Radiological effects from Fission and Thermonuclear Weapons

Gamma and Neutron Radiation for Low Altitude Airburst

Radiation Effects in Humans vs Yield and Slant Range from Detonation

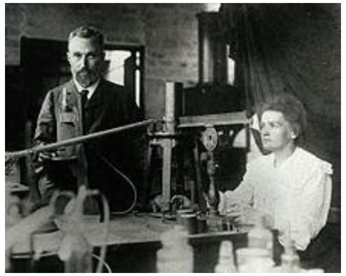
Some from Glasstone and Dolan (Effects of Nuclear Weapons 1977, 2022 – Chap 8)

https://atomicarchive.com/resources/documents/effects/glasstone-dolan/chapter8.html

Radiation Units

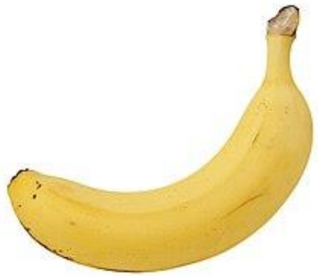
- Curies (Cu) = radiation decay rate from 1g $^{226}Ra_{88}$ (Radium)
  - 1Cu = 37 billion decays/s (1 g Ra at Beginning of Life (BOL))
  - Marie Curie – first woman to receive Nobel prize (Physics 1903)
  - First woman to be a professor Univ Paris (1906)
  - Second Nobel Prize (Chemistry 1911)
  - $^{226}Ra_{88} \rightarrow {}^{222}Rn_{86}$ (α)
  - $^{226}Ra_{88}$ (α) $\tau_{1/2}$=1599y → $^{222}Rn_{86}$ (α) $\tau_{1/2}$=3.82 d → $^{218}Po_{84}$
  - Radon is a gas – one of the leading causes of lung cancer
  - Important to have a well ventilated room (esp basement)
- Roentgen (historical unit – X Ray ionization in air)
  - Defined now as 1R = 2.58x10^{-4} Coulomb/kg
- Becquerel (Bq) = 1 decay/s 1 Cu= 37GBq, 1nCu=37Bq (37 decays/s)
- RAD-rad (Radiation Absorbed Dose) = 100 erg/g = 0.01 J/kg
  - (1 erg=10^{-7}J)
- REM-rem (Roentgen Equivalent Man – bio damage)
  - →Typ 50% lethality (50% chance of death) is ~ 500 REM = 5Sv ←
  - 0.055% increase in cancer per REM (5.5%/Sv)
  - Recommended limit is 100 mrem/yr (1 mSv/yr) not including medical x-ray
  - Typ natural background is ~ 300 mrem = 3mSv
  - Recommended limit for nuclear workers is 5rem/yr (50mSv/yr)
  - Ex: Inside US Capitol building ~ 85 mrem/yr (0.85 mSv/yr) due to radiation from Granite
- **Relationship between RAD and REM depends on radiation particle**
  - REM = RAD * QF where QF = quality factor QF ~ 1 beta, x-ray/ gamma, QF ~ 10-20 alpha, QF ~ 1-10 neutrons
- 1 Gray (Gy) = 100 RAD (1 RAD = 0.01 Gy)
- 1 Sievert (Sv) = 100 REM (1 REM = 0.01 Sv=10mSv)
- BED – Banana Equivalent Dose (150 gram banana)
  - Radioactivity Primarily From radioactive Potassium- ^{40}K
  - 0.0117% of natural K is isotope ^{40}K ($\tau_{1/2}$=1.25 Gyr, 31 Bq/g(of total K))
  - Banana has ~ 0.5g of total K → ~ 15 Bq from ^{40}K (**you are radiaoactive**)
  - **0.1µSv, 10 µREM, ~0.4 nCu**
- Human body regulates ^{40}K so you **do not** accumulate it
  - Typ human has 2.5 g/kg of total K or about 175g in 70 kg person (**this is Potassium from all sources you eat**)
  - **Radiation from ^{40}K in person (70 kg) = 175g *31 Bq/g(of total K) ~ 5400 Bq (decay/s) ~150 nCu ~ 400 bananas**
  - Committed effective Dose = net radiological effect from 50 years of exposure
  - US EPA calculates for ^{40}K in our bodies about 5.02 nSv/Bq over 50 years → 5.02 nSv/Bq * 31Bq/g(total K)*0.5 g~ 78 nSv ~ 0.1µSv
    - The above assumes you come to metabolic equilibrium with bananas

1903 Nobel Prize - "in recognition services they of the extraordinary have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel."



