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Approximating Shielding Effects on Galactic Cosmic Radiation Effective Dose Rate Calculations During Extreme Altitude and Sub-Orbital Flights Using CARI-7/7A

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16. Abstract

The dominant source of ionizing radiation in the aerospace environment is galactic cosmic radiation (GCR). Traditionally, calculations of exposure rates for vehicle occupants in aircraft have not included vehicle structure; while in spacecraft, vehicle structure is considered without atmosphere. This report describes modifications applicable to CARI-7 and CARI-7A to allow inclusion of the effects of vehicle structure on calculations of effective dose rate from GCR throughout a suborbital mission in a lightly shielded vehicle (<20 g/cm2). Required coefficients and an example of the technique are provided for aluminum shielding. While results are considerably different than if shielding were entirely neglected, they vary by less than 8% from the simple approximation of 1:1 substitution of additional atmospheric depth for aluminum.

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1. INTRODUCTION

The dominant source of ionizing radiation in the aerospace environment is galactic cosmic radiation (GCR). Unshielded effective dose rates from GCR have been calculated to be as high as several tens of microsieverts per hour during solar minimum. The dose to vehicle occupants from GCR can be reduced by radiation shielding. However, for aircraft and spacecraft, mass must be kept as low as possible; every kilogram of radiation shielding is one less kilogram of payload or fuel. Historically, aircraft and suborbital spacecraft have most often been constructed as lightly as possible for the expected structural loads and primarily from aluminum-based alloys. This is because of their high strength-to-weight ratios and relatively low cost when compared to other light but high-strength materials such as carbon fiber composites or metals such as titanium.

Because the primary exposure source is galactic cosmic radiation (GCR) and GCR dose rates are low, long-term health effects are the primary concern for crew and passengers. Exposure rates are altitude and latitude dependent (see Friedberg and Copeland [2011] for examples), and it is impractical for commercial aircraft to carry the extra mass of shielding, so dose minimization strategies such as “as low as reasonably achievable” (known as the ALARA principle in health physics and industrial hygiene) are used by individuals and companies to control radiation exposures.

The most important factors when shielding from GCR ions are the atomic mass and the thickness of the shielding. GCR heavy ions are extremely ionizing, and create large nuclear fragments, protons, neutrons, and other secondary GCR radiations as they break up in nuclear collisions with the atoms in the air and vehicle. High energy particles of any type take longer to stop and can liberate more nuclear secondary radiations from air and vehicle atoms than low energy particles of the same sort. Larger atoms in shields provide more opportunity to produce additional neutrons and protons in nuclear collisions.

With enough thickness, shields eventually stop all but the most penetrating of radiations, but effectiveness of any given material at dose reduction varies depending on the particular incident radiation. Shielding effectiveness depends on the local incident radiation spectrum, which for GCR primarily depends on altitude (i.e., the amount of atmosphere the GCR needs to traverse before interacting with the shield) and geomagnetic screening (not all GCR is allowed into the atmosphere, some is turned away by Earth’s magnetosphere). The GCR spectrum changes considerably with respect to altitude, both in the type and the energy distribution of the particles, as it enters and interacts with the atmosphere [Copeland, 2014]. On a commercial airliner, the skin of the fuselage is usually a few millimeters thick (at most) and affords occupants less than 0.5 g/cm^2 of aluminum (Al) as shielding. At commercial aviation altitudes, which typically have more than 190 g/cm^2 of atmosphere above the aircraft (i.e., below 40,000 feet), this is not much additional shielding.

However, combining vehicle structural elements and contents (other passengers, interior finish, overhead luggage, fuel storage, etc.) on a commercial jet (Airbus 340) was calculated to reduce the effective dose rate to the ideally situated passenger by as much as 14% at cruise altitude, if the aircraft were fully loaded [Battistoni et al., 2005]. For the cockpit, the average reduction was about 5% (7.1-7.2

μSv/h instead of 7.5 μSv/h). In the cabin, the most reduction in effective dose was in the middle seating section on centerline (6.4-7.3 μSv/h) and the least reduction was in the corridors between the seats (6.7-7.5 μSv/h). Because of the small reductions and variations based on location at locations the aircrew would frequent (corridors and cockpit), the authors recommended continuation of the practice of ignoring aircraft structure for aircrew dose monitoring (but suggested it was important to consider when taking measurements).

