.82E-02
20043.70c	-3.21E-04
20044.70c	-6.71E-05
20046.70c	-1.04E-03
20048.70c	-1.99E-06
22046.70c	-9.29E-05
22047.70c	-1.43E-04
22048.70c	-1.29E-04
22049.70c	-1.28E-03
22050.70c	-9.40E-05
26054.60c	-9.00E-05
26056.62c	-7.36E-05
26057.60c	-1.16E-03
26058.60c	-2.67E-05
29000.50c	-3.55E-06

Appendix B

HPGe MCNP Material Composition

Positron HPGe Efficiency

c ***** BLOCK 1: CELLS *****

```
1  4 -5.323 -47 45 -46 #2 IMP:P,E=1      $ HPGe
100 4 -5.323 -45 43 -21 20 IMP:P,E=1      $ HPGe dead space bottom disk
101 4 -5.323 -21 47 45 -46 IMP:P,E=1      $ HPGe dead space cylinder
102 4 -5.323 -21 46 -42      IMP:P,E=1      $ HPGe dead space top disk
2   2 -8.96 -20 61 -44          IMP:P,E=1      $ electrode
3   6 -2.7 -23 -40 41          IMP:P,E=1      $ Housing top disk
30  6 -2.7 -23 22 -41 61 IMP:P,E=1 $ Housing side cylinder
4   3 -1.205E-3 -13 33 -34 #100 #101 #102 #2 #1 #3 #8 #9 #10 #30 IMP:P,E=1 $ Air
400 3 -1.205E-3 -63 61 -33 #2 #30 IMP:P,E=1  $ Air in detector hole
5   2 -8.96 -12 32 -33 62 IMP:P,E=1 $ Copper Shielding bottom disk
50  2 -8.96 -12 13 33 -34  IMP:P,E=1 $ Copper Outer shell
51  2 -8.96 -12 34 -35 IMP:P,E=1 $ Copper Top disk
52  2 -8.96 -62 60 -61 IMP:P,E=1 $ Copper Hole disk
53  2 -8.96 -62 63 61 -33 IMP:P,E=1 $ Copper hole cylinder
6   5 -7.31 -11 -32 31 14  IMP:P,E=1  $ Tin Shielding bottom disk
```

```

60 5 -7.31 -11 32 -35 12 IMP:P,E=1 $ tin outer shell
61 5 -7.31 -11 35 -36 IMP:P,E=1 $ tin top disk
62 5 -7.31 -14 -60 48 IMP:P,E=1 $ tin hole disk
63 5 -7.31 -14 62 60 -32 IMP:P,E=1 $ tin hole cylinder
7 7 -11.35 -10 30 -31 14 IMP:P,E=1 $ Lead Shielding bottom disk
70 7 -11.35 -10 11 31 -36 IMP:P,E=1 $ lead outer shell
71 7 -11.35 -10 36 -37 IMP:P,E=1 $ lead top disk
72 7 -11.35 -48 -14 30 IMP:P,E=1 $ lead detector hole
8 1 -1.19 -50 IMP:P,E=1 $ Acrylic bottom
9 2 -8.96 -51 IMP:P,E=1 $ Copper Foil
10 1 -1.19 -52 IMP:P,E=1 $ Acrylic top
11 3 -1.205E-3 -99 1 IMP:P,E=1 $ Outside Lead
999 0 99 IMP:P,E=0 $ graveyard

```

c ***** BLOCK 2: SURFACE CARDS *****

```

1 RCC 0.0 0.0 0.0 0.0 0.0 65.29 25.40 $ Boundary
10 c/z 0.0 0.0 25.40 $ 50.8 $ shield, lead outer radius
11 c/z 0.0 0.0 13.97 $ 27.94 $ shield, lead inner radius
12 c/z 0.0 0.0 13.87 $ 27.84 $ shield, tin inner radius
13 c/z 0.0 0.0 13.71 $ 26.99 $ shield, copper inner radius
14 c/z 0.0 0.0 6.35 $ 5.74 $ shield, bot. detector hole
20 c/z 0.0 0.0 0.67 $ detector, electrode
21 c/z 0.0 0.0 3.1 $ detector, outer radius
22 c/z 0.0 0.0 3.66 $ 3.25 $ housing, inner radius
23 c/z 0.0 0.0 3.81 $ 3.40 $ housing, outer radius
30 pz 0.0 $ shield, lead bottom outside
31 pz 12.7 $ 11.18 $ shield, lead bottom inside

