CARE: Cancer And Radiation Education

New Mexico
Supercomputing Challenge
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Executive Summary

Introduction: Currently, many aerospace companies are working on interplanetary travel. Since space exploration has a lot of harmful radiation, it is important to prevent exposure whenever possible to avoid the injuries that radiation can cause.

Objective: Our goal is to create a simulation that tracks the relationship between radiation, shielding material, and cancer. From this base, we can run experiments to determine what is the most dangerous radiation and what the most efficient radiation barrier is.

Methods: We are using Geant4 to simulate the radiation bombardment on different materials. The cancer simulation takes the results from Geant to determine how a human would react to the radiation that gets through the barrier. The data from the radiation bombardment and cancer code are presented in a user-friendly format by a front end program.

Results: The radiation simulation demonstrates that most barriers are usually effective at blocking radiation. Gamma particles proved to be the most dangerous, killing the subject in the cancer simulation very quickly. These particles were unable to be stopped by any barrier but were partially blocked by lead. Neon and carbon radiation were especially cancer-inducing, but took a while to deliver a fatal dose to the subject. Fast-moving proton radiation was easily blocked by everything except kapton–a protective film often used in space technology–but was still dangerous if it reached the subject.

Recommendations: Given more time, our project would have included a smartphone application on the app store, an expansion of the materials and radiation types we used to experiment with, more research on how radiation barriers wear out over time, and the effects that radiation would have on satellite parts.

Conclusions: We determined that lead was the most effective material, but was disproportionately expensive compared to the less efficient kapton. Due to its low cost, kapton can afford to be far thicker for the same price. Additionally, we discovered that gamma radiation was incredibly difficult to block by any barrier and also was the most deadly of the tested radiations. However, heavy ions cause the most cancer risk before delivering a lethal dose and are still very dangerous to astronauts for that reason. Our most important part of this project was our bombardment simulation in Geant4 since it took the most effort and provided the base for the rest of the project.

Detailed Report

The Problem:

Currently, many aerospace companies and government agencies are focusing on interplanetary travel. This achievement could lead to major developments in technology and our understanding of the universe, as well as how society functions as a whole. Yet, even with these advantages, space exploration has negative consequences. Along with the negative effects that zero-gravity has on the human body, solar radiation goes unchecked without an atmosphere to block it [1]. Health risks range from decreased nervous system functionality to a significantly increased risk of cancer. However, radiation is not just a problem in space. Even within Earth's atmosphere, there are several instances where more knowledge about preventing radiation exposure is necessary: nuclear reactor meltdowns, radioactive material testing, and UV radiation from our sun are all common sources of radiation that must be approached with safety and exposure prevention in mind.

The Objective:

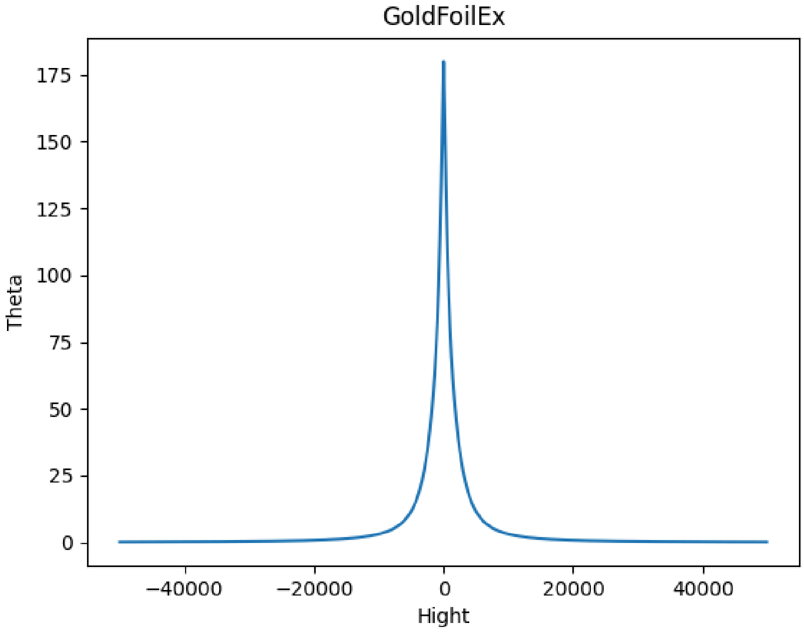
Our objective for this project is to track the relationship between the type of radiation, the materials used to shield it, and the effect that those two factors have on the health of a human behind the shield. Our end product should consist of information about the effectiveness of different materials commonly used for radiation barriers and about the danger that radiation poses to a person–specifically under the conditions of acute radiation exposure. We also want to present these pieces of information in a visually appealing way that can be understood by people who don't have a detailed understanding of the fields of dosimetry or radiation shielding. From this information, we should be able to determine the most effective barrier to keep a human safe for the longest time and determine how dangerous various radiation types are on a biological scale.

