Determining Radiation Damage from Analyzing Neutron Microscopic and Macroscopic Cross Sections

Shannen Moira Mogan Acedillo
Aerospace Engineering
Mentor: Dr. Navid Nakhijri
Kellogg Honors College Capstone Project

ABSTRACT

Radiation is considered one of the most complex problems for long duration manned and unmanned missions, therefore it is important to mitigate the effects of radiation. One solution widely studied is by taking advantage of spacecraft material properties and their ability to protect against radiation. Studies usually analyze the radiation performance in relation to the material thicknesses, however in this study, we will be determining the performance against the amount of radiation damage. Determining the radiation damage of these materials can provide us with enough information to conclude whether the material is best suitable for radiation protection in addition to not ignoring the atomic properties of the material that might be overlooked with other studies. Quantifying radiation damage can be done by analyzing the neutron microscopic and macroscopic cross sections of the materials. The cross sections express the likelihood of an interaction between an incident and a target nucleus. In this study, we will be using the JANIS software to attain cross section data of certain elements that make up the materials and using a MATLAB code to determine the radiation damage. Among all the materials analyzed, boron carbide performed the best. In addition, materials containing high density elements are mostly high performing.

MOTIVATION

Mitigating space radiation problems is an important element of designing future long duration manned and unmanned missions. For example, Galileo, an unmanned spacecraft surveying Jupiter and its moons, has suffered through a range of system failures that can be traced to radiation. Some of these failures include the instruments absorbing sufficient radiation dose to push it out of its original specifications. To reduce these effects as much as possible the design called for conservatively high radiation margins and the usage of elliptical orbits that allow time for annealing and repairing affected system[1]. Simply designing around the radiation problem does not sufficiently mitigate the effects and it can cause even more design challenges.

It is essential to look for ways to protect against space radiation that can be versatile for various missions. A solution that has been widely studied is to take advantage of the properties of spacecraft structural materials. Having the capacity to serve as both part of the structure and a radiation barrier proves to be a cost, weight, and overall a design effective approach. There is currently an abundant about of research in the field of space radiation protection. A study was done by NASA Langley Center on the impact of using four typical materials: aluminum, liquid hydrogen, polyethylene and water to an astronaut's limit in space. Results showed that for long missions for humans, polyethylene is better than liquid hydrogen, even though at large thicknesses liquid hydrogen provides better protection[3]. Boron Carbide, a developed radiation protection coating, is 3.3 times better than aluminum in the electron radiation protection abilities[4]. Another study using GEANT4 and NASA Langley codes were used to analyze dose rates vs depth (g/cm2) for liquid hydrogen, aluminum, polyethylene, and other polymers[5]. A study done on the shielding efficiency vs material thickness of polyethylene composites proved its ability to shield similar to aluminum but offering more light weight material6. Most of the studies about radiation protection performance of different materials mainly consider the material thicknesses and densities in their analysis. This approach overlooks the performance certain materials can provide at an atomic level when bombarded with irradiated particles. It is important to understand the interactions that happen at an atomic level because certain interaction occurs that may either be devastating or beneficial to absorbing or reflecting radiation.

A simple solution is to determine the radiation damage of each material in a certain radiation environment. Radiation damage can be used to quantify radiation protection performances, resulting in the determination of which material is the best. The important quantifying factors of radiation damage are the microscopic and macroscopic cross sections, which look at the interactions happening at an atomic level between the incoming particle and the material. Cross sections will be discussed more in detail in the paper. The overall purpose of this study is to conduct a radiation damage analysis at an atomic level on certain materials to conclude on the material suited with the best radiation protection performance.

THEORY

A. Material Choices: It has been found that materials with high hydrogen content yield better shielding performance[9]. This statement is further supported according to the NIAC Final Report, stating that materials containing hydrogen, boron, and nitrogen are the best radiation shielding materials[10]. Nitrogen, Oxygen, Boron, Carbon and Hydrogen. These elements are also known to be effective in radiation protection[14,15,16]. In this study, these elements are combined to create super effective materials such as Boron Carbide and Kevlar. Therefore, we will focus on materials containing C, H, N, O, and Br. Based on suggestions from past research and material composition, the materials chosen for this study are polyethylene, polyurethane, Nylon6, Kevlar49, SWCNTs, MWCNTs, poly allyl diglycol carbonate, and Boron Carbide.

