

AE9/AP9 Proton Single-Event Effect Kernel Utility

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Abstract

The AE9/AP9 proton single-event effects (SEE) kernel utility is a Python application to generate kernel data files that AE9/AP9 can use to estimate single-event effects rates. Each kernel contains all the information needed to convert from proton flux to SEE rate at various depths of shielding for a specific part. The aim is to provide a fast means of computing SEE rates analogous to the dose-depth calculations that are customarily provided by space environment radiation applications. The utility approximates the effects of shielding using the continuous slowing down approximation (CSDA). CSDA neglects the effects of most nuclear interactions and deflection of the particle trajectory, which can be important under some circumstances. Only spherically symmetric, aluminum shielding is supported. Proton SEE cross section data from laboratory testing are often represented in terms of a parameterized Bendel or Weibull shape. The software supports two different parameterizations of the Bendel shape and the standard parameterization of the Weibull shape. The kernel itself is an Extensible Markup Language (XML) file produced by the utility. This report describes the algorithms used by the utility to generate the XML file, validation of the calculations, and limitations of the utility. Future versions of AE9/AP9 will be able to use such kernels to compute instantaneous, worst-case, and mission-averaged SEE rates.

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1. Introduction

While most single-event effect (SEE) considerations focus on heavy ions, protons can also cause single-event effects. A proton SEE specification will account for two different hazards: the probability of an unrecoverable failure over the course of a mission and the peak rate of recoverable upsets during a mission. The peak rate, of course, requires calculation of the instantaneous rate at each time step. Such a calculation must necessarily be fast. The kernel capability being developed for AE9/AP9 encapsulates the precomputed parts of the flux-to-rate calculation so that at runtime the SEE rate can be computed as a matrix-vector operation on the incident flux [e.g., *O'Brien and Kwan*, 2013]. The AE9/AP9 SEE kernel utility generates the kernel for a particular precomputation (that is, a set of proton energies and shielding thicknesses) in the form of a standard Extensible Markup Language (XML) data file [*O'Brien and Whelan*, 2015] that can be used by AE9/AP9 to compute the SEE rate (or any other radiation effect that varies linearly with the exposure).

The calculation of an expected proton SEE rate involves two primary considerations: the SEE cross section of the sensitive part and the effects of shielding on the incident radiation environment [see, e.g., *Tylka et al.*, 1997]. The SEE cross section is typically obtained by laboratory testing, and is often expressed in terms of parameters of an analytical fit to a Bendel or Weibull shape. The effect of shielding is often represented in terms of one or more idealized geometries for aluminum shields. For the AE9/AP9 SEE kernel utility, only spherical shielding geometry will be considered, only with aluminum as the material, and only using the continuous slowing down approximation (CSDA) range approximation to calculate the changes in the incident proton spectrum due to the shield. CSDA neglects most nuclear interactions and the deflection of trajectories as the protons pass through the shield.

In the following sections, we will describe the equations used for the CSDA shielding effects and for the computation of the SEE rate behind shielding. We will then perform some validation against similar (but not identical) calculations in Campbell et al. [2002] and ESA's Space Environment Information System (SPENVIS) tool (www.spENVIS.oma.be).

All of the relevant calculations and the ability to write the AE9/AP9 standard XML file format are provided in a Python utility with a command line interface (see the Appendix) and a programmatic interface (documented in the source code itself following Python conventions).

2. The Degraded Spectrum

We make the following assumptions to calculate the effects of shielding:

- The geometry is spherically symmetric
- The shielding material is aluminum
- Protons traveling through the shield travel in straight lines, losing energy according to the continuous slowing down approximation (CSDA)

