Solar Cell Displacement Damage Testing Using Co-60 Gamma Rays

2025 Space Power Workshop

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May 1, 2025

Outline

- ***Motivation/Purpose***
- ^{60}Co Gamma Ray Interactions in Matter
- Ionizing vs. Nonionizing Energy Deposition
  - Dose equilibrium conditions
- Ground Testing Impacts and Recommendations
- Summary

Space PV Standards

- AIAA S-111A (currently in revision)
  - Suggests 3 electron energies (0.6, 1.0, 5.0 MeV) and corresponding fluences to produce degradation curves to allow for equivalent fluence (JPL) or DDD analyses

Table 2 — Electron energies and fluences*

Energies (MeV)	Fluences (number of electrons per square centimeter)					
.6	$2x10^{13}$	$2x10^{14}$	$1x10^{15}$	$2x10^{15}$	$4x10^{15}$	
1.0	$3x10^{13}$	$1x10^{14}$	$5x10^{14}$	$1x10^{15}$	$3x10^{15}$	$1x10^{16}$
5.0	$4x10^{12}$	$1x10^{13}$	$4x10^{13}$	$1x10^{14}$	$4x10^{14}$	

*These energies and fluences are recommended except for the fluence of ≥ 1×10^{16} 1 MeV electrons, which is required.

- ECSS-E-ST-209-80C (2023)
  - Only requires 1 MeV electrons

Can we use ^{60}Co gamma rays as a 1 MeV electron surrogate if we understand the physics enough?

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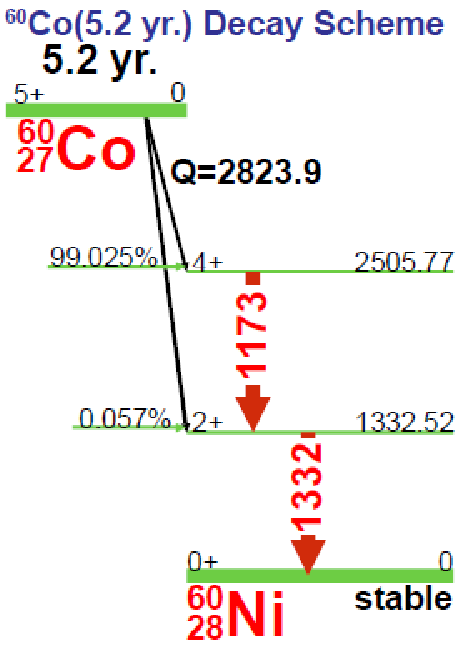
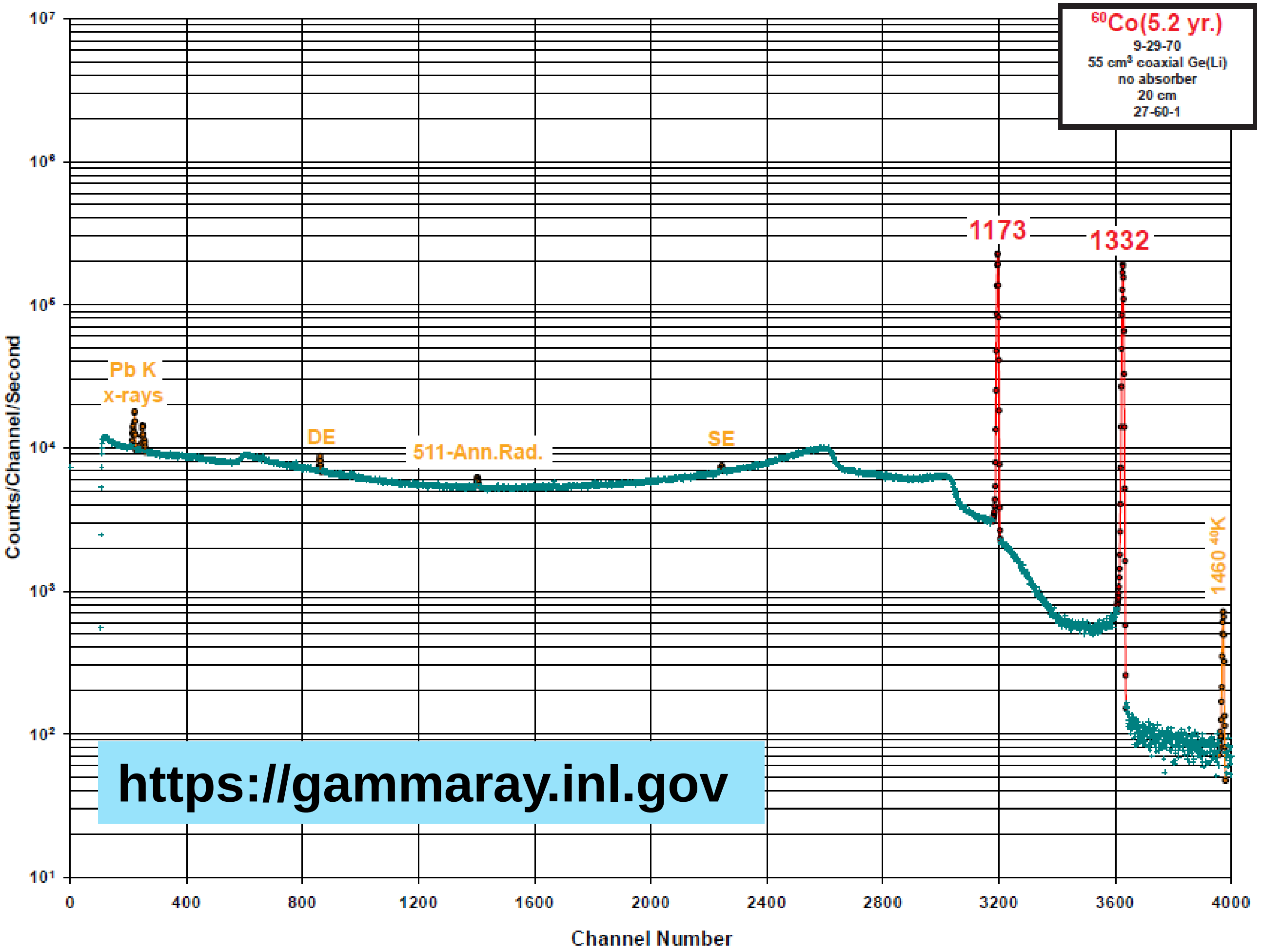
^{60}Co Gamma Ray Analyses

^{60}Co Gamma Spectrum

(2 Gamma Rays: 1.173 MeV & 1.332 MeV) - Commonly represented as single gamma @ 1.25 MeV





Gamma Ray Interactions in Matter

- Gamma rays have ***no mass and no charge***, however they interact with matter to produce secondary *electrons* which can transport and induce TID & DDD in devices

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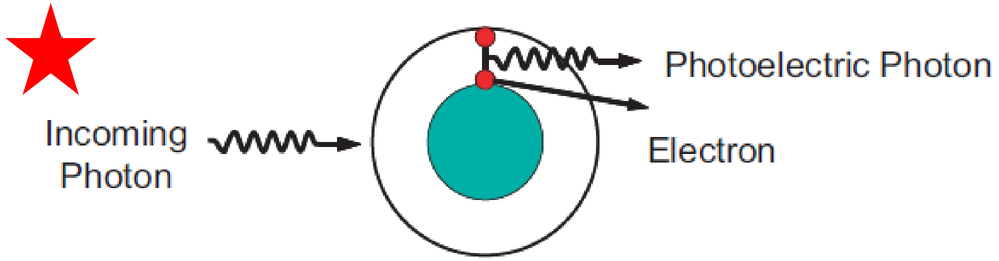
  - **Photoelectric Effect**
    - **Emission of electrons from EM radiation**
    - **Dominates at low energies (~Z^4/E^3 dependence)**



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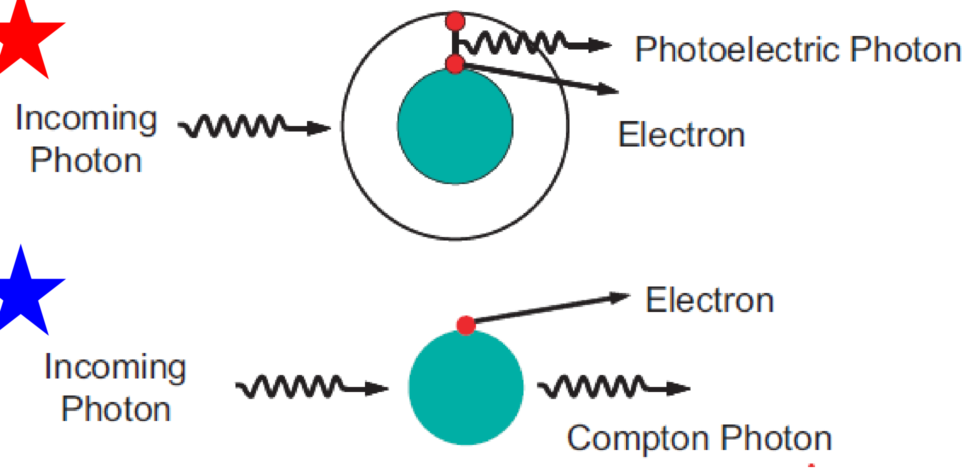
    - **QM elastic scattering of loosely-bound, outer-shell electrons from EM radiation**
    - **Dominates intermediate energies (~Z dependence)**