B. Macroscopic and Microscopic Cross Sections and Radiation Damage: Radiation damage can be quantified by determining the number of displacements per unit of volume per unit of time. Radiation damage is dependent on the microscopic neutron cross section values which express the likelihood of interaction between an incident neutron and target nucleus and this probability is dependent on the type of nucleus involved and the energy of the incoming neutron[11]. The larger the neutron cross section, the more likely a neutron will react with the nucleus since the values represent the effective area the nucleus presented for the incoming neutron given the reaction[10] the macroscopic cross section, Σ, gives the probability of a reaction occurring per unit travel of the incoming neutron. The difference is that microscopic cross sections represent the effective area for a single nucleus presents to incoming particle and that the macroscopic cross section represents the effective area for all nuclei in 1 cm^3 of material. Therefore, macroscopic cross sections can be dependent on multiple elements. Thus, macroscopic cross sections can be used to analyze materials such as composites that have multiple basic elements. Since most of the materials used in the research are composites, this phenomenon will be used to our advantage. It is important to note that the atomic density is a significant variable to incorporate into the analysis as different materials with the same element have different densities and this greatly affects its performance; for example, atomic density can distinguish between single walled carbon nanotubes and multiwalled carbon nanotubes which both have the same elemental composition. So, to quantify radiation damage, one must analyze the different cross sections of various materials under certain incident energy levels. The following equation calculates the radiation damage.

$$R = N\int_{Emin}^{Emax}\int_{Tmin}^{Tmax}\varphi(E_i)\sigma(E_i,T)v(T)dTdE_i\left[\frac{\frac{displacements}{volume}}{time}\right]$$

In order to properly analyze the problem, Equation 1 is discretized to a simpler form : $R = \Sigma * \varphi(E_i)\ [\frac{reactions}{cm^3\text{sec}}]$

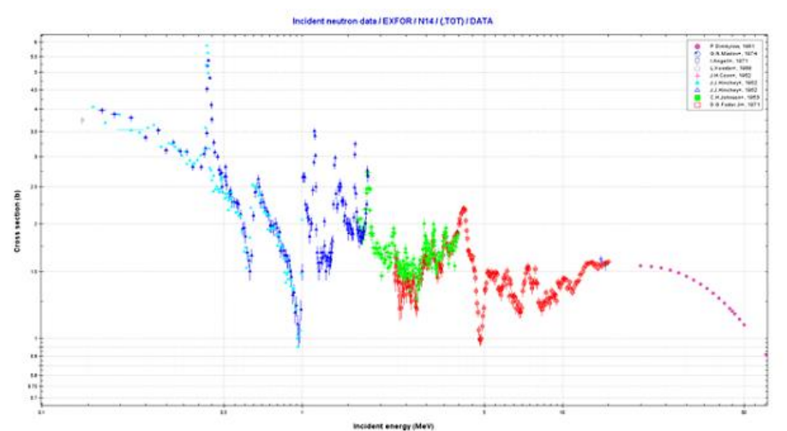


Figure 1. Nitrogen Cross Section vs Incident Energy Plot. *Example plot data retrieved from the JANIS software.*

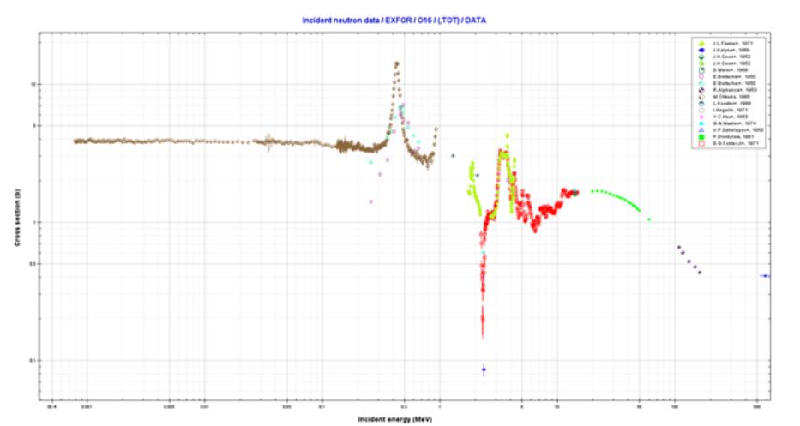


Figure 2. Oxygen Cross Section vs Incident Energy Plot. *Example plot data retrieved from the JANIS software.*

