IRENE: AE9/AP9/SPM Radiation Environment Model

Dose Kernel Validation Testing

V1.55.003

The IRENE (International Radiation Environment Near Earth): (AE9/AP9/SPM) model was developed by the Air Force Research Laboratory in partnership with MIT Lincoln Laboratory, Aerospace Corporation, Atmospheric and Environmental Research, Incorporated, Los Alamos National Laboratory and Boston College Institute for Scientific Research.

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The IRENE (AE9/AP9/SPM) model and related information can be obtained from AFRL's Virtual Distributed Laboratory (VDL) website: https://www.vdl.afrl.af.mil/programs/ae9ap9

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Introduction

This document describes the verification testing results for the total ionizing dose kernel in the AE9/AP9-IRENE V1.55.003 model software release. This kernel replicates dose vs. depth results from SHIELDOSE2 but enables faster effects calculations in the IRENE architecture.

We first provide a brief discussion of how effects kernels are implemented in AE9/AP9-IRENE (full descriptions may be found in [1]-[3]). Precomputed effects "kernels" in the IRENE model suite are used for faster effects calculations, enabling such calculations to be efficiently performed for the numerous time steps, scenarios, etc., involved in producing design confidence levels (CLs). For a radiation effect that is linear with flux or fluence (for a specified particle species and energy), a kernel describes the transfer function between the flux or fluence and the effect. This transfer function is applied in AE9/AP9-IRENE to flux or fluence results, yielding the desired effect quantity for each time step and/or scenario. CLs subsequently constructed then apply accurately for the chosen effect.

Since its first release in 2012, AE9/AP9 has given dose quantities using an implementation of the legacy SHIELDOSE2 code, providing dose vs. Al-shielding depth for several simple geometries and target materials. This flux-to-dose calculation is now represented in the V1.55 dose kernel. As described in [4] and [5], the kernel transform matrix was derived by running many different input spectra in SHIELDOSE2, each spectrum perturbed at a single energy relative to a standard spectrum, enabling derivation of the derivative of the dose-depth curve with respect to input flux. In this case the resulting kernel is the matrix $\overline{K}$ of these derivatives where

$$K_{ik} = \frac{\partial y_i}{\partial j_k}$$

with dose y and flux j. Results presented here describe version 1.0.2 of the kernel XML files.

Method

To validate the new kernel, dose results from the kernel and the IRBEM implementation of SHIELDOSE2 were compared for electrons and protons, all shielding geometries (finite slab, semi-infinite slab, and hemispherical), all eleven target materials, and depths ranging from 5 to 4000 mils (0.13-102 mm). An exponential spectrum was used for both particle species with an e-folding energy of 633 keV for electrons and 14.1 MeV for protons (corresponding in each case to the median of the kernel energy grid).

Results, proton dose

For proton dose, Figures 1-3 show the absolute relative error between SHIELDOSE2 and kernel results as a function of shielding depth, for the three shielding geometry options. Each figure shows results for all eleven target material choices. The relative errors of 1 at the highest and lowest depths are artifacts of round-off effects at those depths.

Relative errors for hemispherical geometry (Figure 1) range from ~1% at low depths to a maximum of ~20% at large depths (500-3000 mils Al). For slab (Figure 2) and semi-infinite slab geometry (Figure 3), relative errors are similar and range from ~0.03% at low depths to a maximum of ~2% at 3500 mils Al. Trends in relative error versus depth are very similar for all target materials with a given shielding geometry.

