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Data for Rapid Evaluation of Vehicle Structure Related Radiation Shielding of Occupants of Extreme-Altitude Aircraft and Spacecraft

Kyle Copeland

Civil Aerospace Medical Institute
Federal Aviation Administration
Oklahoma City, OK 73125

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Final Report

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16. Abstract

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. The dominant source of ionizing radiation in the aerospace environment is galactic cosmic radiation (GCR). Unshielded effective dose rates from GCR are calculated to be as high as several tens of microsieverts per hour. Typical aircraft skin affords occupants less than 1 g/cm2 of Al as shielding. Added shielding of persons is a secondary concern because of limits on vehicle mass. Electronics are typically lightly shielded and redundant so as to avert critical failures or prolonged loss of use. Currently, in-flight dose rate calculations, such as those done by CARI-6 and CARI-7, ignore effects of vehicle structure and contents, as inclusion of such has been shown to increase accuracy by less than 10%, even at SST altitudes, while adding greatly to the calculation complexity by forcing each calculation to be ad hoc (i.e., such calculations typically add considerable complexity to the overall calculations for almost no benefit). However, in suborbital and extreme high-altitude flight, where atmospheric shielding is thin or absent, vehicle shielding can be considerably more important.

This report describes the construction of a database of secondary particle spectra resulting from irradiation of common aerospace materials of varying thicknesses with typical cosmic rays of varying energy. Examples are given for secondary particle spectra resulting from irradiation of aluminum (Al) and polyethylene (PE). These materials are commonly used as structural (Al) and/or shielding (Al and PE) materials for occupants of aircraft and spacecraft. The secondary spectra are calculated using Monte Carlo radiation transport program MCNPX 2.7.0 inside shells with of up to 100 cm thicknesses. The database of materials response matrices will enable programs like CARI and ESRAS to incorporate vehicle shielding of occupants in dose calculations, extending their usefulness to the space environment, where primary shielding of occupants comes from the vehicle.

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Contents

DATA FOR RAPID EVALUATION OF VEHICLE STRUCTURE RELATED RADIATION SHIELDING OF OCCUPANTS OF EXTREME-ALTITUDE AIRCRAFT AND SPACECRAFT

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1. INTRODUCTION

In the U.S., protection of commercial passengers and crew from ionizing radiation is the responsibility of the company operating the aircraft or spacecraft. Ionizing radiation is a threat to both vehicle systems and vehicle occupants. However, because vehicle weight is limited by available thrust, radiation shielding in aircraft and spacecraft must be as light as possible. While important, long-term biological radiation effects such as carcinoma, leukemia, and heart disease do not result in immediate risk to crew or passengers, thus are not considered of primary importance. Radiation protection is focused on the more immediate risk, in-flight device failure, which could lead to the vehicle and its occupants being in immediate mortal danger. Protective strategies for devices include device design, device shielding, and redundancy, all with the goal of minimal added vehicle mass. Protection of persons is usually by means of adopting exposure limits and tracking total career exposure.

During flight under all but the most unusual circumstances, only a conceptus in early pregnancy is in immediate mortal danger from direct effects of ionizing radiation. Once the cell population is sufficiently high, the danger to the unborn and to adult and child vehicle occupants from ionizing radiation arises mostly from stochastic effects. Because the primary exposure source is galactic cosmic radiation (GCR) and dose rates are typically below threshold for deterministic effects (e.g., radiation sickness), long term health effects are the primary concern for crew and any passengers, and the most common strategy used by companies to control radiation exposure of crewmembers is to limit exposure time. For more extensive background information on in-flight radiation exposure and the biologic effect of low doses of ionizing radiation, see Friedberg and Copeland [2011].

For space missions, calculations of dose rate inside the vehicle are traditionally performed on an ad hoc basis for the specific vehicle using a 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]. For aircraft flights, software such as the FAA CARI-6 program is used to calculate in-flight doses, but it and similar programs neglect vehicle structure because it has been shown to have minimal effect on doses at commercial cruise altitudes [O'Brien et al, 2003]. This report describes the calculation of a database of materials response functions that can be used to extend CARI-7 flight dose calculations more accurately into regions where vehicle shielding of occupants is an important consideration.