Marie and Pierre Curie - 1904

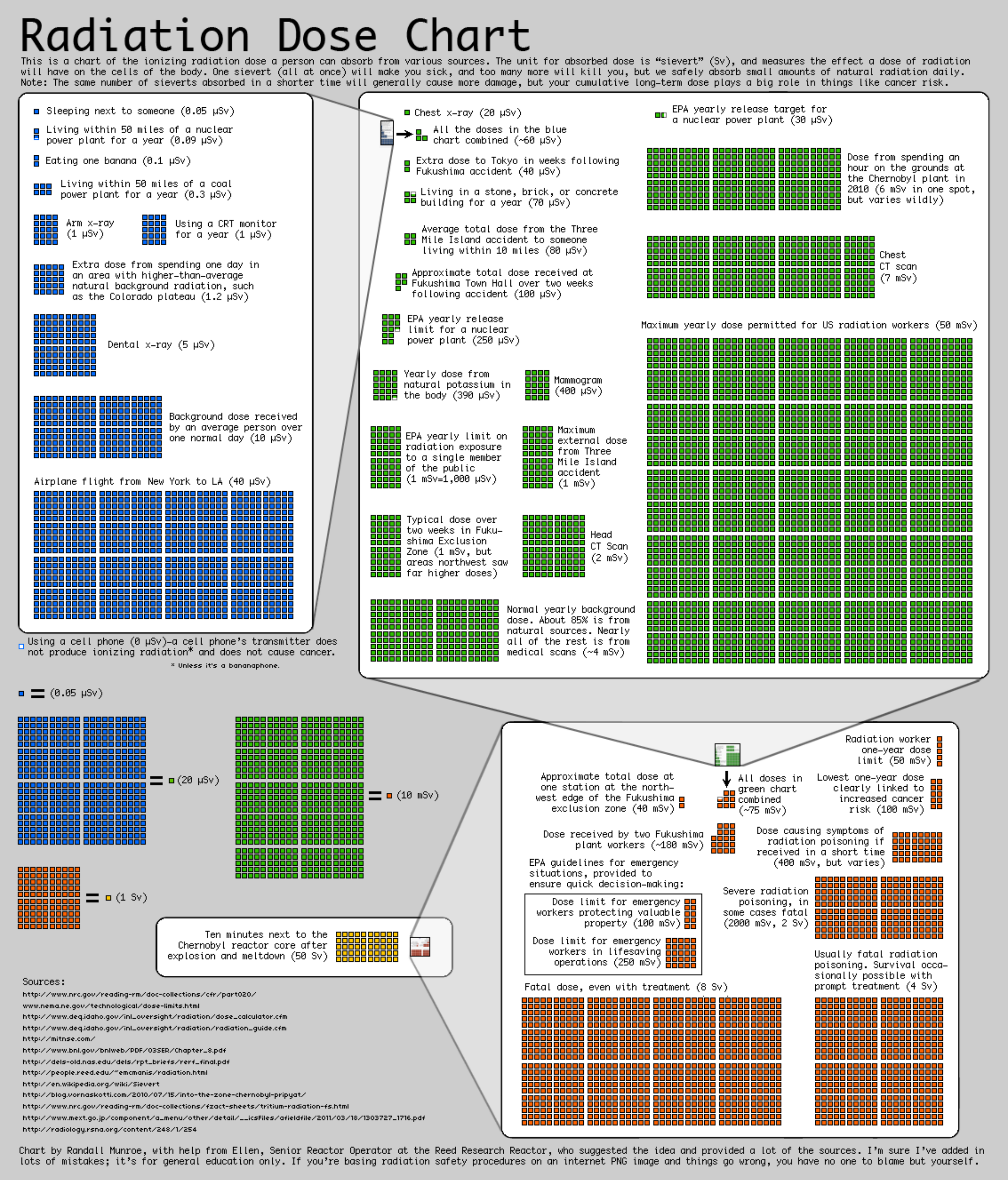
1911 Nobel Prize - "in recognition of her services to the advancement of chemistry by the **discovery of the elements radium and polonium**, by the isolation of radium and the study of the nature and compounds of this remarkable element."