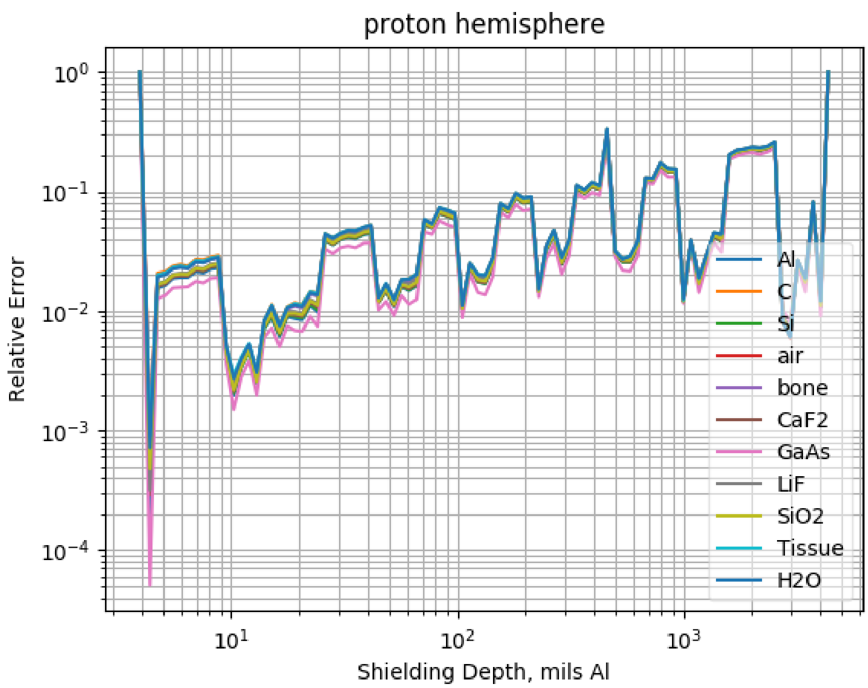

Figure 1. Magnitude of relative differences between SHIELDOSE2 and IRENE dose kernel for proton dose as a function of Al shielding depth, hemispherical geometry, various target materials.

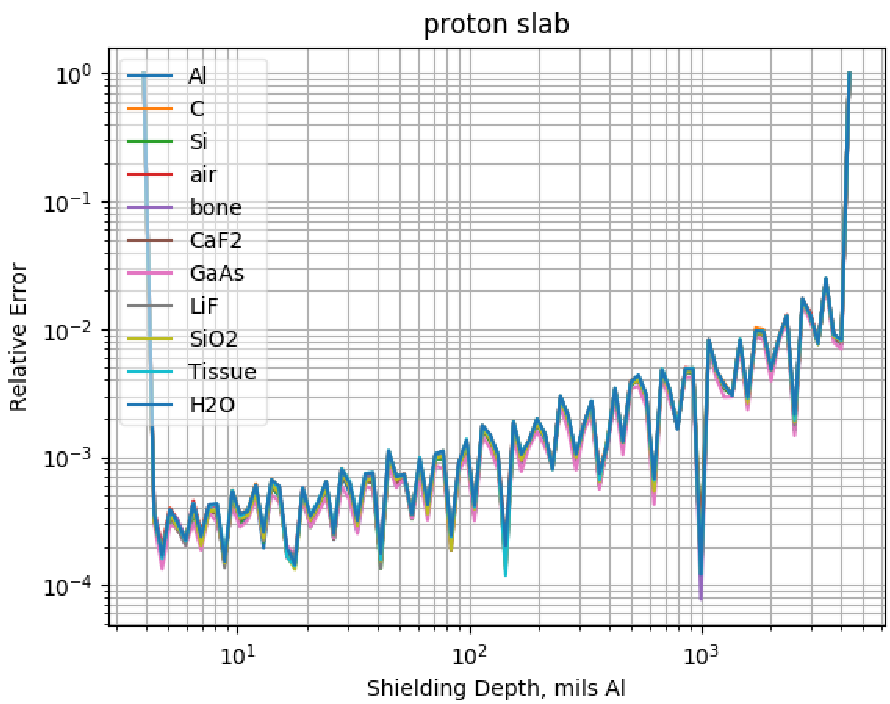

Figure 2. Magnitude of relative differences between SHIELDOSE2 and IRENE dose kernel for proton dose as a function of Al shielding depth, slab geometry, various target materials.

