

An investigation on polymers for shielding of cosmic radiation for lunar exploration

Belur Mohan Sankarshan¹ , Lingaraj Adarsh², Sannathammegowda Krishnaveni², Nagarajan Sowmya^{3,*} , Kulkarni Shrinivasrao⁴ and Holaly Chandrashekara Shastry Manjunatha^{3,5} 

¹Department of Physics, The National Institute of Engineering, Mysuru - 570008, India

²Department of Studies in Physics, University of Mysore, Manasagangothri, Mysuru 570 006, India

³Department of Physics, Government First Grade College, Chikkaballapur-562101, Karnataka, India

⁴Mynaric Lasercom GmbH, Dornierstrasse 19, 82205, Gilching, Germany

⁵Department of Physics, Government First Grade College, Devanahalli-562110, Karnataka, India

*Corresponding author: sowmyaprakash8@gmail.com

Abstract

In outer space, we find many types of radiations that are due to solar flares, radiation belt, cosmic rays, etc. We are fortunate enough to be protected from these radiations on the surface of the Earth, whereas in other celestial objects such as planets and satellites, without a protecting atmosphere, penetration of radiation that may be ionising or non-ionising is inevitable. Hence, studying radiation environment and its effect on such celestial objects is very important for establishing facilities such as satellites, payloads, vehicles and human exploration. For such cases, manufacturing the products with lightweight, thermally stable, flexible, mechanically durable materials is essential and needs to be studied for the radiation effect. Hence, in the present work, we have made an attempt to calculate the rate of absorbed dose in case of polymers such as Polyvinyl Chloride (PVC), polytetrafluoroethylene, Mylar, polystyrene and Zylon for the lunar radiation environment. From the literature, it is found that ions up to iron has a lion share in the ionic radiation in space. The simulations were carried out for ions from hydrogen to iron using the SRIM software with various energies. It is observed that the absorbed dose rate in the polymers increases with the increase in ion mass. Further, the study can be extended to get the information of various flexible materials for these ions from which a suitable material can be chosen for the different space applications.

Introduction

Cosmic rays consists of highly energetic particles, which originate in outer space and travels at the speed of light. They hit the Earth from all sides. Cosmic rays constitute mainly high-energy electrons, positrons, subatomic particles and nuclei of atoms ranging from hydrogen to the heavy elements of the periodic table. It has protons, helium and traces of heavier nuclei all the way up to uranium ⁽¹⁾. These energetic particles are due to space weather, which include galactic cosmic rays, micrometeoroid collisions, solar flares, solar winds and coronal mass ejection. Shock waves from coronal mass ejections and the solar flares can yield solar energetic particles that include electrons, protons and high-energy ions.

Exposure to these highly energetic particles can damage the control systems and solar cells of satellites in outer space and those traversing the planet's van

Allen belts. The shielding from these high-energy particles are naturally done by the Earth's magnetic field and atmosphere. The protons are the main constituent of the solar energetic particle spectrum, which comes out to be nearly 95%. These protons are charged and can ionise cellular components, kill cells at high exposure and cause damage to organs as well as DNA strands posing at most concern. Hence, there is a need to use suitable polymers for space applications ⁽²⁾. The first-ever measurements on the far side, the lunar surface of both charged and neutral particles, has been made by China's Chang E4 lander (LND) ^(3, 4). The LND experiment (The Lunar Lander Neutrons and Dosimetry) measured an average dose equivalent of 1369 $\mu\text{Sv/day}$ on the surface of the Moon, whereas the International Space Station with the DOSIS 3D DOSTEL instruments ⁽⁵⁾ was 731 $\mu\text{Sv/day}$.

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Polymers are used in space suits as they can reduce the impact of solar radiation by up to 50% compared to traditionally used products like aluminium. The high molecular weight and molecular entanglement of polymers lead to remarkable unique properties such as toughness, low density, high and low melting points and electrical resistance. These attributes of polymers make them useful in a broad range of spacecraft applications⁽⁶⁾. In ion irradiation of polymers, the fundamental processes involved are ionisation, electronic excitation, ionisation and chain scission leading to outgassing of small volatile degradation products that even leads to irreversible changes in material properties. In the literature, we find that ion track formation in polymeric solids have been studied for years, yet there is an incomplete understanding of the degradation mechanisms, for certain polymers⁽⁷⁾.