In-flight dose rate calculations for aircraft routes traditionally ignore the effects of vehicle structure and contents because direct inclusion of structure and contents, even in approximate ways, can add greatly to the calculation complexity. For space missions, because of the high cost of the mission and limited possibility of hardware maintenance after launch, vehicle calculations of dose rate inside the vehicle are traditionally performed on an *ad hoc* basis for the specific vehicle using computer files describing the spacecraft structure to below millimeter scales and the specific expected radiation environment for the mission under consideration. A set of tools for this sort of calculation for space missions called OLTARIS is available from a NASA website [Sandridge, 2014]. There are also several commercial software packages available. This report describes a method that can be used with the December 2016 releases of CARI-7 and CARI-7A (or any program that calculates effective dose and/or dose rate from GCR) to approximately incorporate vehicle structure into effective dose calculations, as well as ongoing modifications to CARI-7A to allow more accurate calculations incorporating vehicle structure and contents, as described in DOT/FAA/AM-16/8 [Copeland, 2016].

2. METHODS

Results from prior NASA studies of radiation shielding effectiveness using HZETRN [Wilson et al., 1991;1995], a transport code designed by NASA researchers and used primarily for spacecraft radiation analysis [Kim et al., 1994; Cucinotta et al., 2012], form the basis of the shielding inclusion modifications added to CARI-7A (also applicable to CARI-7). For extremely thin shields (>5 g/cm^2), some materials actually increased the dose equivalent (often used as a surrogate for effective dose, which was not studied) behind them because of secondary neutron buildup. The problem worsened as average atomic mass was increased because it provided more nuclear matter to eject in nuclear collisions. While an electron plasma of extreme density was found to theoretically to be the best shield for GCR (no nuclei to generate neutrons, lots of charged particles for electronic stopping), pure liquid hydrogen is considered the best currently achievable choice. However, because of the low density of liquid hydrogen, this solution is usually impractical. Using current technologies, polyethylene, with its relatively high hydrogen content and low average atomic mass, is the material of choice for spacecraft occupant radiation shields, while aluminum remains the most common structural material. The studies suggested ~1:1 equivalence after penetration of considerable depth.

Thus, for this modification to CARI-7A, the material's depth, H_{shield}, in units of g/cm^2 is added to the length of each atmospheric shower depth, H_{atm}, before evaluation of the dose. The total adjusted dose, D_{adj}, is also modified by the effectiveness of adding the material relative to the effectiveness of adding more air of depth H_{shield} at the depth of atmosphere the shower must penetrate before entering the craft, $K_{craft}(H_{atm,} H_{shield})$, as shown in eq. 1,

$$D_{adj}(H_{atm}, H_{shield}) = D_{atm}(H_{atm} + H_{shield}) \cdot [K_{shield}(H_{atm,} H_{shield})] \quad (1)$$

where $D_{atm}(H_{atm} + H_{shield})$ is the dose from a GCR shower in the atmosphere at depth ($H_{tot} = H_{atm} + H_{shield}$), treating the shielding as added air. The K values for aluminum depths of 0-20 g/cm^2, based on OLTARIS calculations for the 1997 solar minimum are shown in Figure 1 [Sandridge, 2014]. Values of K for depths of aluminum up to 20 g/cm^2 and total depths up to 50 g/cm^2, based on the parabolic fits shown in Fig. 1, are given by equation 2,

$$K = K_o + aH_{tot} + bH_{tot}^2, \tag{2}$$

where K_o, a, and b are parabolic functions of H_{shield} (with coefficients $C0$, $C1$, and $C2$, respectively). Table 1 shows values of K_o, a, and b for aluminum. For calculation at depths beyond 50 g/cm^2, the coefficient values at 50 g/cm^2 are used.