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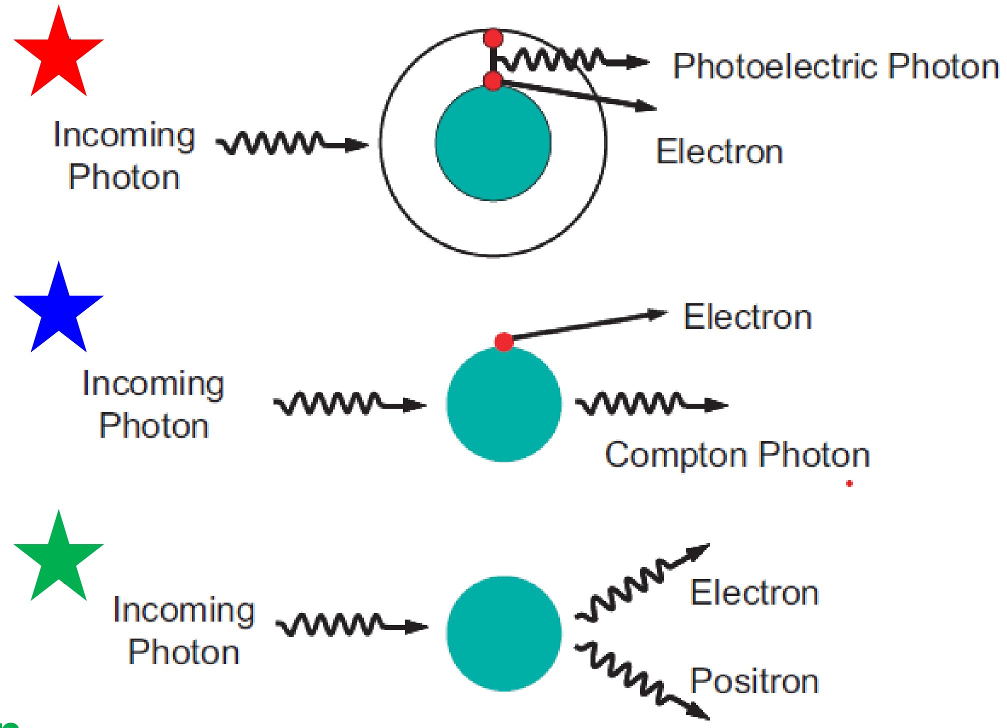
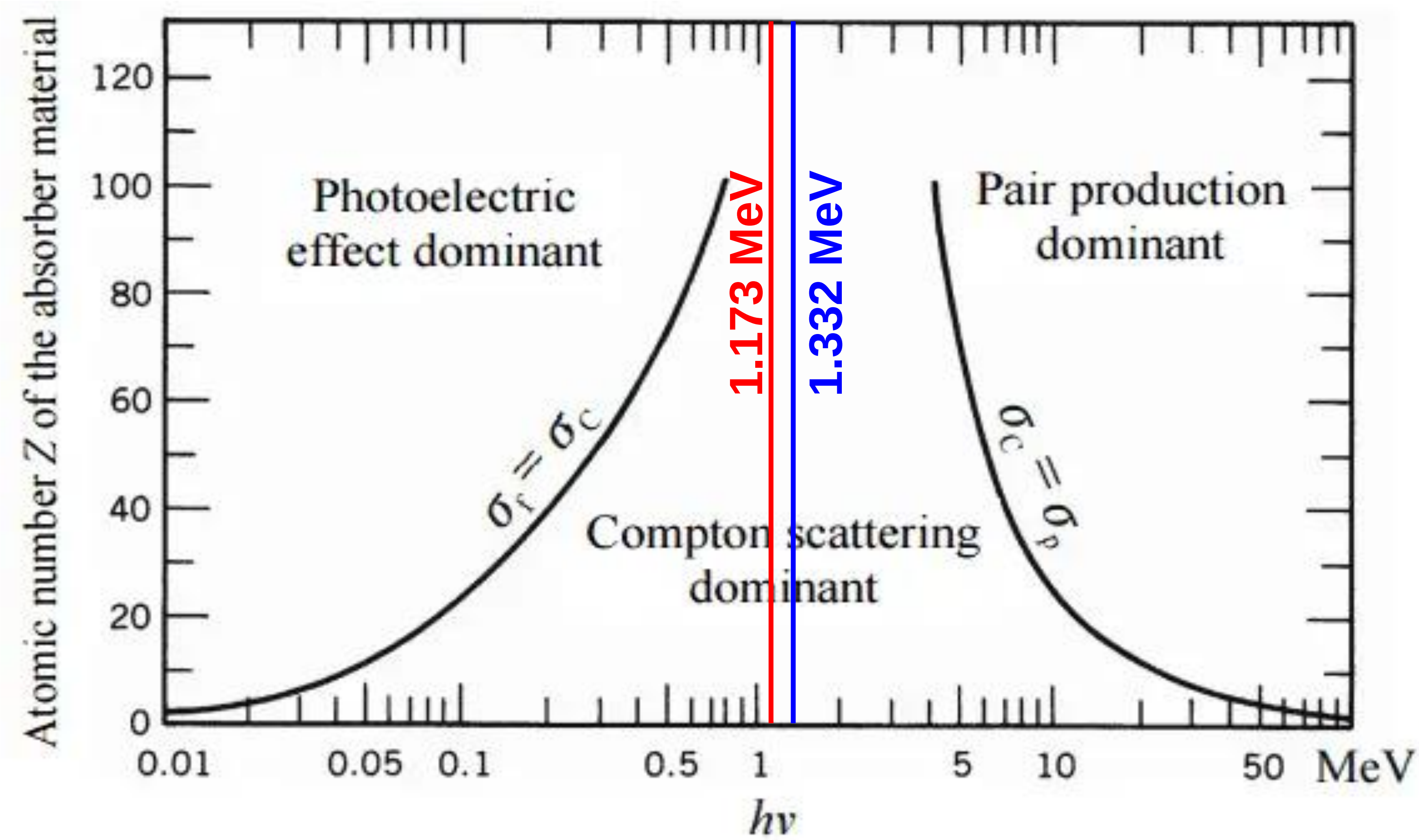
    - **Dominates intermediate energies (~Z dependence)**
  - **–Pair Production**
    - **Electron-positron production**
    - **Dominates @ high enery (~Z^2 dependence)**
    - **Need minimum energy of 1.02 MeV to cause interaction**



^{60}Co gamma rays are heavily used (high and low dose rate) in radiation effects TID testing

Gamma Ray Interactions in Matter

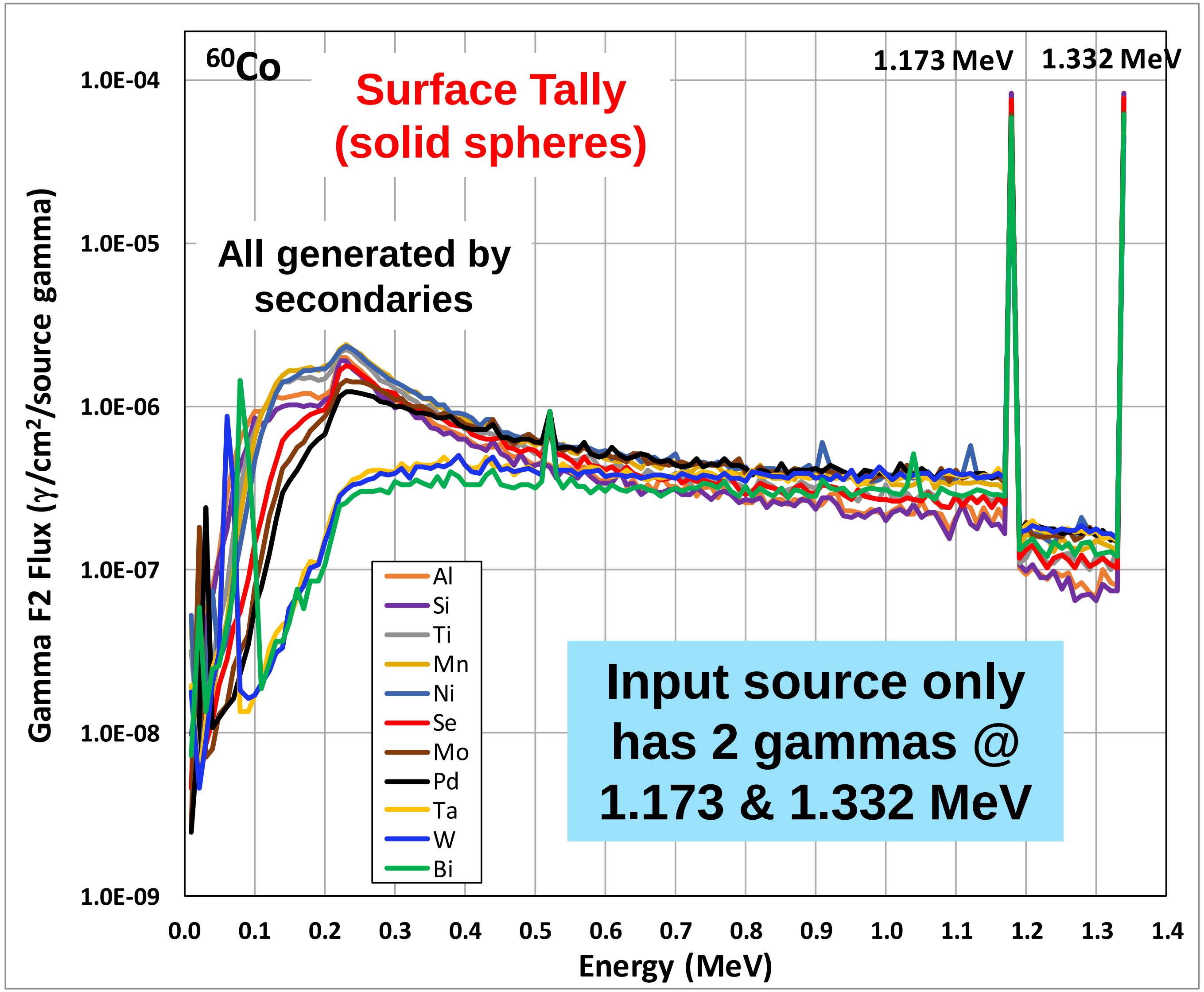


Photon cross sections available via NIST XCOM

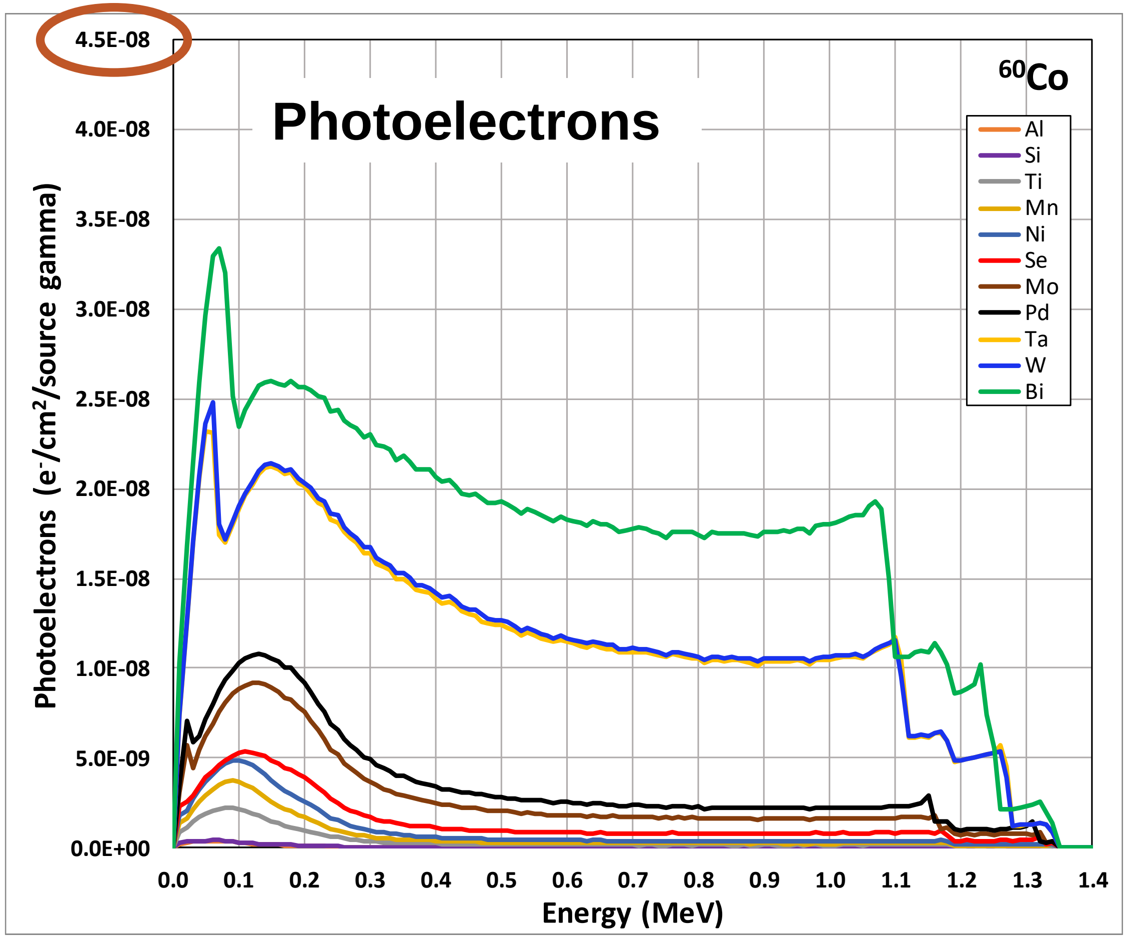
^{60}Co Gamma Ray Analyses – MCNP Simulations

MCNP6 Source Definition

```
c Co60 surface source
c
sdef par=p x=d1 y=d2 z=0 vec=0 0 1 erg=d4 sur=1.6
si1 -50 50
sp1 0 1
si2 -50 50
sp2 0 1
si4 L 1.173 1.332
sp4 D 1 1
```



