A Comparison between Radiation Damage Calculated with NASA-LaRCs HZETRN and with GEANT4

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Abstract

This project uses GEANT4, a Monte Carlo based program, to simulate radiation damage caused by Galactic Cosmic Rays and Solar Particle Events. NASA uses a very different program, the HZETRN, to simulate the passage of particles through shielding materials. The purpose of this project is to determine the sources of discrepancies between the results of GEANT4 and HZETRN seen in the thesis work of C. O'Neill.

Acknowledgements

I would like to thank Professor Kossler for all of his help throughout this project. In addition, C. O'Neill's previous work with GEANT4 formed the basis of this project. By contacting him, I was able to become acquainted with the program and learn how it works.

Contents

1 Introduction

When discussing space radiation, there are three main sources of radiation to consider. First are the inner and outer Van Allen belts which contain high energy electrons trapped in the Earth's geomagnetic field. While these protons have enough energy to cause significant damage to astronauts and equipment, the time spent within these belts is minimal. [1] For this reason, this source of radiation will be ignored for the project. Instead, the project is focusing on the radiation damage caused by both Galactic Cosmic Rays (GCR) and Solar Particle Events (SPE) and looking at the effect of changing the thickness of shielding materials on the resulting radiation damage experienced by astronauts.

Galactic cosmic rays are atomic nuclei that travel close to the speed of light. The majority of GCRs have energies between the values of 100 MeV and 10 GeV. These energies are equivalent to a proton traveling between 43 % to 99.6 % of the speed of light. [2] However, the number of cosmic rays at these higher energies falls off drastically after 1 GeV. [2] GCR spectrum consist mostly of protons and alpha particles, however it also contains heavier particles including carbon, oxygen, silicon, and iron.[3] These high charge and energy (HZE) ions cause a large amount of the damage due to fragmentation when traveling through a shielding material.[1] The fragmentation occurs when an incoming ion collides with a nucleus in the shielding material with enough energy that both of the nuclei can shatter and form two or more smaller nuclei. [4]

Solar Particle Events or Solar Energetic Particles, on the other hand, are created when solar storms cause ions to accelerate to dangerously high energies such that they can penetrate space suits and space ships.[1] These events can last up to a week and the particles are mostly protons. While the protons of SPE are lighter, their higher flux poses a significant risk.

GCRs are a constant source of radiation, however, SPEs are unpredictable and could occur at any time. The Earths magnetic field offers protection from GCR and SPE radiation on the Earth itself, however the concern is with long-term space missions outside of this protection. Radiation damage has always been a concern in space travel, however, as astronauts spend longer periods of time in space, it is even more important to properly shield them from the hazards of radiation. It is interesting to note that heightened solar activity can actually reduce the effects of GCR radiation.[5] This is a result of magnetic fields being carried away from the solar surface. Since it has been shown by several simulations that the relatively thin shielding available for spacecraft cannot affect GCR dose, but can decrease SPE dose, the lowest amount of radiation will be experienced inside a shielded environment during one of these solar storms. This seems counterintuitive, but as long as the astronaut is not caught outside of the spacecraft during one of these infrequent storms, he or she is better off than in the absence of solar storms.

The effects of radiation can be both short and long-term and both are a concern to NASA. The dose of radiation received in Grays is the energy in Joules deposited in a kg of material. Another measure of the relative biological effectiveness (RBE) of radiation is the sievert (Sv). This is obtained by multiplying the dose by an experimentally determined quality factor and is known as Dose Equivalent.[1] This means that the dose equivalent is very similar to dose, however it is simply multiplied by a quality factor. Acute radiation sickness can occur with a radiation dose equivalent greater than 1 Sv througout the course of a day. The ordinary amount of radiation that Americans are exposed to over the course of a year is roughly 300 millirem. [6] This is equivalent to 3 mSv over the course of a year. Receiving over 300 times this yearly radiation dose induces radiation sickness.

In addition, the probability of vomiting and death increases as the radiation dose increases. This radiation sickness is obviously a concern because it could delay or compromise missions. An even more long term effect is the possibility of cancer developing due to the radiation. NASA has set a 3 % risk of induced cancer guideline and is even thinking about lowering this guideline to a lower value[1]. This means that if the lifetime risk for cancer is around 20 %, NASA wants to prevent the lifetime risk of cancer from increasing by 3 % and thus increasing the lifetime risk to 20.6 %. [7] The more reliable information that can be gathered about the shielding of radiation, the more NASA can be confident in sending astronauats on longer missions without sacrificing safety guidelines.