Earlier studies have shown applications of polymers in space^(8–13). Previous researchers thoroughly investigated the applications of ions such as oxygen to iron in the field of medicine to space^(14–20). Therefore, it is essential to understand the degradation mechanism in the polymers like PVC, polytetrafluoroethylene (PTFE), Mylar, polystyrene and Zylon. As the lion share in cosmic ionic radiation is from the elements from atomic number 1 to 26 in the present work, we have conducted simulations to find the stopping power for the ions from hydrogen to iron using the software SRIM 2013⁽²¹⁾.

Method

The ability of a material to slow down energetic particles that travel in its interior is given by the parameter stopping power. In general, stopping power is the amount of kinetic energy lost in relation to the thickness of material travelled for a given target material for a certain type of energetic particle. To understand and to predict the effects of particle radiation in matter, the energy deposited and ion ranges, damage produced by energetic particles information on stopping power is essential⁽²²⁾. The energy is transferred to electrons and to the nuclei of the target material from heavy ion projectile leading to excitation and ionisation of the target⁽²³⁾. These interactions are possible to be analysed using the SRIM software, which is a package concerning the stopping and range of ions in matter. It was introduced in 1985, and major upgrades are made about every 6 years⁽²¹⁾.

In this work, we have obtained stopping power by carrying out SRIM simulations of ions of the first 26 elements of the periodic table (H to Fe) for five polymers, namely, PTFE, Zylon, Mylar, PVC and polystyrene. The energy range was between 10 keV and 10 GeV. Chang E4 lander⁽³⁾ provides the measured

flux of the cosmic radiation over a period of time in the lunar atmosphere. We have taken the average of all the fluxes measured from 3 January 2019 to 12 January 2019 and from 31 January 2019 to 10 February 2019; the absorbed dose for the targets were calculated using the formula⁽²⁴⁾

$$D = \frac{\text{energy}}{\text{mass}} = \frac{\left(\frac{dE}{dx}\right) \times \Delta x \times N}{\rho \times A \times \Delta x} = \Phi \frac{S}{\rho}, \quad (1)$$

where $\frac{dE}{dx}$ is the linear-stopping power, Δx is the range, N is the number of particles/ions, A is the area of cross section, Φ is the fluence and $\frac{S}{\rho}$ is the mass stopping power.

Results and discussion

The investigation on the shielding of cosmic radiation has been carried out using different ions from hydrogen (H) to iron (Fe) on five different polymers, namely, polystyrene, Zylon, PTFE, Mylar and PVC, at various energies. The simulated values such as projected range and stopping power were investigated using SRIM. For instance, Figure 1 shows a plot of the projected range of Fe ions as a function of ion energy in different polymers. In all cases, it is observed that as ion energy increases, the projected range also gradually increases. It is also noticed that the projected range is maximum in case of Fe ions for PVC and smaller for the Zylon polymer. Further, we have plotted the stopping power of all ions from H to Fe in polystyrene and it is shown in Figure 2. The figure displays a maximum value for each ion and decreases with an increase in ion energy. The larger stopping power is observed for Fe and smaller in the case of H. Hence, the stopping power mainly depends on nucleons present in considered ions. A smaller number of nucleons results in smaller stopping power and vice versa. Similarly, the interaction of ions for different polymers were studied by considering stoichiometric ratios. For instance, we have considered the interaction of hydrogen atoms with different polymers such as Mylar, polystyrene, polytetrafluoroethylene (PTFE), PVC and Zylon. The stoichiometric ratios of all polymers and their compositions are tabulated in Table 1. The projected range of each ion at 1 MeV for different polymers is tabulated in Table 2.

Figure 3 depicts a plot of the absorbed dose of hydrogen with different polymers as a function of energy in keV. From the figure, it is inferred that the absorbed dose of hydrogen with different polymers reaches a maximum value when energy is 100 keV and again, the absorbed dose progressively reduces with an increase in energy. This trend is observed because of the stopping

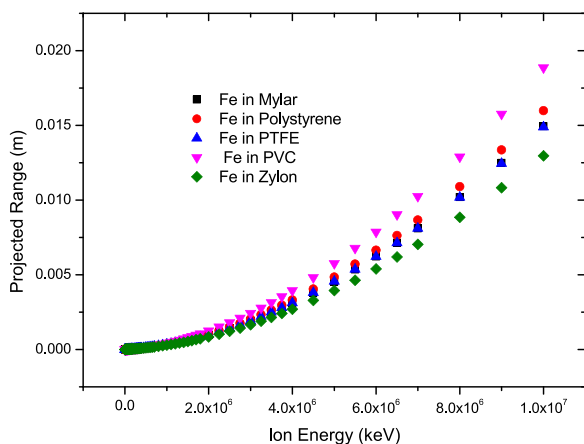


Figure 1. Projected range for the polymers of present interest as a function of ion energy in keV for Fe ions.