The AP9 model will provide the incident flux $j(E)$, and the SEE rate calculation will be performed upon the degraded differential flux $j'(E)$. In general, the degraded differential proton flux $j'(E; T)$ after passing through shielding T is a linear transform of the input differential flux $j(E)$:

$$j'(E; T) = \int_0^\infty j(\tilde{E}) G(E, \tilde{E}) d\tilde{E} \quad (1)$$

Given the CSDA assumption, the Greens function G is a Dirac delta function. In this approximation, a particle has a range before coming to a stop that is a monotonic function of energy, and “uses up” a quantity T of that range when passing through the shield. So, we can write:

$$\rho(E) = \rho(\tilde{E}) - T, \quad (2)$$

where \tilde{E} is the incident energy, E is the degraded energy, and the function $\rho(E)$ provides the range for a particle with energy E . Defining $\mathcal{E}(r)$ as the energy of a proton with range r , we can write the energy change as:

$$E - \mathcal{E}(\rho(\tilde{E}) - T), \quad (3)$$

noting that $\mathcal{E}(r)$ is the functional inverse of $\rho(E)$.

Thus, the Greens function G is given by:

$$G(E, \tilde{E}) = \delta(E - \mathcal{E}(\rho(\tilde{E}) - T)). \quad (4)$$

The integral transform Eq. (1) becomes:

$$j'(E; T) = \int_0^\infty j(\tilde{E}) \delta(E - \mathcal{E}(\rho(\tilde{E}) - T)) d\tilde{E}. \quad (5)$$

Following the integration rule for a delta function, the integral yields

$$j'(E; T) = j(\mathcal{E}(\rho(E) + T)) \left[\frac{d\mathcal{E}}{dr} \Big|_{\rho(E)} \frac{d\rho}{dE} \Big|_{\mathcal{E}(\rho(E)+T)} \right]^{-1}, \quad (6)$$

where we have inverted (3) to obtain $\tilde{E} = \mathcal{E}(\rho(E) + T)$.

We will represent the range r in terms of an areal mass density in g/cm^2 , and energy E in MeV. The areal mass density for any material is the volume mass density (g/cm^3) times the depth of shielding (cm); thus, we can treat other materials in terms of their “Al equivalent” shielding through the areal mass density. The range is related to the energy loss per unit path length (linear energy transfer, stopping power, or dE/dx) of the shielding material as:

$$\frac{d\rho}{dE} \Big|_E = \left(\frac{dE}{dx} \Big|_E \right)^{-1}, \quad (7)$$

where x is the infinitesimal unit of path length in the same units as r . So, dE/dx here has units of $\text{MeV}/(\text{g/cm}^2)$. Combined with the inverse relation between $\mathcal{E}(r)$ and $\rho(E)$, we have:

$$\left(\frac{d\mathcal{E}}{dr} \Big|_r \right)^{-1} = \frac{d\rho}{dE} \Big|_{\mathcal{E}(r)} = \left(\frac{dE}{dx} \Big|_{\mathcal{E}(r)} \right)^{-1}. \quad (8)$$

We can then write the degraded flux equation in terms of dE/dx :

$$j'(E; T) = j(\mathcal{E}(\rho(E) + T)) \frac{dE}{dx} \Big|_{\mathcal{E}(\rho(E)+T)} \left(\frac{dE}{dx} \Big|_E \right)^{-1}. \quad (9)$$

Because we are working with an assumption of spherical symmetry, the flux is assumed to be omnidirectional (i.e., integrated over all angles of incidence), with units of $\text{protons/cm}^2/\text{s/MeV}$.

We obtain our proton range and stopping power data from the International Commission on Radiation Units and Measurements [ICRU, 1993] via the National Institute for Standards and Technology (NIST): <http://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html>. We fit the range-energy relationship to a polynomial in the natural logarithms:

$$\begin{aligned} \ln \rho(E) = & -1.7983558262 + 7.2651699506 \left(\frac{\ln E}{10} \right)^5 \\ & - 3.5612924583 \left(\frac{\ln E}{10} \right)^4 - 7.4063042782 + 10.374405759 \left(\frac{\ln E}{10} \right)^2 \\ & + 14.349695292 \frac{\ln E}{10} - 5.5320017771 \end{aligned} \quad (10)$$