Ionizing radiation related quantities

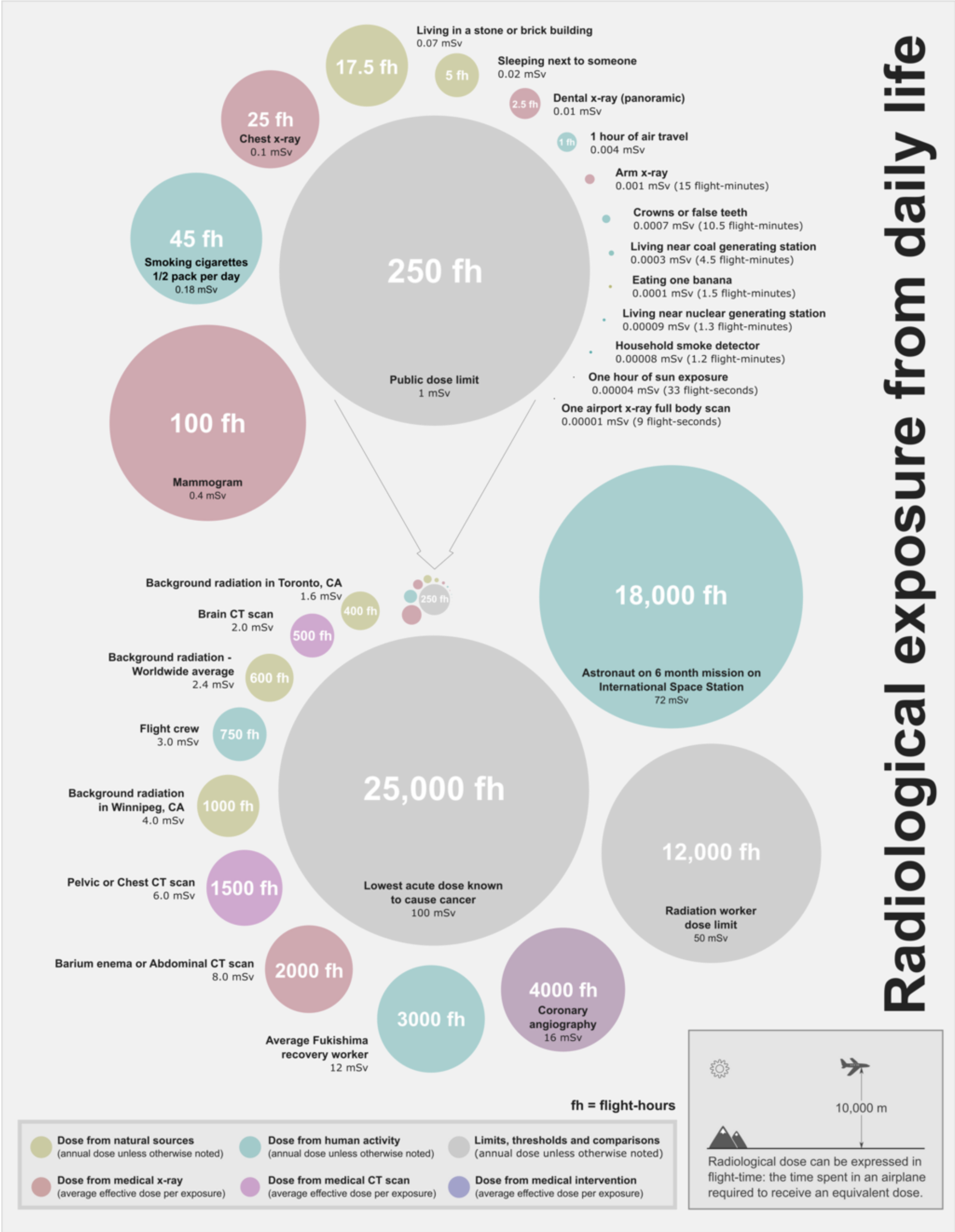
Quantity	Unit	Symbol	Derivation	Year	SI equivalent
Activity (*A*)	becquerel	Bq	s^{-1}	1974	SI unit
	curie	Ci	$3.7 \times 10^{10}\ s^{-1}$	1953	3.7×10^{10} Bq
	rutherford	Rd	$10^6\ s^{-1}$	1946	1000000 Bq
Exposure (*X*)	coulomb per kilogram	C/kg	$C \cdot kg^{-1}$ of air	1974	SI unit
	röntgen	R	esu / 0.001293 g of air	1928	2.58×10^{-4} C/kg
Absorbed dose (*D*)	Gray **= 100 RAD**	Gy	$J \cdot kg^{-1}$	1974	SI unit
	erg per gram	erg/g	$erg \cdot g^{-1}$	1950	1.0×10^{-4} Gy
	rad	rad	$100\ erg \cdot g^{-1}$	1953	0.010 Gy
Equivalent dose (*H*)	Sievert = **100 REM**	Sv	$J \cdot kg^{-1} \times W_R$	1977	SI unit
	röntgen equivalent man	rem	$100\ erg \cdot g^{-1} \times W_R$	1971	0.010 Sv
Effective dose (*E*)	sievert	Sv	$J \cdot kg^{-1} \times W_R \times W_T$	1977	SI unit
	röntgen equivalent man	rem	$100\ erg \cdot g^{-1} \times W_R \times W_T$	1971	0.010 Sv

Radiation Doses



Rad Dose relative to Aircraft Flight Hours (fh)

Typical commercial aircraft flies at 10km altitude



Quality Factor for Neutron in Tissue

REM=QF*RAD

https://www.nrc.gov/reading-rm/doc-collections/cfr/part020/part020-1004.html

[a] Value of quality factor (Q) at the point where the dose equivalent is maximum in a 30-cm diameter cylinder tissue-equivalent phantom.

[b] Monoenergetic neutrons incident normally on a 30-cm diameter cylinder tissue-equivalent phantom.

	Neutron energy (MeV)	Quality factor[a] (Q)	Fluence per unit dose equivalent[b] (neutrons cm^{-2} rem^{-1})
	2.5×10^{-8}	2	980×10^{6}
	1×10^{-7}	2	980×10^{6}
	1×10^{-6}	2	810×10^{6}
	1×10^{-5}	2	810×10^{6}
	1×10^{-4}	2	840×10^{6}
	1×10^{-3}	2	980×10^{6}
	1×10^{-2}	2.5	1010×10^{6}
	1×10^{-1}	7.5	170×10^{6}
	5×10^{-1}	11	39×10^{6}
	1	11	27×10^{6}
	2.5	9	29×10^{6}
	5	8	23×10^{6}
	7	7	24×10^{6}
	10	6.5	24×10^{6}
	14	7.5	17×10^{6}
	20	8	16×10^{6}
	40	7	14×10^{6}
	60	5.5	16×10^{6}
	1×10^{2}	4	20×10^{6}
	2×10^{2}	3.5	19×10^{6}
	3×10^{2}	3.5	16×10^{6}
	4×10^{2}	3.5	14×10^{6}