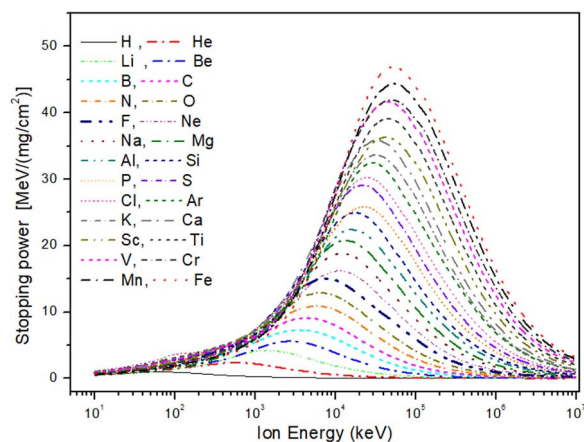


Figure 2. Stopping power for ions from H to Fe in polystyrene as a function of ion energy in keV.

Table 1. Tabulation of different polymers and their composition.

Sl. No.	Polymer	Composition
1	Mylar	$C_{10}H_8O_4$
2	Polystyrene	C_8H_8
3	PTFE	C_2F_4
4	PVC	C_2H_3Cl
5	Zylon	$C_{14}H_6O_2N_2$

power of the material for a particular ion. Amongst all the studied hydrogen interactions with different polymers, it is noticed that hydrogen interaction with polystyrene is found to be maximum.

In addition, we investigated the interaction of He and oxygen ions with different polymers and it is represented in Figures 4 and 5. The figures show an increase in the absorption dose with progress in energy. Further, by reaching the maximum value again, it attains a

Table 2. Projected range for the polymers of the present.

Ions	Ion (Z)	Projected range (in μm) at 1 MeV [4]				
		Mylar	Polystyrene	PTFE	PVC	Zylon
H	1	17.69	20.63	22.96	27.89	17.69
He	2	3.86	4.38	5.64	5.94	3.86
Li	3	3.08	3.48	4.74	4.69	3.08
Be	4	2.72	3.09	4.18	4.76	2.72
B	5	2.08	2.35	3.25	3.69	2.08
C	6	1.86	2.10	2.91	3.31	1.86
N	7	1.71	1.94	2.71	3.07	1.71
O	8	1.73	1.96	2.74	3.10	1.73
F	9	1.62	1.84	2.59	2.91	1.62
Ne	10	1.64	1.98	2.60	2.92	1.64
Na	11	2.06	1.96	2.75	3.08	1.74
Mg	12	2.04	1.78	2.69	3.02	1.72
Al	13	1.86	1.47	2.46	2.75	1.57
Si	14	1.55	1.42	2.06	2.31	1.30
P	15	1.49	1.42	1.97	2.22	1.25
S	16	1.43	1.37	1.89	2.13	1.20
Cl	17	1.35	1.29	1.78	2.01	1.13
Ar	18	1.28	1.23	1.68	1.91	1.08
K	19	1.26	1.21	1.64	1.87	1.06
Ca	20	1.24	1.19	1.60	1.82	1.05
Sc	21	1.21	1.16	1.54	1.77	1.02
Ti	22	1.19	1.15	1.51	1.74	1.00
V	23	1.15	1.11	1.45	1.68	0.97
Cr	24	1.20	1.16	1.49	1.73	1.01
Mn	25	1.21	1.18	1.47	1.89	1.02
Fe	26	1.20	1.18	1.45	1.71	1.02

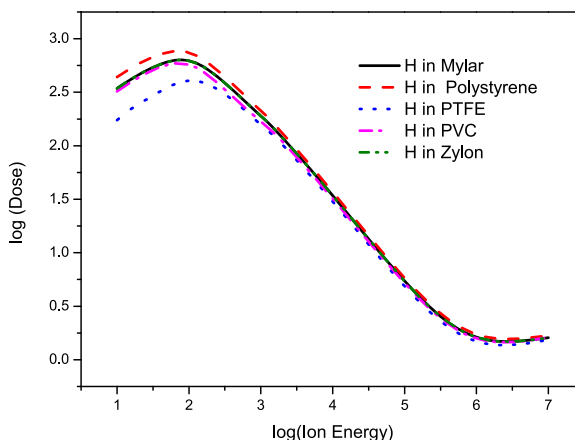


Figure 3. A plot of absorbed dose of hydrogen with different polymers such as Mylar, polystyrene, PTFE, PVC and Zylon as a function of the logarithm of ion energy in keV.

