A Model for Neutron Skin Dosimetry

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Introduction

- At the previous two user-group meetings, neutron skin dosimetry was discussed
- We then began examining elements and forming structure for a neutron dosimetry model for VARSKIN incorporation
- Neutron dosimetry will be classified mechanistically
  - **capture** reactions (n,γ)
  - **absorption** reactions (n,p)
  - elastic (and inelastic) **scatter** (n,n)

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Outline

- Neutron sources
- Exposure scenarios and modeling
- Interaction cross sections
- Charged particle buildup
- Neutron dosimetry
  - capture
  - absorption
  - scatter
- General response functions by mechanism

Neutron Sources

- Fission neutrons and photons
- Reaction neutrons
- Photoneutrons
- Activation neutrons
- Mono-energetic neutrons

- Capture photons and absorption particles

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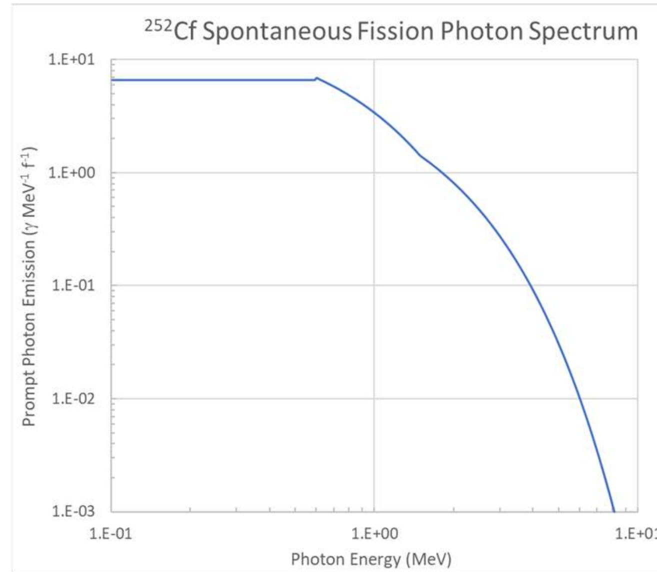
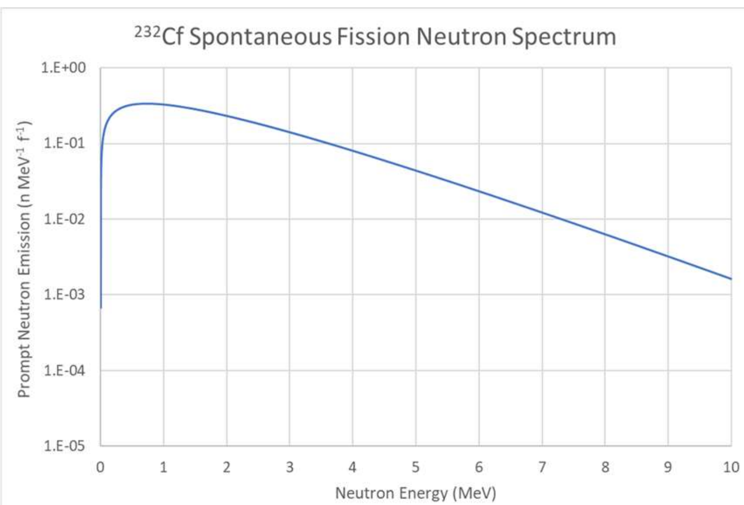
Fission Neutrons & Photons

- fissile or fissionable nuclides
  - ^{233}U, ^{235}U, ^{238}U, ^{239}Pu, ^{232}Th
- spontaneous fission of **^{252}Cf** and other isotopes of the elements:
  - U, Np, Pu, Am, Cm, Bk, Cf, Es, Fm
- fission also results in excitation photon emission
- photon energy spectrum from ^{235}U is well studied and is proven to be a good surrogate for ^{233}U, ^{239}Pu, and **^{252}Cf**



$$N_{p\gamma}(E) = \begin{cases} 6.6 & 0.1 \le E < 0.6\ MeV \\ 20.2e^{-1.78E} & 0.6\ \le E < 1.5\ MeV \\ 7.2e^{-1.09E} & 1.5\ \le E < 10.5\ MeV \end{cases}$$

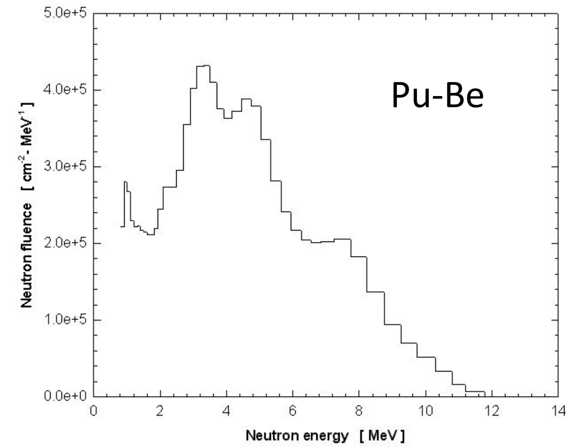


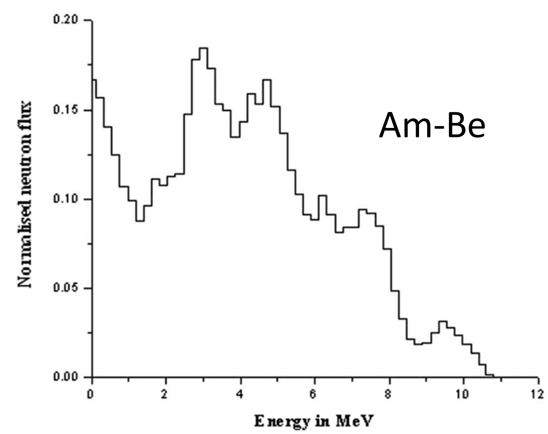
$$N_{pn}(E) = \mathrm{a}e^{-E/b} \sinh \sqrt{cE}$$

where a = 0.6400; b = 1.1750; and c = 1.0401

Reaction Neutrons

- primarily (α,n) reactions
- prominent reaction is $^{9}Be(\alpha,n)^{12}C$ (Q = 5.7 MeV)
- common mixtures: **PuBe**, **AmBe**, PoBe, RaBe, etc
- neutron-energy spectral detail dependent on paired alpha emitter
- this mechanism would also include fusion reactions:
  - $^{2}H(d,n)^{3}He$ $E_n = 2.45$ MeV
  - $^{3}H(d,n)^{4}He$ $E_n = 14.1$ MeV