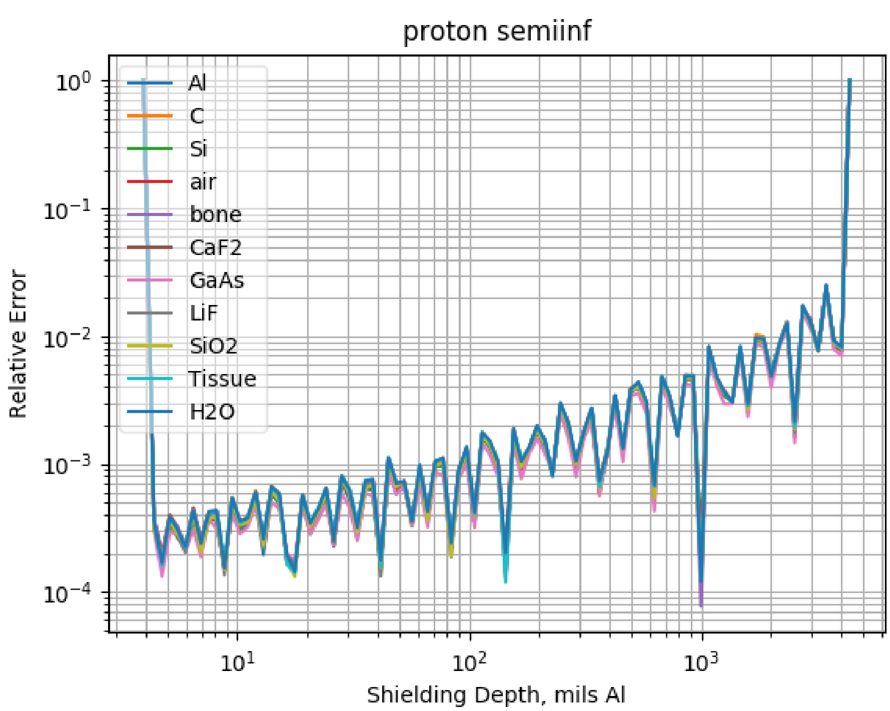

Figure 3. Magnitude of relative differences between SHIELDOSE2 and IRENE dose kernel for proton dose as a function of Al shielding depth, semi-infinite geometry, various target materials.

Results, electron dose

For electron dose, Figures 4-6 show the absolute relative error between SHIELDOSE2 and kernel results as a function of shielding depth, for the four shielding geometry choices. Each figure shows results for all eleven target material choices. As before, the relative errors of 1 at the highest and lowest depths are artifacts of round-off effects at those depths.

Relative errors show similar behavior as a function of depth for the three shielding geometries: hemispherical (Figure 4), slab (Figure 5), and semi-infinite slab (Figure 6). Relative errors vary from ~0.01% at low depths to peaks of ~5-10% at depths near 400 mils Al, then decrease to ~0.2% for larger depths. For all three geometries, the relative error vs. depth curves show much relative scatter between target materials, but the overall trends with depth are similar.

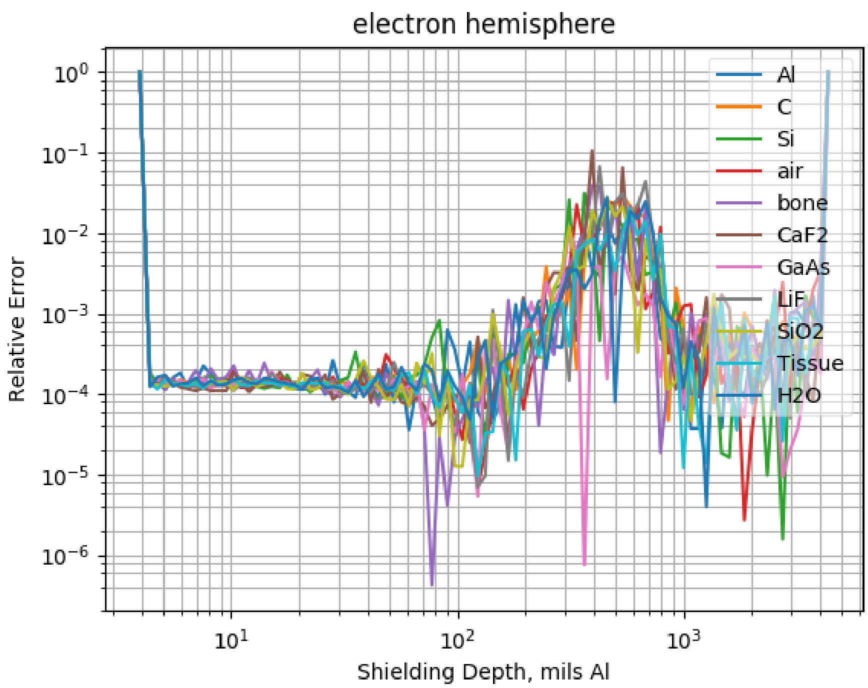

Figure 4. Magnitude of relative differences between SHIELDOSE2 and IRENE dose kernel for electron dose as a function of Al shielding depth, hemispherical geometry, various target materials.