minimum value with an increase in energy. The maximum value of absorption is observed when energy is ~ 10 MeV for oxygen with different polymers. The larger absorption of He and oxygen with polystyrene

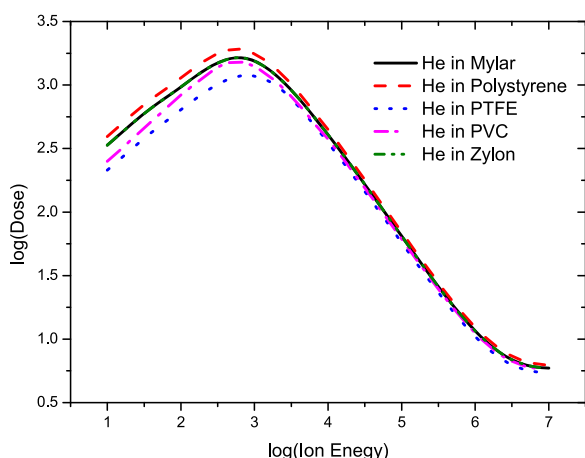


Figure 4. A plot of absorbed dose of helium ions with different polymers such as Mylar, polystyrene, PTFE, PVC and Zylon as a function of the logarithm of ion energy in keV.

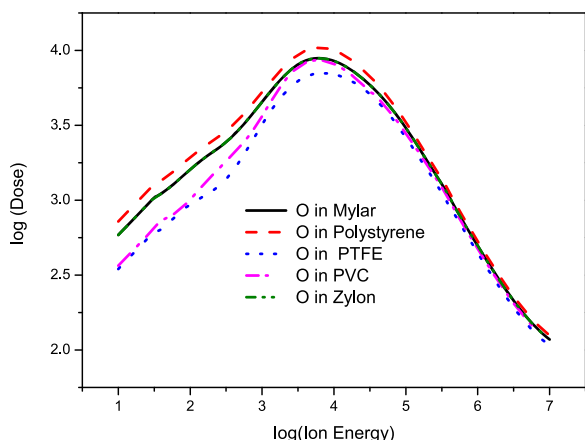


Figure 5. A plot of absorbed dose of oxygen with different polymers such as Mylar, polystyrene, PTFE, PVC and Zylon as a function of the logarithm of ion energy in keV.

is found to be more when compared to other studied polymers.

Also, we looked at how argon interacts with various polymers. This is shown in Figure 6. The figure demonstrates an increase in absorption dosage as energy progresses. By achieving the maximum value of the absorption dose, again, it achieves a low value with increase in energy. When the energy for argon with different polymers is ~ 32 MeV, the maximum value of absorption is seen. When compared to other investigated polymers, polystyrene exhibits greater oxygen absorption.

Furthermore, we explored calcium and iron absorbed dose with different polymers such as Mylar, polystyrene, PTFE, PVC and Zylon. Figures 7 and 8 show a plot of

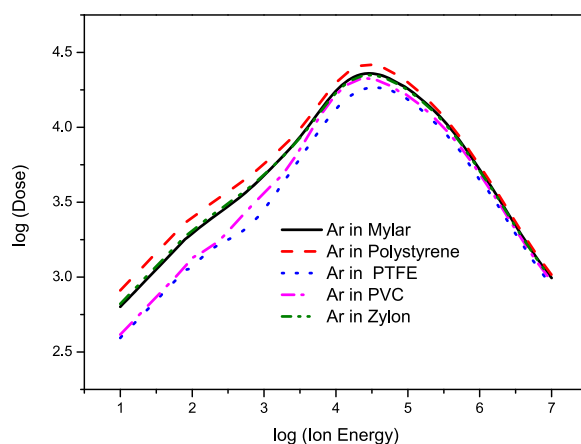


Figure 6. A plot of absorbed dose of argon with different polymers such as Mylar, polystyrene, PTFE, PVC and Zylon as a function of the logarithm of ion energy in keV.