Likewise, we fit the stopping power provided by NIST to a polynomial (which is numerically more stable than differentiating $\ln \rho(E)$):

$$\begin{aligned} \ln \frac{dE}{dx} = & -17.189630021 \left(\frac{\ln E}{10} \right)^8 + 2.7598574128 \left(\frac{\ln E}{10} \right)^7 + 28.988372718 \left(\frac{\ln E}{10} \right)^6 \\ & -9.8627436495 \left(\frac{\ln E}{10} \right)^5 - 8.2584740968 \left(\frac{\ln E}{10} \right)^4 + 10.728698885 \\ & -6.1115303798 \left(\frac{\ln E}{10} \right)^2 - 6.1639217537 \frac{\ln E}{10} + 5.1507890113 \end{aligned} \quad (11)$$

The domain of applicability for both of these fits is 10^{-3} to 10^4 MeV.

Because we will perform later interpolations in terms of range rather than energy, we introduce the concept of differential flux at a given *range* as:

$$\hat{j}(r) = j(\mathcal{E}(r)). \quad (12)$$

Thus, we can write the degraded spectrum as:

$$\hat{j}'(r; T) = \hat{j}(r + T) \left. \frac{dE}{dx} \right|_{\mathcal{E}(r+T)} \left(\left. \frac{dE}{dx} \right|_{\mathcal{E}(r)} \right)^{-1}. \quad (13)$$

3. Proton Single-Event Effect Rate

The proton single-event effect rate U behind shielding T is given by:

$$U(T) = 4\pi \int_{E_0}^{\infty} j'(E; T) \sigma(E) dE, \quad (14)$$

where U has units of upsets/bit/s (or latchups/bit/s, etc.), E_0 is the minimum energy (MeV) required to cause an SEE in the part, $j'(E; T)$ is the degraded spectrum in units of protons/cm²/s/MeV, and $\sigma(E)$ is the upset cross section in cm²/bit. The cross section is given by one of two formulae: Bendel or Weibull.

The two-parameter Bendel cross section is [Stapor *et al.*, 1990]:

$$\sigma(E) = \begin{cases} \sigma_{lim} \left[1 - \exp \left(-0.18 \sqrt{E - E_0} \left(\frac{18}{E_0} \right)^{1/4} \right) \right]^4 & E > E_0 ; \\ 0 & \text{otherwise} \end{cases} \quad (15)$$

The threshold energy E_0 is in MeV, and the limiting cross section σ_{lim} is in cm²/bit. We have chosen this form to highlight the similarity with the Weibull shape. However, conventionally E_0 is denoted A and σ_{lim} is provided implicitly by a second parameter B , with units of MeV:

$$\sigma_{lim} = 10^{-12} \left(\frac{B}{A} \right)^{14}. \quad (16)$$

The four-parameter Weibull cross section is [Petersen *et al.*, 1992]:

$$\sigma(E) = \begin{cases} \sigma_{lim} \left[1 - \exp \left(- \left(\frac{E - E_0}{W} \right)^S \right) \right] & E > E_0 ; \\ 0 & \text{otherwise} \end{cases} \quad (17)$$

The threshold energy E_0 is in MeV, the limiting cross section σ_{lim} is in cm²/bit, the width W is in MeV, and the shape S is dimensionless.

The choice of cross section type and the fit parameters E_0 , σ_{lim} , W , and S are determined from laboratory data. For the purposes of the AE9/AP9 SEE kernel utility, the parameters are required to be provided by the user (see Appendix).

4. Calculating the Kernel

The SEE kernel itself evaluates Eq. (14) numerically for a variety of shielding depths given the cross section shape and fit parameters. The user may specify both the incident energy grid (with N points) and the output shielding grid (with M points). The user may specify linearly spaced grids, logarithmically spaced grids, a logarithmic grid that also includes zero, or even a simple list of values to use as a grid. The shielding grid may also be provided in length units of cm, mm, or mils, rather than areal density, and the utility will convert to areal density using an Al mass density of 2.7 g/cm^3 .