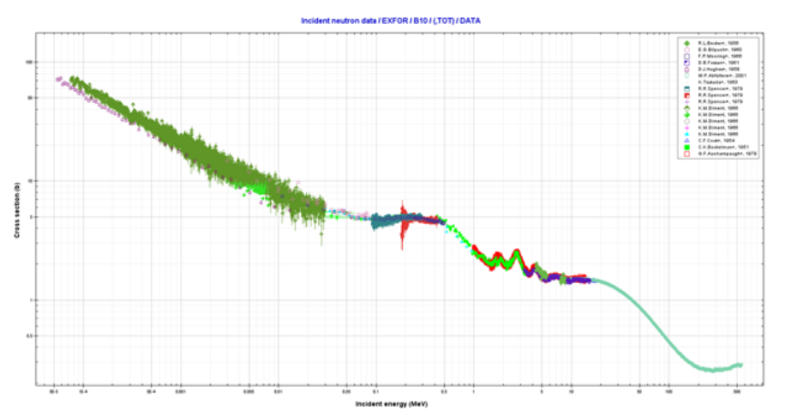
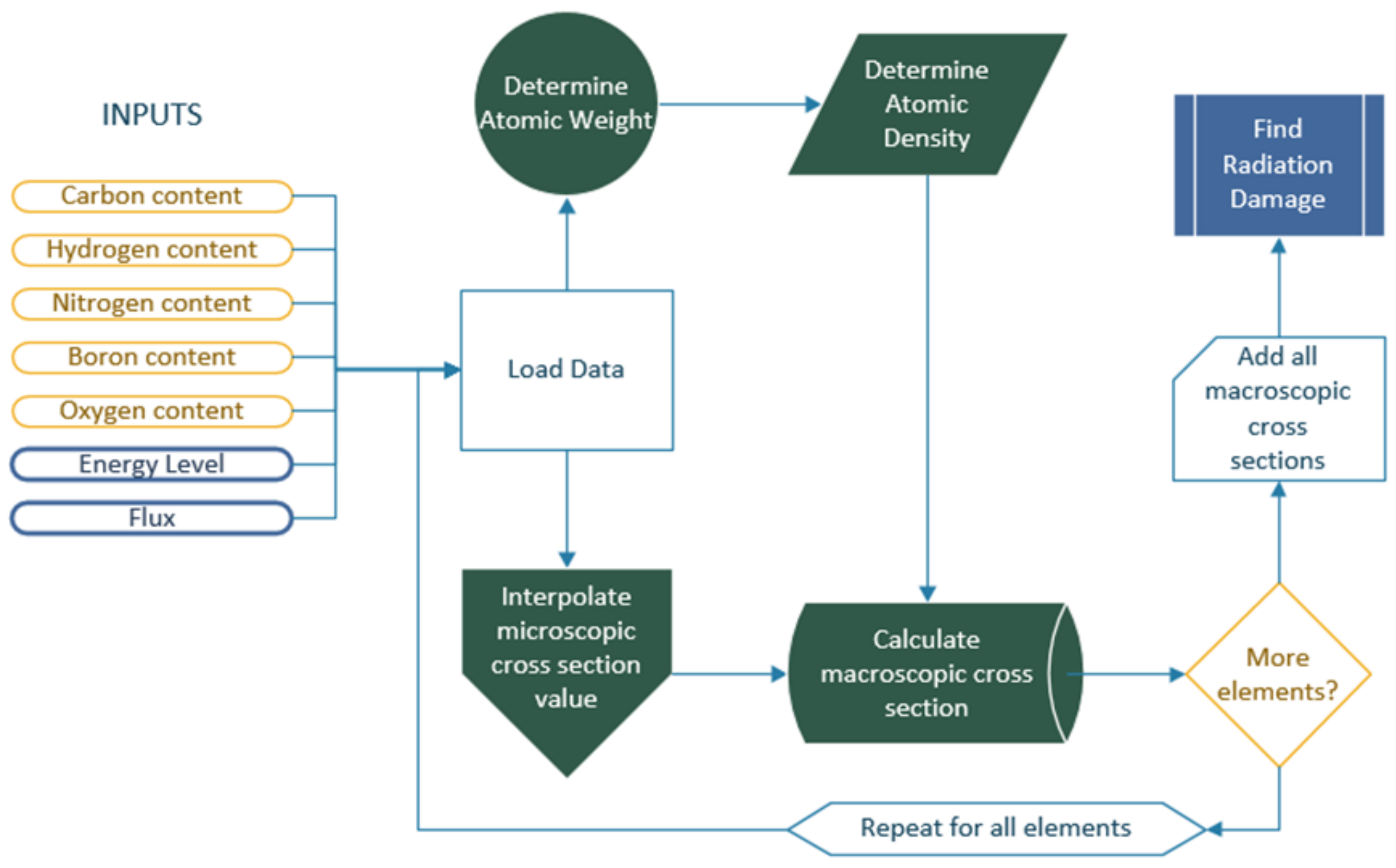