The Solution:

Radiation Section

The radiation simulations used Geant4, a CERN-run toolbox for physics simulations [2]. Gears is a specific version of Geant4 with more intuitive syntax. The results were based on cross-sections (the likelihood two materials will interact) for each particle and barrier. If the bombarding object does not have a cross-section, as is the case for beta particles and slow-moving protons, then its energy is not high enough to penetrate the barrier. Because Geant4 is based on cross-sections, the Δt (time step between start and finish) is not calculated for these particles.

To check the accuracy of Geant's cross-sections, a simulation was written to mimic the gold foil experiment and compare the results of the program to the results of the original experiment. The gold foil experiment [3] measured the scattering effect gold foil had when bombarded with alpha particles; in other words, its cross-section [4]. The results from our program matched the results from the original experiment within an acceptable margin of error. Because Geant properly calculated the cross-section in the gold foil experiment, we assume that the accuracy of similar calculations, like the solar wind simulations, is just as accurate.

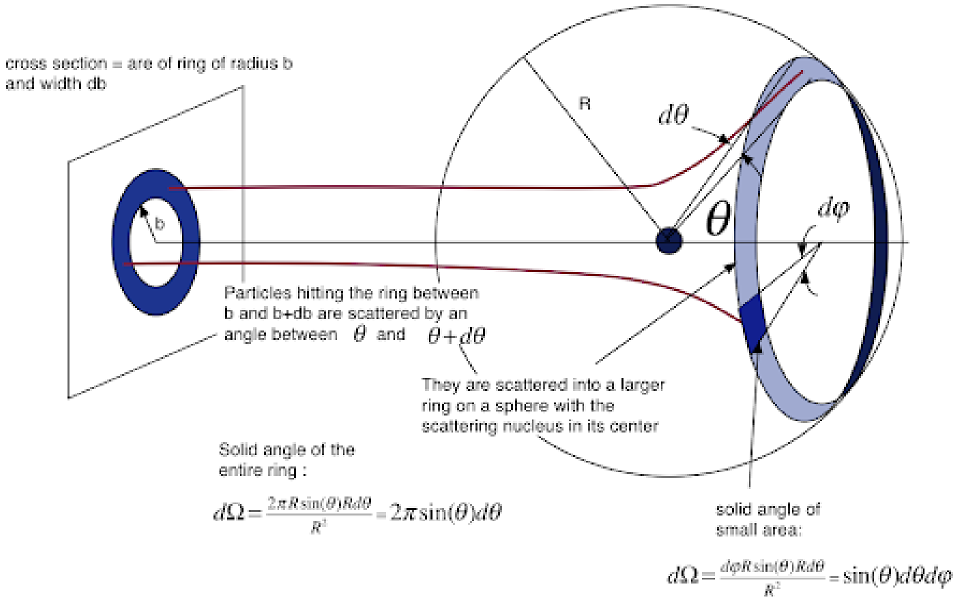


Angle of deflection (degrees) vs. offset (fm)

In order to understand the cross-sections used by Geant, we made a Python program to demonstrate the scattering effect one particle has on the other. This video demonstrates the interaction between an alpha particle and a gold atom similar to that of the gold foil experiment. A similar program was made to demonstrate the relationship between the height change or the angle of approach change and the deflection (scattering) angle. Both of these programs demonstrate a cross-section on a particle scale.

