

ASSESSMENT OF ALUMINUM SHIELDING PERFORMANCE AGAINST GALACTIC COSMIC RAYS ON THE MARTIAN SURFACE USING NASA OLTARIS

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ABSTRACT

Galactic Cosmic Rays (GCRs) represent a persistent radiation hazard for long-duration human exploration beyond Earth's magnetosphere. This study evaluates aluminum shielding under a recorded Martian-surface GCR configuration using NASA's Online Tool for the Assessment of Radiation in Space (OLTARIS) and its HZETRN transport framework. The simulation used the Badhwar–O'Neill 2020 (BO-20) GCR model, 2010 solar-minimum conditions, 687-day mission duration, spherical shielding geometry, and eleven aluminum areal densities from 0 to 100 g cm⁻². Importantly, the recorded OLTARIS job identifies nickel ($Z = 28$) as the selected specific ion; therefore, the particle-resolved and absolute dose results are configuration-specific and are not interpreted as a complete natural-GCR population dose. At zero tissue depth, the recorded absorbed dose decreased from 6.805×10^{-4} to 9.215×10^{-5} mGy day⁻¹ (86.46%); leukemia and solid-cancer dose equivalents decreased by 95.99% and 97.88%, respectively. Energy-integrated particle flux increased from 491.3 to 1477.6 particles cm⁻² day⁻¹, demonstrating radiation-field transformation through secondary-particle production. The extreme high-LET component was strongly attenuated, while the >1 keV μm^{-1} integral flux increased by 53.71%, so this low-threshold quantity is reported as a change rather than a reduction. A separate effective-dose file provided configuration-specific organ outputs but no aluminum-depth index and was therefore not used as a thickness-response curve. The study provides a traceable aluminum reference dataset and identifies the need for a complete-GCR OLTARIS run before the absolute dose can be compared directly with full Martian-surface GCR measurements.

Keywords: Galactic Cosmic Rays; Mars; Aluminum Shielding; OLTARIS; HZETRN; Badhwar–O'Neill 2020; Linear Energy Transfer; Space Radiation; Radiation Protection.

1.0 INTRODUCTION

Human exploration of Mars introduces a radiation-protection problem that differs fundamentally from the low-Earth-orbit environment. Outside Earth's protective magnetosphere, astronauts are continuously exposed to energetic Galactic Cosmic Rays. The Martian atmosphere provides partial attenuation, but its low density and the absence of a global magnetic field leave the surface exposed to a persistent primary and secondary radiation field. Measurements by the Mars Science Laboratory Radiation Assessment Detector established the significance of the Martian surface radiation environment and provide an observational anchor for transport-model studies (Hassler et al., 2014). GCRs contain a broad spectrum of nuclei extending from hydrogen through nickel and spanning a wide energy range. Protons and helium nuclei dominate particle abundance, whereas high-charge and high-energy (HZE) nuclei can make disproportionate contributions to radiation quality and biological effect because of their high ionization density and large Linear Energy Transfer (LET) (Durante & Cucinotta, 2011; Simpson, 1983). A shielding material therefore cannot be judged solely by the reduction in total particle number; the composition and energy distribution of the transmitted field, secondary-particle production and biologically weighted response must also be considered. Radiation protection is a major engineering constraint on long-duration exploration missions. Chronic GCR exposure is associated with increased risks of cancer and other adverse biological outcomes, while uncertainties in heavy-ion radiobiology complicate risk prediction (Durante & Cucinotta, 2011; Cucinotta et al., 2013). The radiation environment and the shielding system must consequently be considered as coupled components of mission design rather than as independent engineering problems. Space-radiation exposure assessment also requires mission-specific treatment of radiation quality, organ dose and uncertainty. ICRP Publication 123 describes the specialized methods used to assess astronaut exposure and organ doses, while NCRP Report 153 identifies the additional information required to formulate radiation-protection recommendations for missions beyond low-Earth orbit (Dietze et al., 2013;

NCRP, 2006). These frameworks reinforce the need to interpret transport calculations in relation to the mission scenario and not as universal terrestrial dose-limit measurements.

Aluminum is an important reference material because of its aerospace heritage, structural utility, manufacturability and relatively low density. However, high-energy ions traversing aluminum undergo electromagnetic energy loss and nuclear interactions. Fragmentation can generate secondary nucleons and light ions, while electromagnetic and hadronic processes can modify the photon, electron/positron, pion and neutron components of the transmitted field (Wilson et al., 1991; Slaba et al., 2017). Increasing shield mass therefore does not necessarily produce a linear improvement in every radiation-response metric.

NASA's Online Tool for the Assessment of Radiation in Space (OLTARIS) is a web-based radiation-analysis platform for spacecraft, habitats, rovers, spacesuits and human-related response quantities. Its transport framework is based on HZETRN and includes response functions for flux, dose, dose equivalent, whole-body effective dose equivalent and LET (Singletary et al., 2011; NASA Langley Research Center, 2026). The Badhwar–O'Neill 2020 model provides an updated description of the GCR environment using modern measurements and an updated treatment of solar modulation (Slaba & Whitman, 2020).

Previous computational studies show that shielding optimization is non-trivial. Slaba et al. (2017) demonstrated that, for some aluminum configurations, dose-equivalent response can exhibit a local minimum near approximately 20 g cm^{-2} because of secondary-particle buildup, particularly neutrons. Other work has shown that secondary radiation can become an important component of the internal spacecraft field (Dobynde & Shprits, 2020), while Mars-focused studies have motivated hydrogen-rich and regolith-based alternatives to aluminum (Al Zaman & Kunja, 2023).

The present study addresses two related needs: a coherent thickness-response dataset for aluminum under a recorded Martian-surface BO-20 solar-minimum scenario, and a coordinated interpretation of physical attenuation, biological response, particle composition, energy spectra and LET. The exact eleven areal-density cases in the raw OLTARIS output are retained. The recorded configuration also identifies nickel ($Z = 28$) as the selected specific ion; this setting is treated as an explicit methodological limitation rather than being generalized to the natural GCR composition. The resulting dataset is intended as a reproducible aluminum reference case for future comparison with hydrogen-rich polymers, regolith and hybrid shielding systems.

1.1 Aim and Objectives

The aim of this study is to assess aluminum shielding performance against Galactic Cosmic Rays on the Martian surface using NASA OLTARIS. The specific objectives were to:

- 1) quantify the reduction in absorbed dose as aluminum areal density increases;
- 2) evaluate leukemia and solid-cancer dose-equivalent responses;
- 3) characterize particle-specific contributions and the changing importance of primary and secondary radiation;
- 4) examine differential and integral LET characteristics of the transmitted field;
- 5) compare the response across eleven areal densities and identify the region of diminishing incremental shielding benefit;
- 6) establish a reproducible computational baseline for future material and hybrid-shield comparisons.

2.0 MATERIALS AND METHODS

2.1 Research Design

A quantitative computational-simulation design was used. Aluminum areal density was the independent variable, while the radiation-response quantities generated by OLTARIS were the dependent variables. All shielding cases retained the same recorded environmental, mission and geometric settings so that differences in response could be attributed to the variation in aluminum areal density.

2.2 Simulation Platform and Recorded Configuration

OLTARIS was used as the primary computational platform. The raw output identifies TARIS FORTRAN code version 5.01 and job name job_1, created on 11 January 2026. The principal datasets include absorbed dose, leukemia

and solid-cancer response, particle-resolved dose, energy-resolved flux, LET and the Martian-surface boundary condition. OLTARIS is built around deterministic HZETRN transport and provides multiple response functions for radiation-protection analysis (Singleterry et al., 2011; NASA Langley Research Center, 2026).

Table 1. Recorded OLTARIS configuration and principal output grids used in the analysis.

Parameter	Recorded setting
Radiation environment	Galactic Cosmic Rays (GCR)
Planetary environment	Martian surface
GCR model	Badhwar–O’Neill 2020 (BO-20)
Solar condition	2010 solar minimum
Mission duration	687 days
Shield geometry	Sphere
Shield material	Aluminum; density 2.7 g cm^{-3}
Specific ion recorded	Nickel, $Z = 28$
Aluminum areal densities (g cm^{-2})	0, 0.1, 0.3, 0.5, 1, 3, 5, 10, 30, 50, 100
Flux grid	125 energy points $\times$ 66 particle categories $\times$ 11 Al depths $\times$ 11 tissue depths
LET grid	1,000 LET points $\times$ 11 Al depths $\times$ 11 tissue depths

Configuration rationale. The 687-day mission duration corresponds approximately to one Martian year (about 668.6 Martian sols), providing a physically meaningful long-duration surface-exposure interval. The 2010 solar-minimum condition was retained because solar modulation is weakest near solar minimum, when the GCR intensity reaching the inner solar system is comparatively high; it therefore provides a conservative reference environment for a GCR shielding study. The nickel ($Z = 28$) setting was not selected as a claim that nickel is more representative than iron or the complete GCR population. The archived OLTARIS job explicitly records nickel as the selected specific ion, and that setting is retained without post-hoc substitution so that the reported results remain traceable to the original simulation. No scientific rationale for preferring nickel over iron is documented in the job record; consequently, nickel-specific findings are treated as configuration-specific rather than compositionally representative.