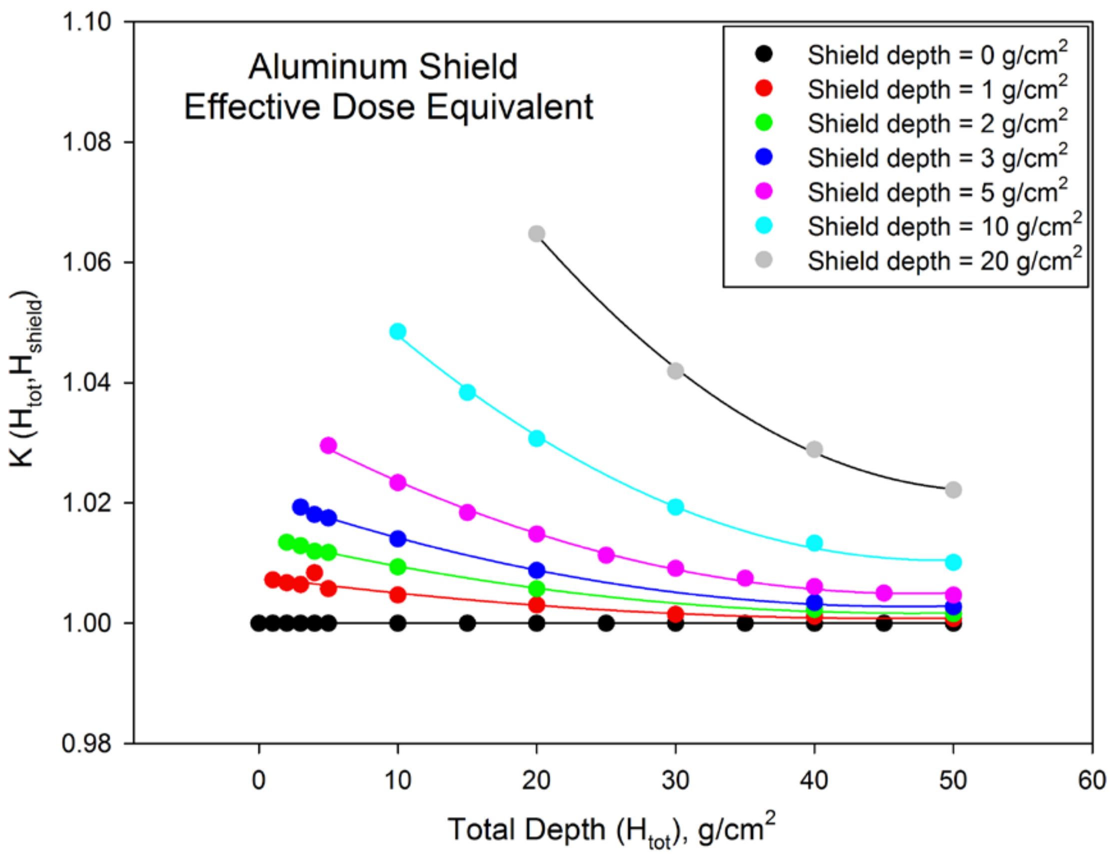

Figure 1. Effective dose correction coefficients K for aluminum, calculated with the NASA tool OLTARIS (curves are parabolic fits to the data).

Table 1. Coefficients for calculation of parameters K_o, *a,* and *b* in equation 2 for effective dose corrections from aluminum shielding calculated with OLTARIS.

Parameter	*C0*	*C1*	*C2*
K_o	1.0012	6.644E-03	0.0
a	-1.457E-05	-2.675E-04	2.846E-06
b	1.914E-07	2.897E-06	-4.383E-08

OLTARIS requires user-defined materials and shielding specifications. The data shown above were generated using the following options: Shielding from 2-layer spherical shields of 0-50 g/cm^2 of dry air at sea level [International Commission on Radiation Units and Measurements, 1993] and 0-20 g/cm^2 of aluminum totaling up to 70 g/cm^2; GCR flux from the Badhwar and O'Neill 2010 GCR model [O'Neill, 2010] for the 1997 solar minimum at a distance of 1 earth orbit average radius from the Sun (1 a.u.), but away from the shielding effects of the Earth; and calculation of effective dose equivalent (the most analogous calculation to effective dose available in OLTARIS).

3. RESULTS

Percent reductions from the added aluminum are given in Table 2. Figure 2 shows results of calculations of effective dose at atmospheric depths of 1 to 50 g/cm^2 (68000 to 155000 ft., 21 to 47 km), the region a stratospheric pressurized balloon flight would ascend into. Results are reported for the following conditions: atmosphere shielding only, treating aluminum as an equal depth in air, and using the correction scheme described above, for a vehicle with 1, 5, 10 and 20 g/cm2 of aluminum shielding the occupants.

Table 2. Relation between percent reduction in effective dose, shielding depth, and atmospheric depth for aluminum shields.