Photoneutrons

- produced in (γ,n) reactions (high-energy electron accelerators)
- in most cases, high-energy photons (> 7 MeV) are required
- however …

  $^{2}H(\gamma,n)^{1}H$ Q = -2.225 MeV

  $^{9}Be(\gamma,n)^{8}Be$ Q = -1.665 MeV
- common lab source of **^{124}Sb-Be** E_{γ} = 1.691 & 2.091 MeV
- produces nearly monoenergetic neutrons (22 & 378 keV, respectively) of very low yield (~55 n/M γ)
- however, the antimony photons generally result in greater dose than the SbBe neutrons

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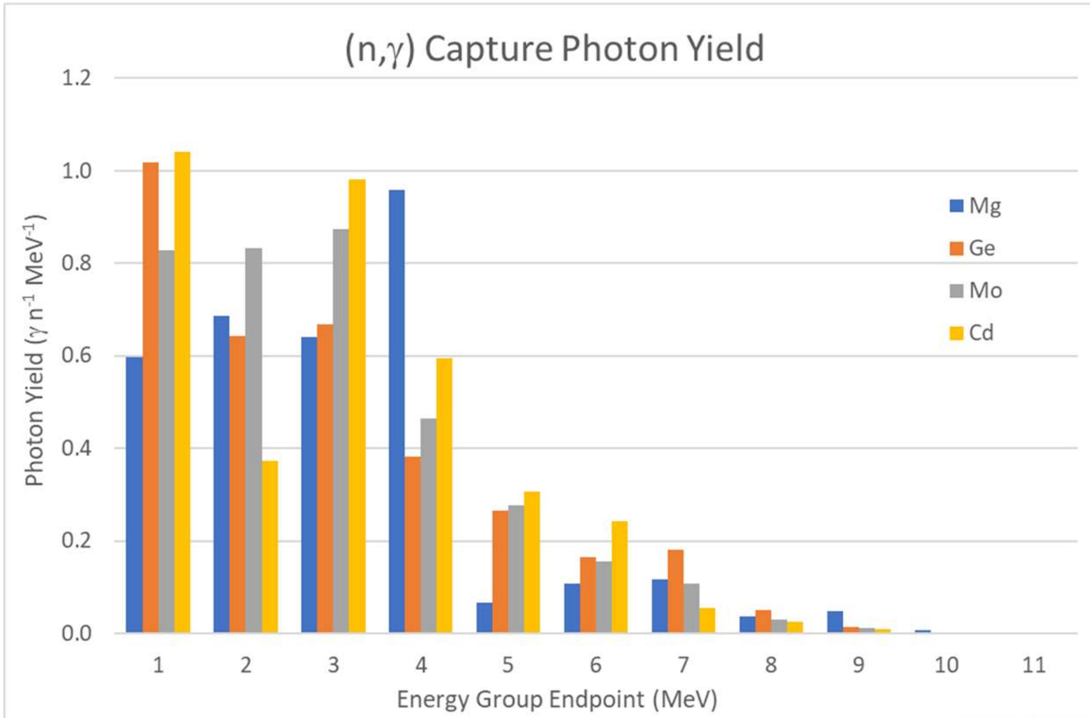
Activation Neutrons

As an example, in water-moderated reactors:

- $^{17}O(n,p)^{17}N$ reaction with a threshold of 7.9 MeV (5 μb cross section)
- the ^{17}N can experience neutron decay ($E_n \sim 1.2$ MeV)
- but more likely, ^{17}N decays by beta emission to ^{17}O
  - leaving it in a highly-excited state
- the excited ^{17}O then decays by neutron emission ($E_n \sim 1$ MeV)

Capture Photons & Absorption Particles

- secondaries created in elements of shielding material or tissue
- thermal neutron capture in shielding to create photons
  - **(n,γ)** reaction
- capture yields shown for a few shielding constituents
- thermal neutron absorption in tissue to create charged particles
  - **(n,p)** reaction



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Exposure Scenarios

- skin exposures are not necessarily due to contamination events
  - but, for example, more likely the result of work conducted in a glove box
- geometry options: point, 1D line, 3D cylinder, parallel beam
- exposure by holding a source (in ‘contact’ with the skin)
  - point or line sources
  - small-to-large cylinders
- exposure from an adjacent source (away from the skin)
  - points, lines and cylinders within about a meter
- parallel beam option useful for greater separation distances
  - across the room in a laboratory situation
- consideration of:
  - attenuation
  - energy-flux degradation
  - photon production

General Neutron Dosimetry

Equivalent dose rate $\dot{H}_{i,j}$ for interactions by neutrons of energy *E*, with element *i*, by mechanism *j*, at depth *d*:

$$\dot{H}_{i,j}(d) = K \cdot \frac{N_A \cdot f_i}{AW_i} \cdot \varepsilon_{i,j} \int_0^\infty \left(f_{cpe}(d,E) \cdot \sigma_{i,j}(E) \cdot \phi'(d,E) \cdot w_{R_j}(E) \right) dE$$

where:
K = energy conversion [J MeV^{-1}];
N_A = Avogadro's number [atoms mol^{-1}];
f_i = atom weight-fraction;
AW_i = atomic weight [kg mol^{-1}];
$\varepsilon_{i,j}$ = interaction energy absorbed locally [MeV];
$f_{cpe}(d,E)$ = fractional charged particle equilibrium;
$\sigma_{i,j}(E)$ = interaction cross section [cm^2 atom^{-1}];
$\phi'(d,E)$ = neutron flux at depth [s^{-1} cm^{-2} MeV^{-1}]; and
$w_{R_j}(E)$ = radiation weighting factor [Sv Gy^{-1}].

$$\varepsilon_{i,s} = \frac{2A_i E}{(A_i+1)^2} \quad (scatter)$$

$$\varepsilon_{i,a} = Q_{i,a} \cdot AF_{i,a} \quad (absorption)$$

A_i is the atomic number of element *i*;
E is the incident neutron energy [MeV];
Q_i is the reaction energy [MeV];
and AF_i is the absorbed fraction.