REM vs RAD conversion factor (Quality Factor – Q = QF)

https://www.nuclear-power.com/nuclear-engineering/radiation-protection/equivalent-dose/roentgen-equivalent-man-rem-unit/

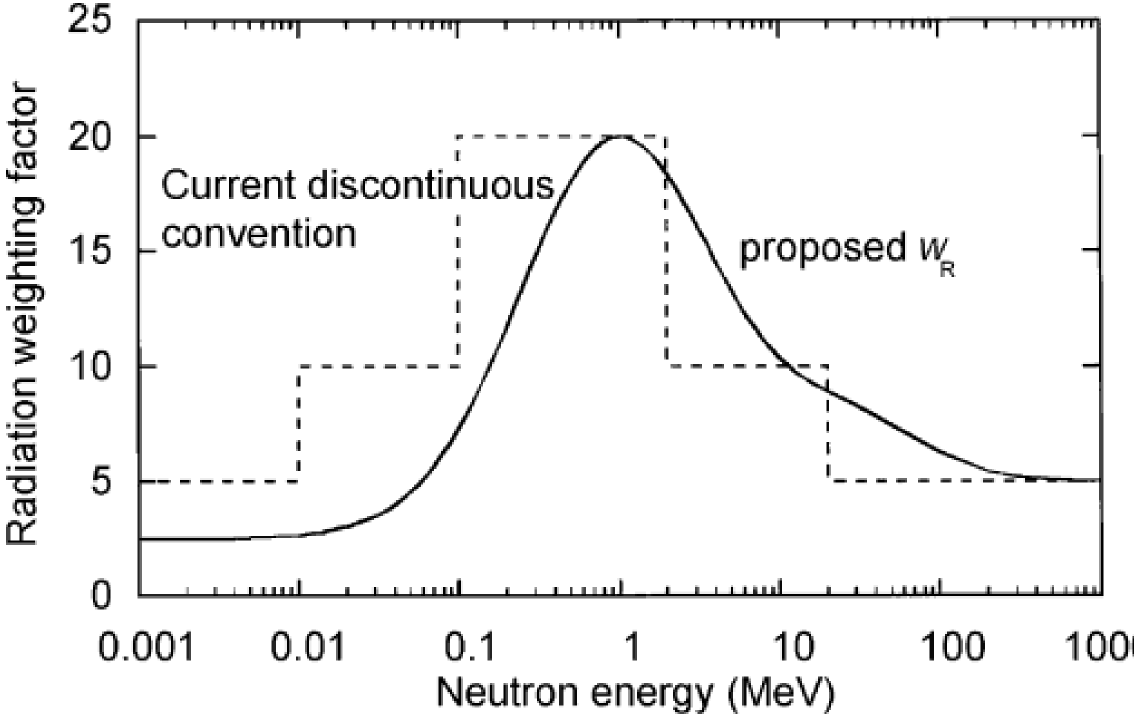
Radiation type and energy range	Radiation weighting factor, w_R
Photons, all energies	1
Electrons and muons, all energies	1
Neutrons, energy <10 keV	5
Neutrons, energy 10–100 keV	10
Neutrons, energy > 100 keV–2 MeV	20
Neutrons, energy > 2–20 MeV	10
Neutrons, energy > 20 MeV	5
Protons, other than recoil protons, energy > 2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20

REM vs RAD conversion factor (Quality Factor – Q = QF) Neutron Energy Fits – Radiation Weighting Factor wR=Q

https://www.nuclear-power.com/nuclear-engineering/radiation-protection/equivalent-dose/roentgen-equivalent-man-rem-unit/

Radiation type and energy range	Radiation weighting factor, wR
Photons, all energies	1
Electrons and muons, all energies	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy nuclei	20
Neutrons	a continuous function of neutron energy (see below)