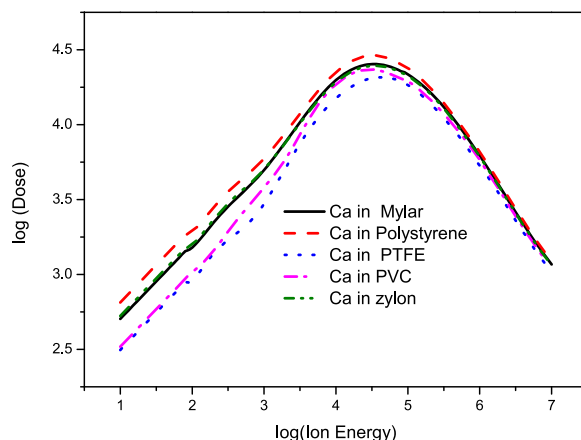


Figure 7. A plot of the absorbed dose of calcium with different polymers such as Mylar, polystyrene, PTFE, PVC and Zylon as a function of the logarithm of ion energy in keV.

the absorbed dose of calcium and iron with different polymers as function of ion energy. In both cases, it is noticed that the larger value of absorption is observed when energy is ~ 32 and 50 MeV, respectively.

Here, we also noticed a larger absorption dose when calcium and iron interact with polystyrene. From the detailed investigations of the absorbed dose of hydrogen, oxygen, argon, iron, calcium and iron with different polymers, it is observed that a larger absorption dose is observed in the case of polystyrene. Polystyrene is a polymer that contains carbon and hydrogen only, i.e. C_8H_8 , whereas in all other polymers, at least one atom with a higher atomic number is chosen. Hence, the absorption rates are maximum in polystyrene. Similar results were also observed for all the atomic numbers that were present in between these studied nuclei.

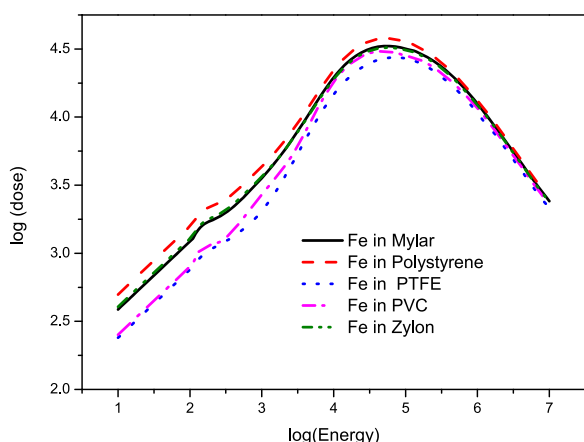


Figure 8. A plot of the absorbed dose of iron with different polymers such as Mylar, polystyrene, PTFE, PVC and Zylon as a function of the logarithm of ion energy in keV.

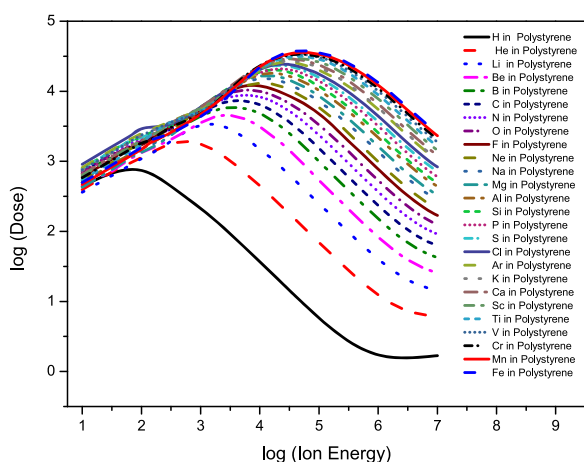


Figure 9. Comparison of the absorbed dose of hydrogen to iron with polystyrene as a function of the logarithm of ion energy in keV.

Hence, we made an effort to compare ions of hydrogen to iron absorption rates in polystyrene. Figure 9 shows a comparison between the absorption dose of different ions with the energy. It is observed that the energy at which the maximum dose is observed increases along with the increase in the mass of the ion. Moreover, the dose for a particular energy is also found to vary with the mass of the ion and increase with increase in the mass of the ion. In all these studied cases, it is observed that larger energy is varied between 50 and 100 MeV. Amongst all these studied ions, iron possesses a larger absorption dose for the polystyrene.

Conclusions

We have carried out ion irradiation studies from hydrogen to iron on the polymers such as polystyrene, Zylon,

PTFE, Mylar and PVC using the SRIM software. It was observed that polystyrene shows the maximum absorption dose compared to other polymers studied such as PVC, Zylon, Mylar and PTFE. Further, ion irradiation from H to Fe on polystyrene was carried out using SRIM. As the atomic number of ions increases, the maximum stopping power or dose is observed to be increased. It is observed that the dose of the polystyrene polymer is higher for all the ionic radiations (H to Fe). The interaction of the polymers with various ions need to be further studied along with various densities for the polymers, which is in progress.

Data availability

Data is available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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