Neutron Interactions and Dosimetry

Chapter 16

F.A. Attix, Introduction to Radiological Physics and Radiation Dosimetry

Outline

- Neutron dosimetry
  - Thermal neutrons
  - Intermediate-energy neutrons
  - Fast neutrons
- Sources of neutrons
- Mixed field dosimetry, paired dosimeters
- Rem meters

Introduction

- Consider neutron interactions with the majority tissue elements H, O, C, and N, and the resulting absorbed dose
- Because of the short ranges of the secondary charged particles that are produced in such interactions, CPE is usually well approximated
- Since no bremsstrahlung x-rays are generated, the absorbed dose can be assumed to be equal to the kerma at any point in neutron fields at least up to an energy E ~ 20 MeV

Tissue composition

Element	ICRU (1977) Muscle	ICRP Skeletal Muscle	Whole Body
H	10.2	10.06	10.5
O	72.9	75.48	67.7
C	12.3	10.78	18.7
N	3.5	2.77	3.1
Other	1.1	0.91	—
Total	100.0	100.00	100.0

*Data are given in percent by weight.

- The ICRU composition for muscle has been assumed in most cases for neutron-dose calculations, lumping the 1.1% of "other" minor elements together with oxygen to make a simple four-element (H, O, C, N) composition

Neutron kinetic energy

- Neutron fields are divided into three categories based on their kinetic energy:
  - Thermal (E<0.5 eV)
  - Intermediate-energy (0.5 eV<E<10 keV)
  - Fast (E>10 keV)
- Differ by their primary interactions in tissue and resulting biological effects

Neutron kinetic energy

- Thermal neutrons, by definition, have the most probable kinetic energy E=kT=0.025eV at T=20C
- Neutrons up to 0.5eV are considered "thermal" due to simplicity of experimental test after they emerge from moderator material
- Cadmium ratio test:
  - Gold foil can be activated through $^{197}Au(n,\gamma)^{198}Au$ interaction
  - Addition of 1mm thick Cd filter, which absorbs all neutrons below 0.5eV, tests for presence of those neutrons

Neutron kinetic energy

- For E<10 keV the dose is mainly due to γ-rays resulting from thermal-neutron capture in hydrogen, $^1H(n,\gamma)^2H$
- For E>10 keV the dose is dominated by the contribution of recoil protons resulting from elastic scattering of hydrogen nuclei
  - Resulting biological effect (and the corresponding neutron quality factor) rises steeply

Kerma calculations

- For a mono-energetic neutron beam having fluence Φ (cm^{-2}), the kerma that results from a neutron at a point in a medium is

$$K = 1.602 \times 10^{-8} \Phi \sigma N_t m^{-1} E_{tr}$$

where σ is the interaction cross section in cm^2/(target atom), N_t is the number of target atoms in the irradiated sample, m is the sample mass in grams, and E_{tr} is the total kinetic energy (MeV) given to charged particles per interaction

Kerma calculations

- The product of $(1.602 \times 10^{-8} \sigma N_t m^{-1} E_{tr})$ is equal to the kerma factor F_n in rad cm^2/n
- Thus the equation reduces to

$$D \overset{CPE}{=} K = \Phi F_n$$

- CPE condition is usually well-approximated for neutron interactions in tissue

Kerma calculations

- F_n values are tabulated in Appendix F
- F_n is not generally a smooth function of Z and E, unlike the case of photon interaction coefficients
- Interpolation vs. Z cannot be employed to obtain values of F_n for elements for which data are not listed, and interpolation vs. E is feasible only within energy regions where resonance peaks are absent

Typical neutron absorption cross section

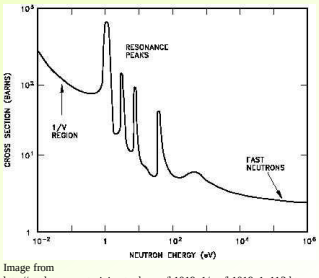
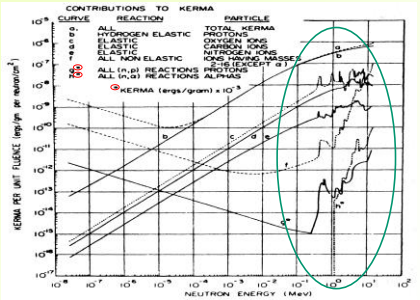


Image from http://nuclearpowertraining.tpub.com/h1019v1/css/h1019v1_113.htm

Resonance peaks occur when the binding energy of a neutron plus the KE of the neutron are exactly equal to the amount required to raise a compound nucleus from its ground state to one of quantum levels