^{60}Co Gamma Ray Analyses – MCNP Electron Generation



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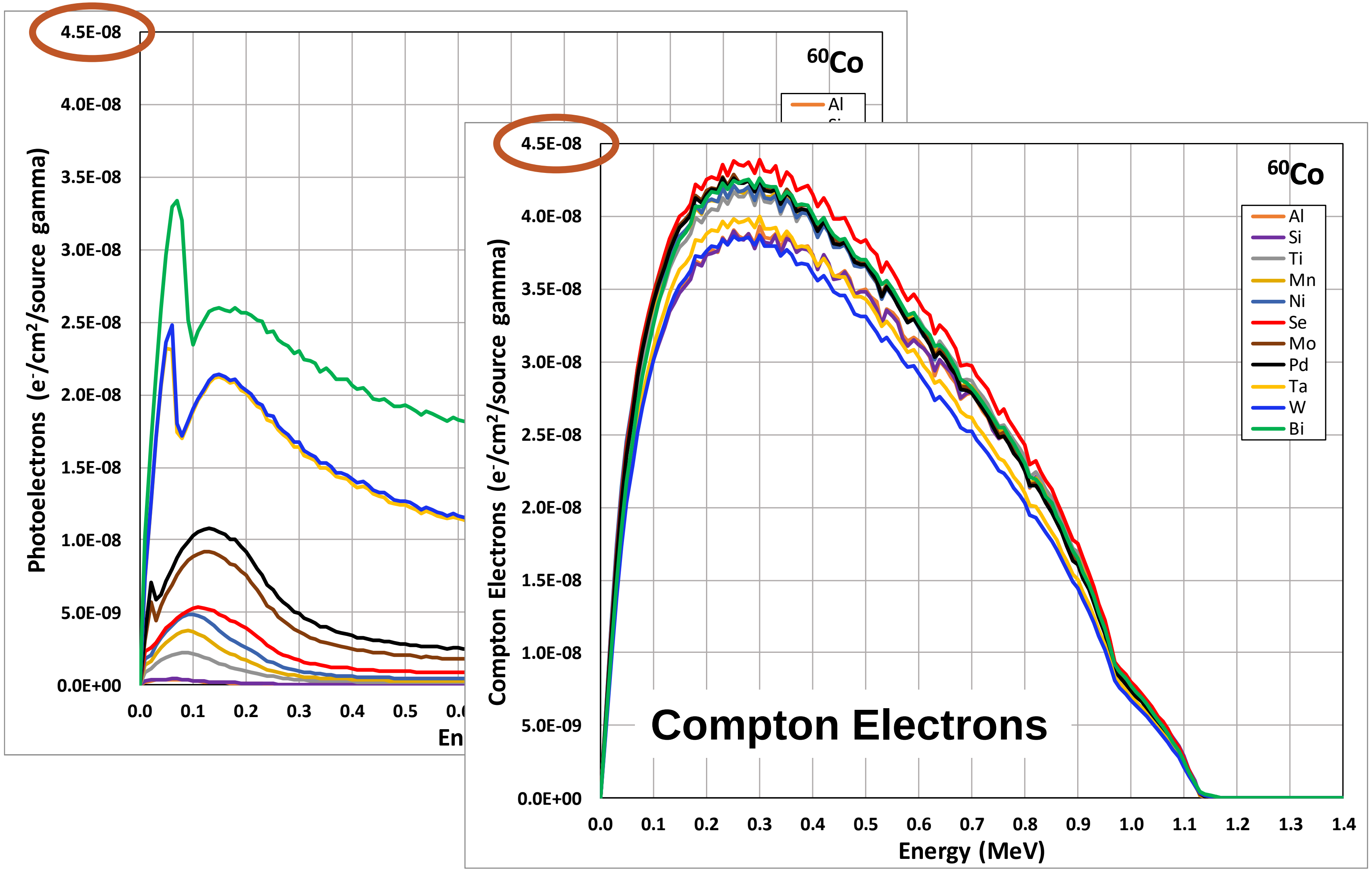

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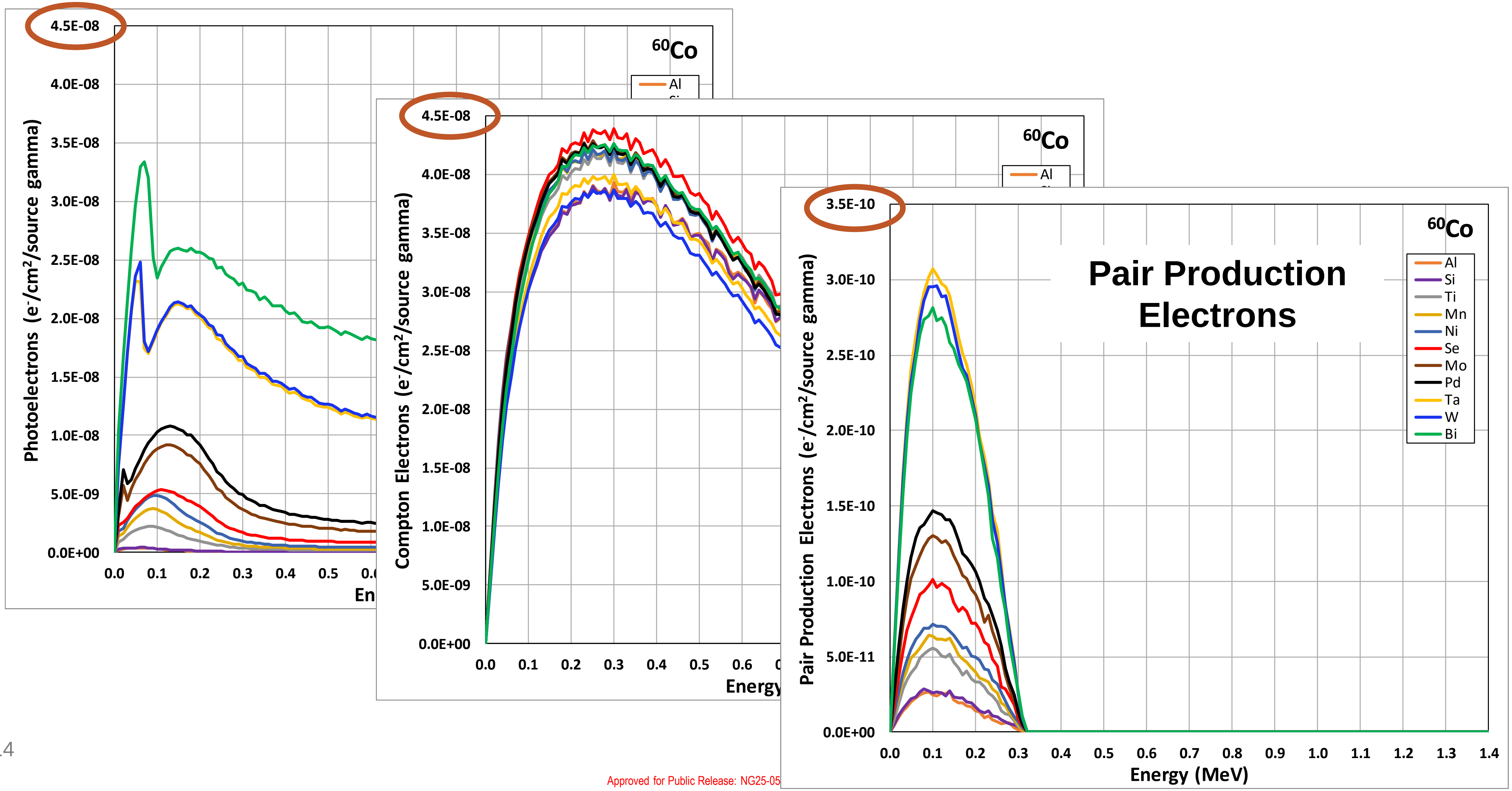
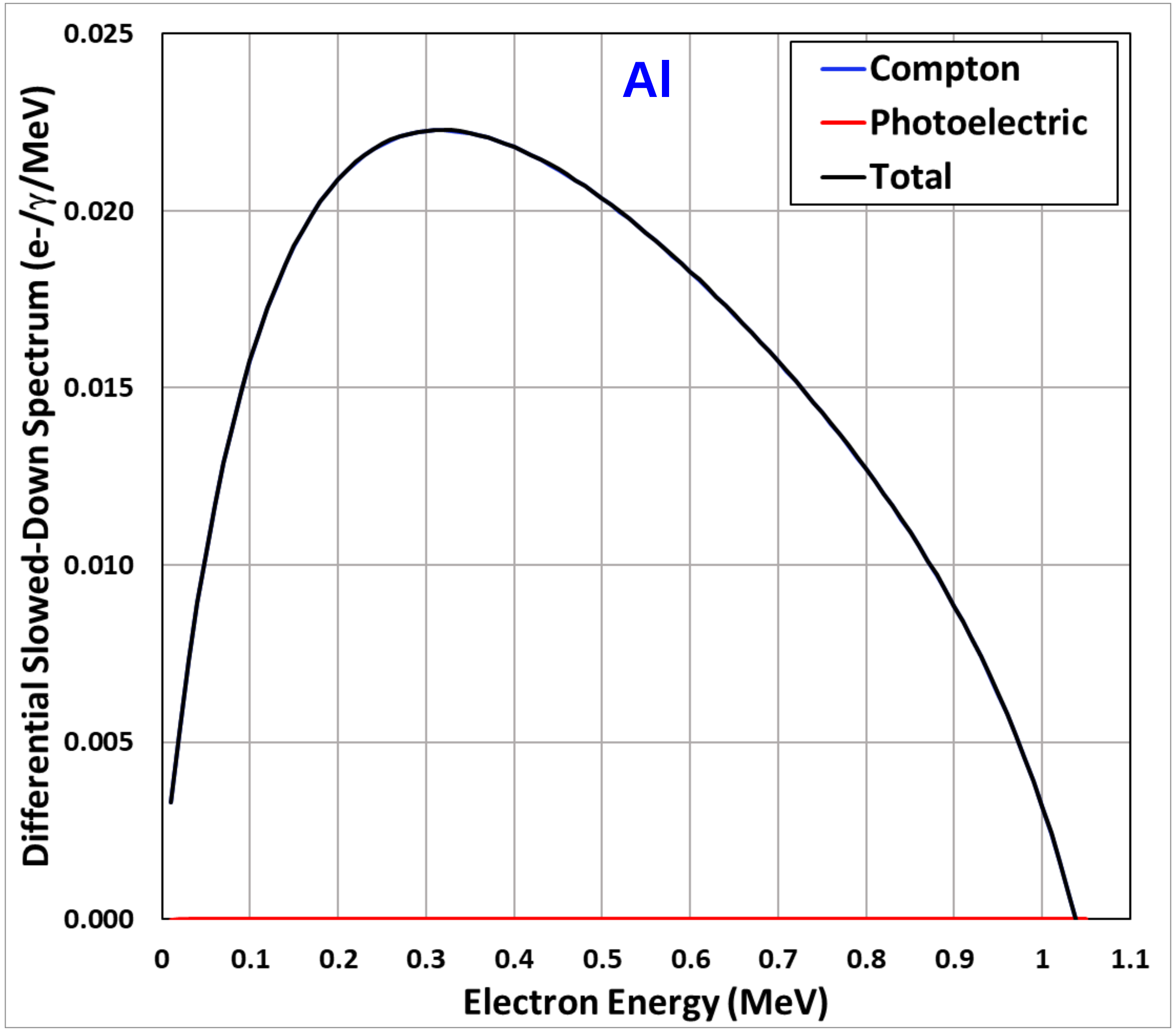
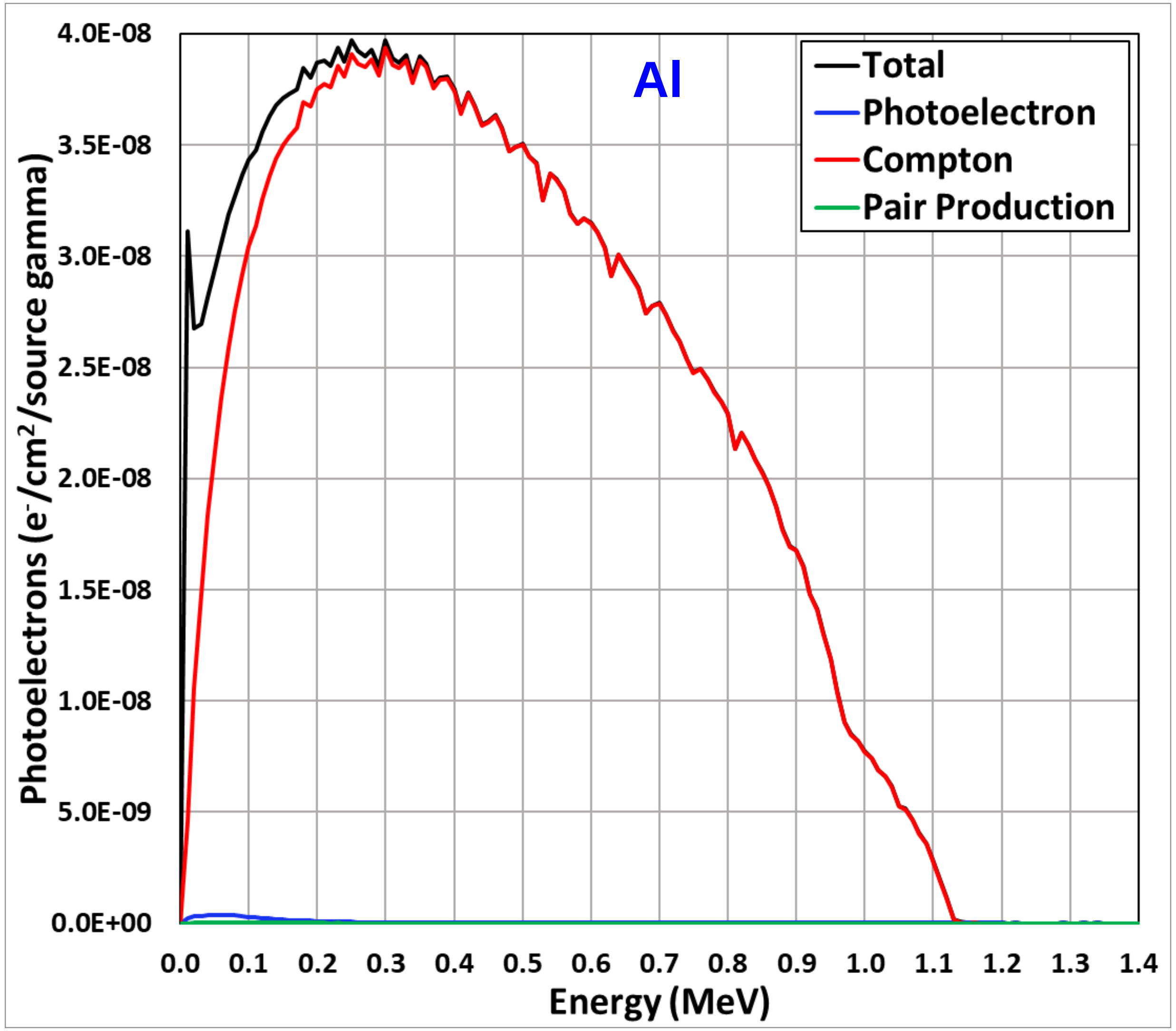