2. METHODS

Monte Carlo radiation transport program MCNPX 2.7.0 (Monte Carlo N-Particle eXtreme) developed at Los Alamos National Laboratory and distributed by the Radiation Safety and Information Computing Center (RSICC) was used to generate secondary particle spectra (Tallied particles were neutrons, pions, protons, photons, muons, electrons, deuterons, tritons, helions, alphas, and heavier atomic fragments up to iron.) inside spherical shells of polyethylene and aluminum resulting from isotropic irradiation of mono-energetic particles [Pelowitz, 2011; RSICC, 2011]. Thickness of shielding ranged from 0.1 cm to 100 cm. Ion kinetic energy ranged from 1 MeV to 100 GeV.

Secondary particle fluence spectra can be converted to various endpoints by the user: effective dose, effective dose equivalent, ambient dose equivalent, absorbed dose in silicon, etc., by means of fluence-to-dose conversion factors such as those published by Pelliccioni [2000] and Sato et al. [2009,2010].

Figure 1 shows the irradiation geometry. Primary particles leave the outer surface, radius 501 cm, directed inward isotropically. They then interact with the shield producing secondary radiation. Secondary radiation that exits the shield in the inner sphere can interact again as it tries to leave the sphere. Tallies of the flux are made at the center of the sphere (neutrons and photons only, due to limitations in MCNPX), just inside the sphere, and just outside the sphere.

3. RESULTS

Figures 2 and 3 show calculated spectra for selected secondary particles under various conditions. Data in each figure are normalized such that the spectra are per incident proton leaving the source surface. Error bars, where visible, represent one standard deviation. Figure 2 shows neutron and photon spectra inside a 10 cm thick polyethylene (specific gravity 0.93) spherical shell irradiated isotropically with 10 GeV protons. Figure 3 shows neutron flux spectra inside 0.1 cm, 0.4 cm, and 5 cm thick Aluminum (specific gravity 2.2) spherical shells irradiated isotropically with 1 GeV protons. The well-known phenomenon of increasing neutron flux with increasing shell thickness for thin layers, leading to increasing dose per incident proton as shielding is added, is evident.

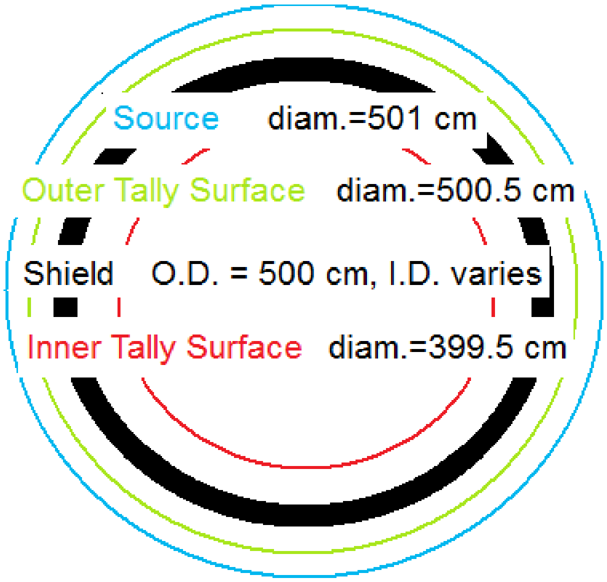

Figure 1. Irradiation and tally geometry. Radiation leaves the source sphere headed isotropically inward, interacts with the shield, and is tallied inside and outside the shield.

4. DISCUSSION

The database described here is being calculated to enable a multi-step dose evaluation process. As an example, for calculations inside the atmosphere, the data can be used to approximate effects of spacecraft shielding since they provide the information needed to convert the secondary cosmic ray spectrum outside the vehicle to a spectrum inside the vehicle, without the need for repeating the Monte Carlo radiation transport calculations. If no atmosphere is present, the data may be used directly for simple shielding effects estimates or in combination for more estimates of the effects of more complex shielding configurations.