Based on the percentage of the particle's occurrence in the solar wind, the distance, a Python program uses the inverse square law ($I = \frac{W}{4\pi r^2}$) to calculate the Δt with the given number of particles [5]. Due to its speed, each simulation is run with

100,000 particles. The program finds the time it takes for that number of particles to hit the barrier. If the bombarding object does not have a cross-section, as is the case for slow-moving protons, then its energy is not high enough to penetrate the barrier. Each of the simulations had a specified .tg (Text Geometry) file that determined the barrier used in the simulation. The barriers used were aluminum, water, lead, concrete, and kapton. The barriers used materials that had the most capability to stop radiation. The thickness of the materials was constant at 50 micrometers, the standard width of a layer of radiation protection. More layers would be used in a real situation.



Cross-section as a measurement of scattering angle and offset(b) [6]

Each radiation type has two programs: one high energy and one low energy. These energies match the realistic speeds of particles emitted in the solar wind with the high energy matching a solar flare and the low energy matching the lowest possible emission. The exact energy per particle was found using a Python program, which reverse-engineered the electron volts needed to achieve the high and low speeds of the solar wind ($300\frac{km}{s}$ - $500\frac{km}{s}$) [7]. The program uses the law of kinetic energy (Ke = $\frac{1}{2}MV^2$) to conserve both the mass and speed into the calculation [8]. After converting the resulting joules to electron volts, the energy is in the proper units to be used by Geant4.

The information from each simulation was saved to a CSV(Comma Separated Values) file, which was then parsed by a Python program; its purpose is to properly organize the number of particles that passed, were absorbed, or were reflected by the barrier. The particle type, number of particles, and their energy were then saved to an Excel file.

Cancer Section

In order for a simulation to estimate the health effects of radiation, it must be able to apply the principles of dosimetry to a situation. Dosimetry is the study of radiation protection and the health effects related to it and uses some theories that are crucial for getting this section of the code to work properly. Dosimetry typically breaks down into three distinct sections: Absorbed dose, Equivalent Dose, and Effective Dose. Absorbed dose governs objective health risks, and uses the unit of Grays [9]. There are two main deterministic effects of radiation exposure that the absorbed dose predicts: Acute Radiation Syndrome (ARS) [10] and Cutaneous Radiation Injury (CRI) [11]. These two injuries scale up as radiation exposure increases and are guaranteed to show up on a radiation victim at high doses. Equivalent dose governs the probability of getting cancer on a full-body scale with the unit of sieverts [12], and can also be used as a metric for overall health. This dosage metric scales with the Linear Energy Transfer (LET) of a radiation wave, and the greater the LET the more damage the radiation can do to DNA [13]. Finally, effective dose governs the probability of getting cancer on a tissue-specific scale [9], which is the limit to our level of accuracy. Different tissues have different vulnerabilities to getting cancer, which is important in determining what type of cancer a person will get. There are several different models for how radiation damage scales with dosage, but we are using the linear no-threshold model [14]. This is the easiest model to program since it follows a linear slope of increasing cancer risk, and is one of the leading theories of cancer prediction being used today. If we use these principles of dosimetry, we can ensure that our predictions of cancer and other damages are accurate to the real world.

Quantity	Definition	New Units	Old Units
Exposure	Charge per unit mass of air 1 R = 2.58 x 10^{-4} C/kg	---	Roentgen (R)
Absorbed dose to tissue T from radiation of type R $D_{T,R}$	Energy of radiation R absorbed per unit mass of tissue T 1 rad = 100 ergs/g 1 Gy = 1 joule/kg 1 Gy = 100 rads	gray (Gy)	Radiation absorbed dose (rad)
Equivalent dose to tissue T H_T	Sum of contributions of dose to T from different radiation types, each multiplied by the radiation weighting factor (w_R) $H_T = \Sigma_R\ w_R\ D_{T,R}$	Sievert (Sv)	Roentgen equivalent man (rem)
Effective Dose E	Sum of equivalent doses to organs and tissues exposed, each multiplied by the appropriate tissue weighting factor (w_T) $E = \Sigma_T\ w_T\ H_T$	Sievert (Sv)	rem

Table indicating the units and definitions for the three levels of dosage we are using. [15]