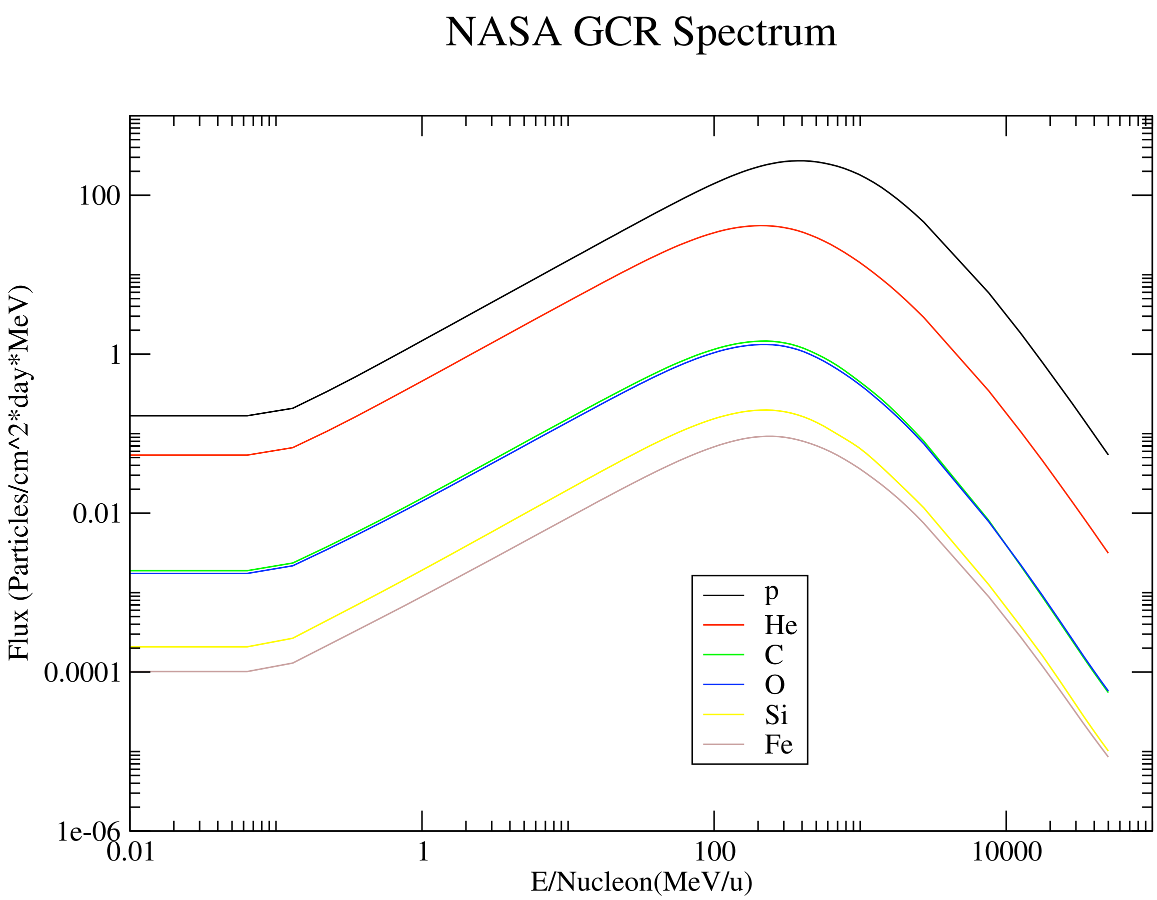

Figure 1: GCR Spectrum obtained from NASA used as an input for GEANT4. It shows the flux versus the energy per nucleon for the six particles we are looking at.

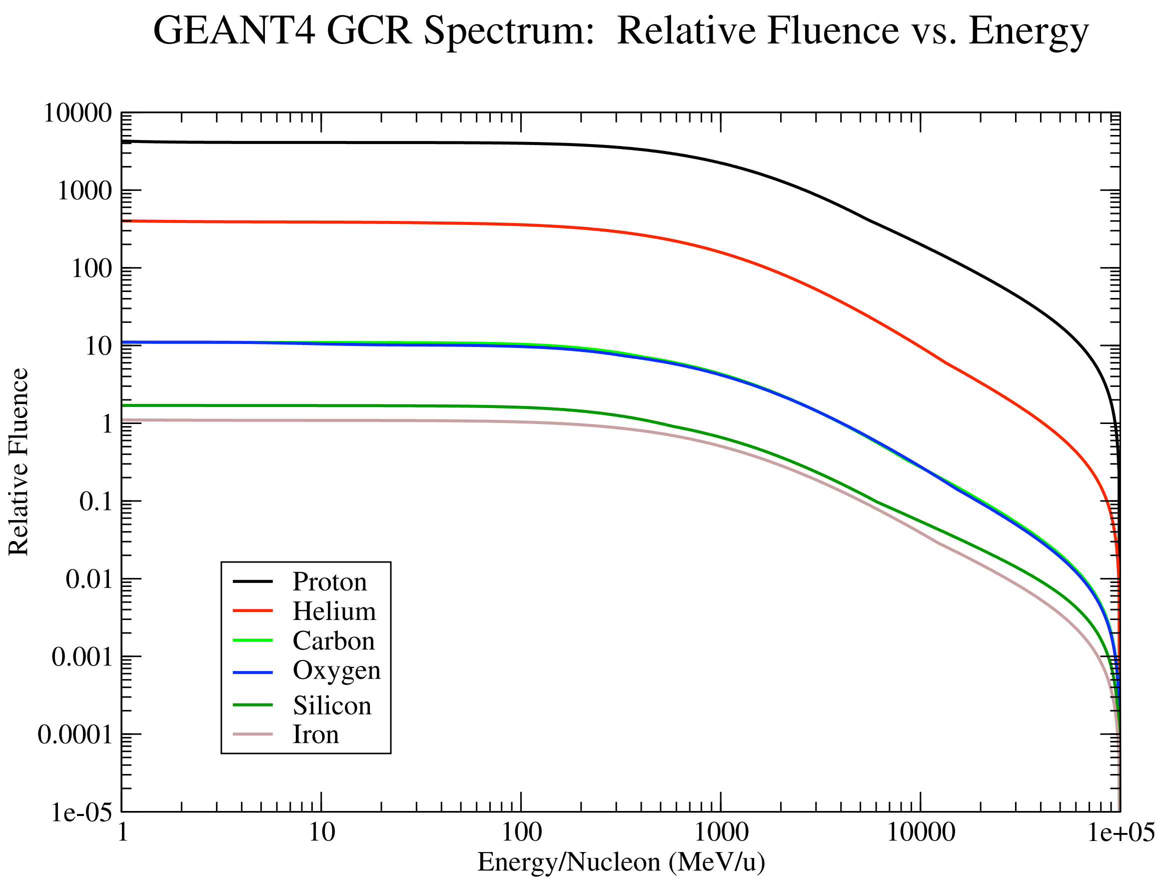

Figure 2: GCR Spectrum that came bundled with GEANT4. It was shown in C.O'Neill's thesis that the results obtained using this spectra did not coincide with NASA's results. The flux was normalized to the same number of particles in NASA's spectra. [8]

2 Passage of Particles Through Shielding Materials

GEANT4 is designed to be able to handle practically any physical process that a particle would undergo when passing through a material. However, it leaves it up to the user to compile these physics lists so that it is unique to the application.