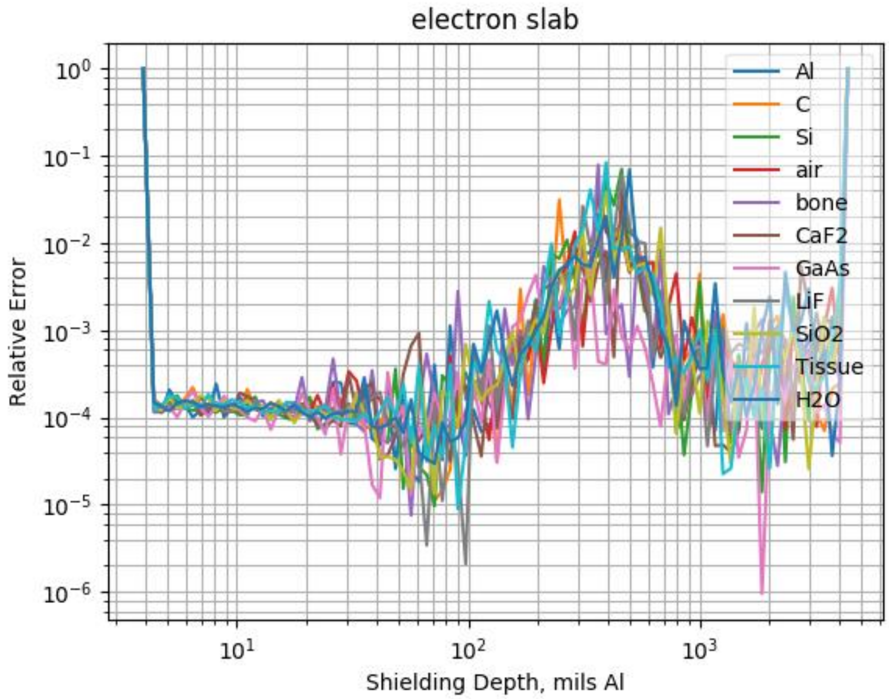

Figure 5. Magnitude of relative differences between SHIELDOSE2 and IRENE dose kernel for electron dose as a function of Al shielding depth, slab geometry, various target materials.

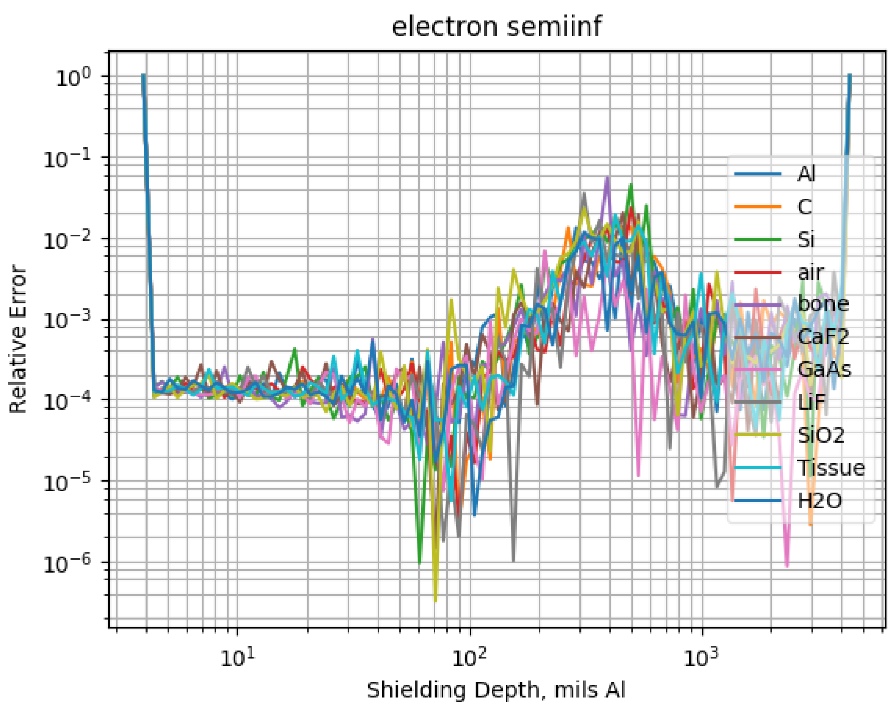

Figure 6. Magnitude of relative differences between SHIELDOSE2 and IRENE dose kernel for electron dose as a function of Al shielding depth, semi-infinite geometry, various target materials.