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

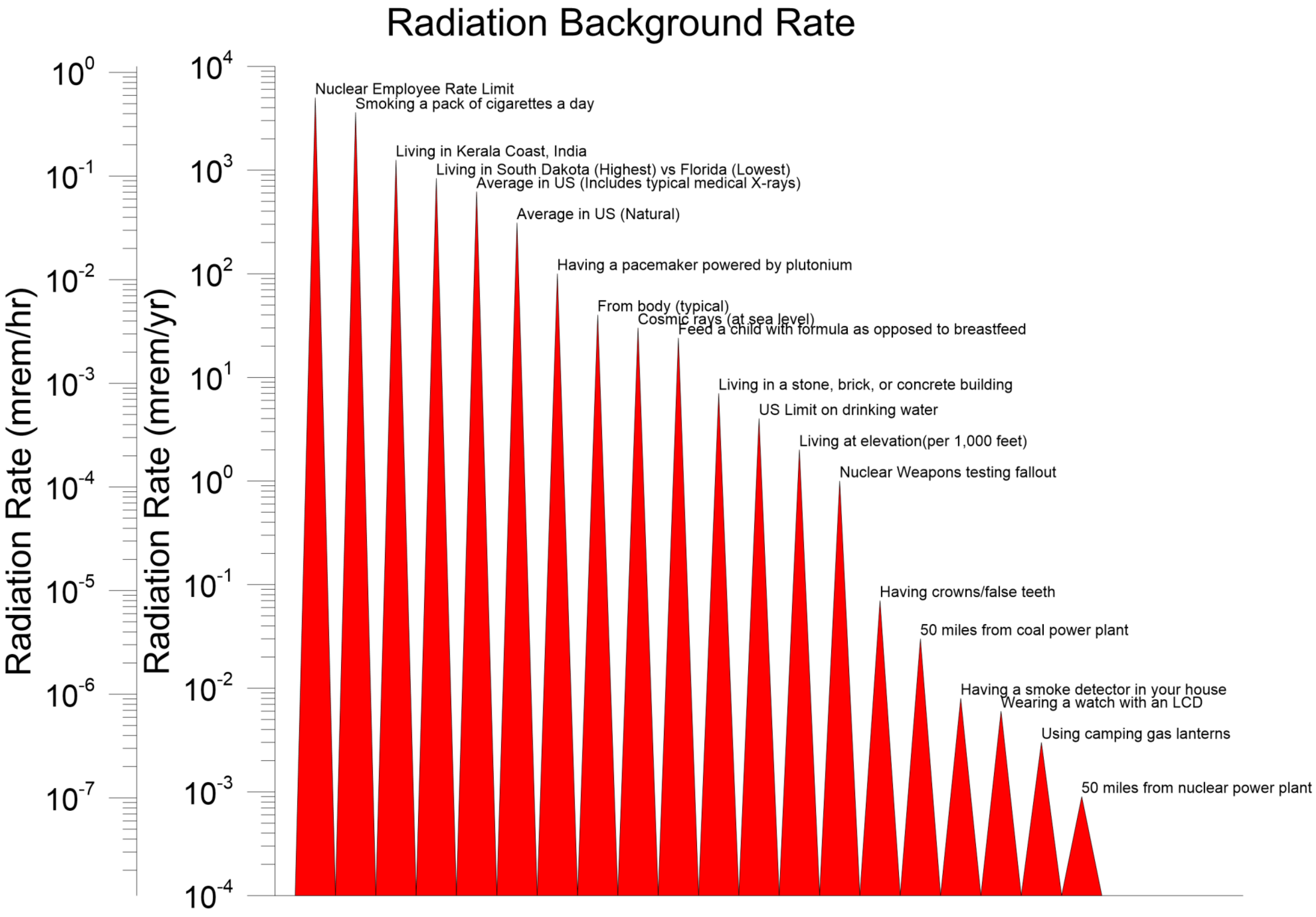


Rad Dose

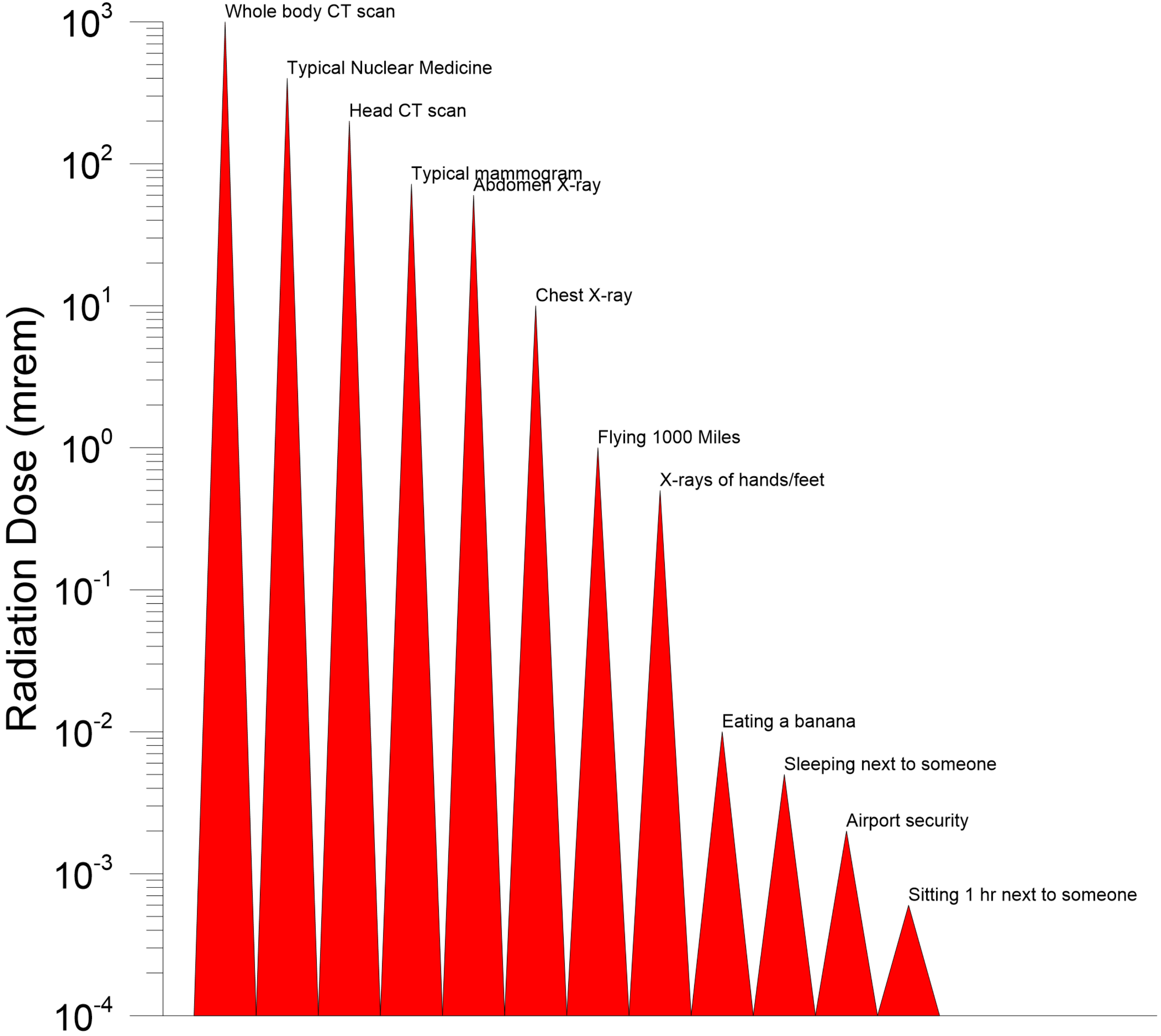
Acute dose=short time
Chronic dose=long time