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Skin Composition for MC Simulation

- simulations are necessary to estimate charged-particle buildup
- epidermis is assumed to be composed of dead and living tissue
  - 70 microns of stratum corneum (15-30% water) simulated by:
    - ICRU 44 adipose tissue (11-21% water; 0.95 g/cm^3)
    - 11.4% **H**; 59.8% **C**; 0.7% **N**; 28.1% **O** (0.3% ‘other’ added as oxygen)
  - living tissue (55-75% water) simulated by:
    - ICRU 44 skin (53-73% water; 1.09 g/cm^3)
    - 10.0% **H**; 20.4% **C**; 4.2% **N**; 65.4% **O** (0.9% ‘other’ added as oxygen)
- therefore, the following cross sections are of importance …

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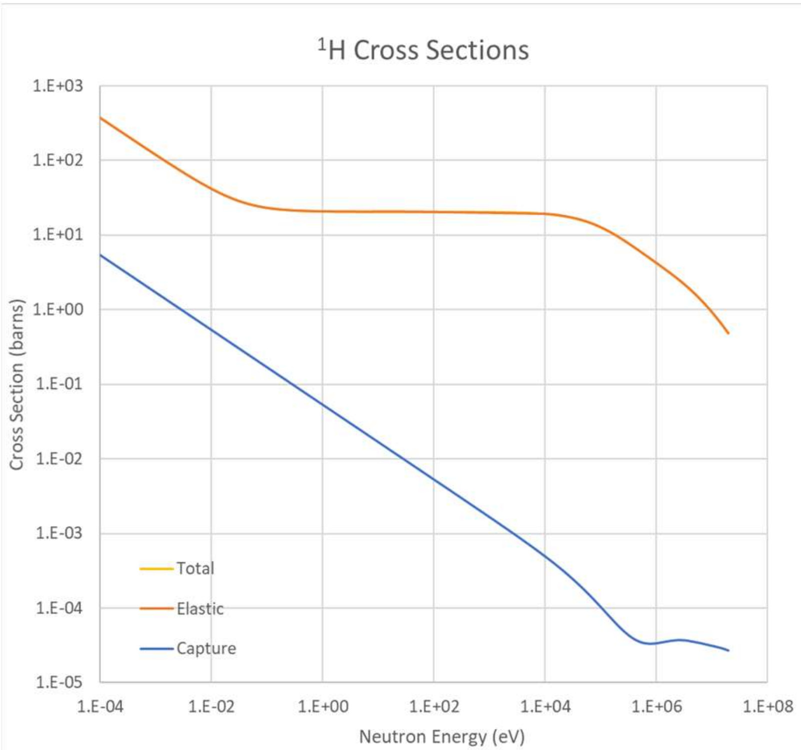
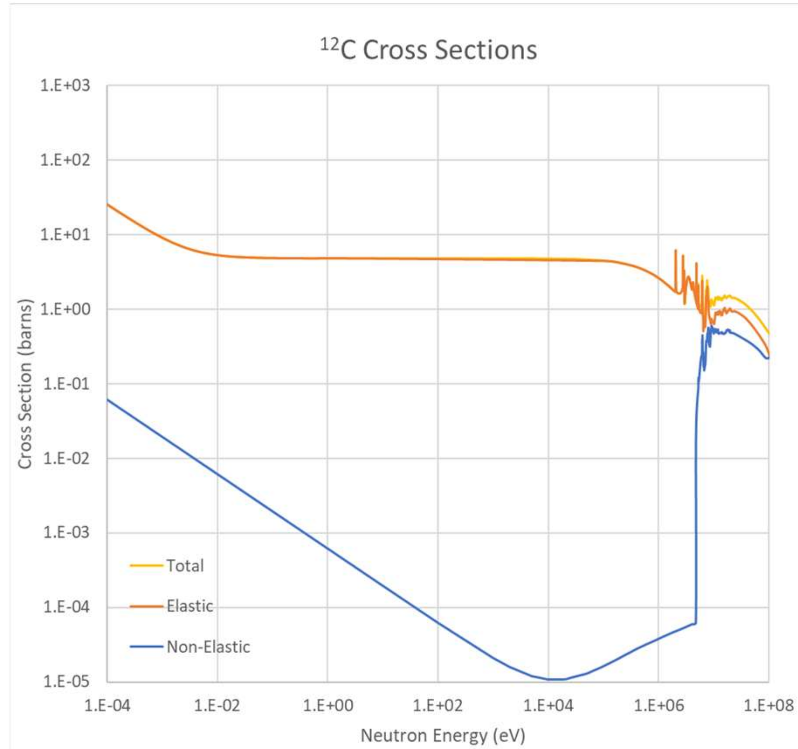
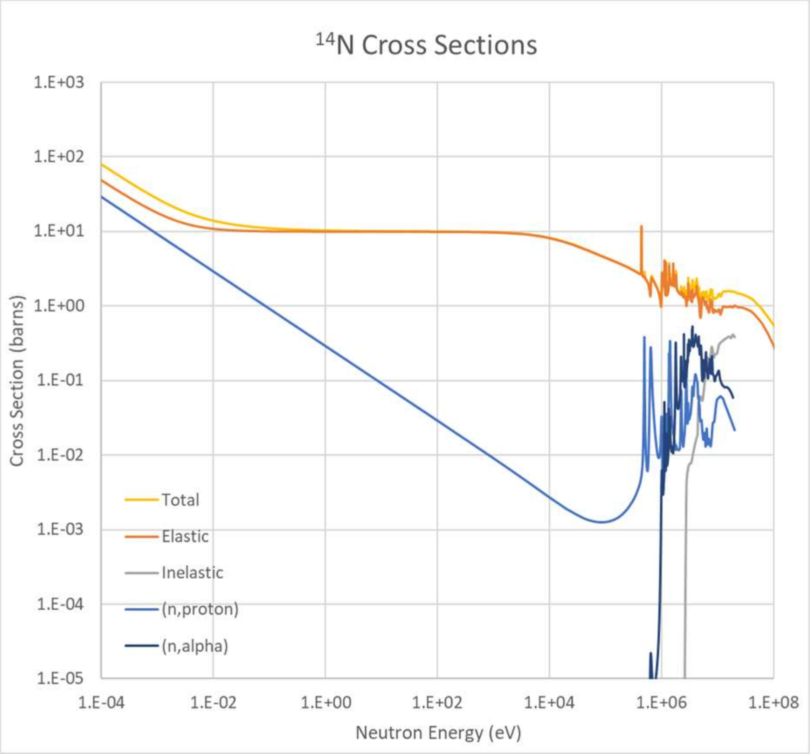
Neutron Interaction Cross Sections