Kerma calculations



Kerma per unit fluence due to various interaction in a small mass of **tissue**

Thermal-neutron interactions in tissue

- Two important interactions of thermal neutrons with tissue:
  - neutron capture by nitrogen, $^{14}N(n,p)^{14}C$
  - neutron capture by hydrogen, $^{1}H(n,\gamma)^{2}H$
- Thermal neutrons have a larger probability of capture by hydrogen atoms in muscle, because there are 41 times more H atoms than N atoms in tissue

Thermal-neutron interactions in tissue

- The nitrogen interaction releases a kinetic energy of E_{tr} = 0.62 MeV that is shared by the proton (0.58 MeV) and the recoiling nucleus (0.04 MeV)
- CPE exits since the range of protons in tissue ~10μm
- Based on known values for σ and N_t/m, kerma factor

$$F_n = 2.74\times10^{-11}\,[\text{rad cm}^2/n]$$

- Dose deposited

$$D_{CPE} = 2.74\times10^{-11}\Phi\,[\text{rad}]$$

Thermal-neutron interactions in tissue

- In the hydrogen interaction the energy given to γ-rays per unit mass and per unit fluence of thermal neutrons can be obtained similarly, but replacing E_{tr} by E_γ = 2.2 MeV (the γ-ray energy released in each neutron capture)
- The energy available: $R_\gamma/\Phi m = 7.13\times10^{-10}\,[\text{rad cm}^2/n]$
- These γ-rays must interact and transfer their energy to charged particles to produce kerma
- Contribution to dose depends on proximity to RE

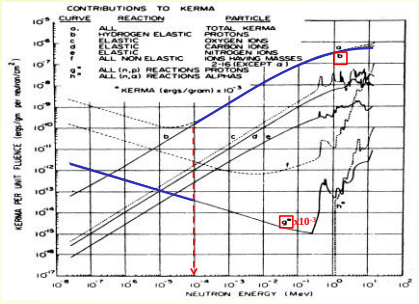
Thermal-neutron interactions in tissue

- In the center of a 1-cm diameter sphere of tissue the kerma contributions from the (*n*, *p*) and (*n*, γ) processes are comparable in size
- In a large tissue mass (radius > 5 times the γ-ray MFP) where radiation equilibrium is approximated, the kerma due indirectly to the (*n*, γ) process is 26 times that of the nitrogen (*n*, *p*) interaction
- The human body is intermediate in size, but large enough so the $^{1}H(n,\gamma)^{2}H$ process dominates in kerma (and dose) production

Interactions by intermediate and fast neutrons in tissue

- It is dominated below 10^{-4} MeV (100eV) by (*n*,*p*) reactions, mostly in nitrogen, represented by curve *g*
- Above 10^{-4} MeV elastic scattering of hydrogen nuclei (curve *b*) contributes nearly all of the kerma

Interactions by neutrons in tissue



Interaction by intermediate and fast neutrons in tissue

- The average energy transferred by elastic scattering to a nucleus is closely approximated (i.e., assuming isotropic scattering in the center-of-mass system) by

$$\overline{E}_{tr} = E\frac{2M_aM_n}{(M_a+M_n)^2}$$

where E = neutron energy,
M_a = mass of target nucleus,
M_n = neutron mass

Interaction by intermediate and fast neutrons in tissue

- Values for $\overline{E}_{tr}$ for different tissue atoms:
  - $E/2$ for hydrogen recoils (changes from 0 when proton is recoiling at 90° to E_{tr} for protons recoiling straight ahead)
  - $0.142E$ for C atoms
  - $0.124E$ for N
  - $0.083E$ for O

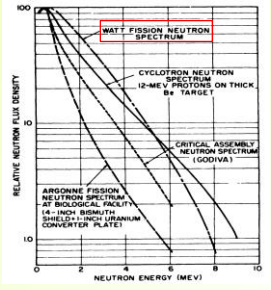
Neutron sources

- Neutrons can be released through processes such as fission, spallation, or neutron stripping
- Fission: splitting atoms in a nuclear reactor
  - n + ^{235}U = n + n + fragments – one n may go back into chain reaction, the other is available
- Spallation: bombarding heavy metal atoms with energetic protons
  - p + heavy nucleus = X * n + fragments
- Stripping: bombarding light metal atoms with protons, α-particles, etc.