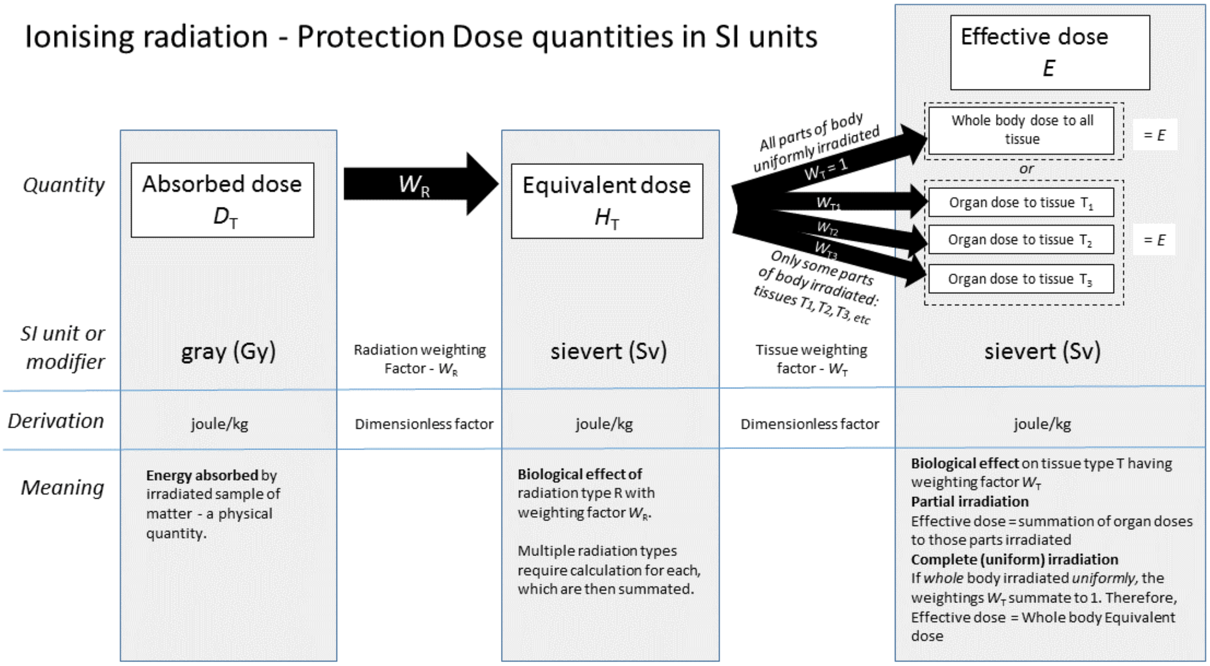
The cancer simulation uses the results from the radiation portion to reach its conclusion. To do this, it takes a target radiation type, barrier type, and radiation speed to look for and then procedurally reads the CSV file until it finds each of those parameters in the same row. From there, it can extract the relevant information for calculating the dosimetry: The two radiation types, the energy per square meter from each radiation type (in KeV/m^2), and the Δt of the radiation bombardment are all saved into variables for easy access later.

To make use of this information, three separate classes define the important factors of the simulation and store crucial information. One is for radiation, which stores its name and the parts of the body that it can hit. One is for deterministic injuries and health effects that can result from radiation exposure. This class stores the injury's name, its current severity, the current symptoms for that level of severity, and a list of all the symptoms of different severities. The final class is for cancers. This class stores the name, what part of the body the cancer affects, the current probability one will develop the cancer given the radiation, and the symptoms that indicate its onset. Three functions are used to translate the units given into the ones used for dosimetry.

To convert electron volts into grays, electron volts must be converted into joules by the scaling factor $(1.6\ *\ 10^{-19})$. Then, the energy must be multiplied by the surface area of the subject to get the net energy that hits the subject, then divided by the subject's mass to get grays: ($G = (J * SA)/M$) [16]. This is the first function the program runs to acquire the relevant units.

Converting grays into an equivalent dose is based on a scaling factor: multiply the grays calculated from the previous function by the LET of the radiation. This conversion turns the output from grays into sieverts, with one sievert indicating a roughly 5.5% chance of getting cancer [14].

Finally, the third function translates the equivalent dose into the effective dose. This factor, also measured in sieverts, has further weighting to account for tissue vulnerability. Some tissues in the body (e.g. the digestive tract) are more susceptible to ionizing radiation than other tissues (e.g. skin). By accounting for this difference, we can better determine which types of cancer are most likely to appear. For simplicity, we have grouped these tissues into ones relating to the skin, bones, lungs, brain, stomach, and reproductive organs of the body.