2.3 Martian-Surface Boundary Condition

The supplied boundary-condition file is labelled “Mars Surface (Isotropic) Flux w/out vehicle” and contains 125 energy points. The exported energy range extends from 0.01 MeV to 1,000,000 MeV; photons, electrons and positrons use MeV, while the other particle categories use MeV/amu. The boundary spectrum was retained as the incident condition for the shielding analysis.

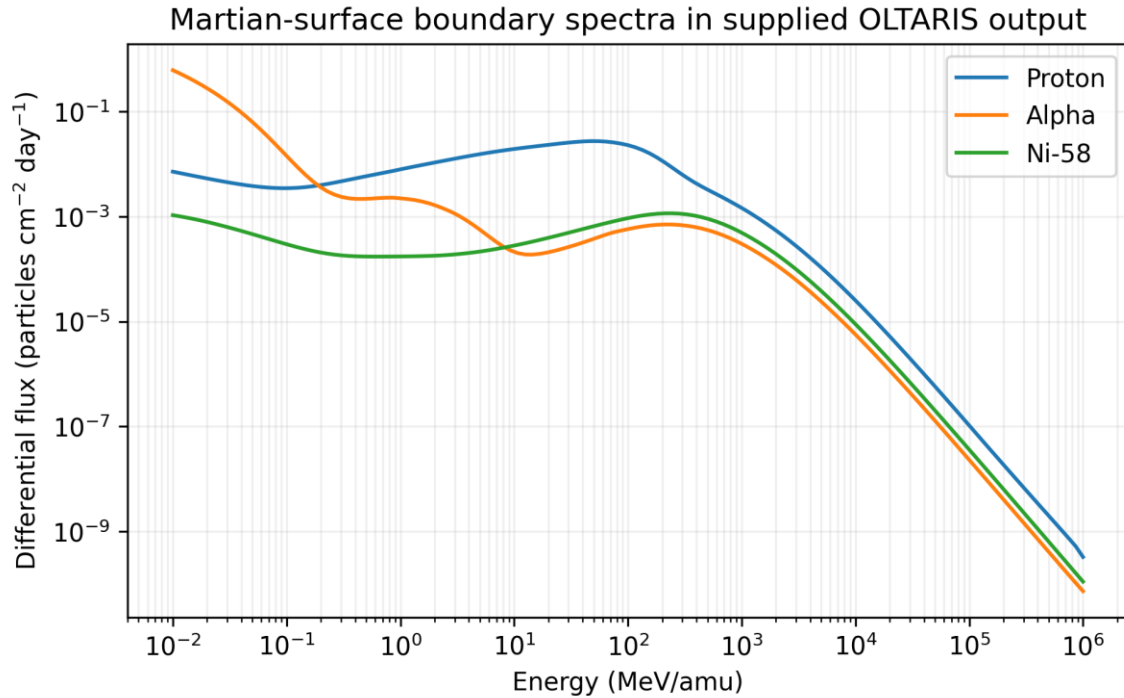


Figure 1. Proton, alpha and Ni-58 components of the supplied Martian-surface boundary spectrum.

2.4 HZETRN Radiation Transport

Independent validation context. HZETRN has been evaluated against measured radiation data in low-Earth orbit, including statistical comparisons with International Space Station measurements, and selected transport components have also been compared with Monte Carlo calculations. These studies provide evidence of transport-model verification and validation under specified conditions, but they do not constitute a direct validation of the present nickel-specific Martian-surface configuration. The present study therefore uses published measurements as a qualitative external reference rather than as a numerical calibration target.

HZETRN is a deterministic transport framework for calculating the propagation of energetic particles through shielding and target media while accounting for continuous energy loss, nuclear interactions and secondary-particle production (Wilson et al., 1991; Slaba, 2013). For explanatory purposes, the coupled transport balance may be represented schematically by:

$$[\partial/\partial x - \partial/\partial E S_j(E) + \sigma_j(E)] \phi_j(x, E) = \sum_k \int \sigma_{k \rightarrow j}(E, E') \phi_k(x, E') dE' \dots \dots \dots (1)$$

where $\phi_j(x, E)$ is the differential flux of particle type j at depth x and energy E ; $S_j(E)$ represents the continuous energy-loss term; $\sigma_j(E)$ represents removal/interactions; and $\sigma_{k \rightarrow j}$ represents production of particle j from particle k . The equation is used here as a schematic representation of the coupled loss-and-production structure rather than as a claim that every numerical detail of HZETRN is captured by the compact form.

2.5 Areal Density and Equivalent Physical Thickness

OLTARIS expresses shielding depth in areal density. For homogeneous aluminum, the corresponding physical thickness was calculated from:

$$t = \rho A / \rho_{Al} \dots \dots \dots (2)$$

where t is physical thickness, ρA is areal density and $\rho_{Al} = 2.7 \text{ g cm}^{-3}$ is the aluminum density. The physical equivalent is provided for engineering interpretation; the transport independent variable remains areal density.

Table 2. Conversion of simulated aluminum areal density to equivalent physical thickness using $\rho_{Al} = 2.7 \text{ g cm}^{-3}$.

Al areal density (g cm^{-2})	Equivalent thickness (cm)
0	0.000
0.1	0.037
0.3	0.111
0.5	0.185
1	0.370
3	1.111
5	1.852
10	3.704
30	11.111
50	18.519
100	37.037

2.6 Radiation-Protection Quantities

Absorbed dose was defined as deposited energy per unit mass:

$$D = dE / dm \quad \dots\dots\dots (3)$$

where D is absorbed dose, dE is deposited energy and dm is the irradiated mass. For conceptual radiation-quality weighting, dose equivalent can be represented as $H \approx DQ(L)$, where $Q(L)$ denotes an LET-dependent quality factor. The biological response functions reported by OLTARIS are NASA-specific response formulations and are therefore not reduced in this paper to a single universal weighting equation. A tissue-weighted effective-dose quantity may be written generally as $E = \sum T wTHT$, where wT is a tissue-weighting factor and HT is the equivalent dose to tissue T .

2.7 Shielding-Efficiency Calculation

For each response quantity R , the percentage reduction relative to the unshielded case was calculated as:

$$SE(\%) = [(R_0 - R_i) / R_0] \times 100 \quad \dots\dots\dots (4)$$

where R_0 is the response at 0 g cm^{-2} and R_i is the response at the selected aluminum areal density. The calculation was applied to absorbed dose, leukemia dose equivalent and solid-cancer dose equivalent.

2.8 Data Processing, Array Mapping and Quality Control

The multidimensional OLTARIS files were interpreted using their recorded array dimensions. The flux database contains 125 energy points, 66 particle categories, 11 aluminum cases and 11 tissue-depth points. The dose and biological-response databases contain the corresponding aluminum and tissue-depth dimensions, while particle-resolved databases include the 66 particle categories. The zero-tissue-depth index was used for the principal thickness-response curves.

Particle-dose fractions were reconstructed in the recorded Fortran ordering and checked to sum to unity within numerical round-off at the analyzed zero-tissue-depth condition. The particle-specific absorbed-dose channels were also summed independently and compared with the corresponding total absorbed-dose series; agreement was obtained to approximately seven significant figures. This internal closure provides a quality-control check on the mapping between the particle and total-response arrays.

Numerical precision was reported to 3–4 significant figures in the principal results tables. These digits describe the reporting precision of the reconstructed OLTARIS output and should not be interpreted as measurement accuracy.

Space-radiation transport and biological-response calculations have model-dependent uncertainties; published comparisons of NASA radiation-risk calculations with available dosimetry have reported agreement on the order of 15% under specified conditions, while uncertainties can be larger for heavy-ion transport and biological-response models (Cucinotta et al., 2013).