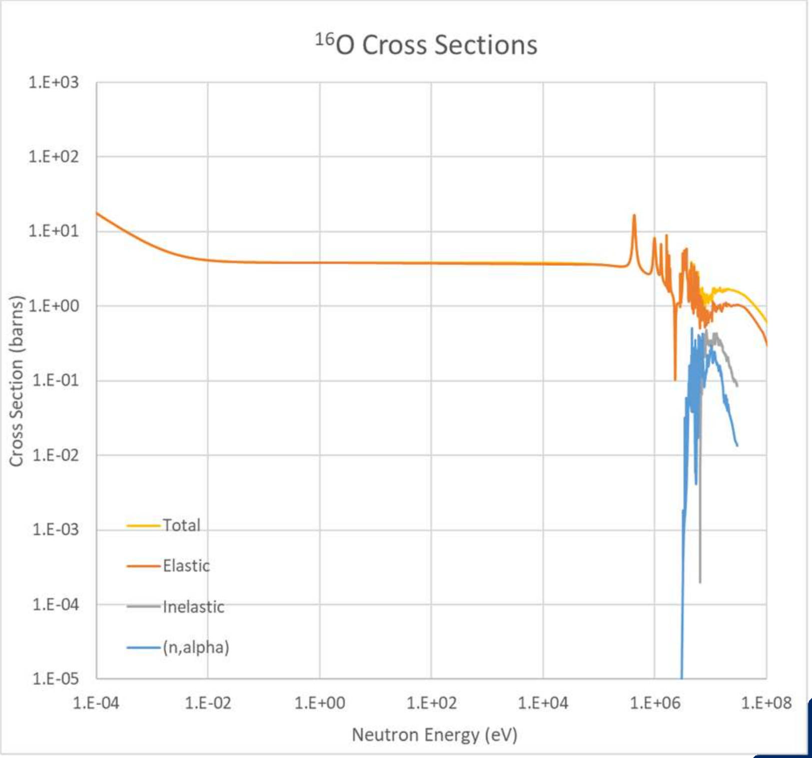




Source: ENDF/B-VIII.0 (LANL)

Neutron Interaction Cross Sections





Source: ENDF/B-VIII.0 (LANL)

Charged Particle Buildup

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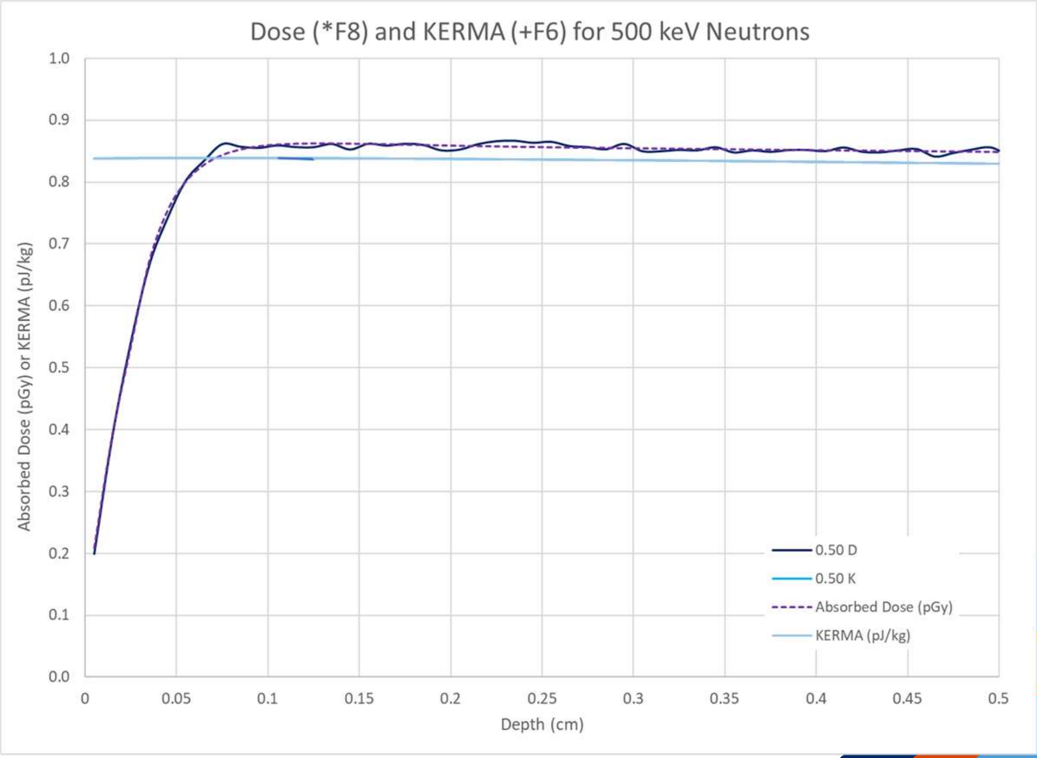
- One of the most important considerations for shallow skin dosimetry:

At 7 mg/cm^2, DOSE is equal to what fraction of KERMA?