High doses tend to kill cells, while low doses tend to damage or change them. Low doses spread out over long periods don't cause an immediate problem to any body organ. The effects of low radiation doses occur at the cell level, and the results may not be observed for many years.

- **0.005 mrem** – Sleeping next to someone
- **0.009 mrem** – Living within 30 miles of a nuclear power plant for a year
- **0.01 mrem** – Eating one banana
- **0.03 mrem** – Living within 50 miles of a coal power plant for a year
- **1 mrem** – Average daily dose received from natural background
- **2 mrem** – Chest X-ray
- **4 mrem** – A 5-hour airplane flight
- **60 mrem** – mammogram
- **100 mrem** – Dose limit for individual members of the public, total effective dose per annum
- **365 mrem** – Average yearly dose received from natural background
- **580 mrem** – Chest CT scan
- **1 000 mrem** – Average yearly dose received from a natural background in Ramsar, Iran
- **2 000 mrem** – single full-body CT scan
- **17 500 mrem** – annual dose from natural radiation on a monazite beach near Guarapari, Brazil.
- **500 000 mrem** – Dose that kills a human with a 50% risk within 30 days (LD50/30) if the dose is received over a **very short duration**.


Radiation Background Rate
Radiation Rate (mrem/hr)
Radiation Rate (mrem/yr)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
Nuclear Employee Rate Limit
Smoking a pack of cigarettes a day
Living in Kerala Coast, India
Living in South Dakota (Highest) vs Florida (Lowest)
Average in US (Includes typical medical X-rays)
Average in US (Natural)
Having a pacemaker powered by plutonium
From body (typical)
Cosmic rays (at sea level)
Feed a child with formula as opposed to breastfeed
Living in a stone, brick, or concrete building
US Limit on drinking water
Living at elevation(per 1,000 feet)
Nuclear Weapons testing fallout
Having crowns/false teeth
50 miles from coal power plant
Having a smoke detector in your house
Wearing a watch with an LCD
Using camping gas lanterns
50 miles from nuclear power plant

Radiation Background Dose



Little Boy U (Hiroshima) neutron Spectra outside weapon
Prompt fission (inside) and Weapon Leakage (outside casing) (Spriggs 2017)