2.9 OLTARIS Output Traceability

Table 3. Traceability of the principal OLTARIS output files used in the analysis.

Raw output	Principal information used
hi_mars_surface_bc.dat	Martian-surface isotropic boundary flux versus energy and isotope
hi_flux_database.dat	Energy-resolved transported flux for 66 particle categories, 11 aluminum cases and 11 tissue-depth points
hi_dose_database_mGy.dat	Absorbed dose across aluminum and tissue-depth indices
hi_dose_frac_database.dat	Particle fractions of absorbed dose
hi_dose_part_database_mGy.dat	Particle-specific absorbed-dose contributions
hi_doseq_NASA_Leukemia_database_mSv.dat	Leukemia dose equivalent
hi_doseq_NASA_Leukemia_frac_database.dat	Particle fractions for leukemia response
hi_doseq_NASA_Leukemia_part_database_mSv.dat	Particle-specific leukemia response
hi_doseq_NASA_Solid_Cancer_database_mSv.dat	Solid-cancer dose equivalent
hi_doseq_NASA_Solid_Cancer_frac_database.dat	Particle fractions for solid-cancer response
hi_doseq_NASA_Solid_Cancer_part_database_mSv.dat	Particle-specific solid-cancer response
hi_diflet_table.dat / hi_diflet_pt.dat	Differential LET response
hi_intlet_table.dat / hi_intlet_pt.dat	Integral LET response
effective_dose_equivalent-2.txt OLTARIS_Organ_Dose_Table.xlsx	/ Whole-body and organ-specific effective-dose output

Because OLTARIS exports response functions with different array dimensions, each result was reported only where its mapping to aluminum areal density and tissue depth was unambiguous. In particular, the supplied effective-dose/organ file does not preserve an explicit aluminum-thickness index and is therefore treated as configuration-specific rather than as a thickness-response dataset.

2.10 Scope and Limitations

- The analysis is computational and does not constitute an experimental measurement.
- The principal shielding geometry is spherical; actual spacecraft and habitat geometries are more complex.
- The analyzed environment is the GCR field represented by the recorded OLTARIS job; Solar Particle Events are not included.
- The recorded configuration includes nickel ($Z = 28$) as the selected specific ion; particle-resolved conclusions are therefore configuration-specific and must not be generalized to the natural GCR composition.

- Numerical REIC and REID files were listed as requested outputs but were not present as independently readable numerical datasets in the reviewed output package; no REIC/REID values are fabricated.
- The supplied effective-dose/organ output provides configuration-specific information but cannot be mapped to a particular aluminum thickness. The nickel-specific setting and the unshielded dose magnitude also prevent direct comparison with full-population Martian-surface GCR measurements. No REIC or REID values are reported because independently readable numerical outputs were not available in the reviewed dataset.

3.0 RESULTS

3.1 Absorbed Dose versus Aluminum Areal Density

Table 4. Absorbed dose at zero tissue depth as a function of aluminum areal density.

Al areal density (g cm ⁻²)	Equivalent Al thickness (cm)	Absorbed dose (mGy day ⁻¹)	Reduction (%)
0	0.000	6.805e-04	0.00
0.1	0.037	6.594e-04	3.10
0.3	0.111	6.422e-04	5.63
0.5	0.185	6.280e-04	7.72
1	0.370	5.973e-04	12.23
3	1.111	5.040e-04	25.94
5	1.852	4.357e-04	35.98
10	3.704	3.202e-04	52.95
30	11.111	1.406e-04	79.33
50	18.519	9.594e-05	85.90
100	37.037	9.215e-05	86.46

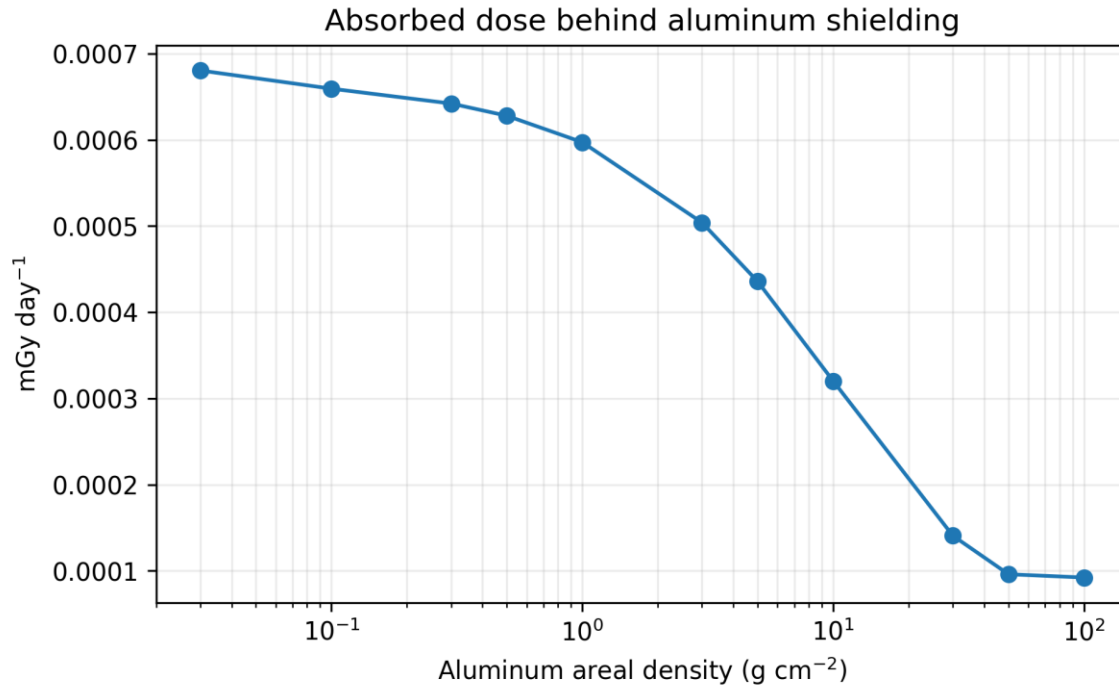


Figure 2. Variation of absorbed dose with aluminum areal density at zero tissue depth.

The absorbed-dose response decreases monotonically across the simulated range. The unshielded value is 6.805008×10^{-4} mGy day⁻¹. The reduction reaches 12.23% at 1 g cm⁻², 35.98% at 5 g cm⁻², 52.95% at 10 g cm⁻² and 79.33% at 30 g cm⁻². At 50 and 100 g cm⁻², the reductions are 85.90% and 86.46%, respectively.

The final increment illustrates diminishing returns for absorbed dose. Increasing areal density from 30 to 50 g cm⁻² adds 6.57 percentage points of reduction relative to the unshielded case, whereas increasing it from 50 to 100 g cm⁻² adds only 0.56 percentage points. This does not imply that 50 g cm⁻² is a universal optimum; it identifies the onset of a region in which additional aluminum produces progressively smaller absorbed-dose gains under the recorded configuration.

3.2 Leukemia and Solid-Cancer Dose Equivalents

Table 5. Leukemia and solid-cancer dose-equivalent responses as functions of aluminum areal density.

Al (g cm ⁻²)	Leukemia (mSv day ⁻¹)	Reduction (%)	Solid cancer (mSv day ⁻¹)	Reduction (%)
0	3.353e-03	0.00	1.284e-02	0.00
0.1	3.302e-03	1.52	1.264e-02	1.51
0.3	3.237e-03	3.48	1.239e-02	3.52
0.5	3.177e-03	5.27	1.215e-02	5.35
1	3.038e-03	9.40	1.161e-02	9.57
3	2.587e-03	22.84	9.846e-03	23.31
5	2.238e-03	33.27	8.481e-03	33.93
10	1.616e-03	51.80	6.065e-03	52.76
30	5.701e-04	83.00	2.012e-03	84.33