- Fractional charge equilibrium is determined in our simulated dead/live epidermis
  - using MCNP6 to calculate the dose-to-KERMA ratio (*F8/+F6) as a function of neutron energy and tissue depth
- For example, incident neutrons of 500 keV result in charged particle equilibrium by a depth of about 0.75 mm
- Plots of D/K show f_{CPE} as a function of depth



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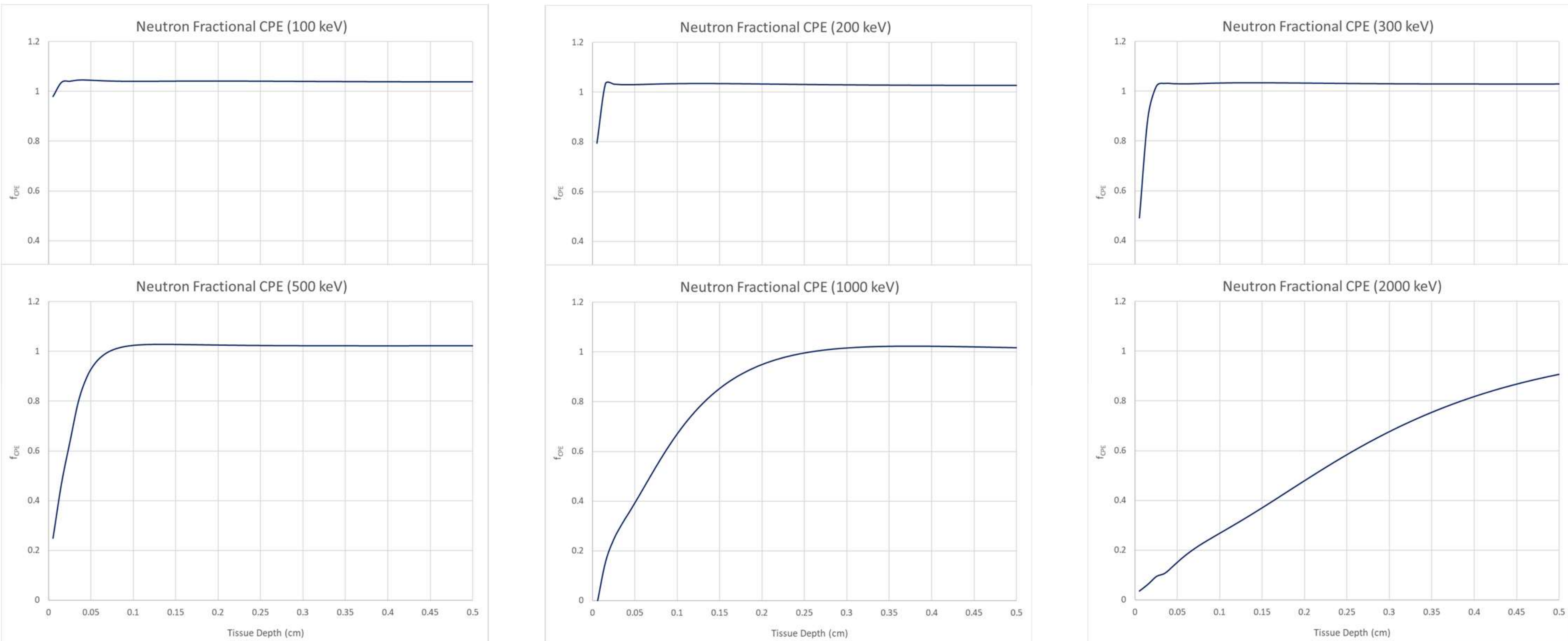
Neutron f_{CPE} in Tissue



Neutron Capture & Absorption Dosimetry

- Dominant at low energies
- Two significant capture/absorption interactions in tissue emerge:
  - $^{1}H(n,\gamma)^{2}H$ [Q = 2.224 MeV]
  - $^{14}N(n,p)^{14}C$ [Q = 0.626 MeV]
- Capture results in the emission of a high-energy photon to be absorbed elsewhere
  - this mechanism may be insignificant when evaluating shallow skin dose
  - but the generation of photons in shielding materials can be significant
- Absorption in tissue results in an energetic proton and carbon recoil, the combined energy of which is deposited within the range of the proton
  - in tissue, a distance of about 10 microns

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Capture/Absorption Dosimetry

$H(d)$, the equivalent dose at depth, *d*, due to neutron capture by ^{1}H or absorption by ^{14}N is calculated using the response function (KERMA factor), $R(E)$, with units of Gy cm^2:

$$H(d) = 1.602x10^{-1} \left(\frac{J}{MeV}\right) \cdot N \cdot Q \cdot AF \int_0^{\infty} \left(w_R(E) \cdot \sigma(E) \cdot f_{CPE}(d,E) \cdot \Phi'(d,E)\right) dE$$

where *N* is the atomic mass density of ^{1}H or ^{14}N (atoms kg^{-1}), *Q* is the reaction energy (MeV), *AF* is the fraction of energy absorbed in tissue, $\sigma(E)$ is the energy-dependent cross section (cm^2 atom^{-1}), $f_{CPE}(d,E)$ accounts for fractional charged particle equilibrium as a function of both depth and energy, w_R is the radiation weighting factor (Sv/Gy), and $\Phi'(d,E)$ is the neutron fluence at depth (cm^{-2} MeV^{-1}).