The three main types of GCR and SPE particles are charged heavy particles, electrons and positrons, and electromagnetic radiation. Heavy particles have a range, such as the minimum amount of absorber that stops a particle. Electromagnetic radiation and electrons do not have a range, however, they experience energy loss in

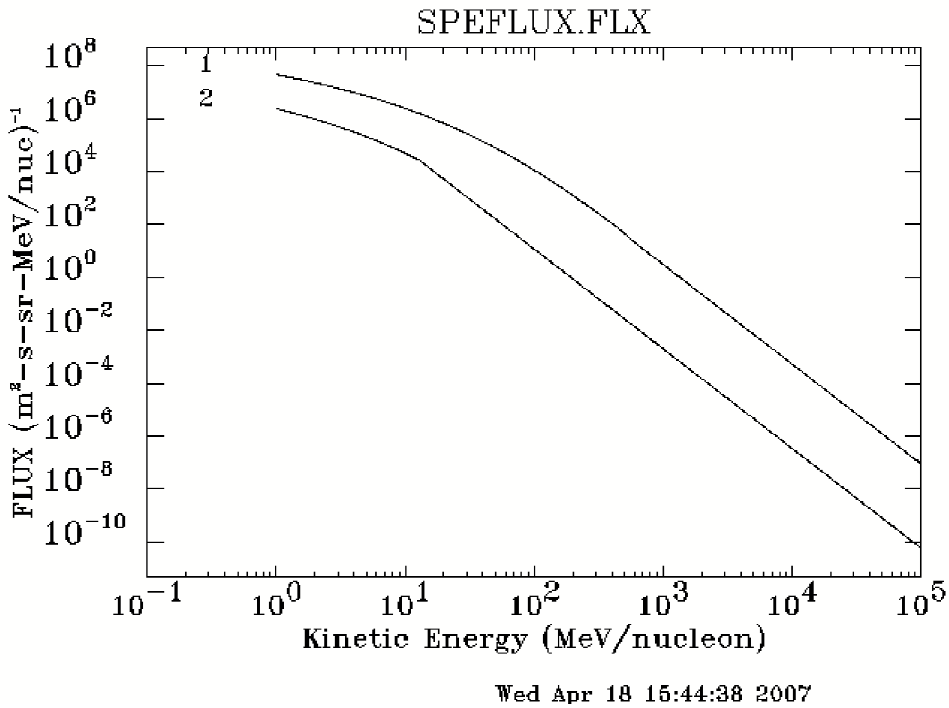

Figure 3: SPE Flux obtained from CREME96 website for protons and alpha particles. The fluxes are represented by the particles' Z value.

a different way. Electromagnetic radiation is absorbed exponentially and energy is removed from a beam of particles. This causes the intensity to decrease according to:

$$-\frac{dI}{I} = \mu dx \tag{1}$$

where μ is the absorption coefficient, and dx is the thickness that is traversed. The behavior of electrons is tougher to deal with due to the large value of e/m. Their trajectories are also very irregular due to scattering. [9]

Rutherford scattering is the process by which an incoming heavy charged particle collides with the nucleus of the target material and the electrostatic repulsion from the target material's nucleus deflects it. This does not usually lead to significant energy losses, but it can significantly change the direction of the particle.[9]

For heavy charged particles (HZE) traveling through a material, collisions with atomic electrons occur. A great deal of the total energy loss occurs in the collisions.

Sometimes the atomic electrons are imparted with enough energy to escape their orbit and move freely in the material.[9] As an example, consider a particle with charge ze as it travels through a medium with N electrons/cm^3. It is assumed that the electrons are free and at rest and that the collision lasts for a short time so that the electron receives the impulse without changing position during the collision. In this case, the impulse is perpindicular to the trajectory of the incoming heavy particle and is represented by the following equation:

$$\Delta p_\perp = \int_{-\infty}^{\infty} e \cdot E_\perp dt = \int e \cdot E_\perp \frac{dx}{v} = z \cdot e^2 \int_{-\infty}^{\infty} \frac{1}{r^2} \cdot \cos\theta \frac{dx}{v} \tag{2}$$

where $E_\perp$ is the perpindicular component of the electric field at position of the electron. The v is the velocity of the heavy particle and is assumed to be constant throughout the collision. If we solve the second integral using Gauss's theorem, we obtain:[9]

$$\Phi = \int E_\perp \cdot 2\pi b \cdot dx = 4\pi z e \tag{3}$$

and

$$\Delta p = \frac{2 \cdot z \cdot e^2}{b \cdot v} \tag{4}$$

Because the energy transferred equals $(\Delta p)^2/2m$, and there are $2\pi N b db \cdot dx$ electrons per length dx that have a distance between b and $b + db$, the heavy ion will lose energy per path length dx equal to:

$$-\frac{dE}{dx} = 2\pi N \int b db \frac{(\Delta p)^2}{2m} = 4\pi N \frac{z^2 e^4}{m v^2} \int_{b_{min}}^{b_{max}} \frac{db}{b} = 4\pi N \frac{z^2 e^4}{m v^2} \log \frac{b_{max}}{b_{min}} \tag{5}$$

For heavier particles, the energy loss to electrons far outweighs the energy loss due to collisions with other nuclei. While lighter particles hit a nuclei, and lose energy in that process, heavier particles can keep going without losing much energy.

The issue of multiple scattering has to be dealt with as well when looking at the passage of different particles through the shielding materials. While Rutherford scattering dealt with a single instance of scattering, a separate process needs to be defined for multiple scattering where there is a cumulative effect of several different smaller nuclear deflections that change the direction of the incoming particle. However, it is hard to tell whether the change in direction θ is a result of just single scattering or multiple scattering. The way it is often dealt with is by defining a θ_1 where a particle that only scatters once is likely to have an angle as large as θ_1. If this is the case, any scattering deflections larger than θ_1 are most likely single scattering events and any deflections less than θ_1 are the result of multiple scattering. This is a simple explanation, but the process of figuring out whether a deflection is the result of multiple scatterings or just one scattering event is much more complicated.[9]

When electromagnetic radiation interacts with matter, three different types of effects are seen. First, the photoelectric effect or photoelectric absorption which is a process that is simulated in GEANT4 and other programs. If an incoming particle has enough energy, it can remove one of the electrons from an inner shell of an atom in the target material. The amount of energy required depends on what shell the electron is being removed from and is described by the equation:

$$E = R \cdot h \cdot c \cdot \frac{(Z - \sigma)^2}{n^2} \tag{6}$$

Rhc is the value 13.605 eV, Z is the atomic number, n is the principal quantum number of the different electronic orbits, and σ is the screening constant and depends on the different shells. Next, Thomson and Compton scattering can occur when incoming photons scatter off of free electrons as opposed to the bound electrons that cause the photoelectric effect. Thomson scattering is the same as Compton scattering, but for low energies. Compton scattering is the process by which there is a change of wavelength or frequency upon scattering and this theory can handle the particles with higher energies. Third, Pair production is another phenomena that GEANT4 can simulate. It is also referred to as materialization and it takes place when a gamma ray is transformed into an electron-positron pair. Since energy has to be conserved, this cannot happen in free space, however, it can occur in the presence of a nucleus or electron. It is possible for the electrons and positrons to gain significant momenta from this pair production mechanism. Pairs can also be produced by heavy particle collisions, electron-electron collisions, and the decay of mesons. [9]

