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A5_7 Neutron activation of the Unity Node of the ISS

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Abstract

The paper describes the calculation of the annual radiation dose of an astronaut on the ISS from gamma rays created by solar neutron activation of the aluminium structure of the Unity Node. It is calculated that the annual dose is 2.32 x 10^{-5} mSv, and the solar neutron flux required to reach the maximum legal annual dose is 828 neutrons cm^{-3} s^{-1}. The results show that the annual neutron activation gamma ray dose is very small compared to the legal limit (some six orders of magnitude smaller).

Introduction

Unity was the second component added to the International Space Station (ISS), having been connected to the Zarya module on 6th December 1998. It is an aluminium connecting module that is 5.5 m long and 4.3 m in diameter [1][2].

When a neutron is captured by Aluminium-27 there are a number of reactions that result in the emission of gamma rays as the new nuclei de-excite [3]. This, coupled with the flux of neutrons at the Earth's position in space, suggests that there should be a flux of gamma radiation emitted from the body of the Unity Node. Without shielding this radiation would be detrimental to the health of the crew of the ISS and the purpose of this paper is to estimate the radiation dose they would receive over the course of a year in space.

Theory

The UK limit of radiation dose for employees of 18 years of age or above is 20 mSv (milli-sieverts) [4]. The sievert describes the effective damage caused by absorption of radiation by the human body and is equal to the absorbed dose (measured in grays) multiplied by a radiation weighting factor (which is dimensionless). For gamma rays the weighting factor is 1 so 1 gray of absorbed radiation corresponds to 1 sievert.

The dose absorbed, D, in time, t, by an object with an energy absorption coefficient, μ, and a mass density, ρ_o, from a beam of EM radiation with photon energy, E_γ, and flux, φ_γ, is [5]:

$$D = \frac{\varphi_\gamma \mu E_\gamma t}{\rho_o} . \qquad (1)$$

The gamma ray flux can be calculated using:

$$\varphi_\gamma = \frac{N}{4\pi r^2} , \qquad (2)$$

where N is the number of gamma rays emitted from the source and r is the distance between the object and the source.

The number of gamma rays emitted from neutron capture reactions is:

$$N = \frac{4}{3} \varphi_n \sigma n_{Al} V , \qquad (3)$$

where φ_n is the neutron flux, σ is the reaction cross section, n_{Al} is the number density of atoms in the neutron target (aluminium), and V is the volume of the target. The factor 4/3 is present as one of the reactions emits two gamma rays and so the mean number of photons produced per reaction is greater than one (see last paragraph of this section).

We model the target (the Unity Node) as a cylinder for simplicity so the volume of its aluminium structure is

$$V = \pi L w (2r - w) , \qquad (4)$$

where V, L, w, and r are the volume, length, wall thickness, and radius of the target respectively.

Combining equations (1), (2), (3), and (4):

$$D = \frac{\varphi_n \sigma n_{Al} L w (2r - w) \mu E_\gamma t}{3 r^2 \rho_o} . \qquad (5)$$

For the purposes of this paper, four neutron capture reactions were considered: $^{27}Al(n,\gamma)^{28}Al$ (hereafter referred to as reaction A), $^{27}Al(n,\alpha)^{24}Na$ (reaction B), $^{27}Al(n,p)^{27}Mg$ (reaction C), and $^{27}Al(n,2n)^{26}Al$ (reaction D). These reactions emit gamma rays of energies 1.778 MeV, 2.754 & 1.368 MeV, 0.843 MeV, and 1.808 MeV respectively. There are some transitions that produce photons of different frequencies with different probabilities and so, for simplicity, we have chosen the most probable emitted photon for each.

The cross sections, σ, of the reactions vary depending on the energy of the incident neutrons and so, since solar neutrons peak in intensity between 30 and 40 MeV [6], the values of σ were taken at approximately 35 MeV (using data from the International Network of Nuclear Reaction Data Centres' EXFOR database [7]). The sum of these values was taken to find the total cross section of the neutron capture reactions. The component cross sections used are 0 barns, 0.002 barns, 0.0078 barns, and 0.022 barns for reactions A, B, C, and D respectively. This gives a total cross section of 0.0318 barns.

The cross section of reaction A is high for thermal neutrons but quickly decreases. Because of a lack of data in the region 30-40 MeV, and the fact that the cross sections for other energies of fast neutron were very low, reaction A was not included in the calculations.

For the purposes of evaluating equation (5), the average photon energy was calculated. Reaction B results in the emission of two gamma rays of energies 2.754 and 1.368 MeV. Reactions C and D emit gamma rays of energies 0.843 and 1.808 MeV respectively [3]. These energies were summed taking into account the contribution of their source reactions to the total cross section, giving an average photon energy of 1.587 MeV.

Results and Conclusions

The dose of radiation received due only to gamma radiation from the neutron activation of aluminium was calculated using equation (5). This was done assuming that:

- the only neutron capture reactions occurring are reactions B, C, and D
- only the most probable photon is emitted when there is a possibility of other transitions in the excited nuclei
- neither the neutrons nor the gamma rays interact with any part of the Unity Node other than the aluminium structure (i.e. they do not interact with any of the other wall materials)
- the absorber of the gamma rays is positioned in the centre of the Unity Node.

The following values were used: $\varphi_n = 9.6 \times 10^{-4}$ neutrons cm^{-2} s^{-1} [8], $\sigma = 0.0318$ b, $n_{Al} = 6.03 \times 10^{28}$ m^{-3}, $L = 5.5$ m, $w = 3$ mm [9] (the wall thickness in Unity is assumed to be the same as in the ESA's ATV), $r = 2.15$ m, $\mu = 3.074$ [5], $E_\gamma = 1.587$ MeV, $t = 1$ year, and $\rho_o = 1000$ kg m^{-3} (approximating human soft tissue density as that of water).

These values result in a calculated dose of 2.32×10^{-5} mSv over the course of a year of constant exposure to the gamma radiation. This value will scale linearly with neutron flux. It is also worth noting that this calculation is only for the Unity Node. The whole ISS would have a larger aluminium volume and this would increase the dose. However, given the size of the ISS, it is unlikely that it would increase it to a significant value given that the calculated dose is six orders of magnitude smaller than the maximum legal annual dose. To reach this dose (20 mSv) in the examined circumstance, a flux of 828 neutrons cm^{-2} s^{-1} would be required.

References

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