Neutron sources

- Most widely available neutron sources:
  - Nuclear fission reactors
  - Accelerators
  - Radioactive sources

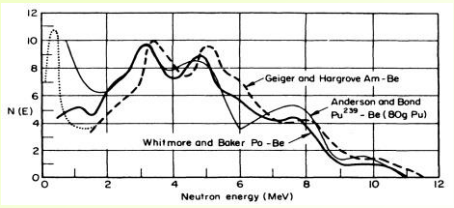
Neutron sources



Fission neutron spectra from reactors

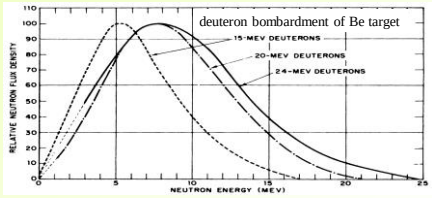
- Fission-like spectra have average neutron energies ~2MeV
- From beam ports of nuclear reactors
- Watt spectrum is an idealized shape for unmoderated reactor neutrons

Neutron sources



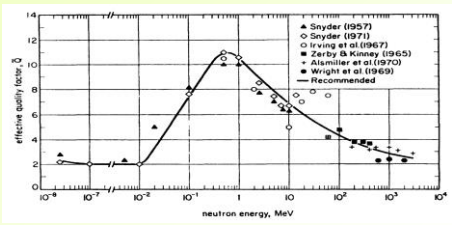
- Several types of Be(α,n) radioactive sources are in common use, employing ^{210}Po, ^{239}Pu, ^{241}Am, or ^{226}Ra as the emitter
- Neutron yields are on the order of 1 neutron per 10^4 α-particles; average energies ≅ 4 MeV

Neutron sources



- Cyclotrons are used to produce neutron beams by accelerating protons or deuterons into various targets, most commonly Be
- The neutron spectrum extends from 0 to energies E_{max} somewhat above the deuteron energy, and have E_{avg} ~$0.4E_{max}$
- Tissue dose rates ~10rad/min at 1m in tissue, γ-ray background ~few %

Neutron Quality Factor



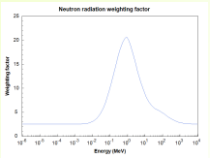
- For purposes of neutron radiation protection the dose equivalent $H = DQ$, where Q is the quality factor, which depends on neutron energy
- The quality factor for all γ-rays is taken to be unity for purposes of combining neutron and γ-ray dose equivalents

Radiation Weighting Factor

- New approach uses *radiation and tissue weighting factors* (updated in ICRP 103 report, 2007); effective dose

$$E = w_T H_T = w_T w_R * D_{T,R}$$

- For neutrons weighting factor is a continuous function of energy; represented as a graph or in functional form



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

Mixed-Field Dosimetry *n* + γ

- Neutrons and γ-rays are both indirectly ionizing radiations that are attenuated exponentially in passing through matter
- Each is capable of generating secondary fields of the other radiation:
  - (γ, n) reactions are only significant for high-energy γ-rays (≥10 MeV, there is a threshold defined by reaction)
  - (n, γ) reactions can proceed at all neutron energies and are especially important in thermal-neutron capture, as discussed for $^1H(n, \gamma)^2H$

Mixed-Field Dosimetry *n* + γ

- Neutron fields are normally "contaminated" by secondary γ-rays
- Since neutrons generally have more biological effectiveness per unit of absorbed dose than γ-rays, it is desirable to account for γ and *n* components separately
- It is especially important in the case of neutron dosimeters to specify the reference material to which the dose reading is supposed to refer

Mixed-Field Dosimetry *n* + γ

- Three general categories of dosimeters for *n* + γ applications:
  1. Neutron dosimeters that are relatively insensitive to γ rays
  2. γ-ray dosimeters that are relatively insensitive to neutrons
  3. Dosimeters that are comparably sensitive to both radiations

Mixed-Field Dosimetry *n* + γ

- While water is a very close substitute of muscle tissue in photon dosimetry, it is not as close a substitute for neutrons
- Water is 1/9 hydrogen by weight; muscle is 1/10 hydrogen
- Water contains no nitrogen, and hence can have no $^{14}N(n,p)^{14}C$ reactions by thermal neutrons
- For 1MeV photon $(\mu_{en}/\rho)_{muscle}=0.99\ (\mu_{en}/\rho)_{water}$, for 1MeV neutron $(F_n)_{muscle}=0.91(F_n)_{water}$