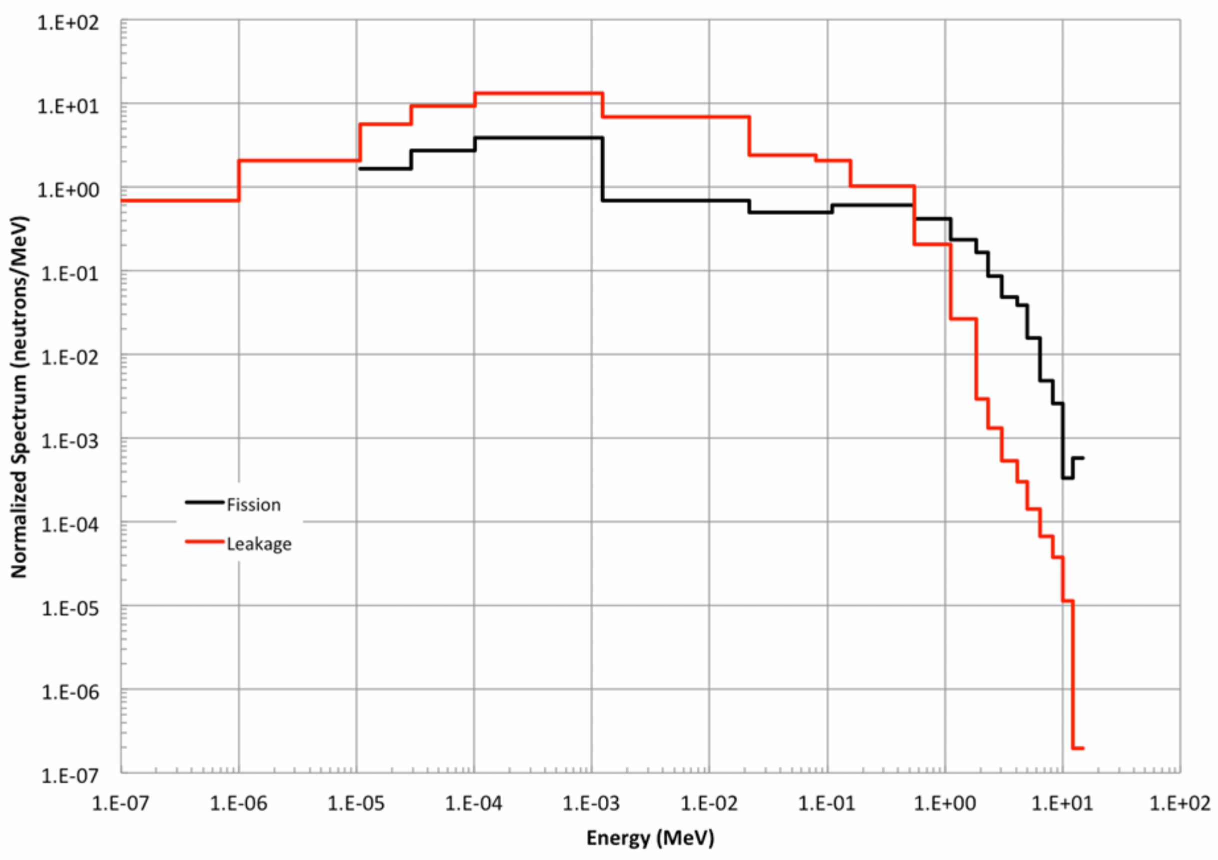


Figure 5. This is a plot of the neutron spectra (normalized to 1 neutron) that was used to estimate the residual radiation source term for the Hiroshima detonation. The average neutron energy of the prompt fission spectrum was 1.46 MeV and the average neutron energy of the leakage spectrum was 0.31 MeV. The prompt fission spectrum was used to estimate the fission-product yield curve, which is used to determine the radionuclides in the fission product source term. The leakage spectrum was used to calculate the air-activation source term and the ground-activation source term.