Figure 3. Boron Cross Section vs Incident Energy Plot. *Example plot data retrieved from the JANIS software.*



INPUTS

- Carbon content
- Hydrogen content
- Nitrogen content
- Boron content
- Oxygen content
- Energy Level
- Flux

Load Data
Determine Atomic Weight
Determine Atomic Density
Interpolate microscopic cross section value
Calculate macroscopic cross section
More elements?
Repeat for all elements
Add all macroscopic cross sections
Find Radiation Damage

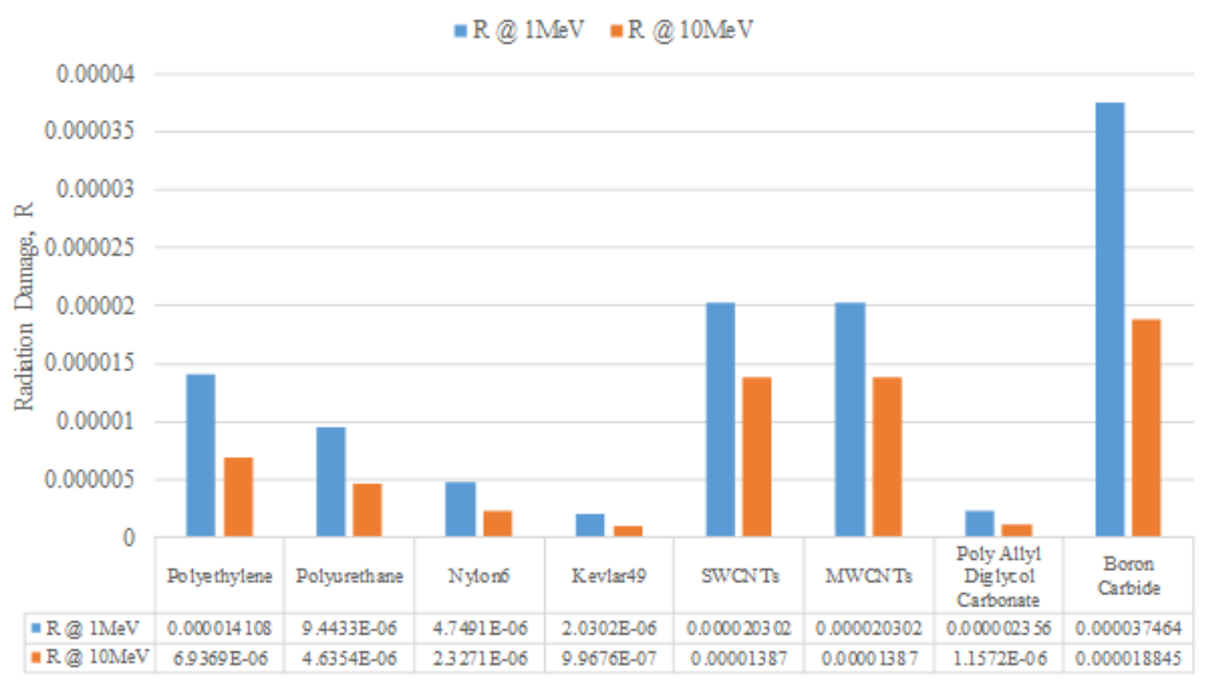
Figure 3 shows a graphical flow of the MATLAB code

METHODOLOGY

As stated previously, the JANIS software will be used to develop a database of the cross sections resulting from various incident energies to basic elements. A MATLAB code will be able to determine the radiation damage experienced through a point in the radiation model. Cross section analysis of different materials under various types of irradiation can be modeled on MATLAB using the JANIS software to generate a database of various incident energies with their respective neutron cross sections for different basic elements.