^{60}Co Gamma Ray Analyses – Electron Generation (Al)



Analytical formulation (SRM 1995 PhD Diss.)



Monte Carlo Transport Simulation (MCNP6)

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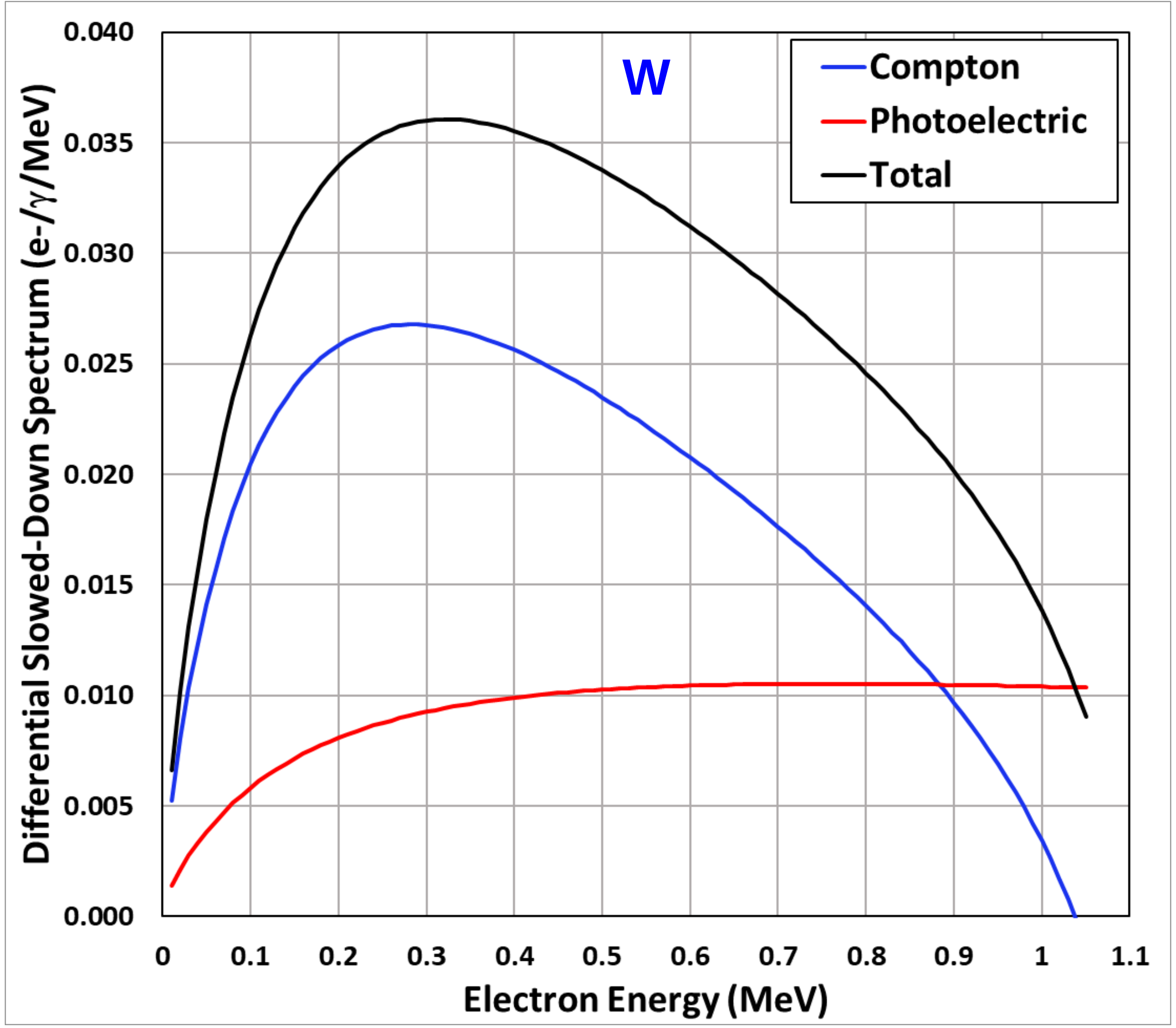

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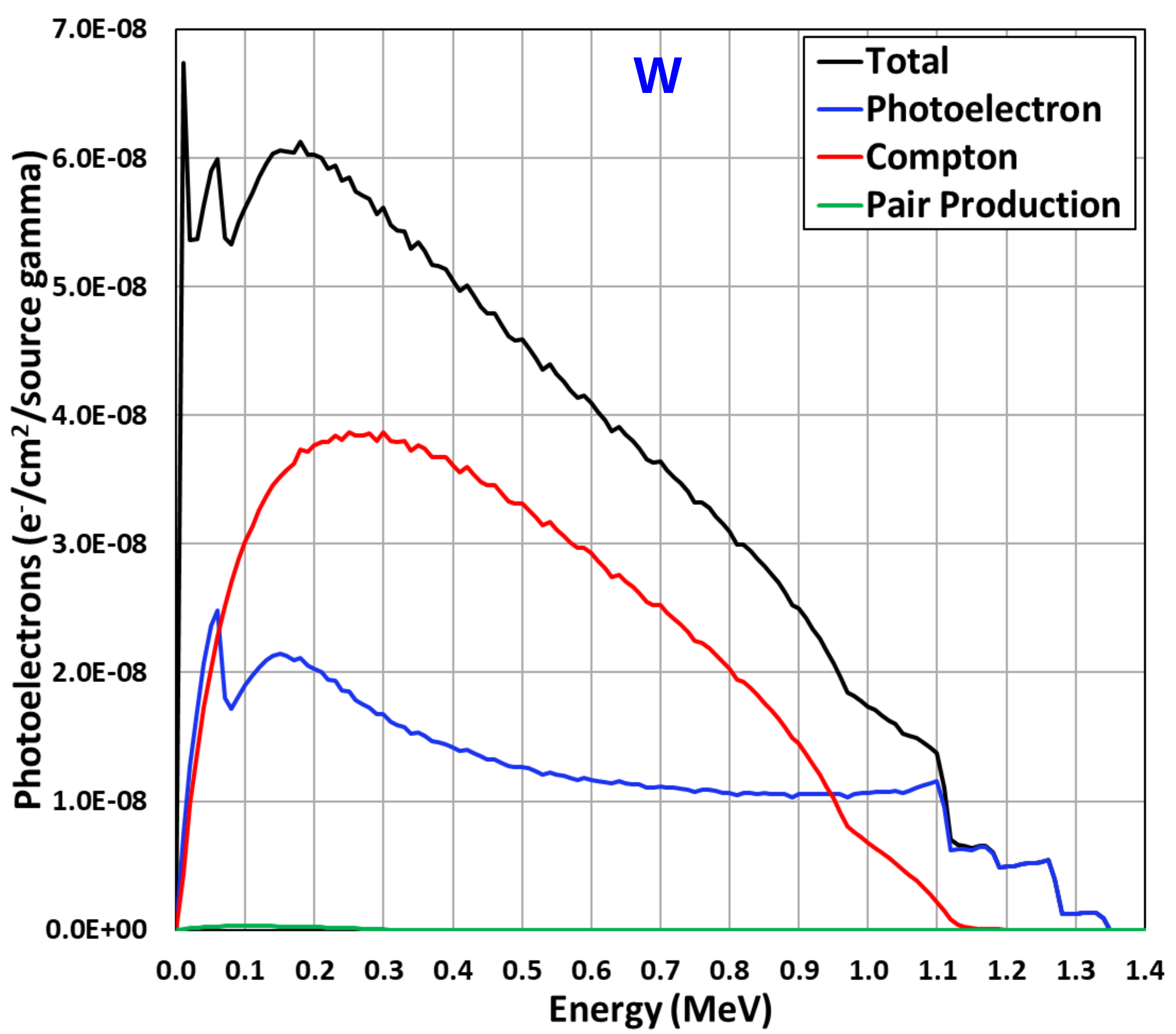

Monte Carlo Transport Simulation (MCNP6)

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- ***Ionizing vs. Nonionizing Energy Deposition from ^{60}Co Gamma Rays***
  - ***Dose equilibrium conditions***
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Ionizing vs. Nonionizing Dose for ^{60}Co Gammas in Al

*Ionizing Dose Calculation

$$\mathbf{TID} = \int \frac{d\varphi(E)}{dE} \frac{dE}{dx}\, dE$$

*Displacement Damage Dose Calculation

$$\mathbf{DDD}(E_{ref}) = \frac{1}{S(E_{ref})^{n-1}} \int \frac{d\varphi(E)}{dE} S(E)^n dE$$