Atmospheric Depth, g/cm^2	Percent reduction from 1 g/cm^2 Al	Percent reduction from 5 g/cm^2 Al	Percent reduction from 10 g/cm^2 Al	Percent reduction from 20 g/cm^2 Al
1	11	34	48	62
5	5.6	22	35	51
10	4.0	16	28	43
20	2.5	11	21	34
30	1.9	8.7	16	28
40	1.7	7.9	14	24
50	1.3	6.2	11	21

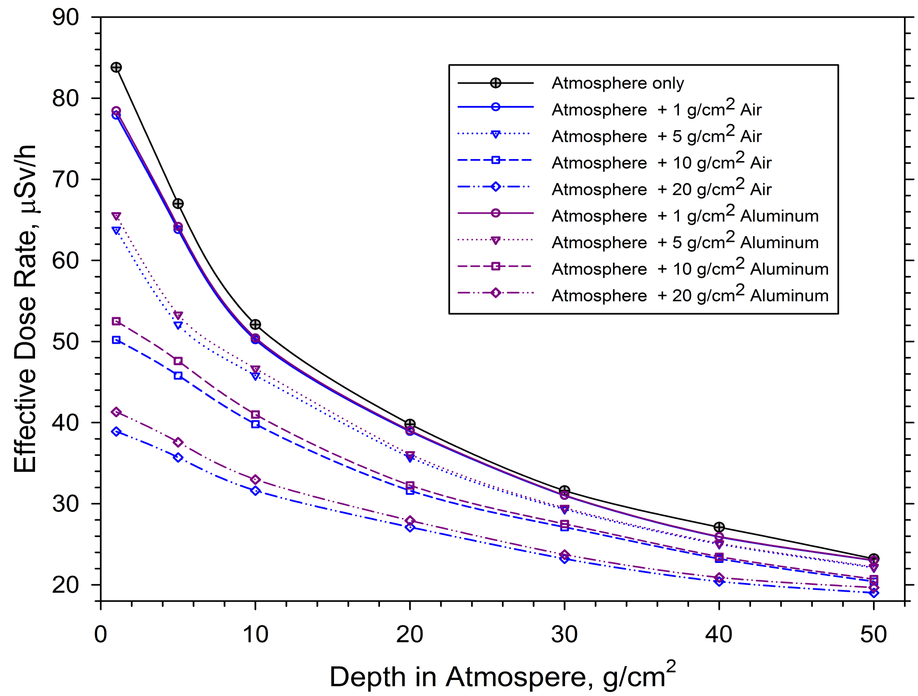

Figure 2. Effective dose rates at selected altitudes calculated with no shielding, with aluminum replaced by an equal depth of air, and using the correction scheme described above, for vehicles with 1, 5, 10 and 20 g/cm^2 of aluminum shielding the occupants.

4. DISCUSSION

As expected, the calculations indicate that more shielding results in more dose reduction, but that the effectiveness of the shielding lessens as depth increases (i.e. lower altitudes). Also, results suggest that with respect to effective dose inside craft that provide shielding of consistently less than 20 g/cm^2, replacing aluminum with additional atmosphere to model vehicle induced shielding is a very good approximation at even the highest altitude studied and improves at lower altitudes. The difference between this approximation and using OLTARIS to calculate a correction was always less than 8% and less than 4% for total depths greater than 50 g/cm2 (altitudes below 68000 ft (21km)).

The technique described above can easily be used with any material, since OLTARIS is a very flexible tool, by repeating the calculations of the coefficients for materials other than aluminum and to dose equivalent (which the previous NASA studies indicated is more sensitive to material selection). For calculations in the atmosphere, the data can be used to approximately include effects of structure in the calculations. If no atmosphere is present, the data may be used directly for shielding effect estimates. As a next step, including directionality to the calculations would allow for more accurate definition of vehicle shielding profiles and is planned as a modification of CARI-7A.

Both MCNPX 2.7.0 [Radiation Safety Information Computational Center, 2011] and its successor MCNP6 include more complete physics models than the HZETRN transport software used by OLTARIS (e.g., it has no muon transport) [Wilson et al., 1991;1995]. Although not enough simulations have been run as of this writing, as high performance computing (HPC) calculated Monte Carlo data become sufficient, the database described in Copeland [2016] will be used to enable a multi-step dose evaluation based on MCNP6 and/or MCNPX results.

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