```

32	pz	12.8	\$	11.28				\$ shield, tin bottom inside
33	pz	12.96	\$	11.43				\$ shield, copper bottom inside
34	pz	53.6	\$	51.82				\$ shield, copper top inside
35	pz	53.76	\$	51.97				\$ shield, tin top inside
36	pz	53.86	\$	52.07				\$ shield, lead top inside
37	pz	65.29	\$	63.50				\$ shield, lead top outside
40	pz	20.64						\$ housing, top outside
41	pz	20.49						\$ housing, top inside
42	pz	20.01	\$	20.31				\$ detector, top
43	pz	16.87	\$	17.17				\$ detector, bottom
44	pz	19.225						\$ detector, electrode, top
45	pz	16.92						\$ detector, dead space bottom
46	pz	19.96						\$ detector, dead space top
47	c/z	0.0	0.0	3.05				\$ detector, dead space cylinder
48	pz	8.8325						\$ Shield, bot detector hole
60	pz	8.9325						\$ tin hole
61	pz	9.0825						\$ copper hole
62	c/z	0.0	0.0	6.25				\$ tin hole cylinder
63	c/z	0.0	0.0	6.1				\$ copper hold cylinder
50	rpp	-3.8085	3.8085	-3.8085	3.8085	20.64	21.091	\$ acrylic bottom
51	rpp	-0.5	0.5	-0.5	0.5	21.091	21.191	\$ foil
52	rpp	-3.8085	3.8085	-3.8085	3.8085	21.191	21.642	\$ acrylic top
99	so	100.0						\$ graveyard - 1 m radius sphere

c ***** BLOCK 3: DATA CARDS *****

SDEF X=d1 Y=d2 Z=d3 ERG=d4 PAR=F

SI1 -0.5 0.5

SP1 0.0 1.0
 SI2 -0.5 0.5
 SP2 0.0 1.0
 SI3 21.091 21.191
 SP3 0.0 1.0
 SI4 A 0. 0.02926 0.05852 0.08778 0.11704 0.1463 0.17556 0.20482 0.23408
 0.26334 0.2926 0.32186 0.35112 0.38038 0.40964 0.4389 0.46816 0.49742
 0.52668 0.55594 0.5852 0.61446 0.64372 0.67298 0.70224 0.7315 0.76076
 0.79002 0.81928 0.84854 0.8778 0.90706 0.93632 0.96558 0.99484 1.0241
 1.05336 1.08262 1.11188 1.14114 1.1704 1.19966 1.22892 1.25818 1.28744
 1.3167 1.34596 1.37522 1.40448 1.43374 1.463 1.49226 1.52152 1.55078
 1.58004 1.6093 1.63856 1.66782 1.69708 1.72634 1.7556 1.78486 1.81412
 1.84338 1.87264 1.9019 1.93116 1.96042 1.98968 2.01894 2.0482 2.07746
 2.10672 2.13598 2.16524 2.1945 2.22376 2.25302 2.28228 2.31154 2.3408
 2.37006 2.39932 2.42858 2.45784 2.4871 2.51636 2.54562 2.57488 2.60414
 2.6334 2.66266 2.69192 2.72118 2.75044 2.7797 2.80896 2.83822 2.86748
 2.89674
 SP4 D 1.300e-04 6.900e-04 1.370e-03 2.060e-03 2.740e-03 3.410e-03 4.060e-03
 4.700e-03 5.320e-03 5.940e-03 6.540e-03 7.130e-03 7.710e-03 8.280e-03
 8.840e-03 9.380e-03 9.910e-03 1.042e-02 1.092e-02 1.141e-02 1.188e-02
 1.233e-02 1.277e-02 1.319e-02 1.359e-02 1.397e-02 1.434e-02 1.469e-02
 1.501e-02 1.532e-02 1.561e-02 1.587e-02 1.612e-02 1.634e-02 1.654e-02
 1.672e-02 1.688e-02 1.701e-02 1.713e-02 1.723e-02 1.729e-02 1.732e-02
 1.732e-02 1.733e-02 1.733e-02 1.730e-02 1.722e-02 1.712e-02 1.702e-02
 1.689e-02 1.673e-02 1.656e-02 1.637e-02 1.616e-02 1.593e-02 1.567e-02
 1.540e-02 1.511e-02 1.481e-02 1.449e-02 1.415e-02 1.381e-02 1.346e-02
 1.308e-02 1.268e-02 1.228e-02 1.186e-02 1.144e-02 1.101e-02 1.057e-02