Capture/Absorption Dosimetry

Some fraction of the photon energy is absorbed in the body, and all kinetic energy is absorbed w/in the range of the proton.

Reaction	wt %*	Atomic weight (kg/mol)	Atomic density (atoms/kg)	Q (MeV)	AF	C_x (J/kg)	w_R (Sv/Gy)
$^{1}H(n,\gamma)^{2}H$	10.0	0.001008	5.97×10^{25}	2.224	0.2856*	6.07×10^{12}	1
$^{14}N(n,p)^{12}C$	4.2	0.0140067	1.81×10^{24}	0.626	1	1.82×10^{11}	10

*ICRU 44 skin

$$H_\gamma(d) = 6.07x10^{12}\ (Sv) \int_0^\infty \left(\sigma_\gamma(E) \cdot f_{CPE}(d,E) \cdot \Phi'(d,E)\right)\ dE$$

$$H_p(d) = 1.82x10^{12}\ (Sv) \int_0^\infty \left(\sigma_p(E) \cdot f_{CPE}(d,E) \cdot \Phi'(d,E)\right)\ dE$$

Neutron Scatter Dosimetry

- Dominant at high energies
- Neutrons transfer kinetic energy by direct collision with the atomic nuclei that make up tissue (H, C, N, and O)
- The majority of energy (>85%) deposited by scatter occurs due to neutron collisions with hydrogen nuclei
- And, collisions with oxygen nuclei account for as much as 15% of scatter dose above 1 MeV

Scatter Dosimetry

$H_i(d)$, the fast-neutron equivalent dose from elastic (and inelastic) scatter with element *i*:

$$H_i(d) = 1.602x10^{-13}\ \left({}^{J}/_{MeV}\right) \cdot N_i \cdot f_i \int_0^\infty \left(E \cdot w_R(E) \cdot \sigma_i(E) \cdot f_{CPE}(d, E) \cdot \Phi'(d, E)\right) dE$$

where the value of f_i, the fractional energy transferred to kinetic of the recoil proton for element *i* during elastic scatter, is:

$$f_i = \frac{2A}{(A+1)^2}$$

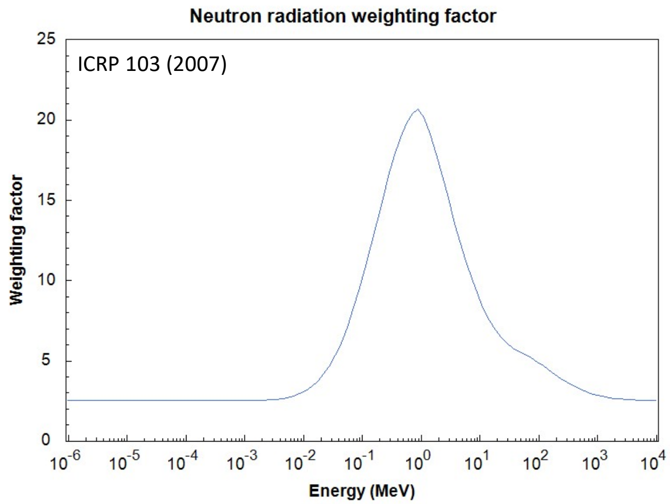
Inelastic scatter events result in the excitation energy being deposited away from the dosimetric space by photons of varying energy. Therefore, we will account for local proton energy deposition, but ignore the energy carried away by photons.

Scatter Dosimetry

Element, i	wt %*	Atomic Density (atoms kg^{-1})	f_i	C_i (J MeV^{-1} kg^{-1})
Hydrogen(1)	10.0	5.97×10^{25}	0.500	4.78×10^{12}
Carbon(12)	20.4	1.02×10^{25}	0.142	2.32×10^{11}
Nitrogen(14)	4.2	1.81×10^{24}	0.124	3.60×10^{10}
Oxygen(16)	65.4	2.46×10^{25}	0.111	4.37×10^{11}