50	2.673e-04	92.03	8.349e-04	93.50
100	1.345e-04	95.99	2.722e-04	97.88

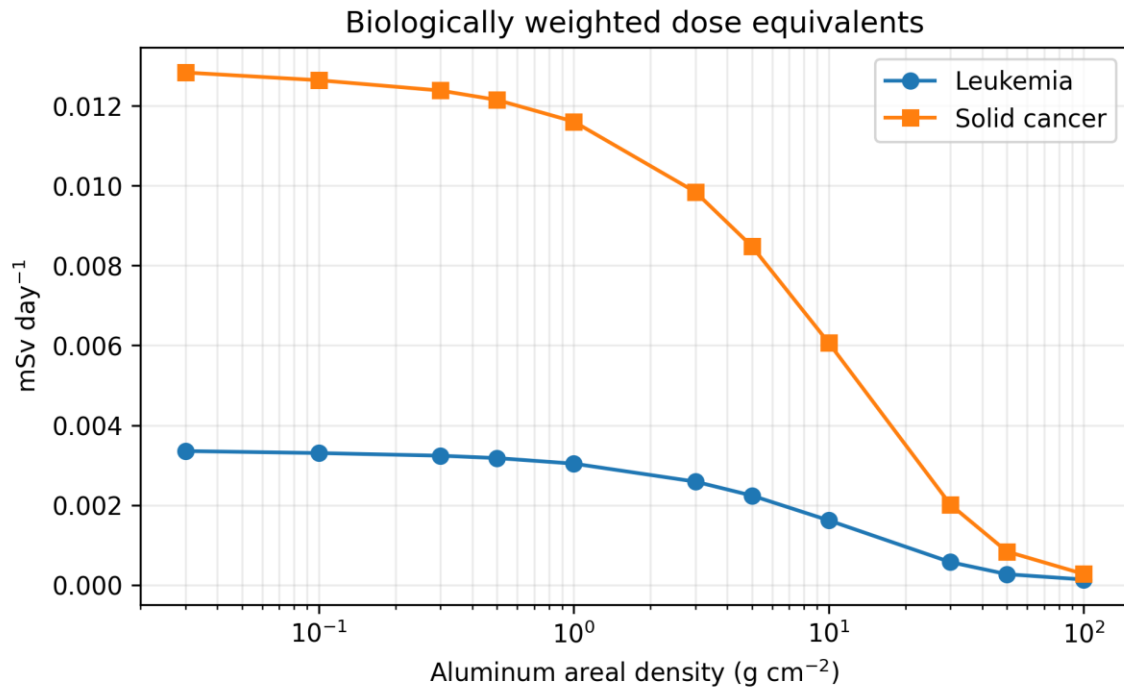


Figure 3. Leukemia and solid-cancer dose equivalents versus aluminum areal density.

Leukemia dose equivalent decreases from $3.353276 \times 10^{-3} \text{ mSv day}^{-1}$ at zero aluminum to $1.344712 \times 10^{-4} \text{ mSv day}^{-1}$ at 100 g cm^{-2} , a 95.99% reduction. Solid-cancer dose equivalent decreases from 1.283731×10^{-2} to $2.722154 \times 10^{-4} \text{ mSv day}^{-1}$, corresponding to a 97.88% reduction. At 10 g cm^{-2} , the reductions are 51.80% and 52.76%, respectively; at 30 g cm^{-2} they are 83.00% and 84.33%; and at 50 g cm^{-2} they reach 92.03% and 93.50%.

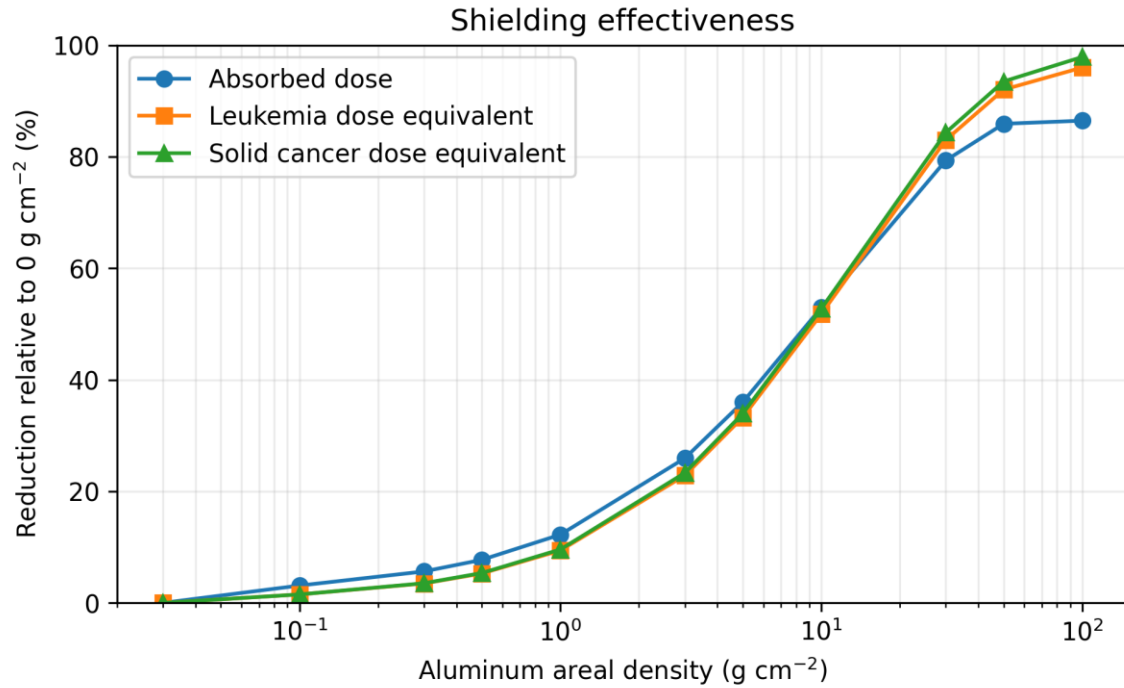


Figure 4. Percentage reduction of absorbed dose, leukemia dose equivalent and solid-cancer dose equivalent relative to the unshielded case.

3.3 Particle-Specific Contribution to Absorbed Dose

Table 6. Selected particle-group fractions of absorbed dose at zero tissue depth, reconstructed from the OLTARIS dose-fraction database.

Al (g cm ⁻²)	Heavy ions	Protons	D/T/He	e±	π±	Photons	μ±	Neutrons
0	96.65	1.64	1.00	0.38	0.17	0.00	0.16	0.00
10	91.80	4.29	2.09	0.96	0.61	0.00	0.24	0.00
30	70.59	15.87	6.16	3.78	3.15	0.00	0.45	0.00
50	42.23	30.84	9.32	9.53	7.47	0.01	0.60	0.00
100	8.20	44.93	8.98	23.50	13.80	0.01	0.57	0.00
Ni-58 at 0 g cm ⁻² (specification result)	89.57*	—	—	—	—	—	—	—

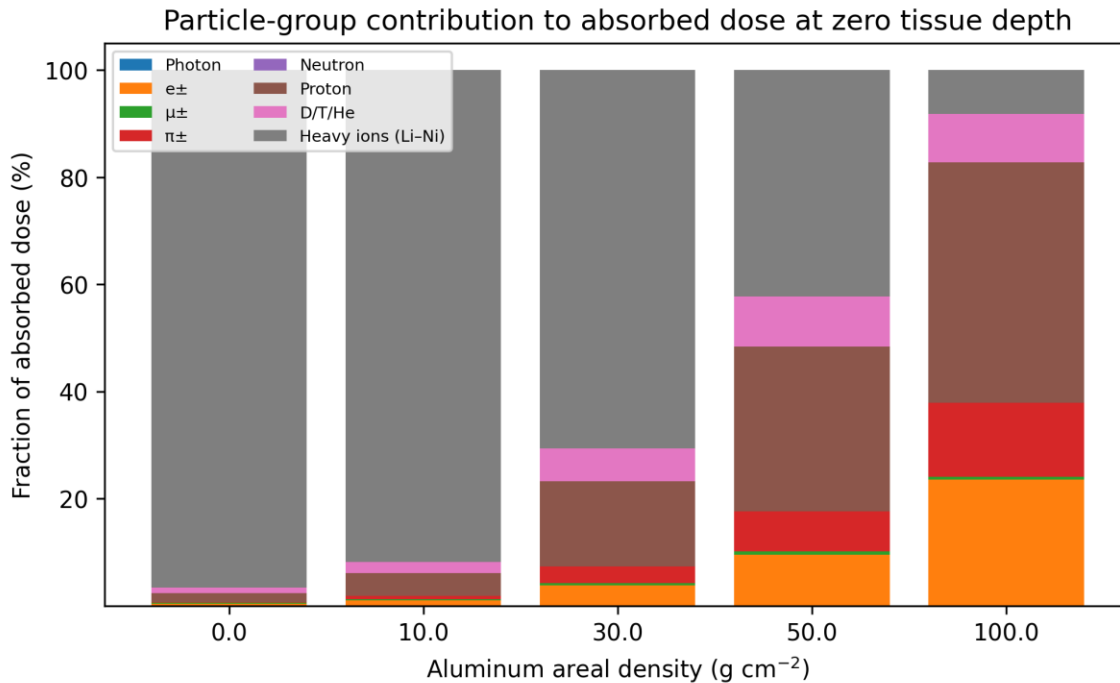


Figure 5. Particle-group contribution to absorbed dose at selected aluminum areal densities.