1.013e-02 9.670e-03 9.210e-03 8.740e-03 8.280e-03 7.820e-03 7.350e-03
6.890e-03 6.420e-03 5.950e-03 5.500e-03 5.050e-03 4.630e-03 4.200e-03
3.770e-03 3.360e-03 2.960e-03 2.580e-03 2.240e-03 1.920e-03 1.610e-03
1.300e-03 1.020e-03 7.600e-04 5.500e-04 3.900e-04 2.600e-04 1.600e-04
7.000e-05 2.000e-05

c

MODE p e

c PHYS:p 100.0 0 0 0 0 J 0 \$ default

c PHYS:e 100.0 0 1 0 0 1 1 1 1 0 0 0 J 0.917 0.001 0 \$ no photons created

c CUT:p j 0.999

c CUT:E j 1E-1

nps 1E6

F18:e 1

FT18 ELC 2

E18 0 1.E-5 1E-3 1023I 0.512

FC8 HPGe Pulse Height Tally

F8:p 1

E8 0 1.E-5 1E-3 1023I 0.512

c -----

c --- MATERIAL CARDS -----

c -----

c

c --- Lucite (density 1.19 g/cc)

M1 1001 -0.080524

1002 -0.000019

6000 -0.599836

8016 -0.318752

8017 -0.000129
 8018 -0.000737
 c --- Copper (density 8.96 g/cc)
 M2 29000 -1.0
 c --- Dry air at STP (density 1.205E-3 g/cc)
 M3 14000 -0.755268
 16000 -0.231781
 18000 -0.012827
 12000 -0.000124
 c --- HP Germanium (density 5.323 g/cc)
 M4 32070 -0.198037
 32072 -0.271824
 32073 -0.077813
 32074 -0.371489
 32076 -0.080803
 c --- Tin (density 7.31 g/cc)
 M5 50000 -1.0
 c --- Aluminum (density 2.6989 g/cc)
 M6 13027 -1.0
 c --- Lead (density 11.35 g/cc)
 M7 82000 -1.0

Appendix C

RS1800 MCNP Material Composition

```
C *****
C
C CELL CARD
C *****
1 4 -2.70 -20 IMP:P,E=1 IMP:N=0
c 2 1 -1.0 -21 IMP:P,E=1 IMP:N=0
c 2 1 -0.001225 -21 IMP:P,E=1 IMP:N=0
c 3 5 -0.93 21 -22 IMP:P,E=1 IMP:N=0
c 2 5 -.93 -22 IMP:P,E=1 IMP:N=0
c 3 5 -.93 -23 IMP:P,E=1 IMP:N=0
c 4 1 -1.0 -24 IMP:P,E=1 IMP:N=0
96 4 -2.70 -97 IMP:P,E=1 IMP:N=0
97 6 -7.14 -98 IMP:P,E=1 IMP:N=0
98 3 -0.001225 -99 #1 #96 #97 IMP:P,E=1 IMP:N=0
99 0 99 IMP:P,E,N=0

C *****
C
C SURFACE CARDS
```

```

c *****
c 20 RPP -15.875 15.875 -14.605 14.605 -0.381 0          $ Shelf 1
c 21 RPP -0.16 0.16 -0.16 0.16 0 0.089                $ TLD 700
c 20 RPP -15.875 15.875 -14.605 14.605 5.969 6.35      $ Shelf 2
c 20 RPP -15.875 15.875 -14.605 14.605 12.319 12.7     $ Shelf 3
20 RPP -15.875 15.875 -14.605 14.605 18.669 19.05     $ Shelf 4
c 21 RCC  -1.05 0 0.75 2.1 0 0 0.45 $ Air
c 22 RCC  -1.35 0 0.75 2.7 0 0 0.75 $ Plastic
c 22 RPP -15.875 15.875 -14.605 14.605 0 0.125
c 23 RPP -15.875 15.875 -14.605 14.605 0.125 0.153
c 24 RPP -15.875 15.875 -14.605 14.605 0.153 0.278
97 RPP -8.89 8.89 -8.89 8.89 24.1300 24.2570
98 RPP -8.89 8.89 -8.89 8.89 24.2570 24.2824
99 RPP -20 20 -20 20 -0.5 40