For electrons travelling through a material at high speeds, the main source of energy loss is the electromagnetic radiation that it emits due to acceleration. If the energy of an electron is really low ($E \ll mc^2$), the loss of energy to radiation is very small compared to ionization losses. The ratio of these losses is represented as:

$$\frac{(dE/dx)_{rad}}{(dE/dx)_{ion}} = \frac{EZ}{1600mc^2} = \frac{EZ}{800} \tag{7}$$

where E is in MeV. This equation shows that when the value EZ is large, the electromagnetic radiation dominates the ionization factor and when EZ is small, the ionization loss is the predominate one. [9]

GEANT4 also deals with many different forms of decay through the G4Decay class which implements both at rest and post-step actions for decaying particles. there are already default tables for more common particles including π, K mesons, Σ, Λ hyperons, and resonant baryons, but the user can also add more modifications. GEANT4 figures out how a particle decays by using different decay models based on the particle. For example, the V-A theory is used for muon decay. [10]

Finally, neutrons produced as secondary particles have to be accounted for in the GEANT code. As opposed to charged particles or gamma rays which lose their energy through electromagnetic effects, neutrons primarily lose energy through nuclear collisions. There are two types of collisions that can occur. The first type is an inelastic collision where the nucleus gets excited by the neutron; the neutron must have at least 1 MeV of energy for this to occur. If it doesn't have this energy, the neutron can only have elastic collisions. To figure out the loss of energy of neutrons in these collisions, a center-of-mass system has to be described. If the nucleus that the neutron strikes has a mass of A and the neutron has a velocity of V_1, this makes the velocity of the center of mass system, v_1 equal to:

$$v_1 = (A/(A+1)) \cdot V_1 \tag{8}$$

and the velocity of the target:

$$v_2 = (-1/(A+1)) \cdot V_1 \tag{9}$$

The neutron velocity is the vector difference between these two velocities and the law of cosines produces:

$$V_1'^2 = (\frac{AV_1}{A+1})^2 + (\frac{V_1}{A+1})^2 - 2V_1^2 A(\frac{1}{A+1})^2 = \frac{V_1^2}{(A+1)^2}(A^2 + 1 + 2A\cos\theta) \tag{10}$$

where V_1' is the velocity of the neutron and θ is the scattering angle in the center-of-mass system.

A lot of the information in this section came from Segre's book Nuclei and Particles and an even more in depth description of these interactions can be gained by consulting that text. [9]

3 HZETRN and GEANT4

HZETRN is a deterministic code that uses a one-dimensional space-marching formulation of the Boltzmann transport equation. The Boltzmann transport equation takes the form of:

$$\Omega \cdot \nabla\Phi_j(x, \Omega, E) = \sum_k \int \sigma_{jk}(\Omega, \Omega', E, E') \cdot \Phi_k(x, \Omega', E') dE' d\Omega' - \sigma_j(E) \cdot \Phi_j(x, \Omega, E) \tag{11}$$

In this equation, σ_j is the total reaction cross section and the σ_{jk} values are the channel changing cross sections. The Ω terms are vectors pointing in the direction of the particles. HZETRN solves this Boltzmann equation for the particle flux, defined as $\Phi_j(x, E)$ where j is the type of the ion with energy E and depth x. This particular equation is known as the time-independent version of the Boltzmann equation.[5] To make solving this equation easier, HZETRN makes a number of assumptions including that the slowing down of particles due to collisions with electrons is continuous and that the incoming nuclei follow the straight-ahead approximation. [11] To make the continuous slowing-down approximation, the σ_{jk}'s are written as atomic terms and the equation is simplified so that the cross section only has the nuclear contributions. The straight-ahead approximation limits HZETRN to only one dimension.[5]

While HZETRN is used for galactic cosmic rays, another program, BRYNTRN is used to simulate the transport of baryons that would be expected in solar particle events. Similarly to HZETRN, it solves the Boltzmann transport equation in BRYNTRN this is made easier by assuming that the energy loss by heavy target fragments and recoil nuclei is deposited locally instead of appearing in the dose received by a human. [12]

Although HZETRN has its advantages, it has a number of shortcomings that are recognized. First, all secondary particles from HZE interaction are presently assumed to be produced with a velocity equal to that of the incident particle; this is a conservative assumption for neutrons produced in HZE particle fragmentations. Next, Meson contributions to the propagating radiation fields are neglected. This could be a problem in the case of pions. If the pions were stopped in the material, they could produce a significant dose.[7] Third, target fragments in HZE reactions are neglected. Although the fragmentation of incoming particles is of primary interest, these target fragments could add to the energy deposited. Finally, there is an angular dependance, and this is neglected in neutron propagation. [5] Due to the many approximations made by HZETRN, it has to be assumed that the particle is coming into the material in only one direction. Because GEANT4 does not make as many assumptions, it offers some advantages over the HZETRN code.

GEANT4 on the other hand, is a monte carlo based code that gains accuracy through repetition. By running many incoming particles, it is possible to bypass the shortcomings of deterministically based codes such as HZETRN. The important aspects of GEANT4's simulation of the passage of particles includes geometry, materials, particle interactions in matter, tracking management, digitisation management, hit management, event management, and track management. [10]

For geometry and materials, GEANT4 runs by setting certain parameters specific to different projects. For this project, each of the different spectra act as the input(See Fig. 1) and the user has to define the layers of the detector targets.[8] The GEANT4 program came with the GCR spectra as seen in Fig. 2, but since this project is trying to make a direct comparison to NASA's data, NASA's input spectra is used to increase the effectiveness of the comparison. In addition, C. O'Neill's thesis showed that the GEANT4 spectra produced results contrary to what NASA found using HZETRN. C.O'Neill's data used GEANT 4 before any changes were made in the code, but to make the best comparison, it is necessary to use NASA's input spectra as opposed to GEANT4's spectra. For the SPE data, spectra were obtained for a worst week scenario of solar particle events.[13] In Fig. 3 the SPE spectra for Protons and Alpha particles can be seen.