The particle-fraction database shows a strong redistribution of absorbed-dose contribution with increasing aluminum. At 0 g cm⁻², the heavy-ion group contributes 96.65% of the absorbed-dose fraction in the recorded configuration, while protons contribute 1.64% and D/T/He contributes 1.00%. At 50 g cm⁻², the corresponding fractions are 42.23%, 30.84% and 9.32%, respectively. At 100 g cm⁻², heavy ions contribute 8.20%, protons 44.93%, electrons/positrons 23.50%, pions 13.80%, and D/T/He 8.98%. The neutron absorbed-dose fraction is numerically negligible in the reconstructed zero-tissue-depth dose-fraction output.

The heavy-ion result requires explicit qualification. The recorded OLTARIS configuration identifies nickel ($Z = 28$) as the selected specific ion, and Ni-58 alone accounts for approximately 89.57% of the absorbed-dose fraction at zero aluminum in this configuration. This value is not a statement about the natural GCR abundance of nickel. It is a configuration-specific response result and is retained to document the recorded transport calculation. The dose-fraction array was also reclassified so that the residual component is reported as D/T/He rather than neutrons; the neutron fraction is effectively zero in this dataset.

* Ni-58 alone accounts for approximately 89.57% of the absorbed-dose fraction at zero aluminum in the recorded nickel-specific configuration. This value is not a natural-GCR nickel abundance and must not be generalized to the complete GCR population.

3.4 Energy-Resolved Particle Spectra

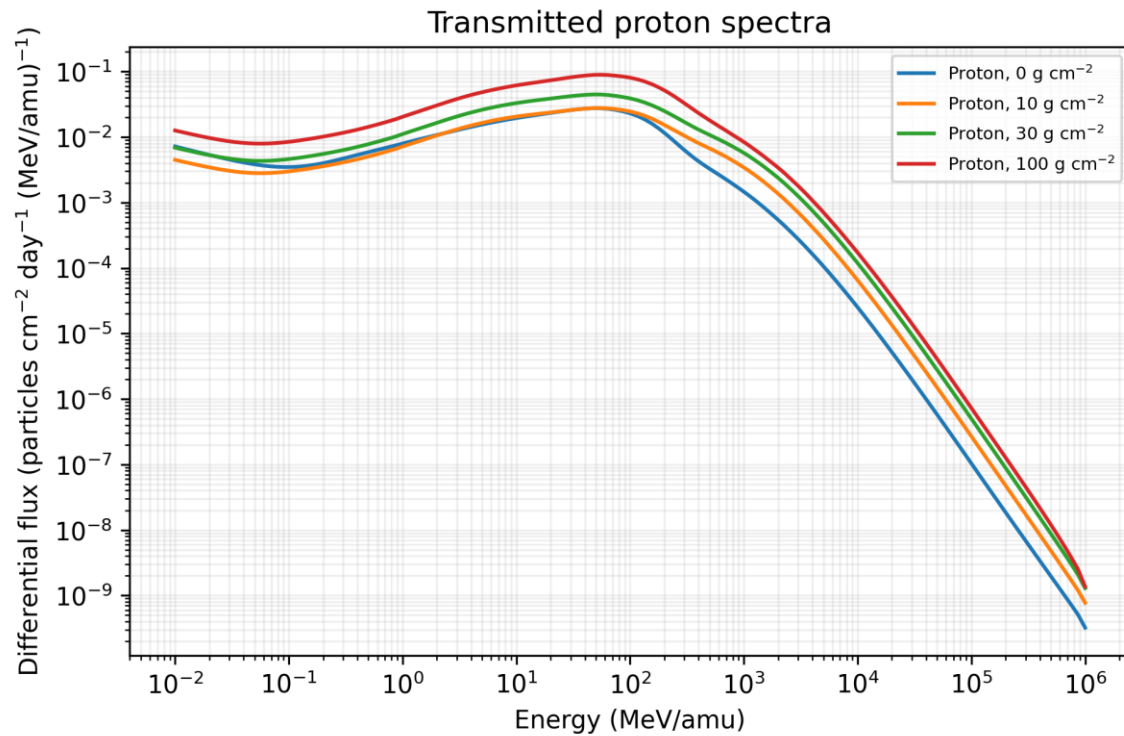


Figure 6. Transmitted proton differential spectra for selected aluminum areal densities at zero tissue depth.

The energy-resolved flux database contains 125 energy points and 66 particle categories. Photons, electrons and positrons use MeV as the energy coordinate, while the other particle categories use MeV/amu. Proton and Ni-58 spectra were therefore evaluated separately using the appropriate MeV/amu coordinate. The proton spectra retain a broad transmitted distribution as aluminum increases, consistent with the combined effects of primary-particle transport and secondary production.

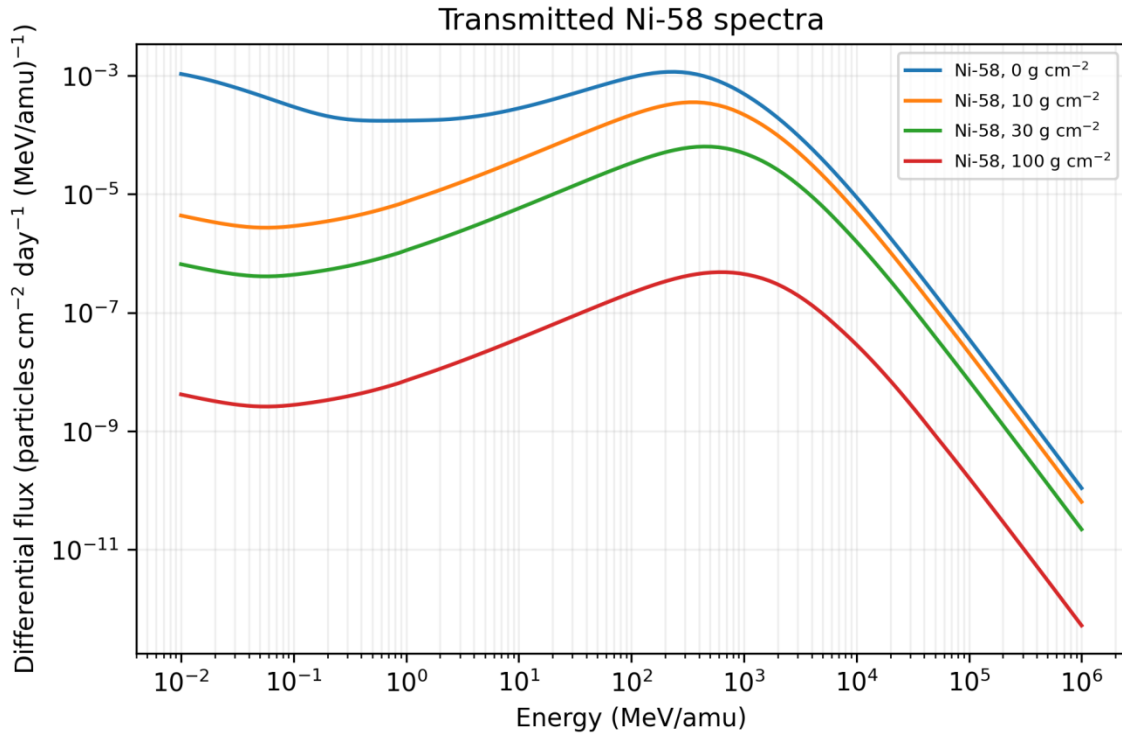


Figure 7. Transmitted Ni-58 differential spectra for selected aluminum areal densities at zero tissue depth.

The Ni-58 spectrum is much more strongly attenuated than the proton spectrum. At the sampled spectral maximum, the differential Ni-58 flux decreases from approximately 1.16×10^{-3} in the unshielded case to about 4.81×10^{-7} at 100 g cm^{-2} . Residual high-energy heavy ions nevertheless remain, showing that thick aluminum suppresses rather than completely eliminates the high-Z component.

3.5 Transported Particle Flux and Radiation-Field Transformation

Table 7. Energy-integrated transported particle flux at zero tissue depth for the unshielded and 100 g cm^{-2} cases. Flux units are particles $\text{cm}^{-2} \text{ day}^{-1}$.

