IRENE Kernels – Present and Future

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Overview

- Kernels are precomputed matrices (tables) that convert flux-energy spectrum into linear radiation effects.
- One goal of kernels is to allow one to use the AE9/AP9 machinery to compute statistics and confidence levels on effects (not just fluxes).
- Kernels are “fast”, allowing calculation of worst-case transients by converting every spectrum to its effects, and this can sometimes remove unneeded conservatism.
- Kernels can address linear effects like dose, displacement damage, single event effects, transmitted internal charging current, and even response of a radiation sensor.

Mathematics

- Start with a generic linear radiation effect y (e.g., ionizing dose) that might depend on depth of shielding d, for a given shielding material and geometry.
- The radiation effect is the convolution of the environmental differential flux $j(E)$ and a Green's function $G(E;d)$

$$y(j(E);d) = \int_0^\infty G(E;d)j(E)dE$$

- We can compute the Green's function as the response of the radiation effect to a delta function energy spectrum

$$G(E;d) = y(\delta(E);d) = \int_0^\infty G(E';\mathrm{d})\delta(E'-E)dE'$$

- We use particle transport codes like GEANT4 to compute $G(E;d)$ on a grid of energies E_i and depths d_k.
- It is also possible to deduce the kernel from multiple runs of an existing code like SHIELDOSE2.
- Then we can turn the convolution integral into a matrix-vector operation

$$y_k = \sum_i G(E_i;d_k)j(E_i)\Delta E_i$$

$$\vec{y} = \underline{\underline{K}}\vec{j}$$

$$K_{ki} = G(E_i;d_k)\Delta E_i$$

- The kernel that we store is K_{ki} (or sometimes $G(E_i;d_k)$, computing ΔE_i at runtime).
- At each time step, we interpolate the model spectrum onto the kernel's energy grid and perform the matrix-vector operation.

XML Specification

- Kernels are provided as XML files.
- The kernel specification is given in Aerospace report ATR-2015-02436.

Table 1. Fields of a Kernel XML File (*see text)

Property	Type	Description
<Description>	Free text	A long description of the quantity being produced
<Tag>	Letters, numbers, underscore	A short tag that identifies the kernel for use in generating file names
<Species>	e-/H+/He+/O+	Particle species appropriate for kernel
<EnergyGridMeV>	<Values> or <File>*	The list of energies E_i, in MeV. All energies must be positive
<Output>	three components listed below	
(Output grid)	<Values> or <File>*	A list of values d_n on the output grid
(Output) <GridUnits>	<Units> or <ShieldingMaterial>*	The units of d_n, or the special case of a shielding material (see text)
(Output) <OutputUnits>	Free text	The units of the kernel output
<Transform>	<Values> or <File>*	A transform matrix $\underline{\underline{K}}$ or $\underline{\underline{K}}_>$ (at least one Transform is required)
(Transform)<TransformType>	Diff/Integral	Type of transform
<ApplyDeltaE>	true/false	"true" indicates the differential transform matrix does not already include ΔE_i, so it must be included at run-time.
<OutputInterp>	None/Linear/Log	"None" indicates d_n is a discrete case number and cannot be interpolated. The user will not be given the option to select an alternate output grid at runtime. "Linear" indicates that linear interpolation in d is permitted, and the user will be allowed to specify an alternate output grid. "Log" indicates that the output should be log-interpolated when the user requests a grid other than d_n (linear interpolation will still be used when y at either end of the interpolation is zero).
<Uses>	One or more <Use> entry	
<Use>	Accumulation/Transient	Accumulation indicates that the kernel is appropriate for whole-mission accumulation, such as dose or damage. Transient indicates usable for transient worst case phenomena.
<Version>	Free text	A version identifier for the kernel. Recommend #.#.# format
<DevelInfo>	Free text	A description of who developed the kernel and when
<SchemaVersion>	Integer	Indicates XML schema version number. Version 1 is described in this report. Only the latest version (as defined in the XSD file) is allowed.