*1 MeV electron fluence equivalent

$$\varphi(E_{ref}) = \frac{1}{S(E_{ref})^{n}} \int \frac{d\varphi(E)}{dE} S(E)^n\, dE$$

*n is a function of parameter & material
*Protons, neutrons & heavy ions: n=1
*Electrons: variable, empirical

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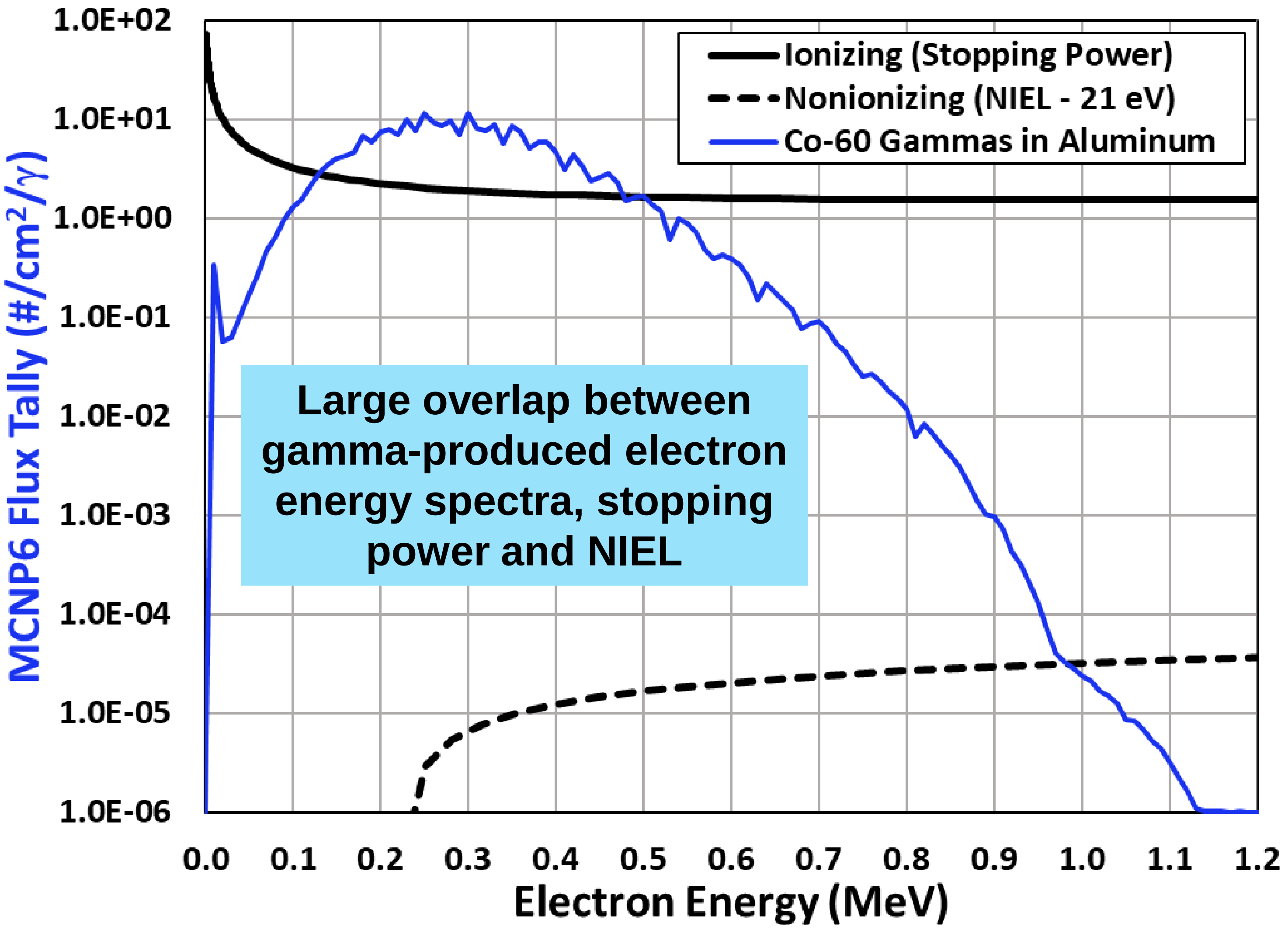

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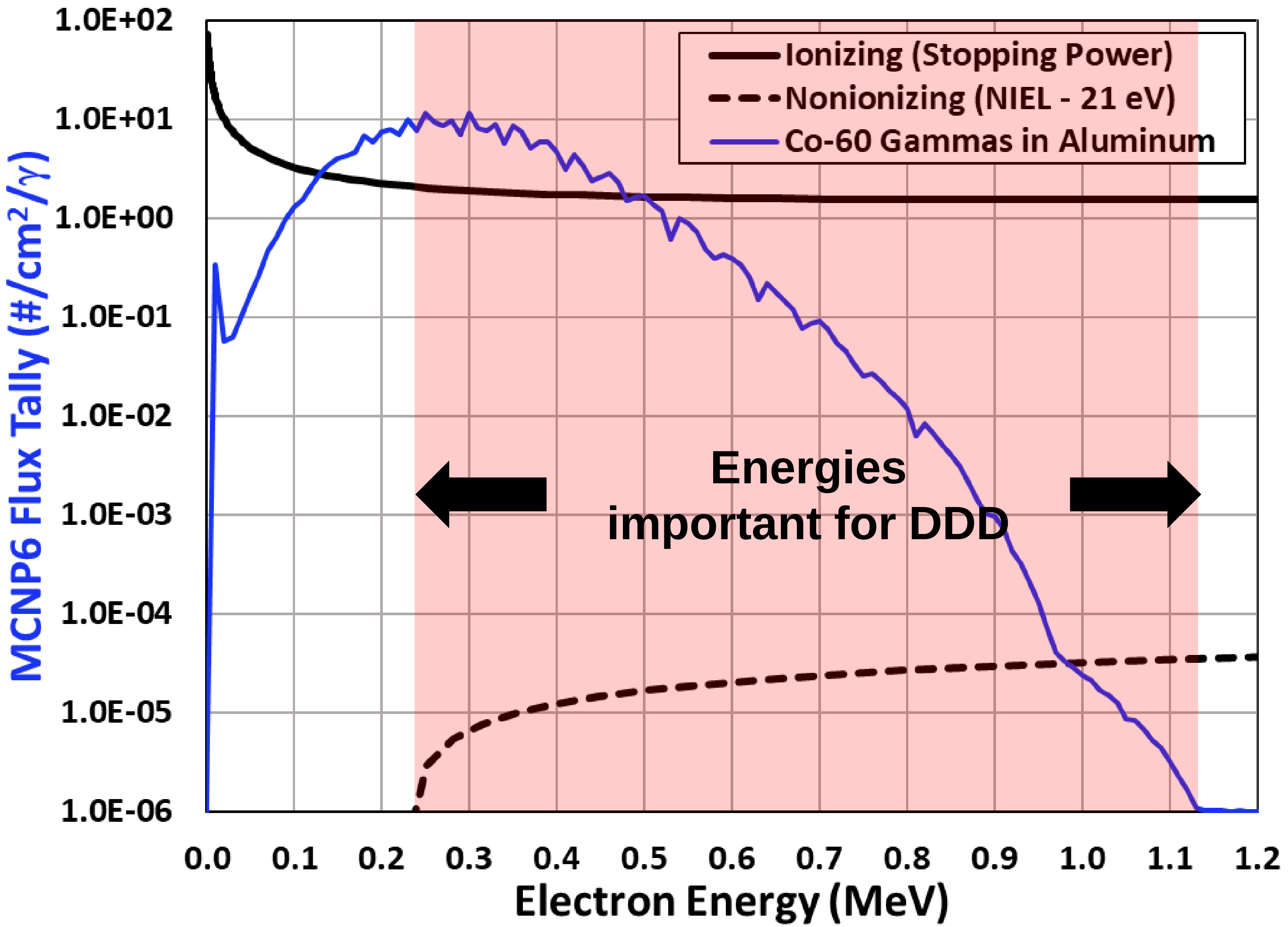

*Dosimetry concerns (2024 SPW talk & NSREC paper)

Gamma Ray-Induced DDD & 1 MeV Electron Fluence

- **Analytical (1993: G.P. Summers *et al. IEEE Trans. Nucl. Sci. 40, 1372* (1993))**
  - Assumes **particle equilibrium** in spherical geometries (optimal electron generation)
  - Calculate equivalent 1 MeV electron fluence from photoelectrons and Compton electrons

$$\varphi(E_{ref}) = \frac{1}{S(E_{ref})^n} \int \frac{d\varphi(E)}{dE} S(E)^n \, dE$$

  - Convert 1 Mrad to equivalent 1 MeV electron fluence **(1 Mrad = 1.9x10^{15} ^{60}Co photons/cm^2)**

TABLE 1
Co^{60} GAMMA-INDUCED DISPLACEMENT DAMAGE[1]

	Average γ-induced Electron NIEL (eV.cm²/g)	1MeV Electron NIEL (eV.cm²/g)	Equivalent 1 MeV Electron Fluence for 1 Mrad(Si) (cm⁻²)
n-Si	13.08	31.42	1.25x10^{13}
p-Si		31.42	8.04x10^{12}
GaAs	9.25	26.5	1.08x10^{13}
InP	14.19	33.5	1.30x10^{13}

[1] Threshold energies: Si = 21eV, Ga and As = 10eV, In = 6.7eV and P = 8.7eV.

*from "Damage Correlations in Semiconductors Exposed to Gamma, Electron and Proton Radiations", G.P. Summers, et al., IEEE Trans. Nucl. Sci. 40, 1372 (1993).

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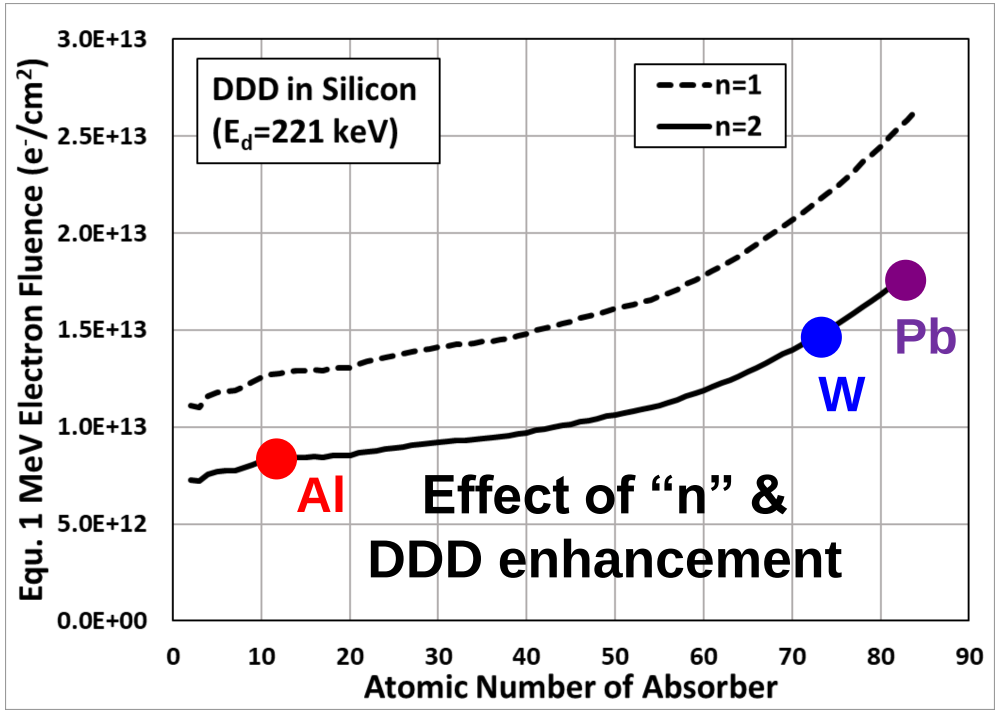