The advantage of this database is that unlike previous published data of this sort, which provide the dose behind various depths of monolithic shielding for a given named input spectrum (e.g. GCR at solar min or missions to Mars cumulative dose), these data can be used to rapidly calculate the approximate dose behind arbitrary shielding, if certain approximations are acceptable, for any input spectrum within the bounds of the database. As the number of primary particles, shielding ma-

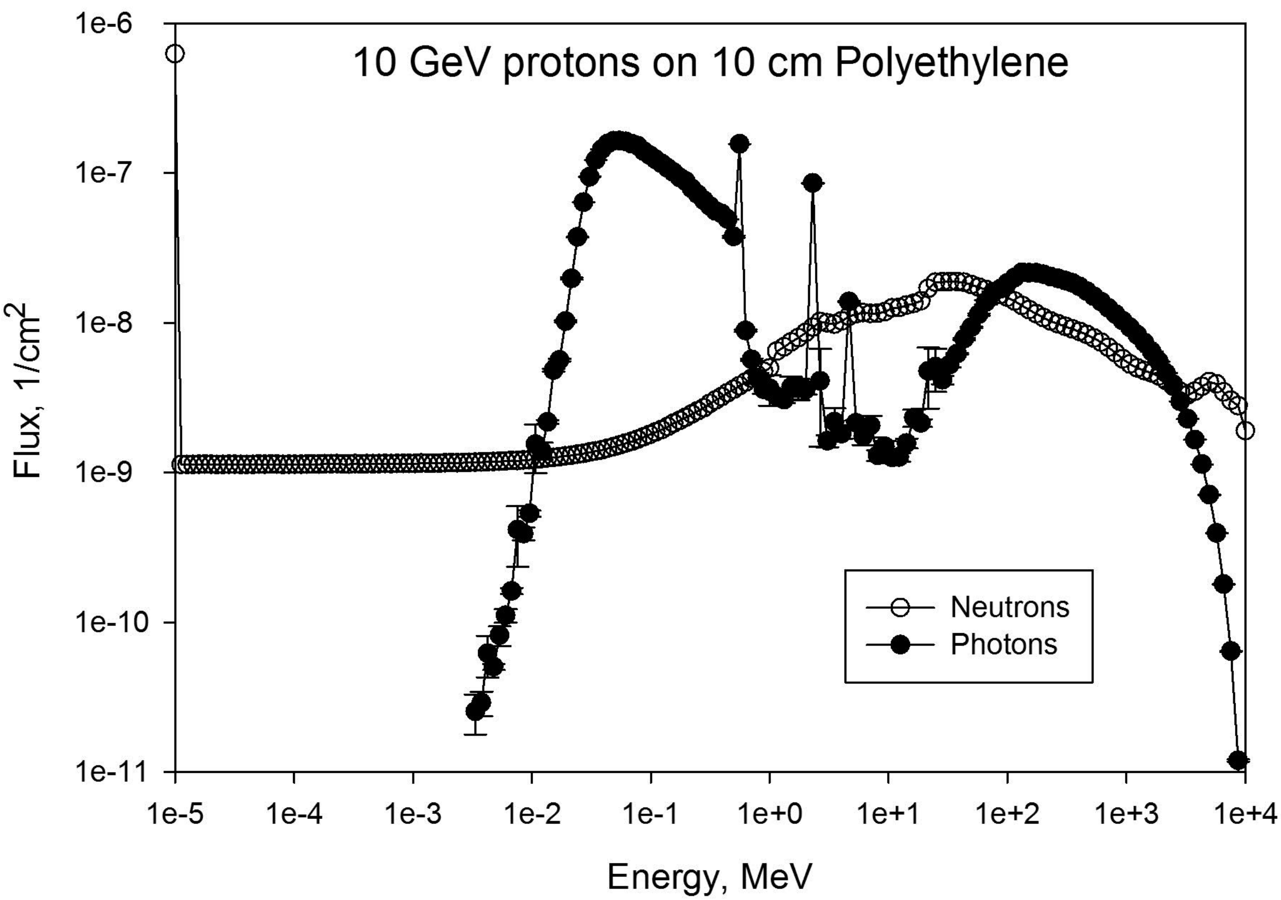

Figure 2. Neutron and photon spectra inside a 10 cm thick polyethylene sphere irradiated isotropically with 10 GeV protons. Data are normalized such that the spectra are per incident proton leaving the source surface (see Figure 1). Error bars represent one standard deviation.