Mixed-Field Dosimetry *n* + γ

- The response of a dosimeter to a mixed field of neutrons and γ-rays

$$Q_{n,\gamma} = AD_{\gamma} + BD_n$$

or alternatively as

$$\frac{Q_{n,\gamma}}{A} = D_{\gamma} + \frac{B}{A} D_n$$

Here A = response per unit of absorbed dose in tissue for γ-rays, B = response per unit of absorbed dose in tissue for neutrons, D_{γ} and D_n are absorbed doses in tissue correspondingly due to γ-rays and neutrons

Mixed-Field Dosimetry *n* + γ

- By convention the absorbed dose referred to in these terms is assumed to be that under CPE conditions in a small imaginary sphere of muscle tissue, centered at the dosimeter midpoint with the dosimeter absent
- Most commonly this tissue sphere is taken to be just large enough (0.52-g/cm^2 radius) to produce CPE at its center in a ^{60}Co beam

Mixed-Field Dosimetry *n* + γ

- An approach of employing two dosimeters (paired dosimeters) having different values of A/B can be used to simultaneously obtain D_{γ} and D_n
- The best dosimeter pair is a TE-plastic ion chamber containing TE gas (for which $B/A \cong 1$) to measure the total *n* + γ dose, and a nonhydrogenous dosimeter having as little neutron sensitivity as possible to measure the γ dose
  - Ideally this paired dosimeter should measure *only* γ-rays
- Closer values of A/B in a pair decrease the accuracy

Mixed-Field Dosimetry *n* + γ

- Often dosimeters insensitive to γ-rays are used in mixed fields to evaluate neutron dose only (A<<B)
  - ☆ – Activation of metal foils ($A \cong 0$)
  - – Fission foils ($A = 0$)
  - – Etchable plastic foils ($A \cong 0$)
  - – Damage to silicon diodes ($A \cong 0$)
  - – Hurst proportional counter ($A \cong 0$)
  - ☆ – Rem meters
  - – Long counters
  - – Bubble detectors

Activation of metal foils

- Since most of radio-activation by photonuclear reactions can occur only above the energy range of γ-radiation (>10MeV), metal foils are only activated by the neutrons in the mixed field
- The resulting activity of a foil is measured by counting γ-rays emitted (G-M counter will work)
- Some activated foils are β-emitters (e.g., in $^{32}S(n,p)^{32}P$ reaction, ^{32}P is a β-emitter)

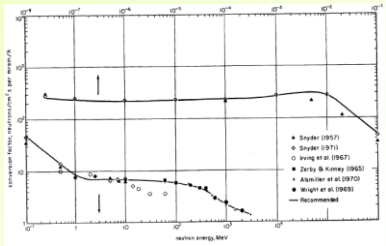
Activation of metal foils

- Thermal neutrons have a fixed activation cross section σ(E)=σ
- Fast neutrons have activation threshold, below which σ(E)=0
- Since different materials have different threshold, a set of foils with different thresholds allows determination of the neutron spectrum

Rem meters

- Instruments designated to measure dose equivalent H, evaluated at the depth in the body where it reaches a maximum for each incident neutron energy
- The ICRP provided the fluence-to-maximum dose-equivalent conversion factor d(E) (units of mrem/(n cm^2)) to the neutron energy incident on the body
- Dose equivalent $H = \int_{E=0}^{E_{max}} \Phi'(E) d(E) dE$, here $\Phi'(E)$ is the energy spectrum of incident neutrons

Rem meters



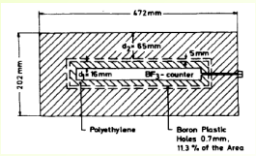
The maximum value of the dose equivalent, $[3600d(E)]^{-1}$ in the body (tissue slab in 30-cm thickness) vs energy of neutrons

Rem meters

- Instruments are based on materials having high capture cross section for neutrons
- Most rem meters employ boron in form of BF_3 gas (very toxic and corrosive); newer instruments use helium gas
- Reactions:
  - $^{10}B + n \rightarrow {}^{7}Li + \alpha + 2790\ keV$
  - $^{3}He + n \rightarrow {}^{3}H + {}^{1}H + 765\ keV$

Rem meters

- For both ^{10}B and ^{3}H the cross section $\sigma \sim 1/\sqrt{E} \sim 1/v$
- Require neutron moderator, typically polyethylene
- Response is proportional to the absorbed dose and the neutron quality



Sectional view of Andersson-Braun rem counter

Summary

- Neutron dosimetry approaches differ from those of photon dosimetry
- Water is not the best tissue-mimicking phantom anymore
- Quality factor for neutrons is energy dependent
- Dosimetry involves measurement of mixed n+γ fields