At a high level, the kernel can be thought of as the matrix \underline{A} in a matrix-vector equation:

$$\vec{U} = \underline{A}\vec{j}. \quad (18)$$

In this equation, the upset rate is specified on a grid of depths T_i :

$$U_i = U(T_i). \quad (19)$$

The incident flux is given on a grid of energies E_k :

$$j_k = j(E_k) = \hat{j}(\rho(E_k)). \quad (20)$$

The kernel matrix \underline{A} is then built to achieve:

$$U(T_i) = \int_{E_0}^{\infty} j'(E; T_i) \sigma(E) dE \approx \sum_k A_{ik} j_k. \quad (21)$$

To compute A_{ik} , we must include the estimate of $j'(E; T)$ from $j(E)$ as another weighted sum (a linear interpolation):

$$\int_{E_0}^{\infty} j'(E; T_i) \sigma(E) dE \approx \sum_{k'} \sigma(E_{k'}) j'_{ik'} \Delta E_{k'} \approx \sum_k A_{ik} j_k \quad (22)$$

$$j'_{ik'} = j'(E_{k'}; T_i) = \hat{j}'(\rho(E_{k'}); T_i) \approx \sum_k j_k \left. \frac{dE}{dx} \right|_{E_k} \left(\left. \frac{dE}{dx} \right|_{E_{k'}} \right)^{-1} v_{k'k;i} = D_{k'k;i} j_k \quad (23)$$

$$D_{k'k;i} = \left(\left. \frac{dE}{dx} \right|_{E_{k'}} \right)^{-1} \sum_k \left. \frac{dE}{dx} \right|_{E_k} v_{k'k;i}, \quad (24)$$

where $\Delta E_{k'}$ is a trapezoidal integration weight, and $v_{k'k;i}$ is an interpolating function:

$$\Delta E_{k'} = \begin{cases} \frac{E_2 - E_1}{2} & k' = 1 \\ \frac{E_N - E_{N-1}}{2} & k' = N \\ \frac{E_{k'+1} - E_{k'-1}}{2} & \text{otherwise} \end{cases} \quad (25)$$

$$v_{k'k;i} = v(E_{k'}, E_k; T_i) = \begin{cases} \frac{r_{k'} + T_i - r_{k-1}}{r_k - r_{k-1}} & r_{k-1} < r_{k'} + T_i \leq r_k \\ \frac{r_{k+1} - r_{k'} - T_i}{r_{k+1} - r_k} & r_k \leq r_{k'} + T_i < r_{k+1}, \\ 0 & \begin{matrix} r_{k'} + T_i < r_1 \\ r_{k'} + T_i > r_N \end{matrix} \\ \text{otherwise} \end{cases} \quad (26)$$

$$r_k = \rho(E_k) \quad (27)$$

$$r_{k'} = \rho(E_{k'}) \quad (28)$$

Note that interpolation is done in the range domain: interpolating flux from incident range r_k onto degraded range $r_{k'}$, where r_k and $r_{k'}$ are points on the same grid. The logic is that a particle with degraded range $r_{k'}$ must have had incident range $r_{k'} + T$. Because $r_{k'} + T$ will not usually correspond exactly to the incident ranges r_k , it is necessary to interpolate. (It is also possible to simply define a special $r'_{k'}$ degraded range grid as the incident grid offset by T ; however, this approach is numerically less stable, especially near energies that just barely make it through the shield). We note that the interpolation treats the incident flux above the last energy grid point as zero, which is usually reasonable for a steeply falling spectrum.

Putting it all together we have:

$$U(T_i) \approx \sum_{k'} \sigma(E_{k'}) \Delta E_{k'} \left(\frac{dE}{dx} \Big|_{E_{k'}} \right)^{-1} \sum_k \frac{dE}{dx} \Big|_{E_k} v_{k'k;i} j_k \approx \sum_k A_{ik} j_k. \quad (29)$$

So the matrix \underline{A} is:

$$A_{ik} = \sum_{k'} \sigma(E_{k'}) \Delta E_{k'} \left(\frac{dE}{dx} \Big|_{E_{k'}} \right)^{-1} \sum_k \frac{dE}{dx} \Big|_{E_k} v_{k'k;i}. \quad (30)$$

5. Validation

We will perform two validations. We will compare the degraded spectrum in a paper by Campbell et al. [2002; CEA02 hereafter] to that produced by the kernel using only CSDA. Then we will compare the SPENVIS and kernel SEE rates for two different electronic parts at different shielding depths.