In this application, the target consists of a layer of polyethylene and a layer of water. Polyethylene, because of it's high hydrogen content, has been shown to be a good shielding material. While polyethylene does not have good thermal or mechanical properties that are necessary in space travel, it generalize other polymers.[14] The water is being used as an approximation of human cells since they mainly consist of water. Both of the thicknesses of these layers can be modified. The thickness of polyethylene is then varied from 0 to 20 centimeters while the water remains constant at 1 centimeter. Water has been shown by NASA to be an accurate model for human cells.[8] The output of a program run are 5 histograms with information about the total energy loss in the gap, total energy loss in the shielding material, the change in energy versus x position, kinetic energy versus x position, and the step length of the primary incoming particle. The term gap refers to the layer of water that is used in this application. The primary histogram of interest is the one that contains the energy deposited in the 1 cm of water. This energy deposited is then used to calculate dose and is used to simulate the effect of changing shield thickness on the dose.

Each particle is tracked as GEANT4 simulates the particle's passage through a material. GEANT4 does this by moving the particle step by step through the material with each step representing a different physics process that the particle could experience as it interacts with the material. Physics processes that are unique to a project are defined in the Physics List within the GEANT4 program. When traveling through a material, particles are represented as being either at rest, along a step, or post step. Each type of particle can only undergo certain physics processes based on its definition within GEANT4. Several examples of steps that GEANT4 can simulate include decay, where a particle is at rest, and the creation of secondary particles and loss of energy when a particle is along a step. Once a particle is at the end of a step, post step is invoked and a secondary particle could be produced by decay or interaction or the original particle continues to the next step. This process continues until the particle is stopped inside of a material. [10]

Particles are defined by several different classes, each containing different types of information about that particle. The G4ParticleDefinition class holds information about the basic properties of the particles including mass, charge, and information about what physical processes it is sensitive to. [10]

4 Progress to Date

The first few weeks of research were spent figuring out exactly how to run GEANT4. GEANT4 is a very complicated program and it was necessary to figure out how to run everything again. Because this project is a continuation of C. ONeills work, it was difficult figuring out exactly what all of the files represented and how to import all of the spectra into GEANT4. One of GEANT4's main drawbacks is the amount of work it takes to get acquainted with all of the nuances of the program. Once everything was sorted out, it was possible to start running the spectra through the program.

It was possible to run the program with GCR spectra obtained from NASA. C. O'Neill's research used the GCR spectra that came with GEANT4 and he ran into problems when comparing the data to NASA's data. While NASAs radiation dose was pretty much constant with changing shielding material depth, C. ONeills results decreased dramatically before leveling out. This project resumes where C. O'Neill's ended. Unfortunately, even when using the GCR spectrum that NASA provided as the input, the results still did not agree with the HZETRN results from NASA. At this point, it seemed likely that something had to be wrong with the GEANT4 code because both NASAs results and results using other Monte Carlo based codes[15] showed that GCR radiation dose did not increase or decrease when the shielding thickness was increased.

It was discovered that the main problem with the results was a consequence of the way the Monte Carlo code was integrating the spectra. The Monte Carlo based code is a process used to simulate data and this project is considering the process by which an initial energy is chosen for a given particle. The NASA GCR spectra serves as the probability distribution of GCR energies. For a particular particle such that $dP/dE(E)dE$ is the probablity of an energy between E and $E + dE$, one then integrates this and normalizes, obtaining:

$$IP(E) = \frac{\int_0^E dP/dE'dE'}{\int_0^\infty dP/dE'dE'} \tag{12}$$

Then one uses a numeric random number generator to choose a number, r, between

0 and 1[7] and an energy, E_s is chosen as indicated in Fig. 4

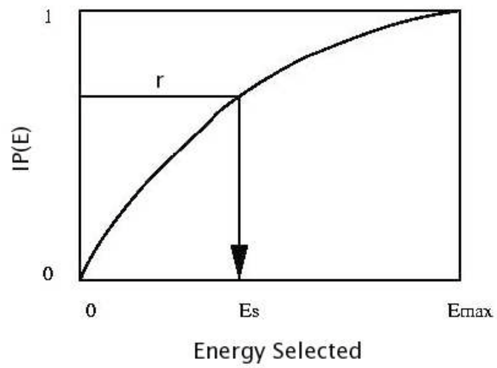

Figure 4: Monte Carlo selection of Energy

Originally, the code assumed that the spectra consisted of evenly spaced points. However, the NASA GCR spectra used to run the program had a lot of data clustered around the lower energies and data that was more spread out as the energy was increased. This discrepancy turned out to have a huge effect on the results. To correct this mistake, the code was modified to take the difference between one energy and the next energy and then multiplied this difference by the average of the probability of energy to get an approximate integral of the spectra.

The difference between the results from the original code and results from the modified code is obvious in Fig. 5. The energy does not change nearly as much with changing shielding thicknesses as it did before the code was changed and it should be at least a little bit closer to NASAs results once all of the incoming particles are combined together. However, there is still a decrease in the energy deposited as the shielding thickness is increased. This trend is also seen in all of the other ions which is promising. The modified code allowed for much less change in dose with changing shield thickness as seen in Fig.6.