Particle equilibrium assumed – 1st notice of DDD enhancement

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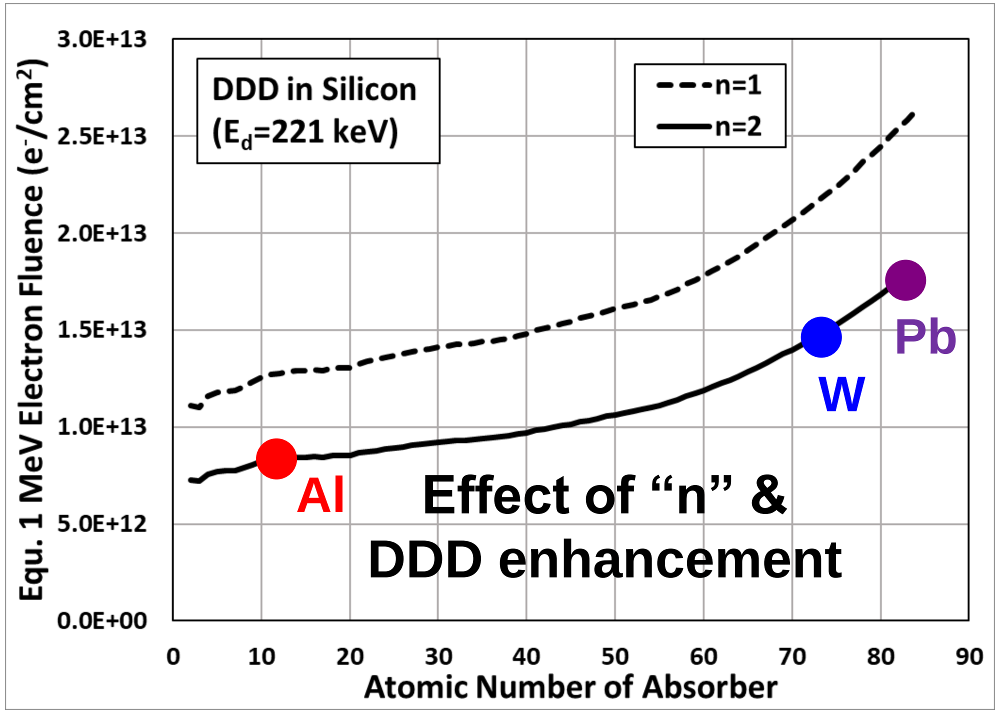

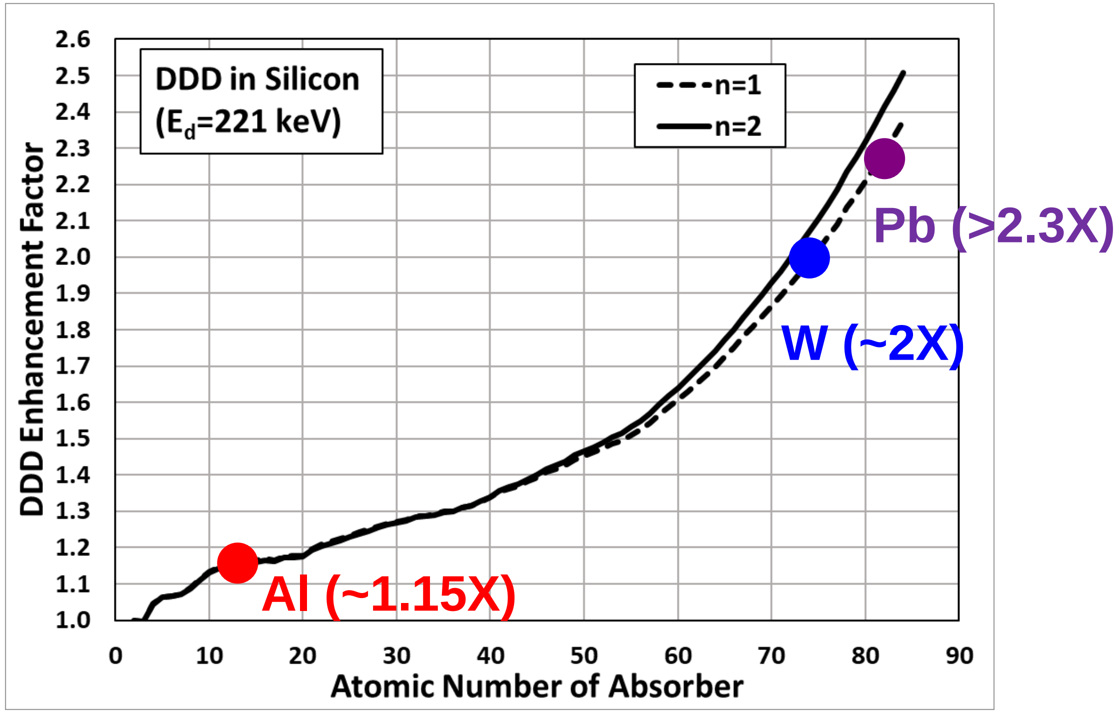

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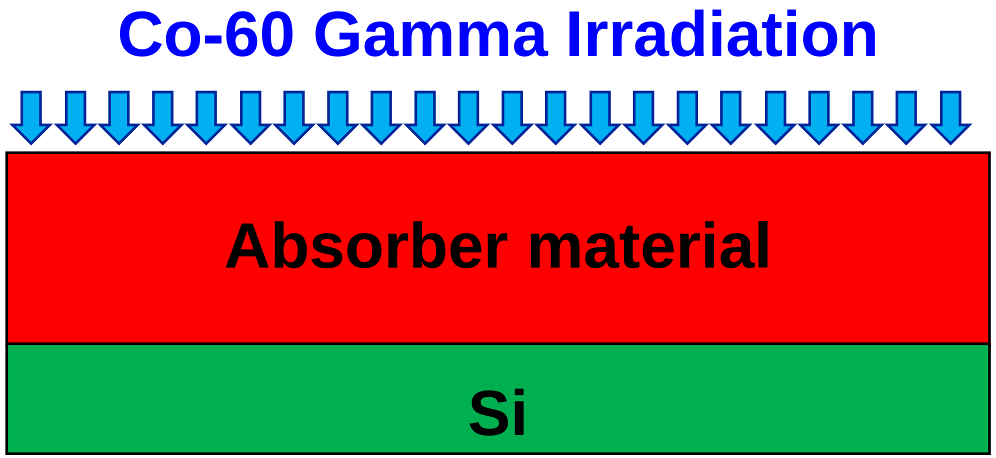
Equilibrium Conditions – DDD Deposition

- **Monte Carlo Transport Simulations (2012-2018 & current references)**
  - Particle equilibrium condition explored
    - Balance between electron generation and attenuation



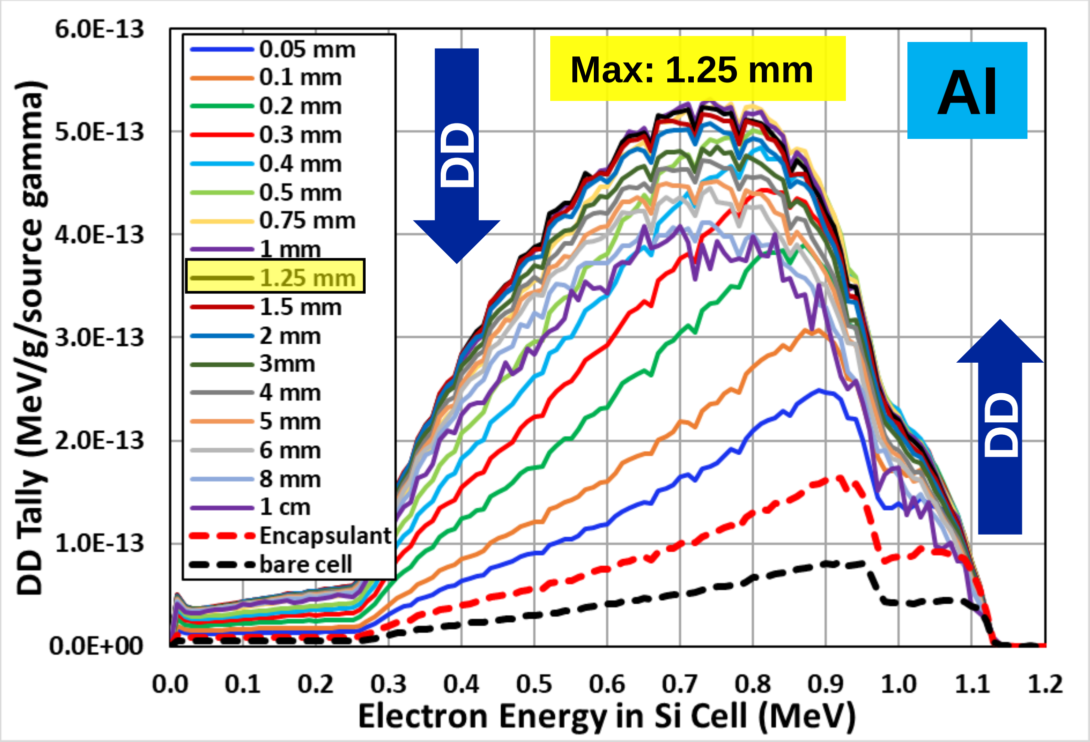
***For constant active region (Si) thickness**

- **Case 1: Absorber too thin**
  - Incomplete electron generation
- **Case 2: Absorber too thick**
  - Complete electron generation, but self-attenuation
  - Possibility of dose enhancement (TID & DDD)

Particle equilibrium effects difficult to quantify analytically --- need Monte Carlo transport techniques

Equilibrium Conditions – DDD Deposition - ^{60}Co

- **Monte Carlo Transport Simulations (2012-2018 & current references)**
  - Determines gamma interactions in materials and produces relevant energy spectra
  - TID and DDD tallies in sensitive volumes
  - 1 MeV electron simulations give the proper normalizations



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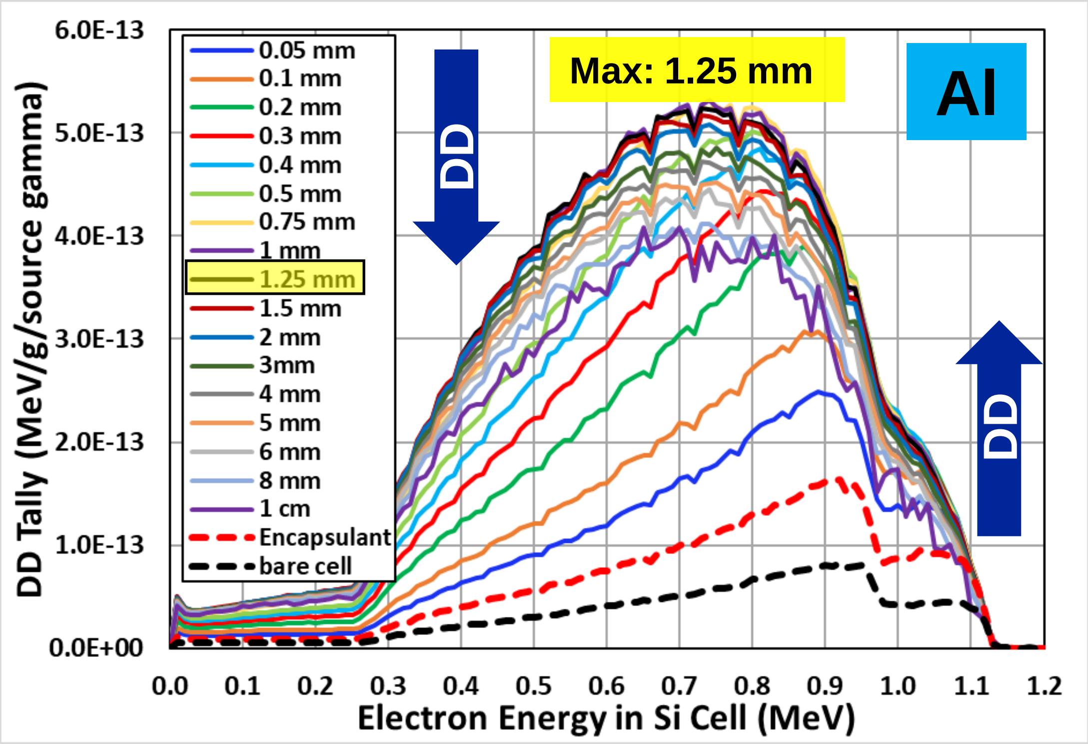