What a kernel looks like (Greens' function)

- This proton displacement damage kernel is developed in TOR-2013-00529.
- MULASSIS was used to compute displacement damage for protons at specified incident energies.
- Spherical geometry used.

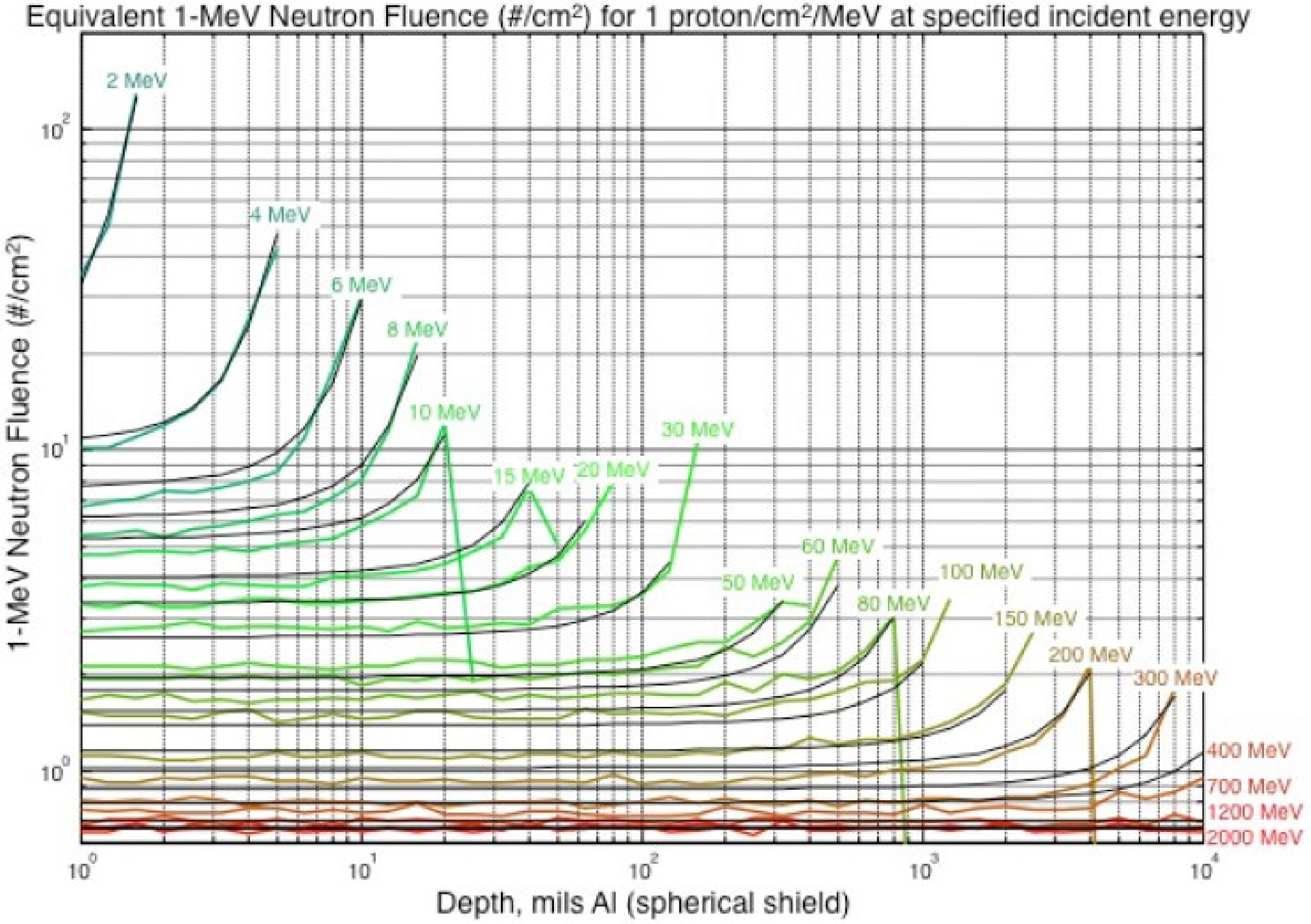

Figure 1. Calculated (color) and fitted (black) impulse response: equivalent 1 MeV neutron fluence to monoenergetic protons.