```

```

c *****

```

```

c                               DATA CARDS

```

```

c *****

```

```

NPS 1E9

```

```

c -----

```

```

c                               SOURCE SPECIFICATIONS

```

```

c -----

```

```

SDEF      POS=0 0 37.1 AXS=0 0 1 EXT=0

```

```

      VEC=0 0 -1  DIR=D2 PAR=2 ERG=D3 WGT=1

```

```

Mode P E

```

```

c Angular binning for source bias in RS1800

```

```

SI2  -1.0 0.9396 1.00000000

```

c c Fraction of solid angle for each bin

SP2 0.0 0.969846 0.030153

c c Probability of particle occouring in angular bin

SB2 0.0 0.0 1.0

c Energy Bins

SI3 4.14E-07 1.6000E-02 1.7000E-02 1.8000E-02 1.9000E-02 2.0000E-02

2.1000E-02 2.2000E-02 2.3000E-02 2.4000E-02 2.5000E-02

2.6000E-02 2.7000E-02 2.8000E-02 2.9000E-02 3.0000E-02

3.1000E-02 3.2000E-02 3.3000E-02 3.4000E-02 3.5000E-02

3.6000E-02 3.7000E-02 3.8000E-02 3.9000E-02 4.0000E-02

4.1000E-02 4.2000E-02 4.3000E-02 4.4000E-02 4.5000E-02

4.6000E-02 4.7000E-02 4.8000E-02 4.9000E-02 5.0000E-02

5.1000E-02 5.2000E-02 5.3000E-02 5.4000E-02 5.5000E-02

5.6000E-02 5.7000E-02 5.8000E-02 5.9000E-02 6.0000E-02

6.1000E-02 6.2000E-02 6.3000E-02 6.4000E-02 6.5000E-02

6.6000E-02 6.7000E-02 6.8000E-02 6.9000E-02 7.0000E-02

7.1000E-02 7.2000E-02 7.3000E-02 7.4000E-02 7.5000E-02

7.6000E-02 7.7000E-02 7.8000E-02 7.9000E-02 8.0000E-02

8.1000E-02 8.2000E-02 8.3000E-02 8.4000E-02 8.5000E-02

8.6000E-02 8.7000E-02 8.8000E-02 8.9000E-02 9.0000E-02

9.1000E-02 9.2000E-02 9.3000E-02 9.4000E-02 9.5000E-02

9.6000E-02 9.7000E-02 9.8000E-02 9.9000E-02 1.0000E-01

1.0100E-01 1.0200E-01 1.0300E-01 1.0400E-01 1.0500E-01

1.0600E-01 1.0700E-01 1.0800E-01 1.0900E-01 1.1000E-01

1.1100E-01 1.1200E-01 1.1300E-01 1.1400E-01 1.1500E-01

1.1600E-01 1.1700E-01 1.1800E-01 1.1900E-01 1.2000E-01

1.2100E-01 1.2200E-01 1.2300E-01 1.2400E-01 1.2500E-01

1.2600E-01 1.2700E-01 1.2800E-01 1.2900E-01 1.3000E-01
 1.3100E-01 1.3200E-01 1.3300E-01 1.3400E-01 1.3500E-01
 1.3600E-01 1.3700E-01 1.3800E-01 1.3900E-01 1.4000E-01
 1.4100E-01 1.4200E-01 1.4300E-01 1.4400E-01 1.4500E-01
 1.4600E-01 1.4700E-01 1.4800E-01 1.4900E-01 1.5000E-01
 1.5100E-01 1.5200E-01 1.5300E-01 1.5400E-01 1.5500E-01
 1.5600E-01 1.5700E-01 1.5800E-01 1.5900E-01 1.6000E-01

c Probability Distribution

SP3 0.0 1.8453E+08 1.9347E+08 2.0019E+08 2.0552E+08 2.0933E+08
 2.1154E+08 2.1254E+08 2.1225E+08 2.1082E+08 2.0855E+08
 2.0574E+08 2.0225E+08 1.9830E+08 1.9416E+08 1.8969E+08
 1.8512E+08 1.8028E+08 1.7560E+08 1.7093E+08 1.6624E+08
 1.6139E+08 1.5685E+08 1.5234E+08 1.4794E+08 1.4352E+08
 1.3937E+08 1.3534E+08 1.3135E+08 1.2750E+08 1.2381E+08
 1.2019E+08 1.1664E+08 1.1327E+08 1.1003E+08 1.0687E+08
 1.0379E+08 1.0087E+08 9.8024E+07 9.5244E+07 9.2617E+07
 9.0007E+07 8.7522E+07 8.396E+08 6.0134E+08 8.0560E+07
 7.8386E+07 7.6283E+07 7.4218E+07 7.2283E+07 7.0344E+07
 6.8506E+07 2.3330E+08 6.4988E+07 1.0650E+08 5.5339E+07
 5.4144E+07 5.2923E+07 5.1795E+07 5.0665E+07 4.9562E+07
 4.8466E+07 4.7418E+07 4.6361E+07 4.5339E+07 4.4332E+07
 4.3345E+07 4.2384E+07 4.1433E+07 4.0522E+07 3.9602E+07
 3.8706E+07 3.7849E+07 3.6984E+07 3.6142E+07 3.5339E+07
 3.4526E+07 3.3733E+07 3.2979E+07 3.2211E+07 3.1477E+07
 3.0749E+07 3.0035E+07 2.9341E+07 2.8656E+07 2.7981E+07
 2.7325E+07 2.6678E+07 2.6042E+07 2.5422E+07 2.4810E+07
 2.4212E+07 2.3615E+07 2.3044E+07 2.2481E+07 2.1915E+07