Discussion

Overall, kernel results are mostly within ~2% of SHIELDOSE2 results, excepting differences of up to 5-10% in electron dose at 300-800 mils Al for all shielding geometries and up to 20-30% in proton dose at 400-3000 mils Al for hemispherical shielding. The differences for proton dose in hemispherical geometry exhibits a bimodal pattern (Figure 1). Figure 7 shows the proton dose vs. depth curves for hemispherical geometry from both SHIELDOSE2 and the IRENE kernel for the simple exponential particle energy spectrum used above. The SHIELDOSE2 results tend to oscillate between two slightly different curves, while the IRENE kernel emulates the upper of the two curves. The large differences in the kernel results thus appear to be linked to non-physical behavior in the SHIELDOSE2 results.

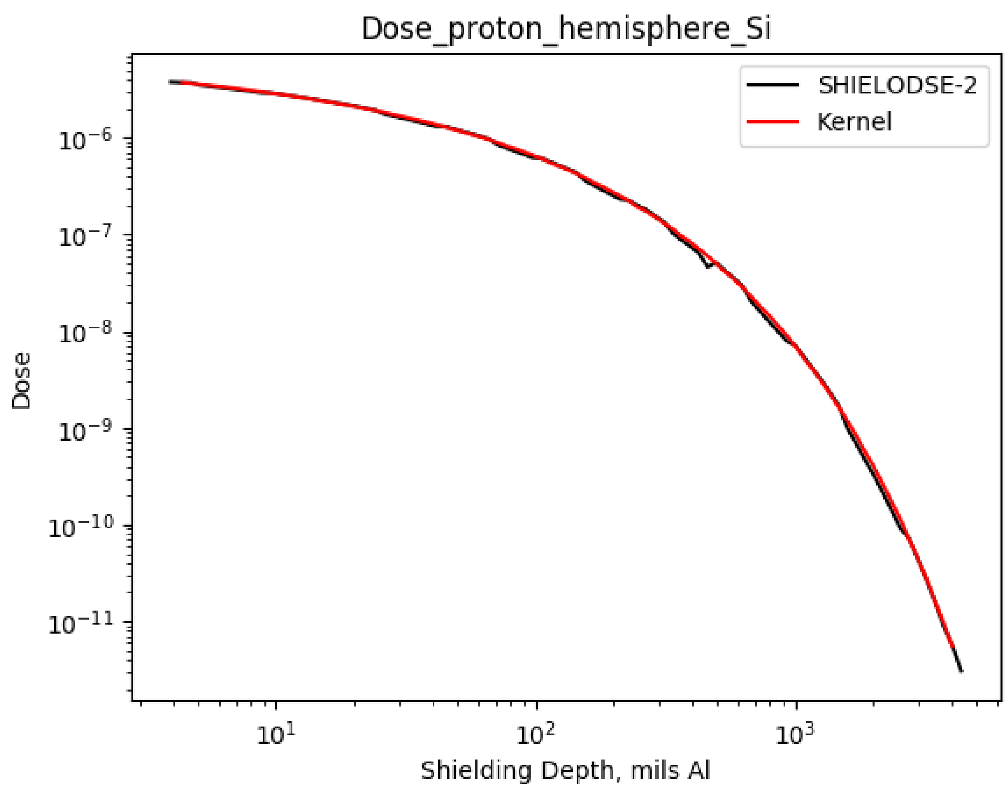

Figure 7. Proton dose vs. shielding depth from SHIELDOSE2 and IRENE dose kernel for hemispherical geometry.

The original SHIELDOSE2 code calculates dose for selected depths based on derivatives of spline fits to slab results and consequently may produce dose results that vary by 10-20% as a result of this approximation [1]. Further, SHIELDOSE2 exhibits significant sensitivity to the set of input depths provided; AE9/AP9 introduces ghost depths to stabilize the SHIELDOSE2 outputs, but this creates a complex interaction with the spline derivatives that may enhance the error factor on spherical dose outputs from SHIELDOSE2. As a result, the spherical kernels for protons were computed without these ghost depth points. In short, given that the SHIELDOSE2 accuracy is of order 10-20%, the performance of the kernels shown here is deemed acceptable. We also note that various SHIELDOSE2 implementations yield results observed to differ generally by less than 5-40% [6]

References

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[2] T. P. O'Brien and B. P. Kwan, "Incorporating radiation effects into AE9/AP9," *IEEE Trans. Nucl. Sci.*, vol. 65, no. 1, pp. 457-461, 2018, doi:10.1109/TNS.2017.2758322.

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