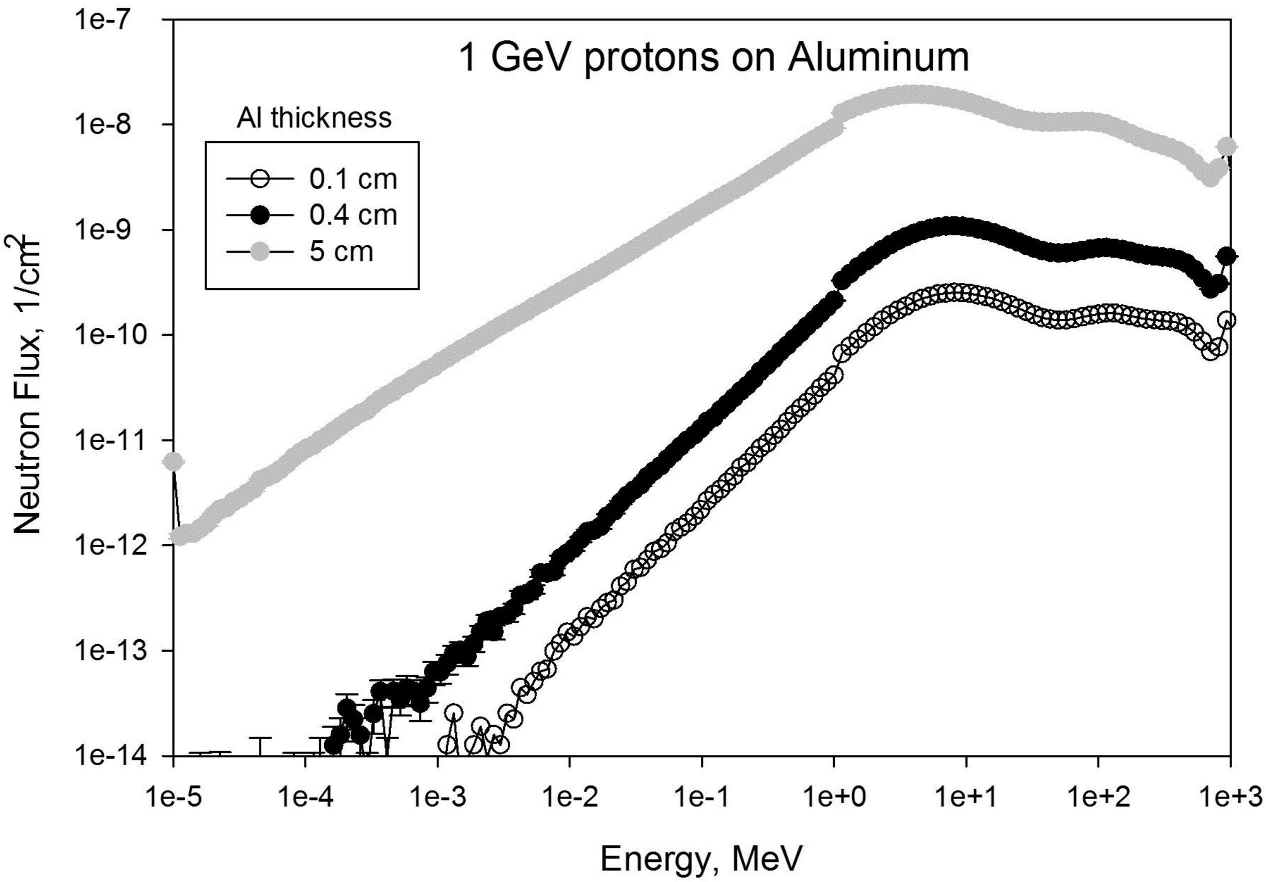

Figure 3. Neutron spectra inside 0.1 cm, 0.4 cm, and 5 cm thick aluminum spherical shells. The shells are irradiated isotropically with 1 GeV protons. Data are normalized such that the spectra are per incident proton leaving the source surface (see Figure 1). Error bars represent one standard deviation.

terials, and depths thereof expands, this database will be an increasingly powerful tool that can be integrated into existing dose calculators such as CARI-7, the FAA's GCR dose calculation software, enabling more accurate estimates of doses on extreme-altitude and space flights, where the dominant source of occupant shielding is from the vehicle rather than Earth's atmosphere.

As time and computing resources permit, future activities may expand the target materials to include carbon, hydrogen, water, and other frequently used aerospace materials. The source particles will eventually include all common GCR secondary radiations and atomic nuclei up to iron. As each subset is completed, it will be made available from the author.

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