Kernel in practice

- Compared to the direct MULASIS calculation, which apparently had some poor statistics in some cases, the proton displacement damage kernel produces smoother, more credible results.
- And, of course, the kernel runs much faster.

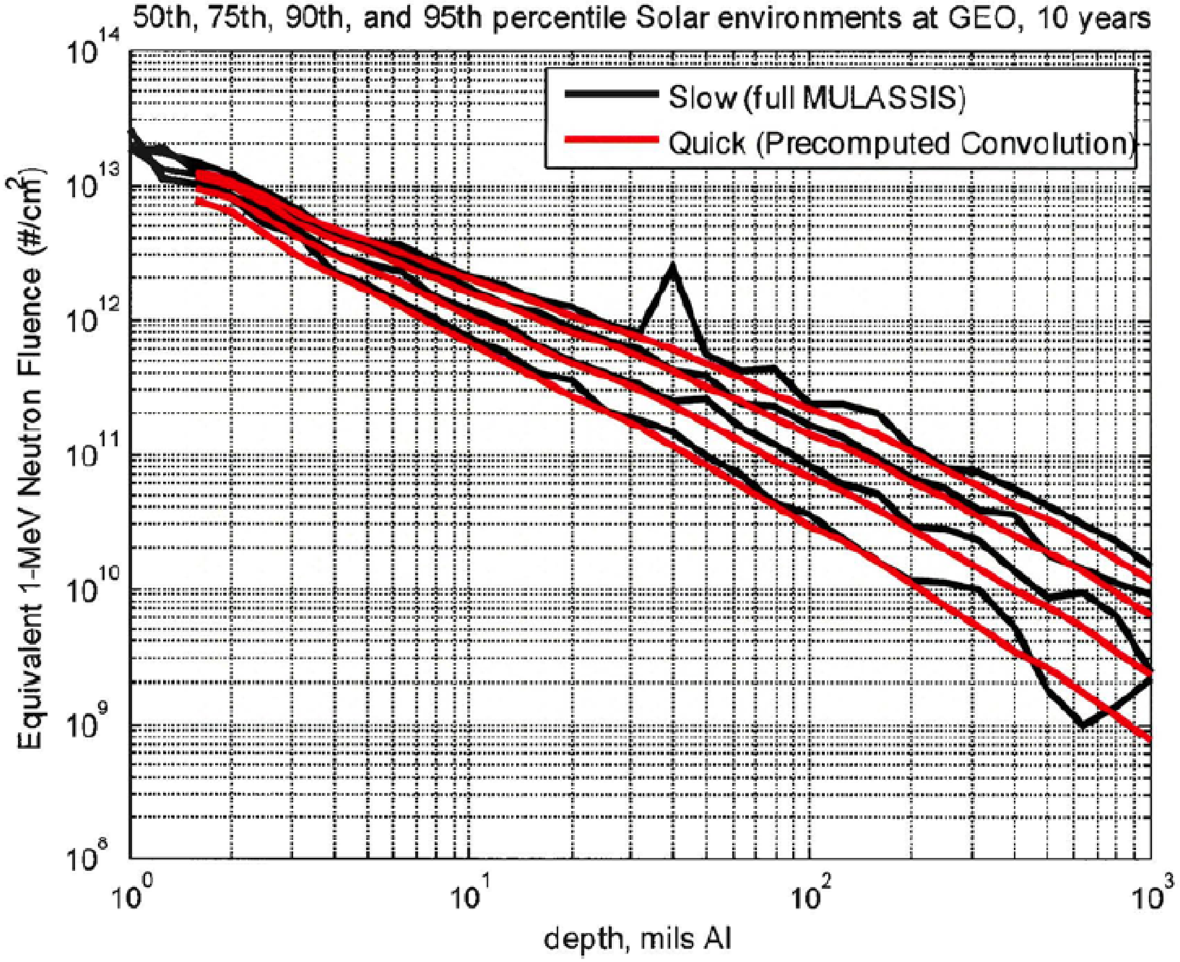

Figure 2. Comparison of full MULASSIS calculation and pre-computed kernel calculation for 4 percentiles of the solar proton environment at geostationary orbit.