Quantity	Absorbed dose D_T	W_R	Equivalent dose H_T		Effective dose E
SI unit or modifier	gray (Gy)	Radiation weighting Factor - W_R	sievert (Sv)	Tissue weighting factor - W_T	sievert (Sv)
Derivation	joule/kg	Dimensionless factor	joule/kg	Dimensionless factor	joule/kg
Meaning	**Energy absorbed** by irradiated sample of matter - a physical quantity.		**Biological effect of** radiation type R with weighting factor W_R. Multiple radiation types require calculation for each, which are then summated.		**Biological effect** on tissue type T having weighting factor W_T **Partial irradiation** Effective dose = summation of organ doses to those parts irradiated **Complete (uniform) irradiation** If *whole* body irradiated *uniformly*, the weightings W_T summate to 1. Therefore, Effective dose = Whole body Equivalent dose

The relationship between absorbed dose, equivalent dose, and effective dose [17].

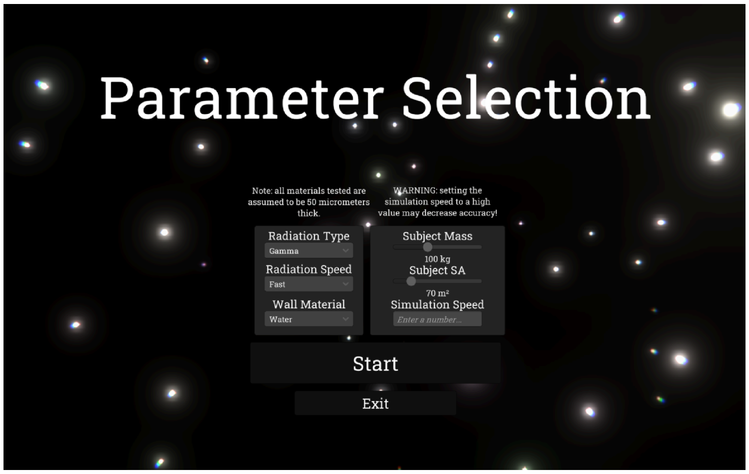
For each iteration of the script, we calculate these three values and add them to a total. The grays are used to determine the severity of the deterministic effects of radiation, such as ARS or CRI. Meanwhile, the effective dose is used to calculate the probability of each type of cancer that we have accounted for, ensuring that each cancer's probability is based on the effective dose of the specific tissue type it affects. In the end, the time elapsed is increased by the Δt of the radiation, and the script is looped.

This loop is repeated until the subject has reached a threshold of radiation exposure where it would be impossible for them to survive: When deterministic effects have reached their maximum severity at 30 grays, or when the total equivalent dose has reached around 50 sieverts. These thresholds pertain only to acute radiation exposure, however; the same dosage over a longer time period may delay symptoms of radiation poisoning as seen in the Plutonium Injection Experiments during the Manhattan Project [18].

Front End Section

In order to easily collect results, as well as fulfill the parameter of having the streamlined, easily comprehensible simulation we defined at the beginning of the project, we created a visualization of the simulation process. While this segment is mainly centered around the output of the cancer portion, it also helps present the findings of the radiation portion in a more visually appealing way than Geant's technical rendering software. As a good starting point for a visualization, we chose Unity Game Engine for its premade 3D graphics engine, easy-to-use particle system to show radiation effects, and intuitive UI(User Interface) design system to display the important values of the simulation.

Unity development is split up into "scenes" – separate zones where you can compile each part of an application, improving performance. For this simulation, we have two scenes: one to set the parameters for the simulation, and one to present the results of said parameters in action.