2.1372E+07 2.0835E+07 2.0301E+07 1.9783E+07 1.9271E+07
 1.8766E+07 1.8266E+07 1.7784E+07 1.7304E+07 1.6826E+07
 1.6366E+07 1.5910E+07 1.5452E+07 1.5006E+07 1.4577E+07
 1.4137E+07 1.3708E+07 1.3295E+07 1.2875E+07 1.2463E+07
 1.2059E+07 1.1661E+07 1.1260E+07 1.0869E+07 1.0481E+07
 1.0095E+07 9.7148E+06 9.3396E+06 8.9578E+06 8.5891E+06
 8.2244E+06 7.8480E+06 7.4813E+06 7.1254E+06 6.7544E+06
 6.3891E+06 6.0325E+06 5.6676E+06 5.3009E+06 4.9430E+06
 4.5636E+06 4.1681E+06 3.7835E+06 3.4045E+06 3.0234E+06
 2.6516E+06 2.2146E+06 1.4582E+06 7.2015E+05 0.0000E+00

c

c -----

c TALLY CARDS

c -----

FMESH4:P GEOM=XYZ ORIGIN= -0.5 -0.5 19.2

IMESH=15.5 JMESH=0.5 KMESH=20.1

IINTS=16 JINTS=1 KINTS=1 OUT=CF

FM4 5.0373442668230317E17

c

de4 1.0000e-03 1.5000e-03 2.0000e-03 3.0000e-03 3.2029e-03 3.2030e-03
 4.0000e-03 5.0000e-03 6.0000e-03 8.0000e-03 1.0000e-02 1.5000e-02
 2.0000e-02 3.0000e-02 4.0000e-02 5.0000e-02 6.0000e-02 8.0000e-02
 1.0000e-01 1.5000e-01 2.0000e-01 3.0000e-01 4.0000e-01 5.0000e-01
 6.0000e-01 8.0000e-01 1.0000e+00 1.2500e+00 1.5000e+00 2.0000e+00
 3.0000e+00 4.0000e+00 5.0000e+00 6.0000e+00 8.0000e+00 1.0000e+01
 1.5000e+01 2.0000e+01

c


```

df4  5.76559800e-10  2.85476400e-10  1.68594480e-10  7.75688400e-11
      6.82429091e-11  7.49132687e-11  4.89314880e-11  3.14873100e-11
      2.18192400e-11  1.21059936e-11  7.59668400e-12  3.20560200e-12
      1.72663560e-12  7.38682200e-13  4.37858640e-13  3.28249800e-13
      2.92300920e-13  3.08481120e-13  3.72465000e-13  5.99788800e-13
      8.56108800e-13  1.38028320e-12  1.88971920e-12  2.37576600e-12
      2.83842360e-12  3.69357120e-12  4.46797800e-12  5.33866500e-12
      6.12044100e-12  7.51338000e-12  9.88594200e-12  1.19829600e-11
      1.39374000e-11  1.58309640e-11  1.95444000e-11  2.32290000e-11
      3.25125900e-11  4.20044400e-11

```

c

c -----

c Material CARDS

c -----

c -----

c -----

c --- MATERIAL CARDS -----

c -----

c

c *****Tissue*****

c Tissue = -1.00

M1 1000 -0.104472

6000 -0.232190

7000 -0.024880

8000 -0.630238

11000 -0.001130

12000 -0.000130

15000 -0.001330

16000 -0.001990

17000 -0.001340

19000 -0.001990

20000 -0.000230

26000 -0.000050

30000 -0.000030

c

c *****Calcium Fluoride*****

c Density = -3.18

M2 9000 -0.486659

 20000 -0.513341

c

c *****Air*****

c Density = -0.001225

M3 6000 -0.00010055769

 7000 -0.71472144

 8000 -0.25053713

 18000 -0.034640872

c

c *****Aluminum*****

c Density = -2.7

M4 13000 -1.0

c *****Polyethylene*****

c Density = -0.93

M5 1001.62c 0.666590

 1002.24c 0.000077

6000.24c 0.333333

c Zinc

c Density = 7.14

c Material Composition:

M6 30000 -1.0