One final problem encountered was found after modifying the code. For any of

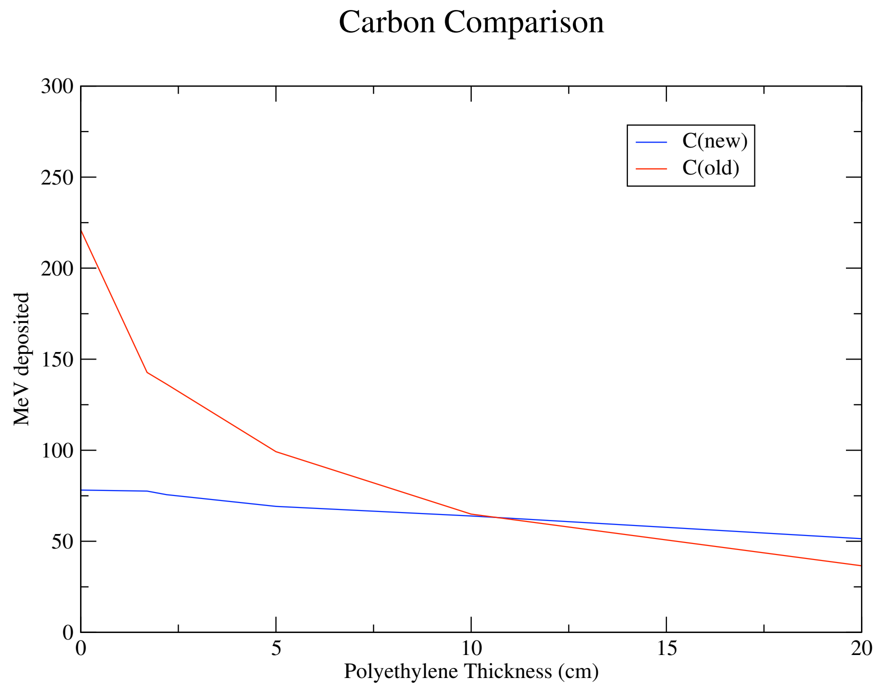

Figure 5: Comparison between original code and modified code for Carbon

the ions above carbon, the histograms were empty for energy deposited in the water. The program was running correctly for all of the previous particles and nothing else had changed. It turned out that the x-axis for the histogram had to be increased to accommodate the higher charge ions because they were depositing higher amounts of energy than was initially thought. Once this was modified, data for oxygen, silicon, and iron could be collected. This is significant because this was not a problem encountered before the code modification. The old code was severely underestimating the amount of energy deposited in the water for the heavier ions.

Because there was a much better trend with the individual ions after the code change, they were combined to form a more complete picture of the shielding characteristics of polyethylene for a complete spectrum of incoming particles.

The next step was to see how the data compared to data obtained using HZETRN. The data obtained from NASA was in dose which is measured in centiGrays per year (cGy/yr). Before it was possible to make a comparison between the data, the results

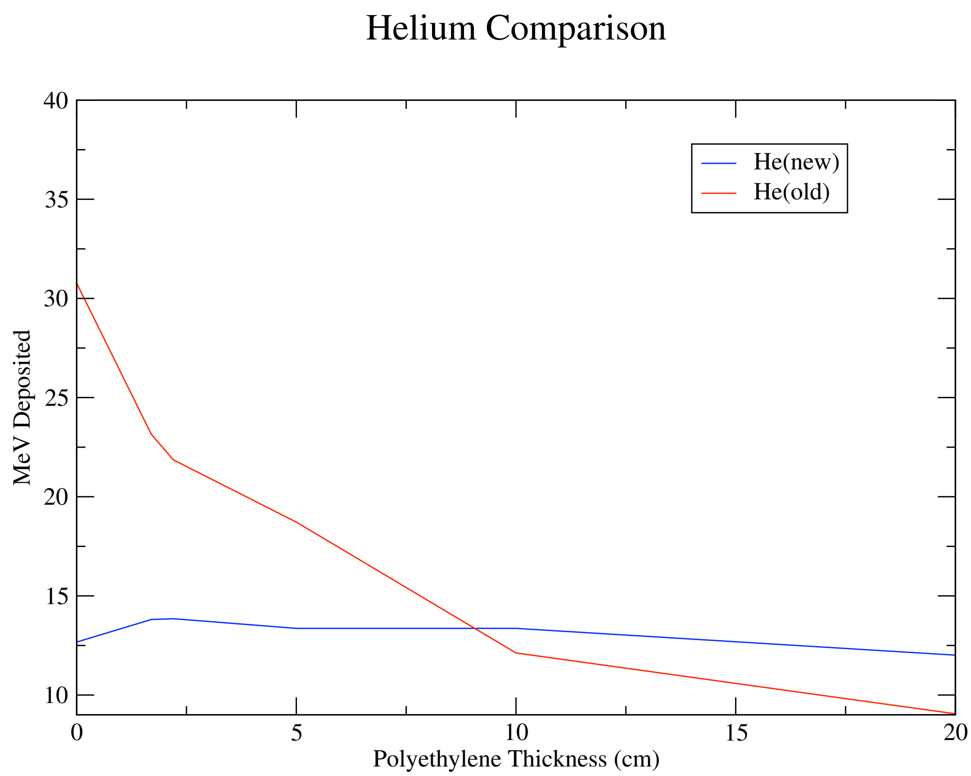

Figure 6: Comparison between original code and modified code for Helium

obtained in MeV had to be converted to cGy/yr. The equation for dose is:

$$Dose = \sum_z \Phi_z \cdot Q_z \tag{13}$$

where Φ_z is the total flux of the incoming spectra and

$$Q_z = (\frac{E_{Gz}}{N_{Gz}}) \cdot 10^6 \cdot e \cdot A \tag{14}$$

where $\frac{E_{Gz}}{N_{Gz}}$ is the energy per nucleon in MeV and is the value given in Histogram 5. e is the value 1.6×10^{-19}, the factor of 1×10^6 converts the MeV to eV, and A is the area of the target. Because the energy needs to be deposit into a kg of water, the Area is taken as 10^3 cm^2 so that when it is multipied by 1 cm thick water, the result is 10^3 cm^3. The density of water is 1 g/cm^3 and this is how 1 kg of water is obtained.

To obtain the total flux, the NASA GCR spectra were sent through a program that was able to approximately integrate it according to the equation:

$$\Phi_z = \sum_i (E_i) - (E_{i+1}) \cdot \frac{1}{2} \cdot (F_i + F_{i+1}) \tag{15}$$

where E_i is the energy value on the x-axis of the GCR Spectra (See Fig. 1) and F_i is the value of the flux on the y-axis of the same graph.

The result of these equations is in the units of Grays per day, which is not exactly the units necessary for comparison. The final step was to multiply by 3.65×10^4 to convert it into cGy/yr to coincide with NASA's units.