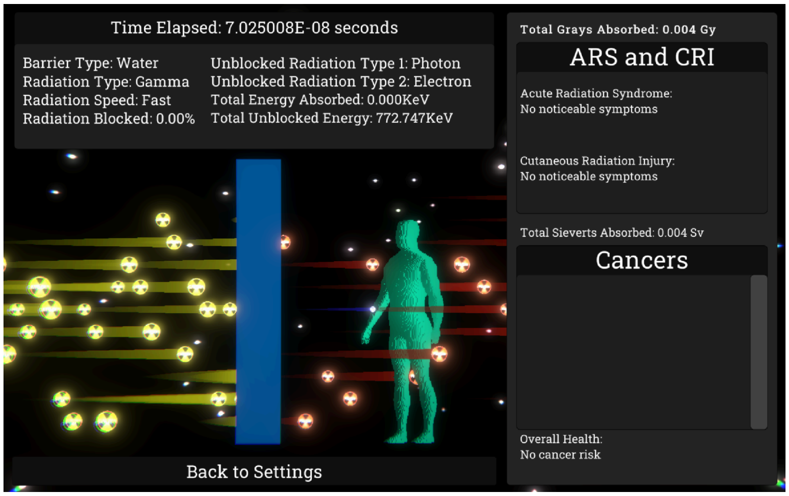
Note: all materials tested are assumed to be 50 micrometers thick.

WARNING: setting the simulation speed to a high value may decrease accuracy!

Radiation Type: Gamma
Radiation Speed: Fast
Wall Material: Water
Subject Mass: 100 kg
Subject SA: 70 m²
Simulation Speed: Enter a number...

Image of the Front End's starting screen.

The starting scene allows the user to modify the parameters of the simulation through a set of dropdown boxes, sliders, and text inputs. With these tools, the user can customize the radiation type, barrier material, radiation speed, and even the physical properties of the subject such as mass or surface area. Note that the selection screen only accounts for results that break through at least one of the radiation barriers—radiation types that are too weak are not included since the results will always be zero. As a bonus, the speed of the simulation can be changed to run simulations more efficiently since most of the timesteps in the radiation section are less than one attosecond (10^{-18} of a second) by default. Once the parameters are set, the application can be run to view results.



Time Elapsed: 7.025008E-08 seconds

Barrier Type: Water
Radiation Type: Gamma
Radiation Speed: Fast
Radiation Blocked: 0.00%

Unblocked Radiation Type 1: Photon
Unblocked Radiation Type 2: Electron
Total Energy Absorbed: 0.000KeV
Total Unblocked Energy: 772.747KeV

Total Grays Absorbed: 0.004 Gy

Acute Radiation Syndrome:
No noticeable symptoms

Cutaneous Radiation Injury:
No noticeable symptoms

Total Sieverts Absorbed: 0.004 Sv

Overall Health:
No cancer risk

Image of the Front End's simulation screen.

Upon loading the second scene, the settings selected on the starting screen are fed into the cancer section of the project, which uses those settings to generate the outcomes of the simulation. The outputs from the radiation portion are shown on the top panel along with the simulation parameters, and the output from the cancer portion is displayed on the side panel. Through this organization, the UI easily communicates the more important project outputs and makes it easier to log the results once the simulation is complete.

The scene also takes steps to ensure that the simulation has proper visuals to correspond with the data shown, adjusting the color of the radiation particles based on the radiation emitted in the data, along with the emission rate of each radiation type based on how much energy makes it through the barrier. The color of the barrier is also adjusted to indicate the barrier material. Combined with the format of the UI, we have a user-friendly way to present the data we generate.

The Results:

Barrier Effectiveness:

Every type of radiation penetrated the kapton barrier, proving it to be the weakest barrier tested (Refer to Appendix A for raw data). Gamma particles penetrated all the provided barriers with varying success. Lead demonstrated the most resistance to gamma radiation, followed by aluminum, concrete, water, and kapton. For every instance of gamma radiation, the majority of the remaining particles were beta particles (electrons). This results from the photoelectric effect, in which the bombarding gamma particles knock an electron off of its orbital on the barrier. Gamma radiation, therefore, has a higher health consequence from resulting beta particles than it does with resulting gamma particles.

The beta particles and slow protons are slow enough that they do not have a documented cross-section. Consequently, we assume the bombarding particle is absorbed and does not make it past the barrier.

Subject Longevity:

Gamma was the most destructive radiation type by far. Although it had a low LET, gamma rays had significantly more overall energy and particles getting through the barrier. Gamma radiation caused every type of cancer due to its piercing quality and ended the simulation in approximately 5 milliseconds using fast particles, at which point the subject had received a lethal dose. When the particles moved slowly, the subject reached a lethal dose of approximately 2.8 seconds with most barriers. Only lead shielded the subject effectively for 21 seconds. The simulation ended with a 53% chance for digestive cancer at maximum and a low of 1.7% chance for skin cancer. An exception to this rule was using lead shielding, which resulted in the lowest probability of digestive system cancers at a 26.4% chance.