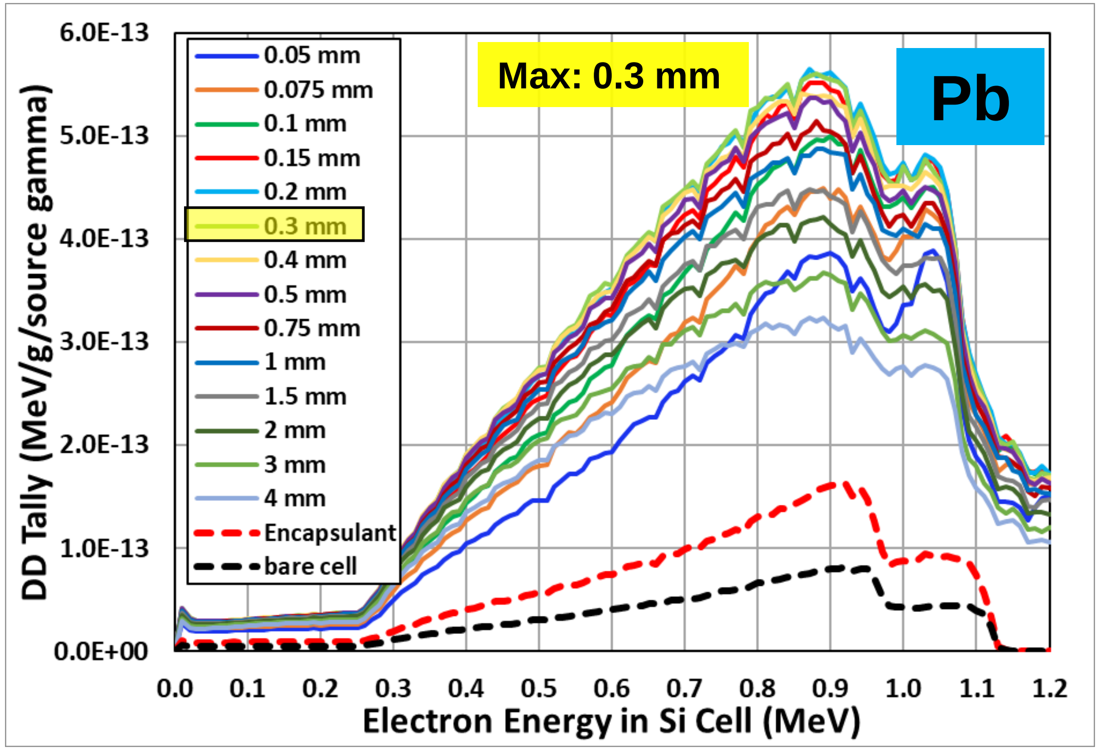

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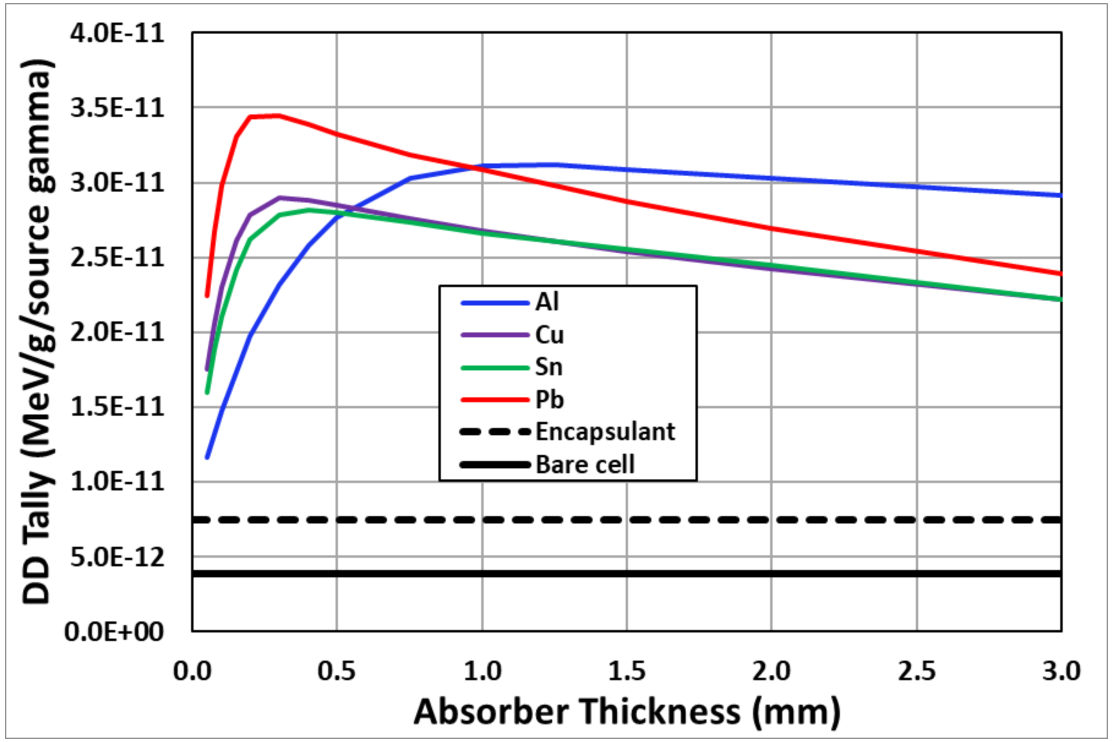

Different particle equilibrium effects are noted with absorber

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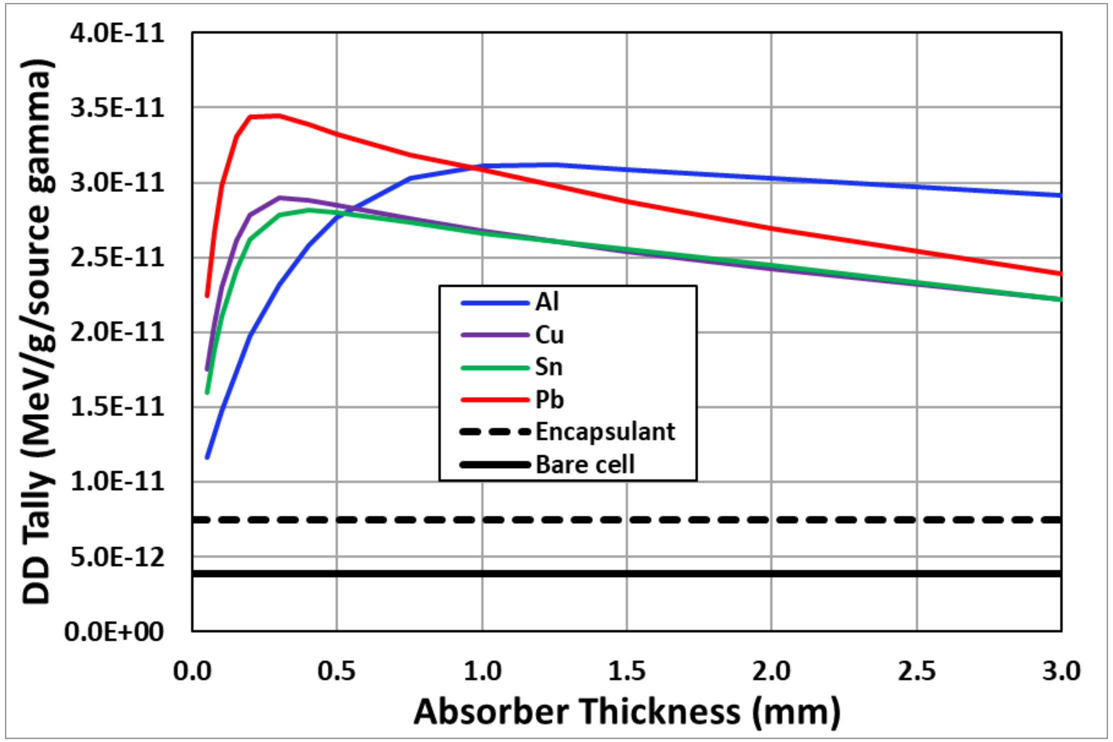
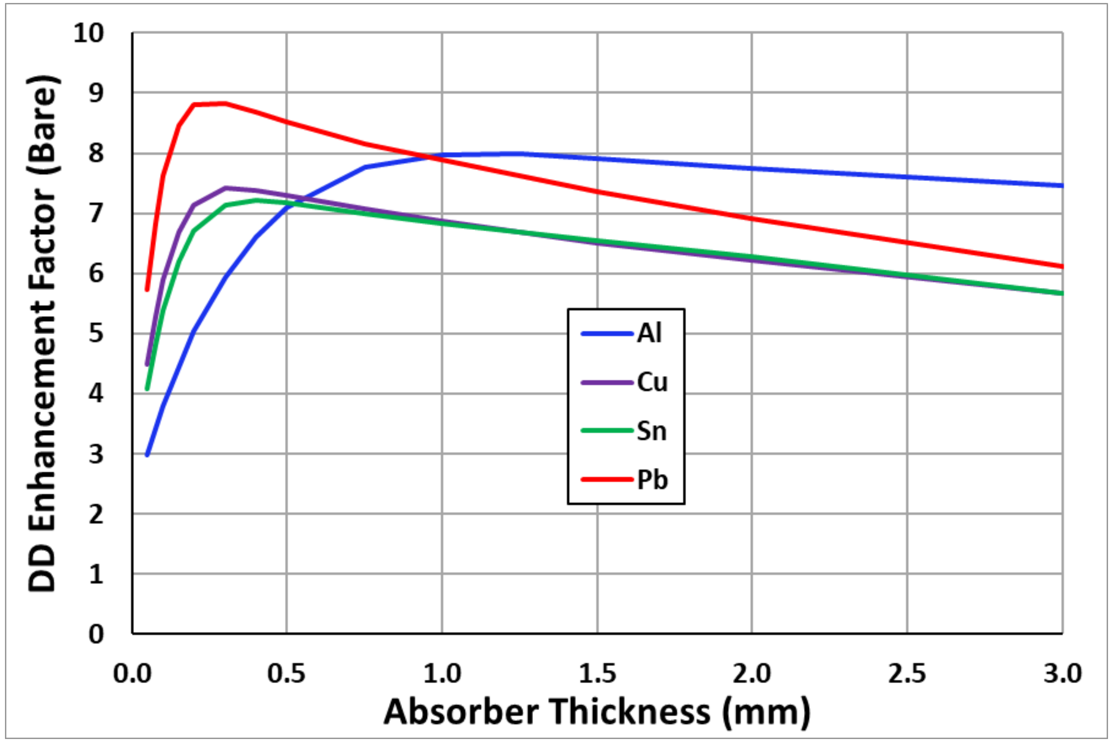
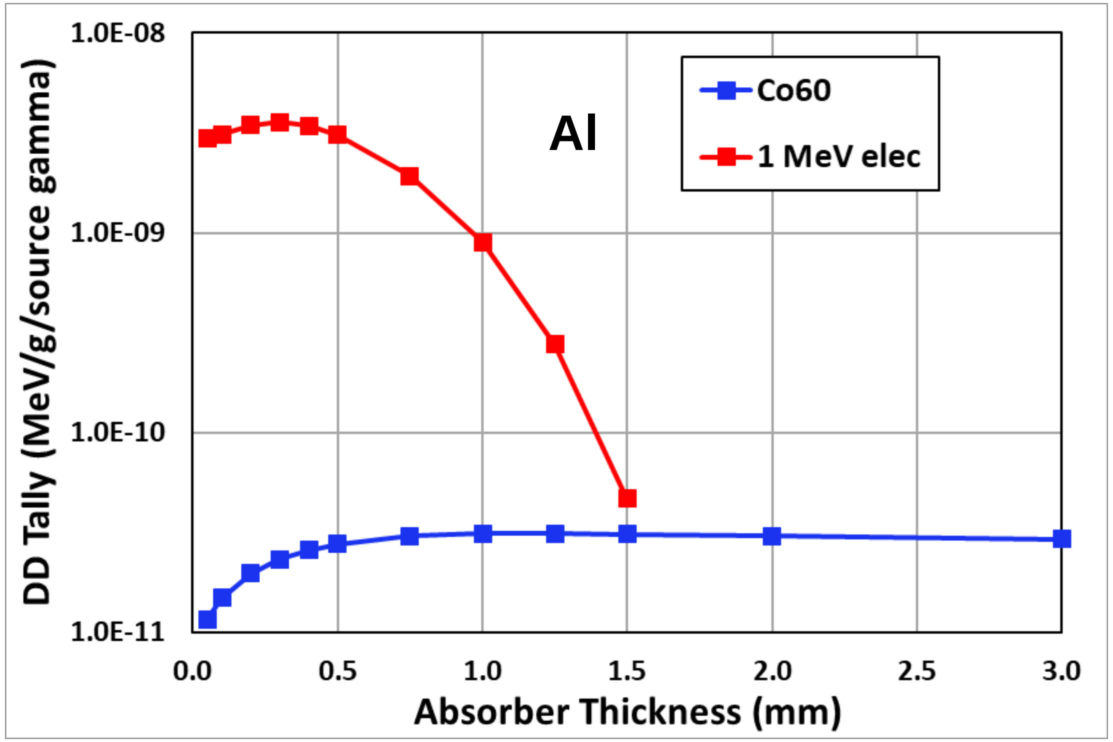