Quantity	0 g cm ⁻²	100 g cm ⁻²	Change
Total integrated particle flux	491.32	1477.58	+200.7%
Photon flux	315.15	923.30	+193.0%
e± flux	7.52	64.18	+753.7%
Proton flux	9.06	42.80	+372.6%
Li–Ni heavy-ion flux	1.84	0.097	–94.7%
Ni-58 flux	1.5658	0.00182	–99.88%

A key transport result is that total energy-integrated particle flux increases from approximately 491.3 to 1477.6 particles $\text{cm}^{-2} \text{ day}^{-1}$ between 0 and 100 g cm^{-2} , even though absorbed dose decreases. This apparent contradiction reflects the distinction between particle number and deposited energy. Nuclear interactions in aluminum attenuate and fragment primary high-Z ions while producing larger numbers of secondary particles, particularly lighter charged particles and electromagnetic secondaries. Thus, particle-number attenuation is not an appropriate standalone measure of shielding performance.

3.6 Differential and Integral LET

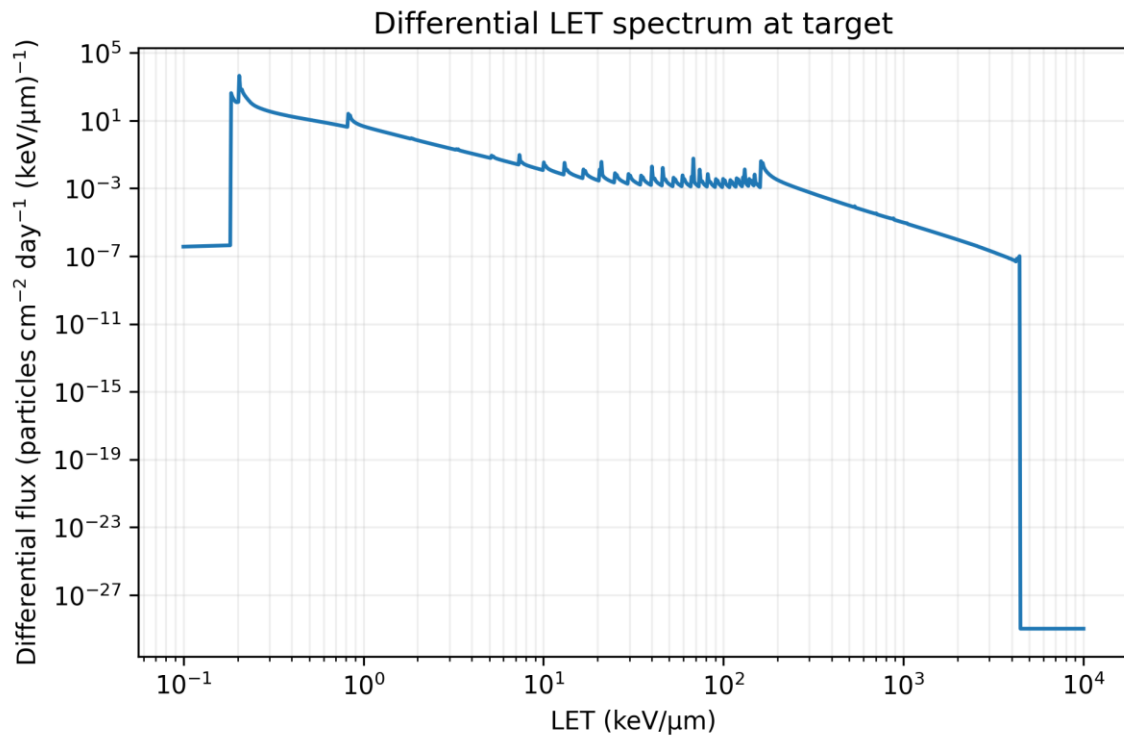


Figure 8. Differential LET spectrum at the OLTARIS target, plotted from the raw differential-LET output.

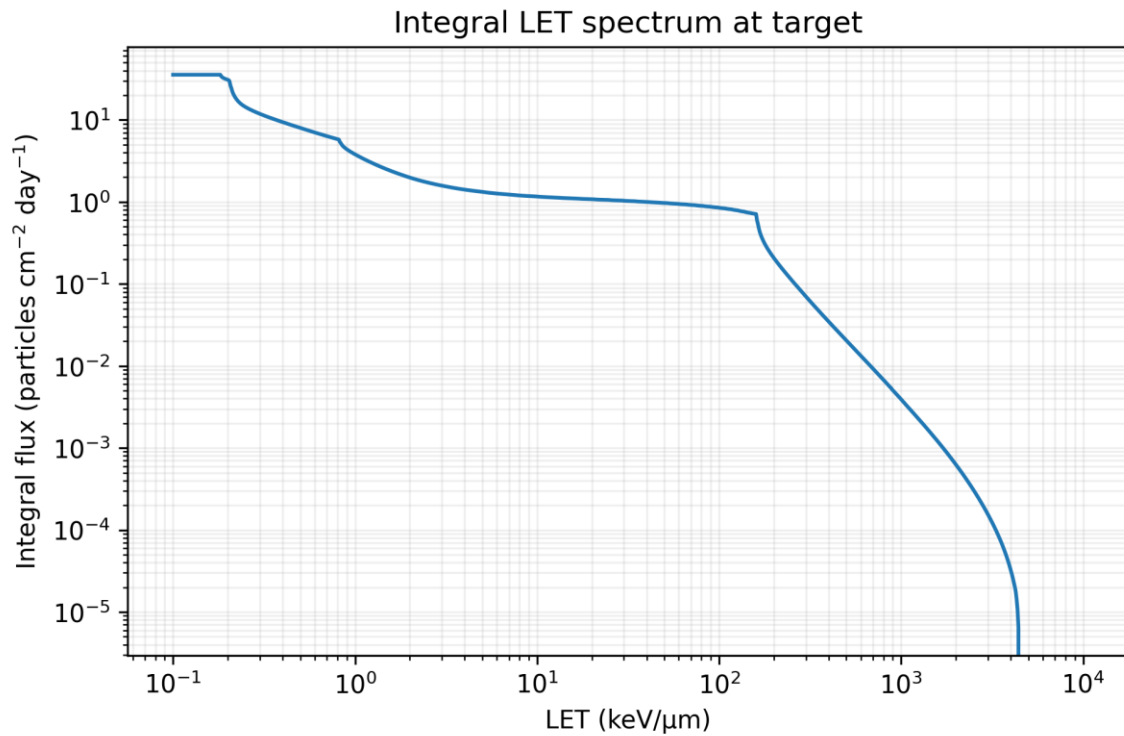


Figure 9. Integral LET spectrum at the OLTARIS target, plotted from the raw integral-LET output.

The LET outputs contain 1,000 sampling points spanning approximately 0.1 to 10,000 keV μm^{-1} . The differential spectrum contains both low-LET and high-LET components, while the integral spectrum decreases with increasing LET because the extreme-LET population is comparatively small. The supplied transport data show strong suppression of the high-LET tail with increasing aluminum.

Table 8. Cumulative integral LET flux at selected thresholds for the unshielded and 100 g cm^{-2} cases. Flux units are particles $\text{cm}^{-2} \text{ day}^{-1}$.

LET threshold (keV μm^{-1})	Integral flux at 0 g cm^{-2}	Integral flux at 100 g cm^{-2}	Change (%)
1	4.1889	6.43868	+53.71
10	1.91968	0.229309	-88.05
100	1.69591	0.015790	-99.07
1000	0.0203396	8.3301×10^{-5}	-99.59

Above 10, 100 and 1000 keV μm^{-1} , the cumulative flux changes by -88.05%, -99.07% and -99.59%, respectively, between 0 and 100 g cm^{-2} . In contrast, the >1 keV μm^{-1} integral flux increases by +53.71%. The column is therefore reported as “Change (%)”, with positive values denoting increases and negative values denoting decreases. The increase at the low threshold is consistent with the production of additional lower-LET secondary particles and should not be interpreted as a failure of the shield to suppress the extreme high-LET component.

3.7 Effective Dose and Organ-Specific Output

The supplied effective-dose output reports a total effective dose equivalent of 1.195622511 mSv, a daily value of 0.001740353 mSv day^{-1} and an annualized value of 0.635228845 mSv year^{-1} . Because the exported file does not identify the aluminum areal-density index associated with these values, they are reported as configuration-specific outputs and are not assigned to a particular shielding thickness.