The dose of the different particles was obtained using these equations and after adding all of the ions together for each thickness of polyethylene it was possible to make a comparison to the NASA data [16]. The trends are very similar between the two, but since they are not the same material, a direct comparison wasn't possible. The HZETRN data that was available for comparison with GEANT4 data made use out of the Martian Regolith as the shielding material. Regolith is defined as a layer of unconsolidated rocky material covering solid rock. NASA wanted to see how effective shielding material made from Martian rocks and regolith was affected by radiation. By adding an epoxy, and thus increasing the hydrogen content, NASA speculated that the regolith could serve as a shielding material if structures were to be built on the surface in the future. This is important because it makes sense to use materials already present on Mars for building structures.[16] If there is more knowledge about the shielding characteristics of martian regolith, a plan for its utilization as a building material can be determined. The elemental constituents of the regolith were also found in the article that contained the regolith data.[16] The regolith consists almost entirely of five different elements and has a density of 1.4 g/cm^3. The elements and their percentage composition are as follows: Oxygen (62.5%), Silicon (21.77 %), Iron (6.73 %), Magnesium (6.06%), and Calcium (2.92 %). [16] Using GEANT4's ExN03DetectorConstruction source file, a new Martian Regolith target was added as the elements that were not already included in the code including Magnesium, Iron, and Calcium. Instead of using Polyethylene when running GEANT4, the regolith material was used so that there was a more direct comparison to the HZETRN data. The necessary conversion to dose was made and the new data were added to the graph that compared GEANT4 polyethylene dose to HZETRN Martian Regolith dose. To show the impact of the error in the code, the original data obtained before the code was changed was included in the same graph as all of the other dose comparisons (See Fig. 7).

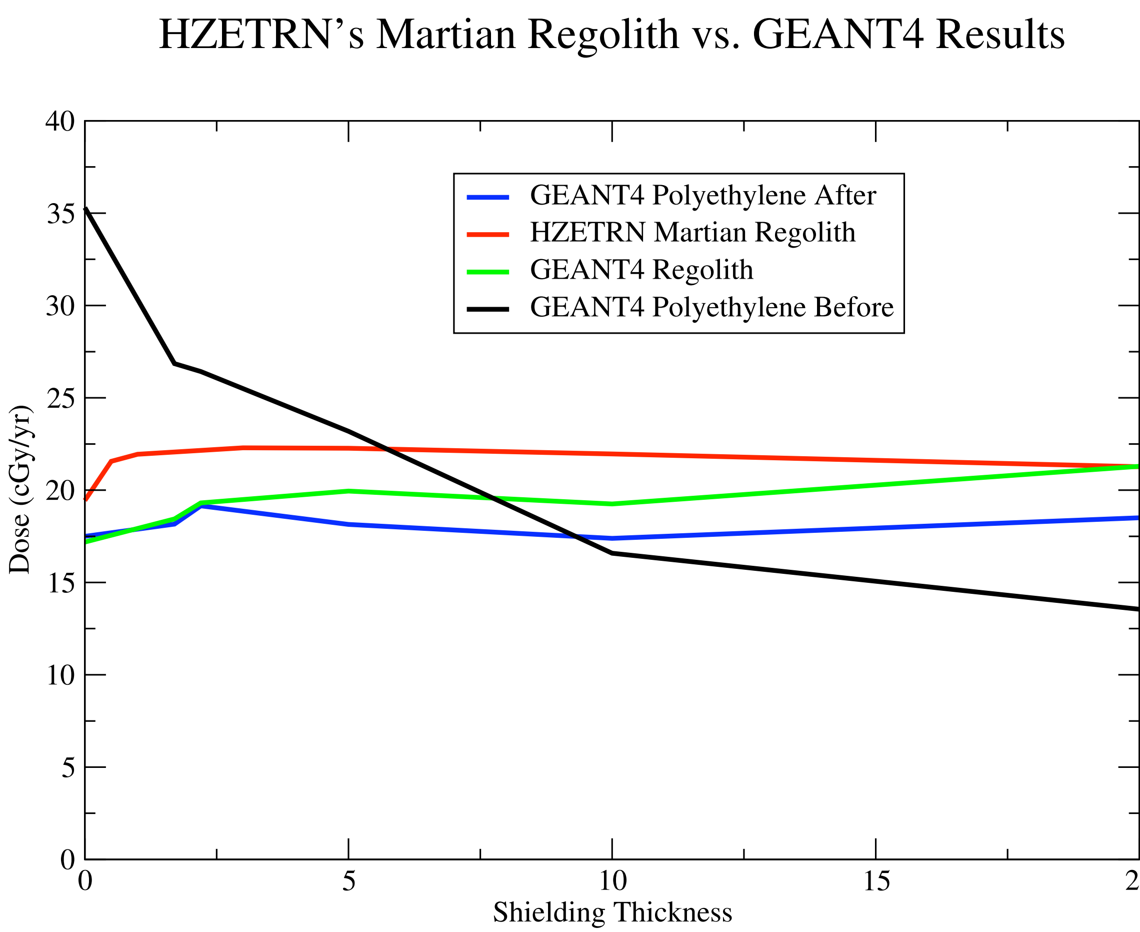

Figure 7: Comparison between HZETRN results and GEANT4 results. The martian regolith environment was simulated to get an accurate comparison. We included the Polyethylene data before the code was changed to show the effect of the code change.

As seen in Fig. 7, the change in code was necessary. It was later discovered that Dr. Susan Guatelli, author of the CERN cosmic ray simulation examples code was aware of this problem with the code and had updated it in the newest version. The Polyethylene looks very similar to the Martian Regolith data obtained by NASA, however it is shifted downward. The GEANT4 regolith data that were collected shifted the curve up a bit more and improves confidence in the results.

The SPE results were not as promising as the GCR results because the shapes of the graphs were different. Using two different SPE spectra, it was not possible to replicate results found using BRYNTRN. To make comparisons between the BRYNTRN data and our data, we converted the energy deposited in the water from MeV to Gy/event in a matter similar to that used for the GCR data. The only differences were that the time interval considered was a week and the flux was converted from per radian to per 2π radians.