A. JANIS Data: To first conduct the study, the JANIS software is used to gather data for all the basic elements: Carbon, Hydrogen, Nitrogen, Oxygen, and Boron. This output data is comprised of incident energies and the resulting microscopic cross sections as shown in plots in Figures 1-3. As shown in the data, the cross-section area is directly dependent of the incident energies but do not have a distinct relationship or trend. The figures also show that cross sections usually are lower at higher energy levels, this can be seen clearly on the Boron and Hydrogen trends. The raw data is from the JANIS database which is a library of all the values that have been experimentally found in various papers through the decades.

B. MATLAB Analysis: The MATLAB code is made to determine the radiation damage of each material by analyzing the elemental properties. Figure 3 shows a graphical flow of the MATLAB code. The code has been formatted in a way any material can be analyzed given that that material is only composed of the 5 main elements. The user can input the carbon, hydrogen, nitrogen, boron, and oxygen content of the material. The other inputs needed are the incident particle energy experienced, and the particle flux. Tables of microscopic cross sections vs energy levels for each material are generated by the JANIS Software and are stored in a data-base. Recalling the JANIS data shown in the previous section, we used the data points to determine the corresponding cross section of the inputted energy level by interpolating the microscopic cross section value. The atomic weight and density of each element is also calculated given the elemental composition. Then, the macroscopic cross section of one element of the material is calculated. The code will run again for the other elements in the material composition. All the macroscopic cross sections of each element are then summed to find overall macroscopic cross section of the material. Once the final macroscopic cross section is found, the radiation damage, or the number of reactions within a unit of volume, and time can then be calculated.



	Polyethylene	Polyurethane	Nylon6	Kevlar49	SWCNTs	MWCNTs	Poly Allyl Diglycol Carbonate	Boron Carbide
R @ 1MeV	0.000014108	9.4433E-06	4.7491E-06	2.0302E-06	0.000020302	0.000020302	0.000002356	0.000037464
R @ 10MeV	6.9369E-06	4.6354E-06	2.3271E-06	9.9676E-07	0.00001387	0.00001387	1.1572E-06	0.000018845