Table 9. Highest reported organ/tissue values in the supplied configuration-specific effective-dose output.

Organ/tissue	Reported value (mSv)
Skin	2.811755
Lens	2.511715
Retina	2.054261
Salivary glands	2.024076
Testes	1.909711
Brain	1.844914
Muscle	1.749302
Hippocampus	1.698419
Lungs	1.558088
Thyroid	1.498002

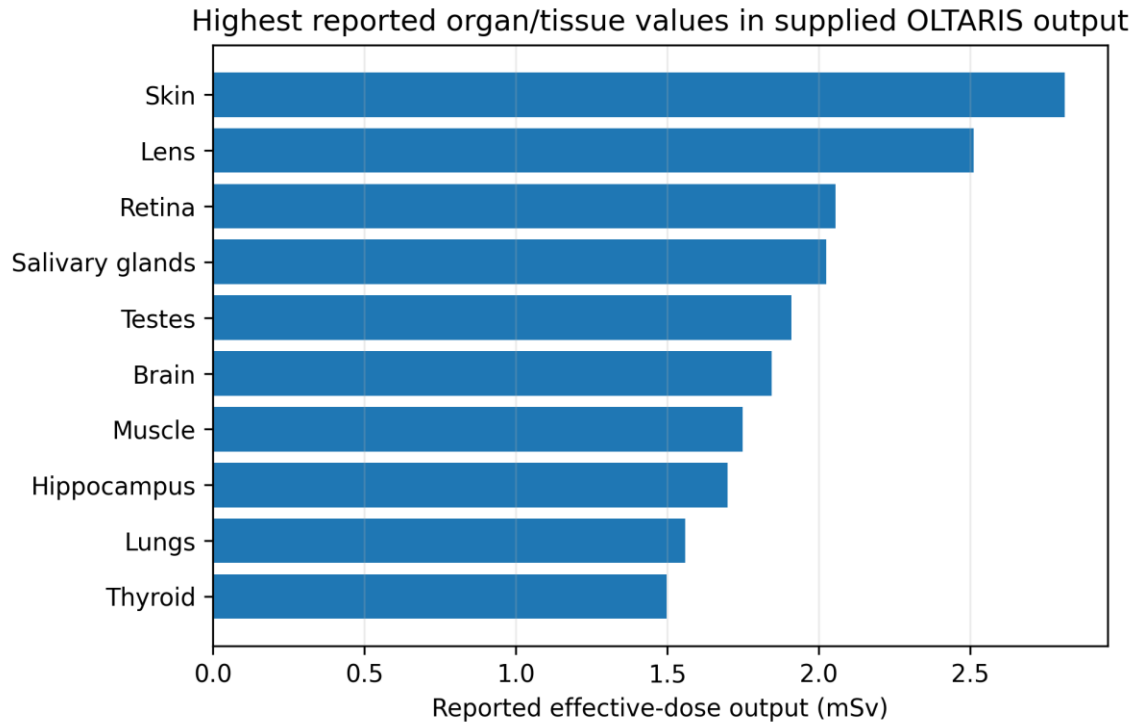


Figure 10. Highest reported organ/tissue values in the supplied OLTARIS effective-dose output.

The highest reported organ/tissue values occur in skin, lens, retina, salivary glands and testes, followed by brain and muscle. These values illustrate the heterogeneity represented by organ-specific response functions, but they should not be interpreted as independent measurements or as a thickness-response curve because the supplied effective-dose file does not preserve the corresponding aluminum-depth index.

3.8 Depth-Dependent Absorbed Dose

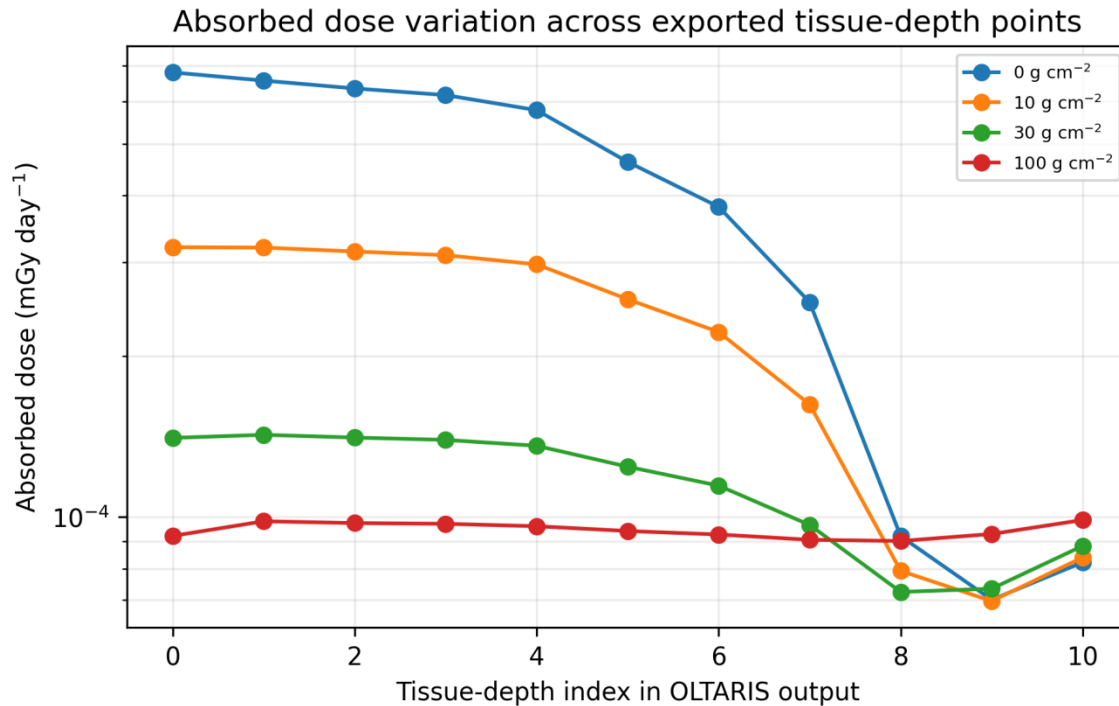


Figure 11. Absorbed dose across the exported tissue-depth points for selected aluminum areal densities.

The absorbed-dose database contains eleven tissue-depth points in addition to the eleven aluminum cases. The resulting profiles show that dose is not spatially uniform within the target. For selected aluminum areal densities, the magnitude and shape of the depth profile change as charged particles lose energy, fragment and generate secondary radiation. The 0, 10, 30 and 100 g cm⁻² profiles demonstrate that shielding and tissue transport act together: increasing aluminum changes both the dose entering the target and the subsequent depth distribution.

4.0 DISCUSSION

4.1 Shielding Response and Diminishing Returns

The principal thickness-response curves show substantial attenuation across the simulated aluminum range, but the incremental benefit is not proportional to added areal mass. Absorbed dose falls by 79.33% at 30 g cm⁻² and 85.90% at 50 g cm⁻², while the increase from 50 to 100 g cm⁻² yields only a further 0.56 percentage-point reduction in absorbed dose. The biological response quantities continue to decline more strongly, indicating that different response functions do not necessarily exhibit identical shielding efficiency.

The present monotonic response should not be interpreted as evidence that all aluminum configurations have a monotonic dose-equivalent response. Slaba et al. (2017) reported a local minimum near approximately 20 g cm⁻² in certain aluminum configurations, followed by increased dose equivalent associated in part with secondary-particle buildup. The difference is scientifically useful: geometry, environment, response function, transport configuration and target definition can alter the location and even the existence of a minimum. The present study identifies 30–50 g cm⁻² as a configuration-specific transition region for the recorded response; it should not be interpreted as a universal optimum.

4.2 Biological Response versus Physical Dose

Leukemia and solid-cancer dose equivalents decrease more strongly than absorbed dose over the simulated range. At 100 g cm⁻², the reductions are 95.99% and 97.88%, respectively, compared with 86.46% for absorbed dose. This separation demonstrates why absorbed dose alone is insufficient for interpreting space-radiation protection. The

biologically weighted quantities respond to particle type, energy and radiation quality in addition to total energy deposition.

The configuration-specific effective-dose output complements the thickness-dependent curves but cannot be used to infer organ-dose trends with aluminum because the supplied text export does not preserve the aluminum-depth index. Retaining this distinction prevents an otherwise plausible but unsupported thickness-dependent interpretation.