Carbon ion radiation was blocked entirely by every barrier except kapton. With fast-moving radiation the subject received a lethal dose in .65 seconds, having absorbed 2.5 grays and 50 sieverts. The subject received an 88% chance of stomach cancer at maximum and a 2.8% chance of skin cancer at minimum. When the radiation was slow, however, the simulation lasted for 18.5 minutes and ended when the subject had absorbed 14.25 grays and 50 sieverts of radiation.

Similarly to carbon, neon ion radiation couldn’t pierce any radiation barrier except kapton. At high particle speed, the subject reached a lethal dose in .4 seconds, with similar statistics to carbon. At low particle speeds, however, the subject could survive for two full days before reaching a lethal dose with 2.5 grays and 50 sieverts of radiation absorbed.

Proton radiation could not get through any radiation barrier except for kapton, and only at high speeds. The subject lasted for two minutes in this scenario before reaching a dosage of 16 grays or 50 sieverts. This type of radiation only made it through to the skeletal system, with a 35.5% chance of getting skeletal cancer and a 2.8% chance of getting skin-related cancers (Refer to Appendix B for raw data).

The Conclusion:

The radiation portion proved that Gamma radiation was the most dangerous form of bombardment for an interplanetary traveler because of its ability to penetrate all of the barriers. Even though only a fraction of the solar wind is gamma particles, it is the most likely to affect a passenger because of its high wavelength penetrability. Beta particles, even though they didn't penetrate the shield, expose the subject through the photoelectric effect from the gamma rays. Because the gamma rays penetrate every one of our shields at the given thickness, beta particles are guaranteed to generate alongside gamma radiation. After gamma and beta particles, the subject would be at the highest risk of being exposed to heavy ions such as carbon, magnesium, and neon. Any other shield than kapton will protect the passenger from this radiation and bombarding protons.

The most efficient barrier was lead, followed by aluminum, concrete, water, and kapton. Lead, even though it did not successfully block gamma particles, did prove to be the most effective. Kapton was the least efficient at stopping radiation despite its frequent use in NASA spacecraft [19]. However, when considering cost, kapton is the most cost-effective barrier of the materials we experimented with with the exception of water, and lead is the least cost-effective along with concrete [20][21]. There are also other factors to take into account, such as ease of application to space shuttles and the possibility of increasing the layers of the barrier to accommodate the inefficiency of the barriers when blocking certain particles.

Overall, gamma radiation caused the most damage since it had so much total energy compared to the other radiation types. On the other hand, subjects exposed to slow-moving neon radiation survived the longest. However, proton radiation did the least tissue damage, as the subject was only exposed to radiation that could not pass the skeletal system. More efficient gamma protection is clearly needed, since not only is it incredibly lethal if somebody is exposed to it, but it also proves difficult to block; the only material capable of protecting the subject for more than two seconds was lead. More research should be done on heavy ions like carbon and neon as well since they contribute greatly to the chance that an individual will get cancer if exposed.

Over the course of this project, our most significant achievement was the radiation bombardment simulation in Geant. This segment of code required the most overall setup and learning how the library worked before we could use it, and served as the foundation for every other part of the project with the results it generated (See Appendix C for a link to our code repository).

The Recommendations:

There is significant room for expanding the current scope of this project. During the early stages of the development process, we ended up settling on a fixed list of materials and radiation types. By expanding this list, we can improve how comprehensive our final results are.

Additionally, our Front End could be transformed into a smartphone app to both spread information and be more easily accessible to people who want to learn more about radiation shielding and dosimetry.

During our presentations in February, we received some good suggestions from the interviewers concerning how we could expand our scope. This included the idea to elaborate more on how the barriers themselves would hold up over time, as prolonged radiation exposure would eventually break down the efficiency of each barrier. The second recommendation we got was to look into how dosimetry might also apply to how radiation affects technology in space, like satellites or space stations, to see how long these components would last with different protective measures taken.