Figure 4. Radiation Damage of Materials at 1 MeV and 10 MeV

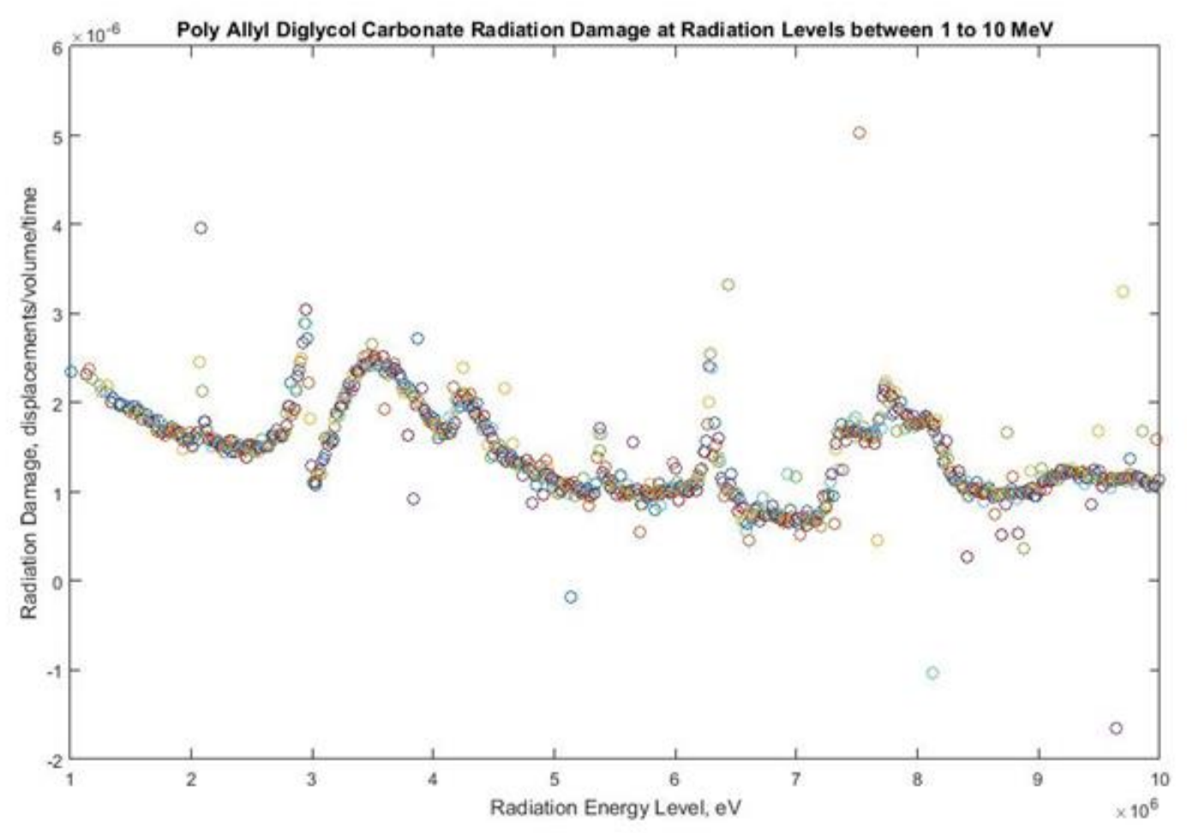
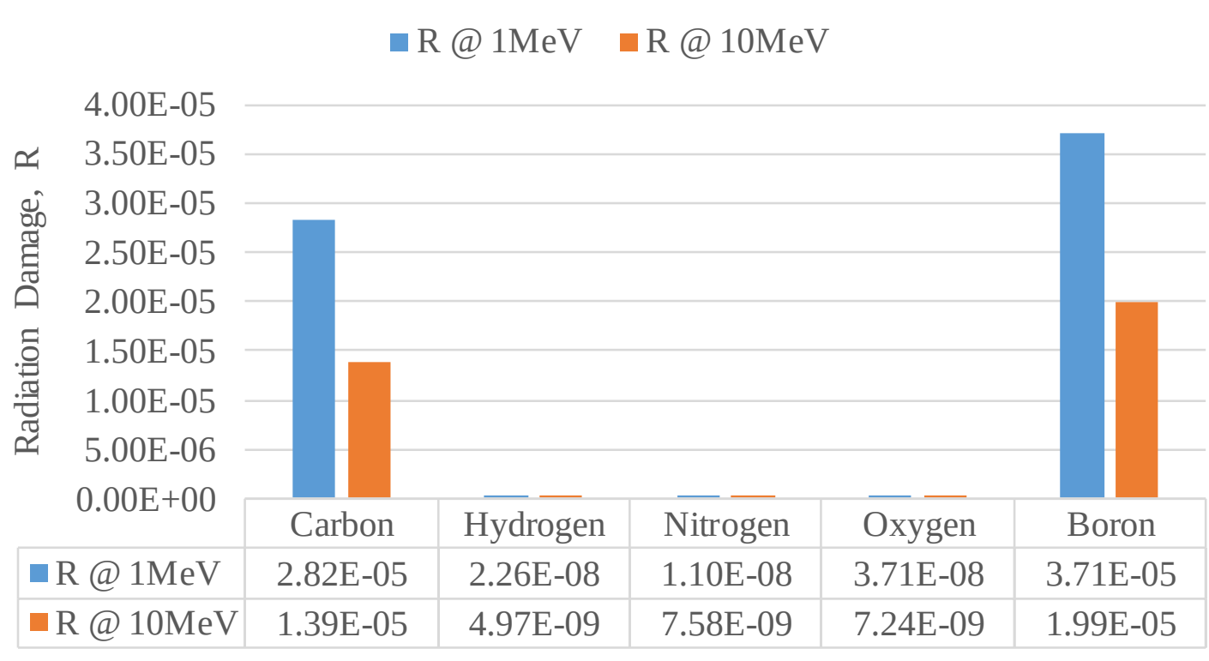