We compute the degraded spectrum behind several depths of aluminum for an incident trapped proton spectrum from CEA02. We manually digitized the incident and degraded spectra from Figure 4 of CEA02. Figure 1 shows the comparison between the CEA and kernel (CSDA) methods. Considering that the CEA02 spectra were manually digitized from a figure, the agreement with CSDA is acceptable.

Next, we move on to the comparison of actual SEE rates between the kernel and SPENVIS, for a long-term solar proton spectrum. Figure 2 shows the comparison for two parts chosen from the SPENVIS library [Petersen, 1998]. The IBM 6M DRAM has Bendel parameters $A=5$, $B=3.1$, both in MeV. The TC514100 DRAM has Bendel parameters $A=22$, $B=19.9$ MeV. The figure shows that at all shielding depths, the two calculations agree very well.

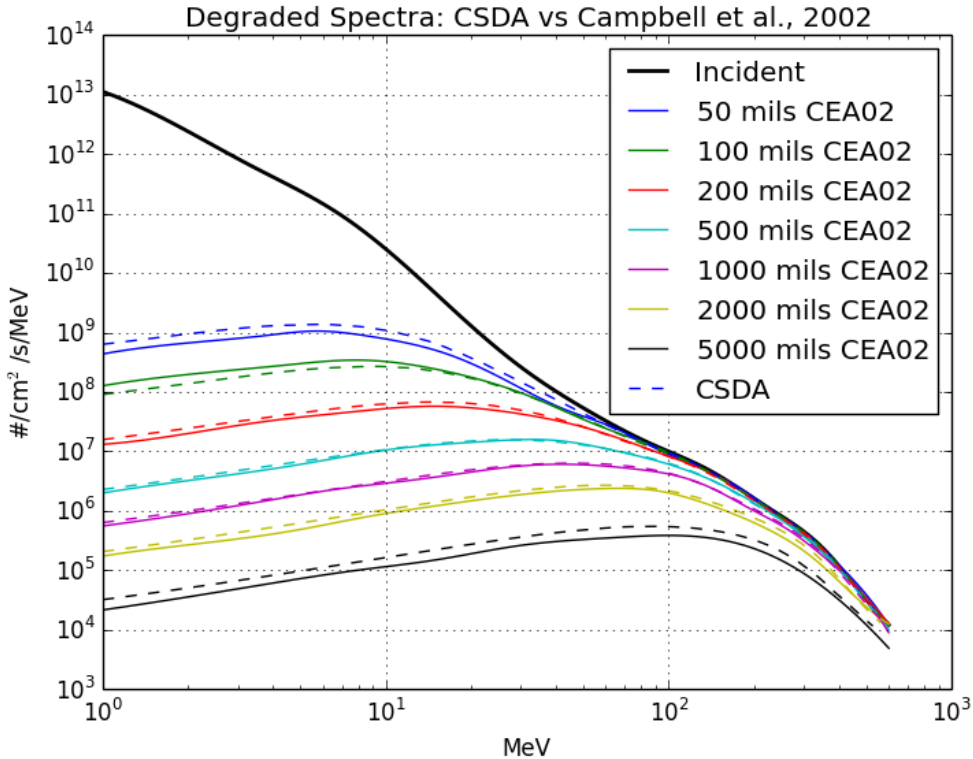


Figure 1. Comparison of Campbell et al. [2002] (solid lines, CEA02) and CSDA (dashed lines) degraded spectra for two different shielding depths, mils Al.