4.3 Radiation-Field Transformation and Secondary Particles

The increase in total transported particle flux from approximately 491.3 to 1477.6 particles $\text{cm}^{-2} \text{ day}^{-1}$ is one of the clearest demonstrations that shielding does not simply remove radiation. The heavy-ion transport component is strongly suppressed, while protons, electrons/positrons, photons and pions become increasingly important. The proton flux rises by approximately 372.6%, whereas Ni-58 decreases by approximately 99.88%. These changes are consistent with the coupled loss-and-production structure of the transport problem (Wilson et al., 1991; Dobynde & Shprits, 2020; Slaba, 2013).

The practical implication is that particle flux, absorbed dose and radiation quality should be treated as complementary metrics. The recorded calculation shows that aluminum can reduce high-Z transport while increasing the number of lower-energy secondary particles. Consequently, particle count alone does not establish shielding adequacy; dose and radiation-quality metrics must be considered together.

4.4 LET and Radiation Quality

The LET results show preferential suppression of the extreme high-LET component. The cumulative flux above 100 and 1000 $\text{keV } \mu\text{m}^{-1}$ falls by 99.07% and 99.59%, respectively, between 0 and 100 g cm^{-2} . At the same time, the low-threshold integral response can increase because of secondary-particle production. This behavior illustrates that shielding changes the radiation-quality distribution, not merely its overall magnitude. The persistence of a residual high-LET tail also supports continued use of LET- and particle-resolved metrics in radiation-protection assessment (Durante & Cucinotta, 2011; Simpson, 1983).

Qualitative comparison with MSL/RAD measurements. Independent observations provide an important scale reference for the Martian radiation environment. Hassler et al. (2014), using the Mars Science Laboratory Radiation Assessment Detector (RAD), reported an absorbed-dose rate of approximately 0.21 mGy day^{-1} and a dose-equivalent rate of approximately 0.64 mSv day^{-1} at Gale Crater during near-solar-maximum conditions. A later analysis of MSL/RAD observations under solar-minimum conditions reported 0.314 mGy day^{-1} absorbed dose and $0.721 \pm 0.042 \text{ mSv day}^{-1}$ dose equivalent (Zeitlin et al., 2022). The unshielded absorbed-dose rate reconstructed here, $6.805 \times 10^{-4} \text{ mGy day}^{-1}$, is therefore not numerically comparable with those full-population surface measurements. The difference is expected from the recorded nickel-specific configuration and demonstrates why the present results must not be interpreted as a complete Martian-surface GCR dose estimate. The RAD measurements nevertheless support the broader physical premise that the Martian surface has a persistent GCR radiation field and provide an observational benchmark for a future complete-GCR OLTARIS calculation.

4.5 Comparison with Previous Studies

The present findings are consistent with the broader OLTARIS literature in showing that mission environment, shielding geometry, target definition and response function are coupled inputs (Singleterry et al., 2011; NASA Langley Research Center, 2026). The use of BO-20 provides a contemporary GCR environment description (Slaba & Whitman, 2020). The monotonic response observed in the recorded nickel-specific configuration differs from the local-minimum behavior reported for some aluminum calculations (Slaba et al., 2017; Yadav et al., 2025). Yadav et al. (2025), for example, reported a dose-equivalent minimum at 20 g cm^{-2} in a FLUKA calculation using a complete GCR particle population. The difference between that result and the present monotonic response is therefore not evidence of contradictory transport physics; the two studies use different particle configurations, target models and transport setups. The present dataset should consequently be interpreted as a configuration-specific transport case rather than as a complete-GCR shielding optimum.

Mars-focused work has also demonstrated the potential value of regolith and hydrogen-rich materials. Al Zaman and Kunja (2023), for example, investigated regolith/polymer and regolith/LiH combinations against aluminum references. The present aluminum dataset therefore serves most usefully as a controlled reference for subsequent

comparisons, provided that future simulations use the complete GCR population and matched mission, geometry and response settings.

4.6 Scientific Contribution and Engineering Implications

The principal contribution of the study is the integration of multiple OLTARIS response classes into a single traceable aluminum thickness-response dataset for a Martian-surface scenario. Rather than relying on one shielding factor, the analysis connects absorbed dose with biologically weighted responses, particle composition, energy spectra, LET and configuration-specific organ outputs. The combination reveals a consistent physical narrative: aluminum attenuates the high-Z component and reduces the principal dose-response quantities, but it simultaneously transforms the transmitted field through secondary-particle production.

From an engineering perspective, the equivalent physical thicknesses are substantial at the upper end of the simulated range. A 100 g cm^{-2} aluminum areal density corresponds to approximately 37 cm of solid aluminum if represented as a uniform layer. This is better interpreted as an areal-mass trade-study point than as a realistic spacecraft wall. Practical systems are likely to require distributed mass, hydrogen-rich consumables, water, regolith or multilayer/hybrid architectures. The present $30\text{--}50 \text{ g cm}^{-2}$ region is therefore best treated as a candidate transition range for subsequent optimization, not as a final design recommendation.

5.0 CONCLUSION

This study evaluated the response of aluminum shielding under a recorded Martian-surface BO-20 GCR configuration using NASA OLTARIS/HZETRN. The analysis retained the eleven aluminum areal densities represented in the raw output: 0, 0.1, 0.3, 0.5, 1, 3, 5, 10, 30, 50 and 100 g cm^{-2} . The OLTARIS record explicitly identifies nickel ($Z = 28$) as the selected specific ion; consequently, the absolute dose and particle-fraction results are configuration-specific rather than full natural-GCR estimates.

At zero tissue depth, the recorded absorbed dose decreased by 86.46% across the simulated aluminum range, while leukemia and solid-cancer dose equivalents decreased by 95.99% and 97.88%, respectively. These percentages describe changes within the same recorded configuration and are not intended as validation of a full Martian-surface GCR dose rate.

Particle-resolved analysis showed that the transmitted field changes qualitatively as aluminum thickness increases. The heavy-ion fraction decreases sharply, whereas proton, D/T/He, electron/positron and pion fractions increase within the reconstructed dose-fraction dataset. The energy-integrated total particle flux can increase even while absorbed dose decreases, demonstrating the importance of secondary-particle production and radiation-field transformation.

The supplied effective-dose/organ output provides configuration-specific information but cannot be mapped to a particular aluminum thickness. The nickel-specific setting and the unshielded dose magnitude also prevent direct comparison with full-population Martian-surface GCR measurements. No REIC or REID values are reported because independently readable numerical outputs were not available in the reviewed dataset.

Within the recorded configuration, aluminum produces substantial attenuation of the selected transported radiation component. The result should not be generalized to the full natural GCR environment until a complete-population OLTARIS calculation is performed. The approximately $30\text{--}50 \text{ g cm}^{-2}$ region is a useful transition range for further optimization studies. Future work should repeat the calculation with the complete GCR particle population and compare aluminum directly with polyethylene, Martian regolith, hydrogen-rich materials and hybrid shielding systems using identical mission and response settings.

DATA AVAILABILITY

The numerical results reported in this manuscript were reconstructed from the OLTARIS output files generated for job_1 on 11 January 2026, including the absorbed-dose, leukemia, solid-cancer, particle-dose, dose-fraction, LET, flux and Martian-surface boundary-condition datasets. The supplied effective-dose/organ table was used only for the configuration-specific organ analysis. The underlying numerical files can be provided as supplementary material subject to the applicable data-sharing arrangements.

AI Assistance

The author also acknowledges the use of ChatGPT-assisted language and editorial tools during preparation of this manuscript. AI assistance was used to support language refinement, grammatical editing, structural organization, and presentation. The author remains solely responsible for the scientific content, interpretation of the NASA OLTARIS results, numerical values, conclusions, and final form of the manuscript.

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Author contributions: Abubakar Muhammad Abba designed the simulation study, processed the OLTARIS outputs, performed the quantitative analysis and drafted the manuscript. The co-author reviewed the scientific framework and manuscript.

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Code availability: No custom transport code was developed. Radiation transport was performed through NASA OLTARIS.

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NOMENCLATURE

Symbol	Meaning	Unit
GCR	Galactic Cosmic Rays	—
HZE	High Charge and Energy particle	—
LET	Linear Energy Transfer	keV μm^{-1}
D	Absorbed dose	Gy
H	Dose equivalent	Sv
E	Effective dose / effective-dose quantity	Sv
Q(L)	Radiation-quality factor	—
REIC	Risk of Exposure-Induced Cancer	%
REID	Risk of Exposure-Induced Death	%
ρ_A	Areal density	g cm^{-2}
ρ_{Al}	Aluminum density	g cm^{-3}