Figure 5. Poly Allyl Diglycol Carbonate Radiation Damage and Radiation Levels Between 1 and 10



	Carbon	Hydrogen	Nitrogen	Oxygen	Boron
R @ 1MeV	2.82E-05	2.26E-08	1.10E-08	3.71E-08	3.71E-05
R @ 10MeV	1.39E-05	4.97E-09	7.58E-09	7.24E-09	1.99E-05

Figure 6. Radiation Damage of Elements at 1 MeV and 10 MeV

RESULTS AND CONCLUSIONS

As shown in Figure 4, at 1 MeV energies, Poly Allyl Diglycol Carbonate and Kevlar performed the best. Surprisingly, Boron Carbide did the worst. At 10 MeV levels, the results show that at Poly Allyl Diglycol Carbonate and Kevlar performed the best again. This is due to the fact that these two materials contained the most hydrogen, 14 and 18 atoms respectively. Boron Carbide had no hydrogen atoms. Interestingly, all of the materials performed better at high energy of 10 MeV, where most of the materials reduced the radiation damage by one half. CNTs on the other hand seemed to perform better at high energies than the rest of the materials since the radiation damage decreased to a little more than half of the radiation damage at 1 MeV.

A graph was also generated to determine the trend of the radiation damage at energies between 1 and 10 MeV. This was done on Poly Allyl Diglycol Carbonate and the results are shown in Figure 5. Interestingly, the trend does not follow a strict pattern but can be seen as to decrease and increase at every factor of ten increments. Future work will be conducted on this on other materials and at different energy ranges. To further explain these phenomena, the basic elements were analyzed. Figure 6 shows the radiation damage of each single element at 1 MeV and 10 MeV. The results show that the radiation damage that hydrogen, nitrogen, and oxygen produced is negligible as compared to carbon and boron, which generated significantly worse radiation damage. This explains the phenomena of the best and worst performing materials—the materials containing the most hydrogen, nitrogen, and oxygen performed better. It is important to note that these single elements also achieve less radiation damage explaining the phenomena stated earlier. This shows that the materials' capability to perform better at different energies are dependent on the composition as well as thickness and density, as these two are the focused on widely with other studies.

The results show that the composition of a material is just as important as its thickness and density and any other properties when determining its radiation protection properties. The interesting trends between carbon nanotubes degrading much less at high energies as compared to other materials and the materials showing less radiation damage at high energy levels can sprout new studies. Studies involving radiation damage over time and even developing materials used only at high radiation energy levels. The results from this study provided a successful approach to another way to analyze radiation protection. In addition, past work suggested that materials with high hydrogen content would perform the best, and this study further supports that.

CODE MODIFICATIONS

Before, the MATLAB code worked with only one value of a radiation energy level and flux value. The code was modified to incorporate a set of flux values. These flux values were derived from what radiation exposure certain orbital trajectories experience. This was done to see the correlation between the radiation damage within a simulated radiation environment. This would also make the model dynamics rather than static, where the radiation damage would increase over time. Ultimately, this would achieve a radiation damage analysis on an orbital trajectory with given radiation values at each point.

FUTURE WORK

In further studies, I would like to dive deeper in the phenomena mentioned earlier in Figure 5 and expand the study to multiple materials. This would increase the range of certain types of materials that I can study and find more interesting trends such as the ones found in this study. In addition, I would like to compare the radiation damage directly to the cross sections and determine if there is any trend associated between the two factors. In regards to the collaborative work, I would like to make the models, orbital and radiation, as realistic as possible.

COLLABORATIVE WORK: Optimizing Europa Trajectories With the Least Amount of Radiation Damage

An important application is incorporating it into a spacecraft design mission to Europa, where studies show that the overbearing problem to work around is radiation. Working alongside Dr. Nakhjiri and Nicole Curtis-Brown, we developed a set of codes to determine the best Europa orbital trajectory by calculating how much radiation damage each trajectory accumulates and choosing the trajectory with the least amount of damage. This is done by first iterating a set of random Europa orbital trajectories, running the trajectories in a radiation model to collect flux values at each point in space, and input those values into the radiation code to determine the radiation damage for each studied trajectory.

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