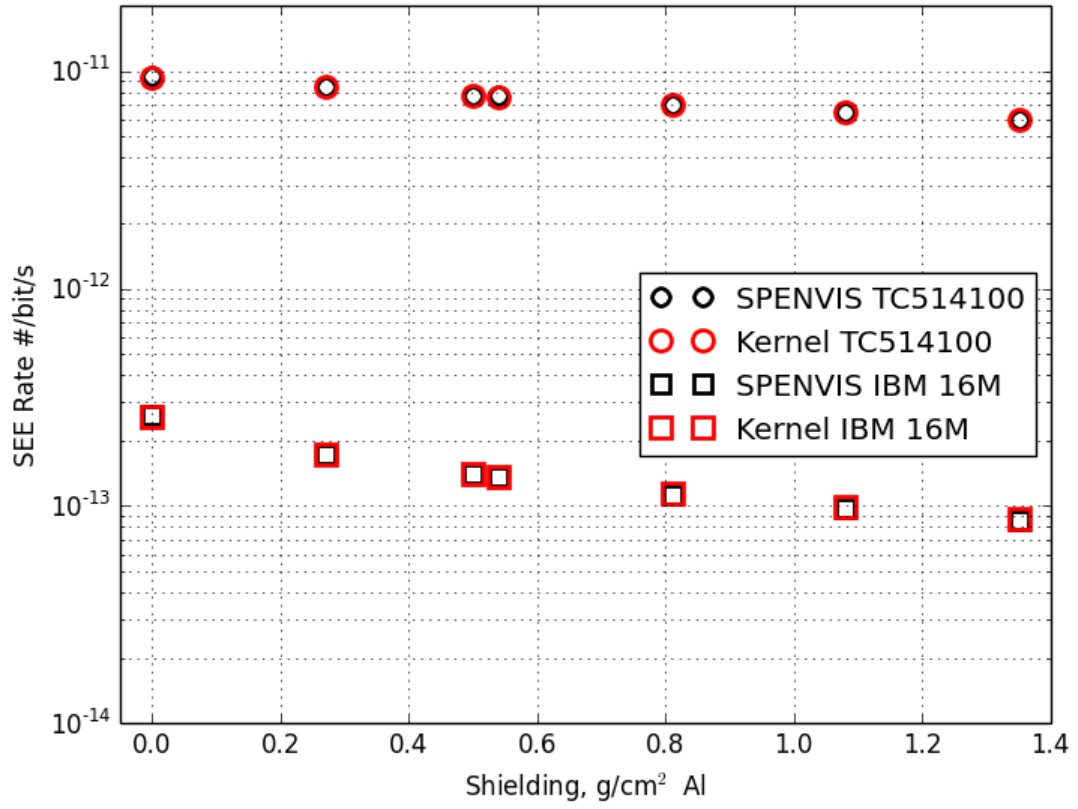


Figure 2. SEE rate computed by SPENVIS and the kernel for two parts.

6. Summary

We have described a utility for generating AE9/AP9 kernels that provide a proton SEE rate calculation. The kernel utility accounts for spherical aluminum shielding of arbitrary thickness and accommodates SEE cross sections specified as either Bendel or Weibull shapes. The kernels can, in turn, be used by the AE9/AP9 code to convert from flux to SEE rate at various shielding depths, and can, thereby, utilize the dynamics and statistical machinery of AE9/AP9 to support orbit trade studies and first-order shielding analysis. Thus, in addition to producing mean and worst-case specifications of proton flux, AE9/AP9 would be able to produce mean and worst-case specifications of SEE rate for selected parts.

Because the kernel utility uses the CSDA approximation, it does not account for most nuclear interactions in the shielding, which can modify the degraded spectrum used for the SEE rate calculation. Nonetheless, the degraded spectra match a published example at depths from 50 mils to 2000 mils Al. Likewise, the computed SEE rates agree with SPENVIS very well at depths from 0 to 1.4 g/cm².

We note that it would certainly be possible in the future to use a more sophisticated tool to pre-compute the nuclear effects of shielding and incorporate those into the utility and the kernel. Such a change would affect the polynomials used in the kernel utility, and would change the numbers in the kernel files generated by the utility. However, such a change would be seamless from the perspective of how AE9/AP9 interacts with the kernel.