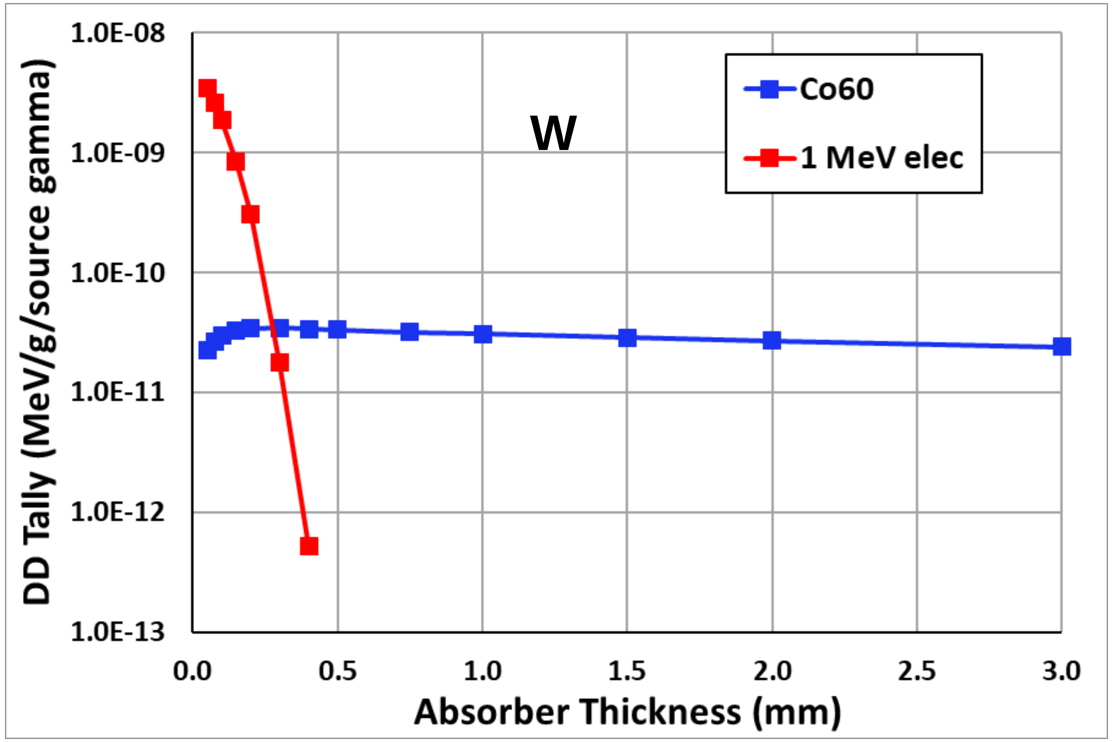


Different particle equilibrium effects are noted with absorber material

Particle Equilibrium – DDD Deposition - 1 MeV Electrons

- **Monte Carlo Transport Simulations (2012-2018 & current references)**
  - 1 MeV electron simulations to find proper ground test correlation
  - Nonlinear dependence found with *different* equilibrium condition





Different particle equilibrium effects are noted between ^{60}Co gammas and 1 MeV electrons

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- ^{60}Co gamma rays can be very convenient – low cost, large area, high dose rate
  - Published, nominal **1 Mrad=10^{13} e^-/cm^2** will require 1 Grad to get 10^{16} e^-/cm^2
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  - Facility/solar cell/array geometry
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  - TID vs DDD (2024 SPW presentation)
    - TID dosimeters will overestimate the amount of electron flux for DDD-based irradiations
- Electron irradiations still necessary for full radiation qualification
  - Need 1 MeV (and another > 1 MeV OR ^{60}Co) to determine "n" factor

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Summary

- Gamma rays interact in matter to produce secondary electron energy spectra which can transport into sensitive volumes to deposit both TID and DDD
- Absorber material and thickness are important quantities
  - Dose equilibrium
  - Dose enhancement possible
- Analytical analyses show many trends but necessarily assume dose equilibrium which is not the usual case in practice
- ***Monte Carlo transport simulations can be useful in identifying trends and help in test plan development***
- 1 MeV electron irradiations are still required for damage correlations
- ^{60}Co gamma rays can be a convenient electron source for *continued* work
- More data are needed… (wait for next year ☺)

A Few Relevant References…

- 1993: IEEE Trans. Nucl. Sci. 40, 1372 (1993)

"Damage Correlations in Semiconductors Exposed to Gamma, Electron and Proton Radiations"

- 1994: IEEE Trans. Nucl. Sci. 41, 1945 (1994)

"Co^{60} Gamma Ray and Electron Displacement Damage Studies of Semiconductors"

- 1994: IEEE First World Conference on Photovoltaic Energy Conversion (WCPEC)

"Co^{60} Gamma Ray Irradiations of Solar Cells: A New Way to Predict Space Radiation Damage"

- 1995: UMBC Ph.D. Dissertation (SRM)

"Electron- and Gamma-Induced Displacement Damage Effects in InP Semiconductor Devices"

- 2012: IEEE Trans. Nucl. Sci. 59, 3117 (2012)

"Equivalent Displacement Damage Dose for On-Orbit Space Applications"

- 2017: IEEE Trans. Nucl. Sci. 64, 991 (2017)

"Gamma and Electron NIEL Dependence of Irradiated GaAs"

- 2018: J. Appl. Phys. 123, 095703 (2018)

"Gamma Non-Ionizing Energy Loss: Comparison with the Damage Factor in Silicon Devices"

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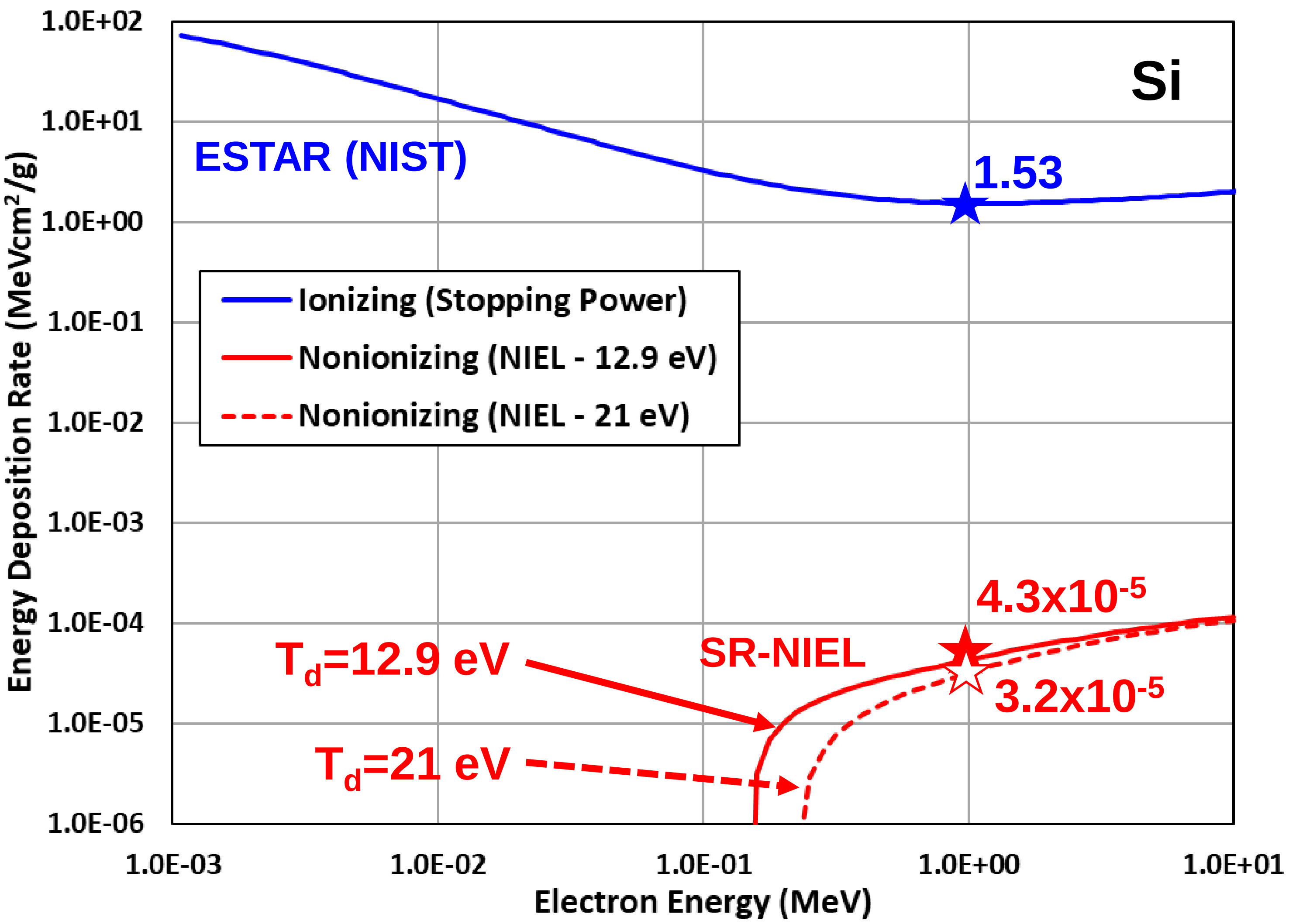
Ionizing vs. Nonionizing Dose Calculations



***Although most of the electron energy is lost due to ionization effects (stopping power, dE/dx), displacement damage is the primary solar cell (pn junction) damage mechanism (NIEL) and has a minimum energy to produce a displacement (T_d)**

***Ionizing Dose Calculation**

$$\mathrm{TID} = \int \frac{d\varphi(E)}{dE} \frac{dE}{dx}\, dE$$

***Displacement Damage Dose Calculation**

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