*ICRU 44 skin; 0.8 wt% of “other elements” has been added to oxygen

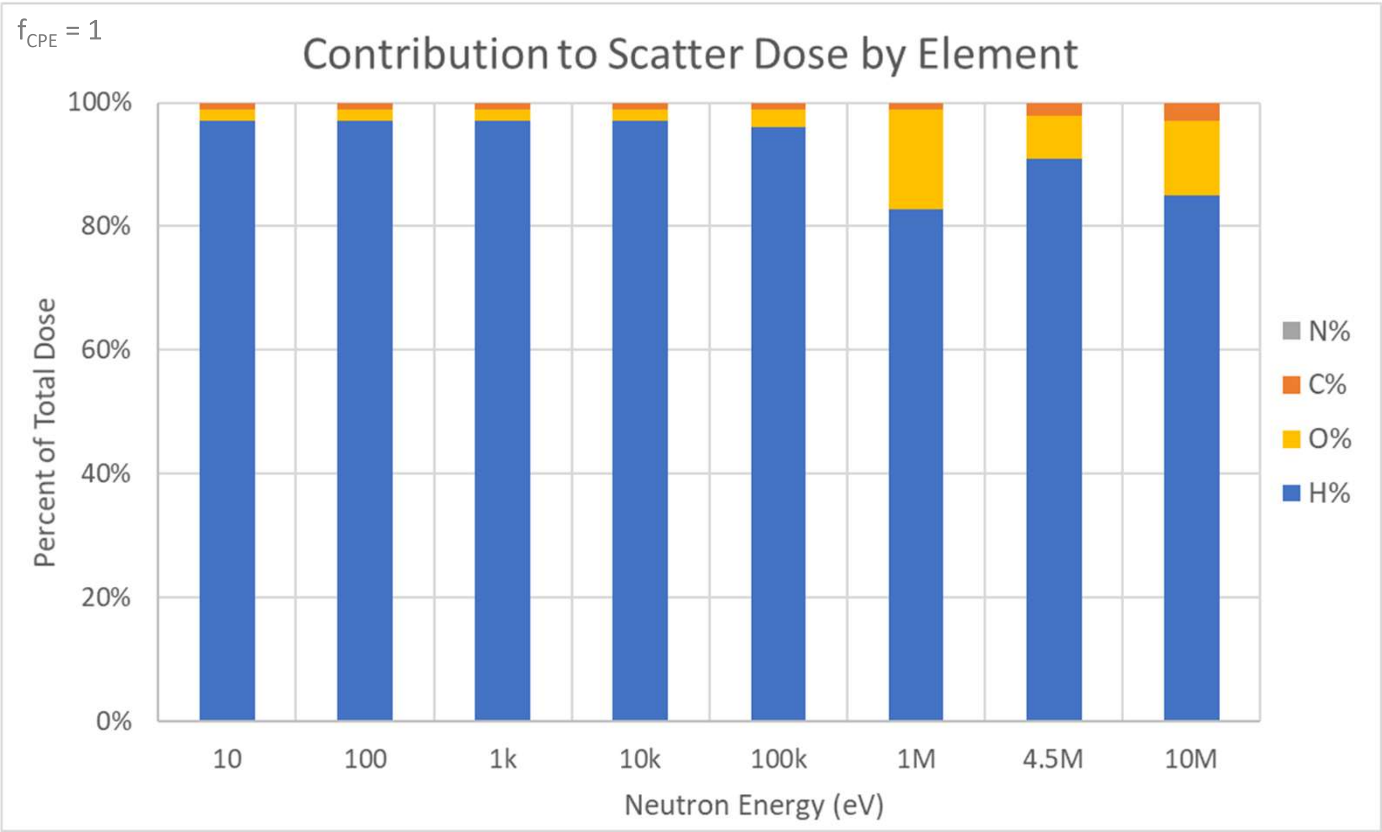
$$w_R = \begin{cases} 2.5 + 18.2e^{-|\ln(E_n)|^2/6}, & E_n < 1\ MeV \\ 5.0 + 17.0e^{-|\ln(2E_n)|^2/6}, & 1\ MeV \le E_n \le 50\ MeV \\ 2.5 + 3.25e^{-|\ln(0.04E_n)|^2/6}, & E_n > 50\ MeV \end{cases}$$



$$C_i = 1.602x10^{-13}\ \left({}^{J}/_{MeV}\right) \cdot N_i \cdot f_i$$

$$H(d) = \sum_i \left[C_i \int_0^{\infty} \left(E \cdot w_R(E) \cdot \sigma_i(\mathrm{E}) \cdot f_{CPE}(d,E) \cdot \Phi'(d,E) \right) dE \right]$$

Contribution to Scatter Dose



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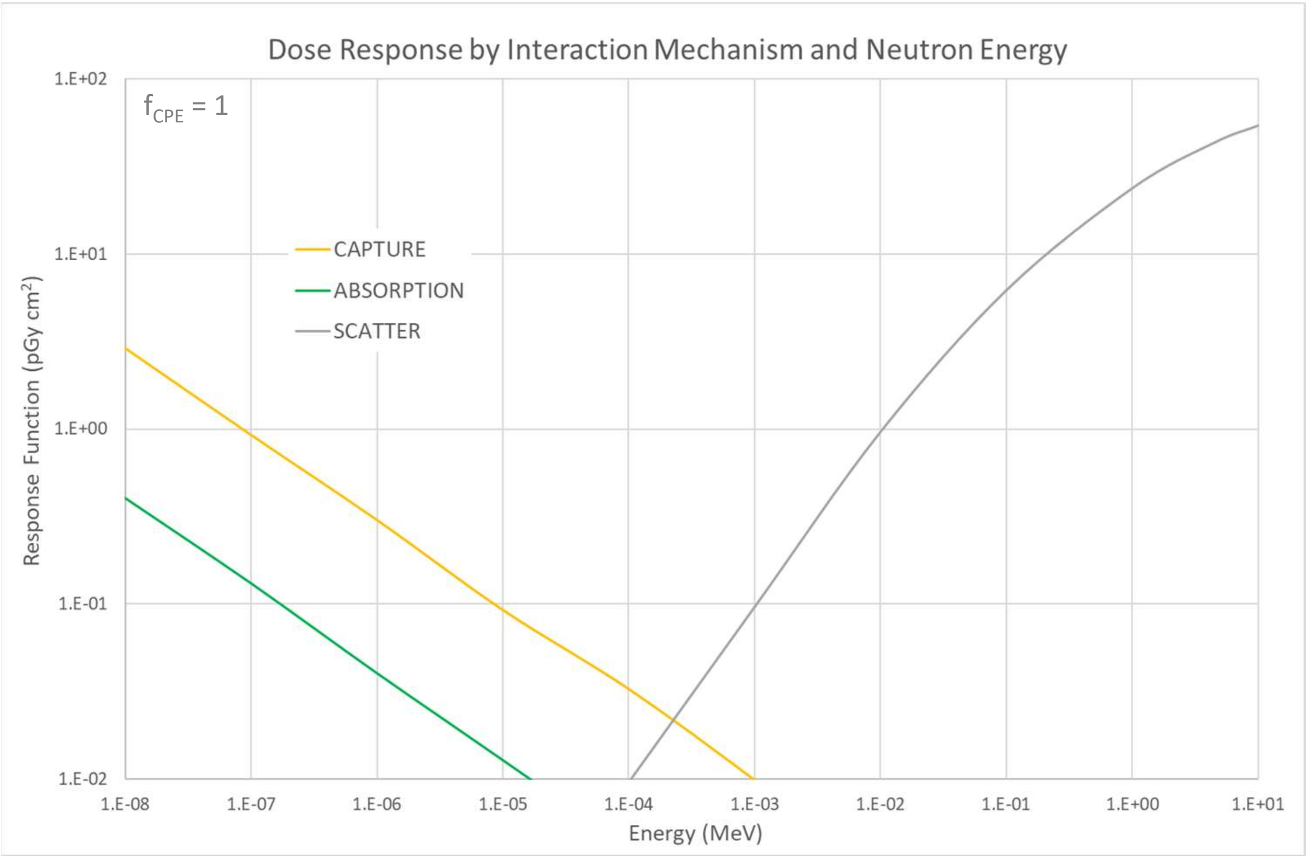
Response Function by Mechanism