Because the AE9/AP9 kernel utility produces its output in units of areal mass density (g/cm²) of aluminum, it is possible to approximate the effects of other shielding materials. The equivalent aluminum shielding for a given thickness of another material can be computed by converting to areal mass density, and the kernel can then be used by assuming interactions are equivalent to those in the same areal mass density of aluminum. This approximation is quite common and should be generally acceptable for orbit trade studies. The kernel utility does not do the material conversion; rather, the conversion will be done at run time by the AE9/AP9 application.

SEE rates are more susceptible to nuclear interactions than are some other effects, such as ionizing dose. The CSDA and Al-equivalence approximations are not always robust enough to replace a specialized SEE rate calculation code like CREME (Cosmic Ray Effects on Micro-Electronics) [Tylka *et al.*, 1997; Marcus *et al.*, 2012]. Further, the kernel approach does not (presently) allow for angular dependence of the incident flux, and the angular dependence of the proton SEE rate remains an open research area. While the proton SEE kernels are suitable for orbit trade studies and shielding studies, they should be spot checked with more sophisticated tools like CREME when generating radiation environment specifications. This is especially important if elements heavier than silicon are in close proximity to the sensitive volumes in the parts.

7. References

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Appendix—SEE Rate Utility Command-Line Interface

The AE9/AP9 SEE rate utility creates an XML kernel file for use with AE9/AP9. A cross section and a tag are required. Options are available to specify the shielding grid and the primary proton energy grid. The utility can be invoked on the command line as:

```
python ae9ap9_see_kernel.py arguments
```

Here, *arguments* represents one or more user-supplied options.

Special arguments:

- help print this help message
- test run a predefined test

Normally required command line arguments (user supplied-values in *italics*):

Specifying the cross section:

- BendelAB=*A*, *B* specify Bendel shape with parameters *A*, *B*
- BendelAslim=*A*, σ_{lim} specify Bendel shape with parameters *A*, σ_{lim}
- Weibull=*E₀*, σ_{lim} , *W*, *S* specify Weibull shape

Exactly one cross section option is required

A and *E₀* are the energy threshold in MeV

B is the second Bendel parameter in MeV

σ_{lim} is the limiting cross section in cm²/bit, $\sigma_{lim} = 10^{-12}(B/A)^{14}$

W is the energy scale factor for the Weibull in MeV

S is the shape parameter for the Weibull

Specifying the kernel Tag:

```
--Tag=tag
```

The kernel tag cannot have spaces or special characters

Exactly one tag option is required. The tag is used by AE9/AP9 to generate filenames when saving kernel outputs.

Optional command line arguments:

Specifying the output file name (optional):

```
--xmlfile=filename
```

The filename can be a local file or it can include a full path as well

If the filename is not specified, then one is created by appending ".xml" to the *tag*

Specifying the shielding grid (optional):

```
--Tgrid=first:last/N first to last in N evenly spaced steps
```

```
--Tgrid=first:last/N/log first to last in N logarithmically spaced steps
```

```
--Tgrid=first:last/N/0log zero followed by first to last in N-1 logarithmic steps
```

```
--Tgrid=first:step:last first to last with specified step size (last may not be included)
```

```
--Tgrid=first,second,third,...,last complete list of grid points
```

At most one --Tgrid option is allowed

The default is --Tgrid=0.01:7/30/0log

Specifying the shielding unit (optional):

```
--Tunit=milsAl mils Al
```

```
--Tunit=cmAl cm Al
```

```
--Tunit=mmAl mm Al
```

```
--Tunit=g/cm2 g/cm2 areal density
```

At most one --Tunit option is allowed

The default is --Tunit=g/cm2

Specifying the energy grid in MeV (optional):

- `--Egrid=first:last/N` first to last in *N* evenly spaced steps
- `--Egrid=first:last/N/log` first to last in *N* logarithmically spaced steps
- `--Egrid=first:step:last` first to last with specified *step* size (last may not be included)
- `--Egrid=first,second,third,...,last` complete list of grid points

Arguments follow same format as `--Tgrid`, except there is no `0log` option

At most one `--Egrid` option is allowed

The default is `--Egrid=1:1E3/50/log`

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