From TOR-2013-00529

Planned changes to the kernel specification

- Explicitly exclude time (/s) from output units, time unit will be determined from input spectrum.
- Deprecate the option to accept integral fluxes as inputs (can create undesired negative outputs).
- Deprecate data in external files (makes file management needlessly harder).
- Extend kernel specification to support multiple species:
  - Total dose (ionizing or non-ionizing) from protons and electrons.
  - SEE from protons and heavy ions.
- Support HDF5 and JSON kernel files in addition to XML.
- (Someday) allow for angular dependence.
  - Will require attitude as well as ephemeris.
  - Will likely leverage IRBEM Response Function Library (RFL, https://github.com/PRBEM/IRBEM-extras/tree/main/rfl).

Effects Kernels in v1.55-1.57

- V1.55-1.57 introduces dose vs. depth kernel derived from SHIELDOSE2.
  - These kernels give essentially the same results as SHIELDOSE2 with some improvements in numerical stability.
  - We add a full sphere (4π) to complement the SHIELDOSE2 half sphere (2π) dose.
  - Note: SHIELDOSE2 does not give accurate results for depths <0.1 mm (4 mils) Al equivalent.
- Future kernels that already exist:
  - Shielding material library to use density equivalent for non-Al shielding.
  - Dose vs depth for hollow shell Al shielding.
  - Displacement damage for protons and electrons in Si and GaAs.
  - Proton SEE kernels for spherical Al shielding.
  - Internal charging transmitted electron current.
  - SEE kernels for sphere and slab shielding for protons and heavy ions at https://github.com/PRBEM/IRBEM-extras/tree/main/csda_rpp. (Kernel calculations but not presently able to output kernel files).

Kernel needs

- Dose-depth kernel for thin depths.
    - Covering 2.5 nm – 0.1 mm (10^{-4} – 4 mils) Al equivalent.
    - Addresses plasma effects (10 eV – 200 keV).
    - Also includes heavy ion effects (O^+, He^+).
- Third-party software that outputs kernels for non-idealized geometries. E.g., build/ingest CAD-like representation of component of interest and export kernel for dose, SEE, or penetrating electron current at select internal volumes.

Summary

- We will roll out more kernel capabilities in future “minor” releases, v1.5x, v1.6x.
- We plan to update the kernel XML definition to allow multi-species kernels and other improvements.
- We need to develop some additional effects kernels.
- We would like third-party software tools to start supporting output of kernels.

Bibliography (Aerospace Technical Reports)

- TOR-2013-00529, Using Pre-Computed Kernels to Accelerate Effects Calculations for AE9/AP9: A Displacement Damage Example
- ATR-2015-02436 Specification for Radiation Effects Kernels for Use with AE9/AP9
- TOR-2015-02707 AE9/AP9 Proton Single-Event Effect Kernel Utility
- TOR-2016-01203 AE9/AP9 Internal Charging Kernel Utility—Beam-Slab Geometry Adapted to Hemispherical Shell for Aluminum Shields
- ATR-2016-01756 Developing AE9/AP9 Kernels from Third-Party Effects Codes
- ATR-2016-03268 AE9/AP9 Proton Displacement Damage Kernels (version 2)
- TOR-2017-00514 AE9/AP9 Electron Displacement Damage Kernels
- TOR-2018-02829 An AE9/AP9 Kernel for Ionizing Dose from Electrons Incident on Hollow Aluminum Shells
- ATR-2022-00960 Using Continuous Slowing Down Approximation and the Right Parallel Piped Model to Estimate Single Event Effects Rates (also https://github.com/PRBEM/IRBEM-extras/tree/main/csda_rpp)

- Most of these reports are available at the IRENE web site (https://www.vdl.afrl.af.mil/programs/ae9ap9/tech-docs.php).

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