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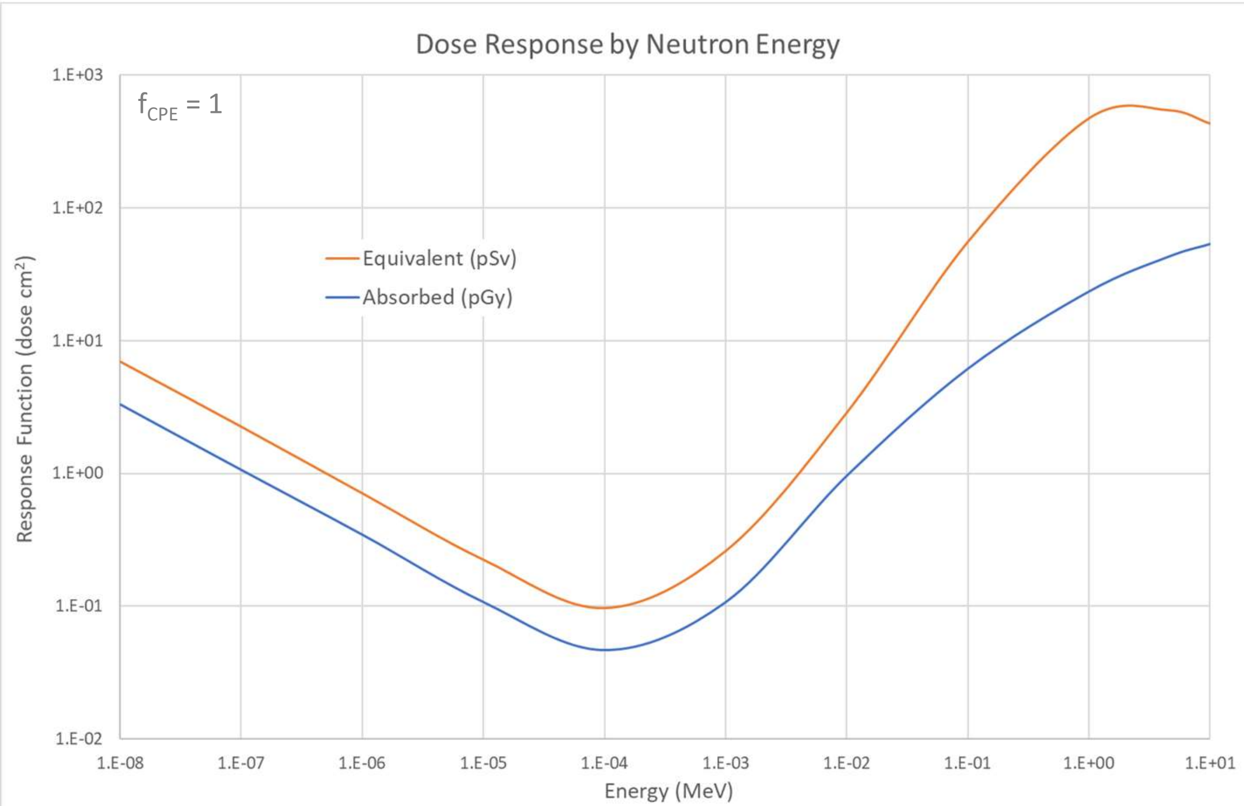
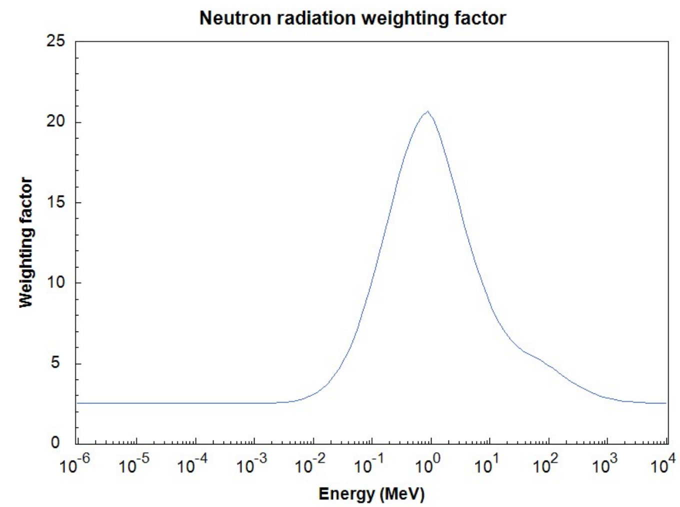
Response Functions - Absorbed & Equivalent Dose





Summary

- Neutron sources
  - monoenergetic, ^{252}Cf, PuBe, AmBe, SbBe, etc
- Interaction cross sections
  - for H, C, O, N
  - elastic scatter and absorption
- Charged particle buildup
  - great importance for shallow dosimetry above ~100 keV
- Neutron dosimetry
  - capture/absorption mechanism – dominant at thermal energies
  - scatter mechanism – dominant at medium-to-high energies
- Response functions
  - deep dose
  - dose per unit fluence

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