Fig. 8 demonstrates that not much agreement was obtained between the two programs for SPE spectra. This could be due to many different reasons including the fact that different transport modeling programs using different input spectra can produce significantly different results. [17] While all of the sets of data reach about the same point for 10 cm of shielding thickness, they are completely different for thinner shielding materials. Both of the GEANT4 results decrease sharply around 2.2 cm while the decrease of the BRYNTRN results was much less pronounced. One possible explanation for this discrepancy could be the fact that the BRYNTRN data only had 3 points of data for 1, 5, and 10 cm of shielding material.[18] If there were another couple points of data available, it could be possible that the results are actually much closer than Fig. 8 indicates. More data points could make the comparison between the two sets of data much easier. It is also important to note that the BRYNTRN results only included protons and did not test for alpha particles mostly because data for those types of particles are minimal for the earlier SPE events. [18]

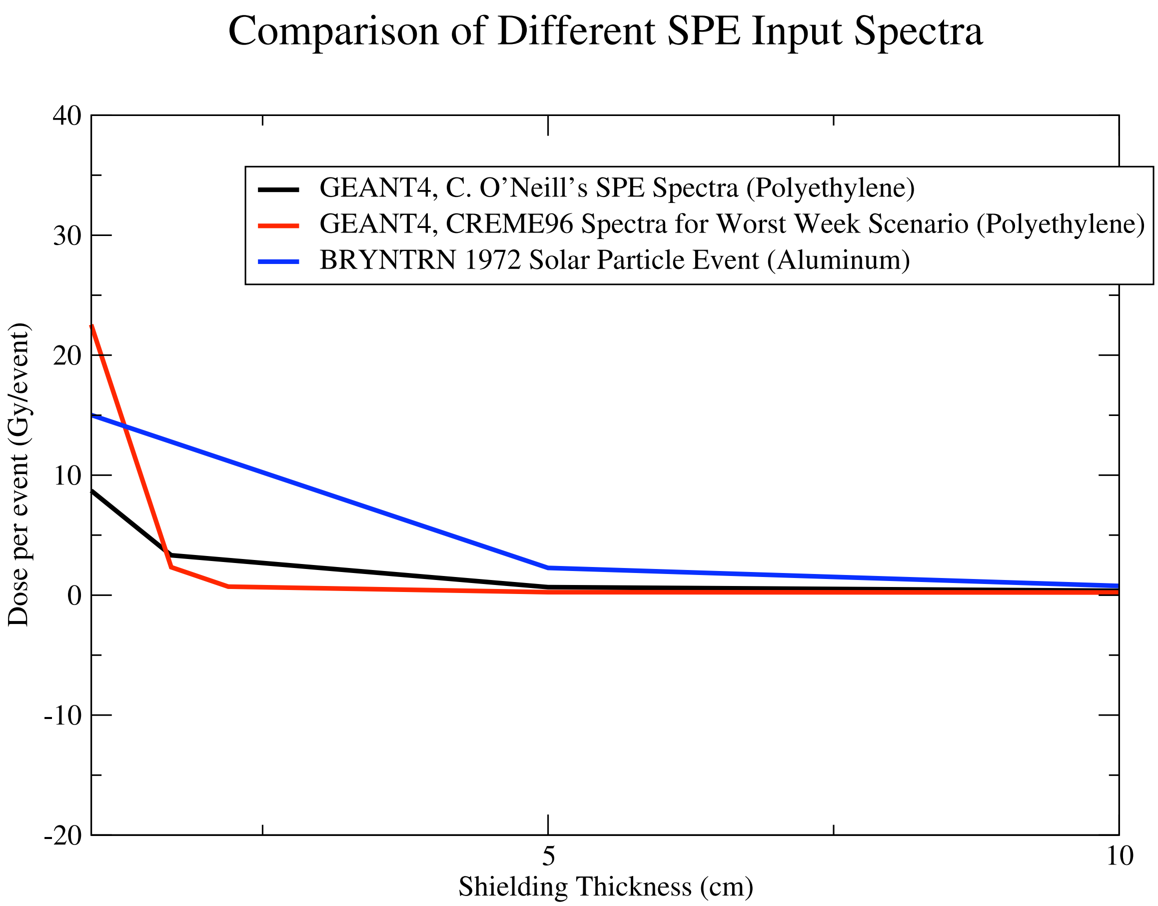

Figure 8: Comparison between BRYNTRN SPE data and GEANT4 SPE data. Two different SPE spectra were used for GEANT4.

5 Future Work

There is still work that could be done on this project in the future. There were a lot of different problems in the GEANT4 code, and it was possible to fix those problems. Since GEANT4 updated the code as well, more work could be done with the newest version. This could increase confidence in the results if the newer release of GEANT4 produced the same results. In addition, it would be useful to see if GEANT updated their version of the GCR spectra. If they are using the same GCR spectra that came with GEANT4, it would be interesting to see what the data would look like when running the GEANT4 GCR spectra with the updated GEANT4 code. Obtaining data for other shielding materials could also prove useful to show the wide range of shielding possibilities. In addition, code could be added to the program to add a new histogram that gives the dose and the dose equivalent of the deposited radiation.

6 Conclusion

In his thesis, C. O'Neill used Polyethylene as a shielding material instead of martian regolith. However, this should not account for the results that he saw because the only discrepancy should be a shift of the graph. His main problem dealt with the shape of the curve for GCR dose when compared to shielding thickness. This project sought to more closely replicate results obtained by NASA using the HZETRN code. The major obstacle of this project was the discovery of incorrect code within GEANT4. Once the code modification was made and this error was corrected, it was possible to make a more direct comparison to NASA's results. The results using the newly modified code and Polyethylene as a shielding material produced a similar shape to NASA's data. After creating a regolith shielding material in GEANT4, the results were within 5 % of NASA's results. GEANT4 also updated their code and this new version included a fix to the error that was found when resolving the discrepancies between results. Because this code change was discovered by the authors of GEANT, there is much more of a reason to trust the data that the modified version of GEANT4 produced. For even more confidence in results, it would be useful to install the newest version of GEANT4. Finally, HZETRN may be updated in the future to include all 3 dimensions. This could actually prove very useful because it might actually reduce some of the discrepancy seen between GEANT4 and HZETRN. HZETRN's main disadvantage is the fact that it can only operate in one dimension due to it's assumptions, so this could help increase confidence in all results. [19]

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