The Acknowledgements:

We would like to thank our mentor Mario Serna for helping significantly with setting up and teaching us how to use the Geant4 code library. Without him, this project would have taken a lot more time to get up and running. Additionally, we have Regina Hunter to thank for reviewing this paper and making sure that we submitted our best work. Finally, we would like to thank the Supercomputing Staff for a wonderful year of coding. Our team had a couple of rocky points with getting set up and scheduling the interviews for days when our team was available, but the Supercomputing Staff always responded quickly to our requests. While there may not be another year of the Supercomputing Challenge, this year was a great sendoff to a wonderful competition.

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Appendix A: Results of Radiation Bombardment

	Aluminum	**Water**	**Concrete**	**Kapton**	**Pb**
Alpha fast	**0**	**0**	**0**	**0**	**0**
Alpha slow	**0**	**0**	**0**	**0**	**0**
Gamma fast	**100,000**	**100,000**	**100,000**	**100,000**	**100,000**
Gamma slow	**97524**	**99815**	**97998**	**100,000**	**6278**
Beta fast	**NCS**	**NCS**	**NCS**	**NCS**	**NCS**
Beta slow	**NCS**	**NCS**	**NCS**	**NCS**	**NCS**
Carbon fast	**0**	**0**	**0**	**84496**	**0**
Carbon slow	**0**	**0**	**0**	**155**	**0**
Magnesium fast	**0**	**0**	**0**	**82701**	**0**
Magnesium slow	**0**	**0**	**0**	**0**	**0**
Neon fast	**0**	**0**	**0**	**82844**	**0**
Neon slow	**0**	**0**	**0**	**1**	**0**
Proton fast	**0**	**0**	**0**	**265**	**0**
Proton slow	**NCS**	**NCS**	**NCS**	**NCS**	**NCS**

Number of particles remaining after bombardment

**NCS = No Cross Section*

Appendix B: Results of Cancer Simulation

Rad Type	**Barrier Type**	**Rad Speed**	**Survival Time**	**Cancer Types**	**% chance of cancer (Highest and lowest)**	**Gray and Sievert levels**
Gamma	Water	Fast	0.000495 seconds	All types of cancer	53% digestive, 1.7% skin	30sv, 30gy
Gamma	Water	Slow	2.734 seconds	All types of cancer	53% digestive, 1.7% skin	30sv, 30gy
Gamma	Aluminum	Fast	0.000495 seconds	All types of cancer	53% digestive, 1.7% skin	30sv, 30gy
Gamma	Aluminum	Slow	2.799 seconds	All types of cancer	53% digestive, 1.7% skin	30sv, 30gy
Gamma	Concrete	Fast	0.000496 seconds	All types of cancer	53% digestive, 1.7% skin	30sv, 30gy
Gamma	Concrete	Slow	2.783 seconds	All types of cancer	53% digestive, 1.7% skin	30sv, 30gy
Gamma	Lead	Fast	0.000496 seconds	All types of cancer	53% digestive, 1.7% skin	30sv, 30gy
Gamma	Lead	Slow	21.894 seconds	All types of cancer	26% digestive, 1.7% skin	30sv, 30gy
Gamma	Kapton	Fast	0.000496 seconds	All types of cancer	53% digestive, 1.7% skin	30sv, 30gy
Gamma	Kapton	Slow	2.726 seconds	All types of cancer	53% digestive, 1.7% skin	30sv, 30gy
Carbon	Kapton	Fast	0.646 seconds	All types of cancer	88% digestive, 2.8% skin	50 sv, 2.5 gy
Carbon	Kapton	Slow	1155.67 seconds	All types of cancer	88% digestive, 2.8% skin	50sv, 14.25 gy
Neon	Kapton	Fast	0.388 seconds	All types of cancer	88% digestive, 2.8% skin	50 sv, 2.5 gy
Neon	Kapton	Slow	169205.4 seconds	All types of cancer	88% digestive, 2.8% skin	50 sv, 2.5 gy
Proton	Kapton	Fast	114.9204 seconds	skin, bone cancer	35.8% bone, 2.8% skin	50sv, 16 gy

Results from the Cancer Effects Portion. Note that only situations in which the subject is exposed to some degree of radiation are on this list.

Appendix C: Link to Code Repository

https://github.com/HadwynLink/SCCTeam42-2023-2024