Fat Man (Pu implosion) and Little Boy (U gun) Weapon Gamma Spectra

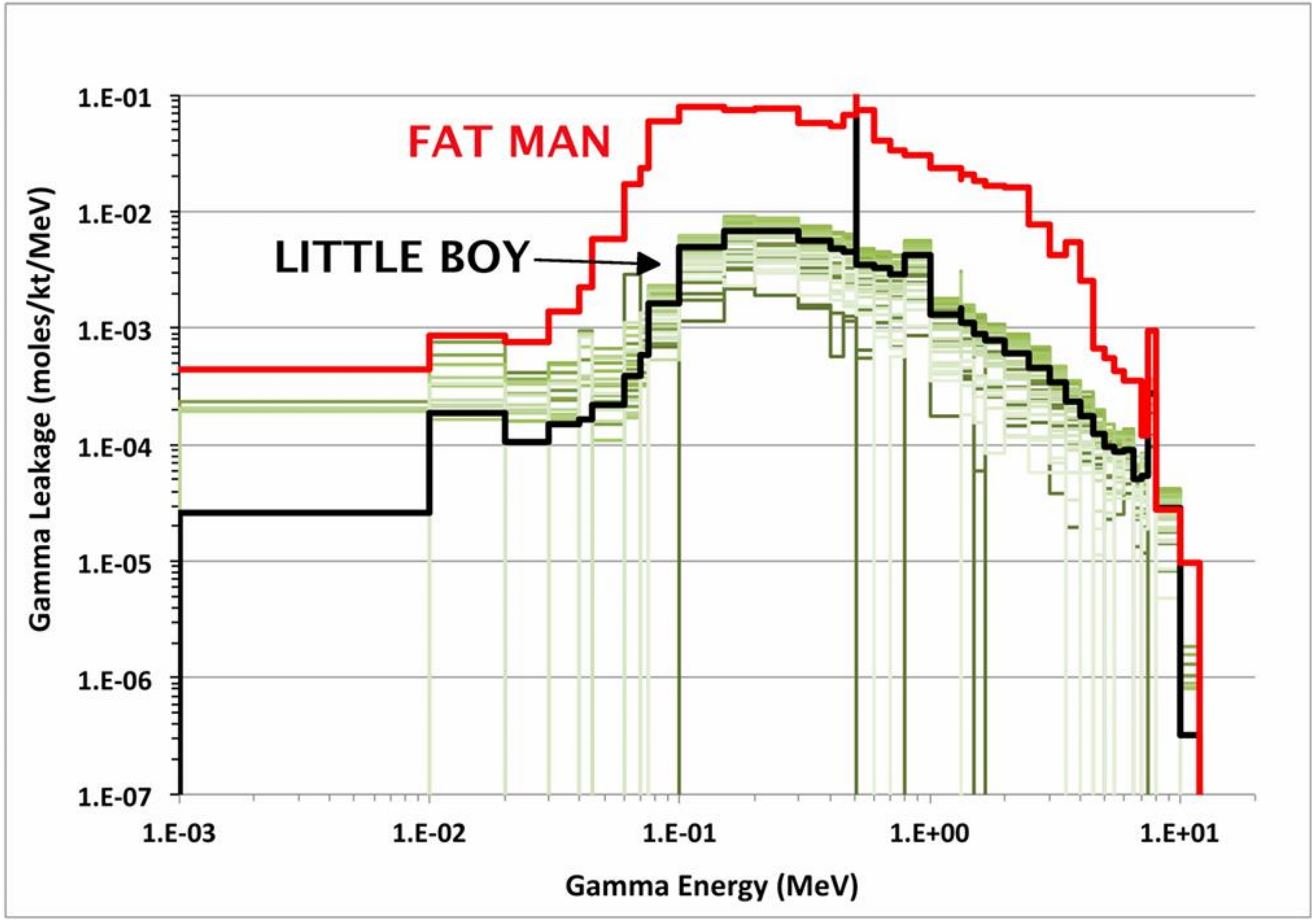


Figure 3: Gamma spectra for Fat Man and Little Boy. The total Little Boy output (sum over all angles) is shown along with the 40 individual segment tallies scaled up to the full sphere. The segment tallies illustrate the two-dimensional variation of the output.

Fat Man (Pu implosion) and Little Boy (U gun) Weapon Neutron Spectra

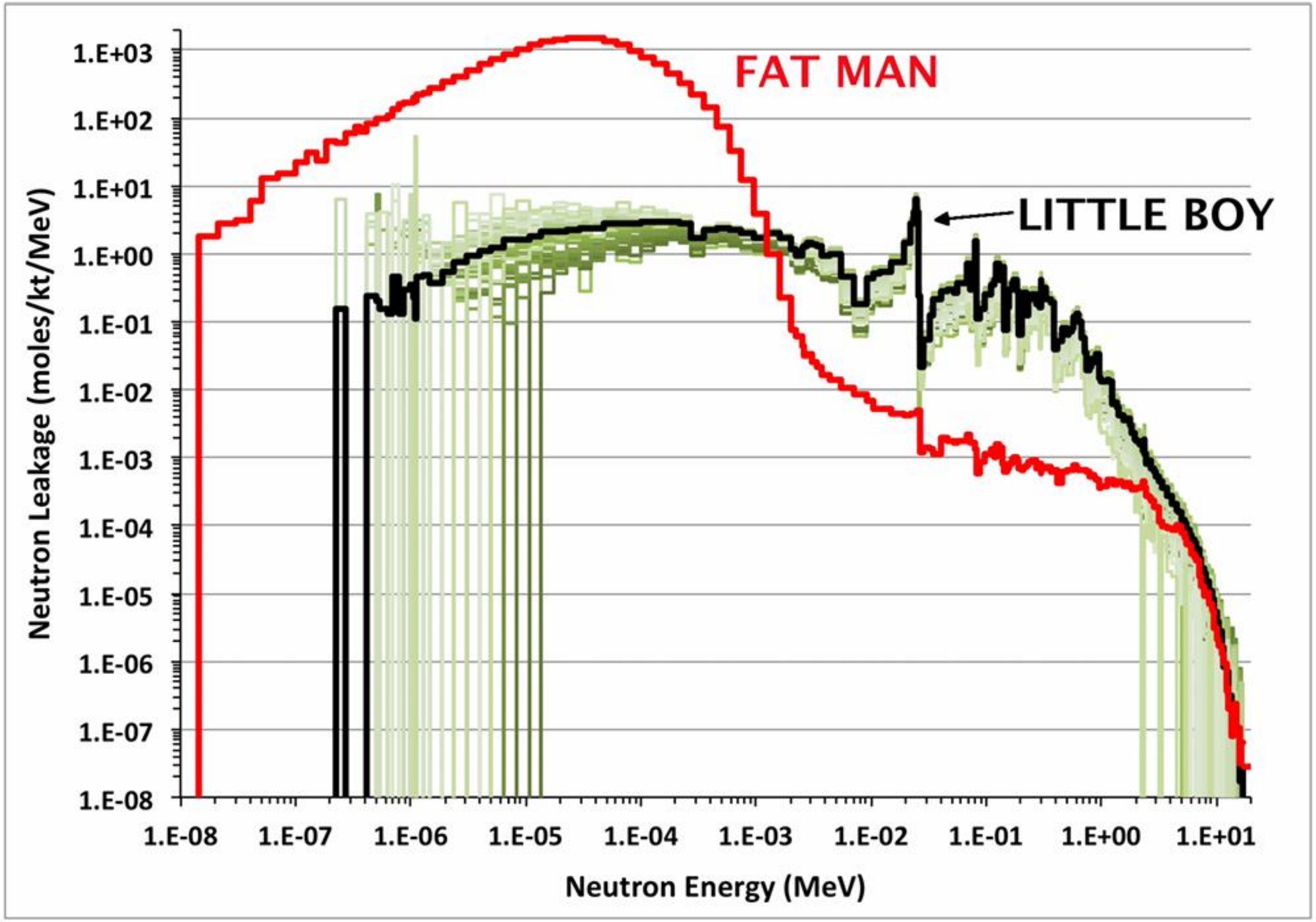


Figure 2: Neutron spectra for Fat Man and Little Boy. The total Little Boy output (sum over all angles) is shown along with the 40 individual segment tallies scaled up to the full sphere. The segment tallies illustrate the two-dimensional variation of the output.

Fat Man (Pu implosion) and Little Boy (U gun) Weapon Gamma vs Angle

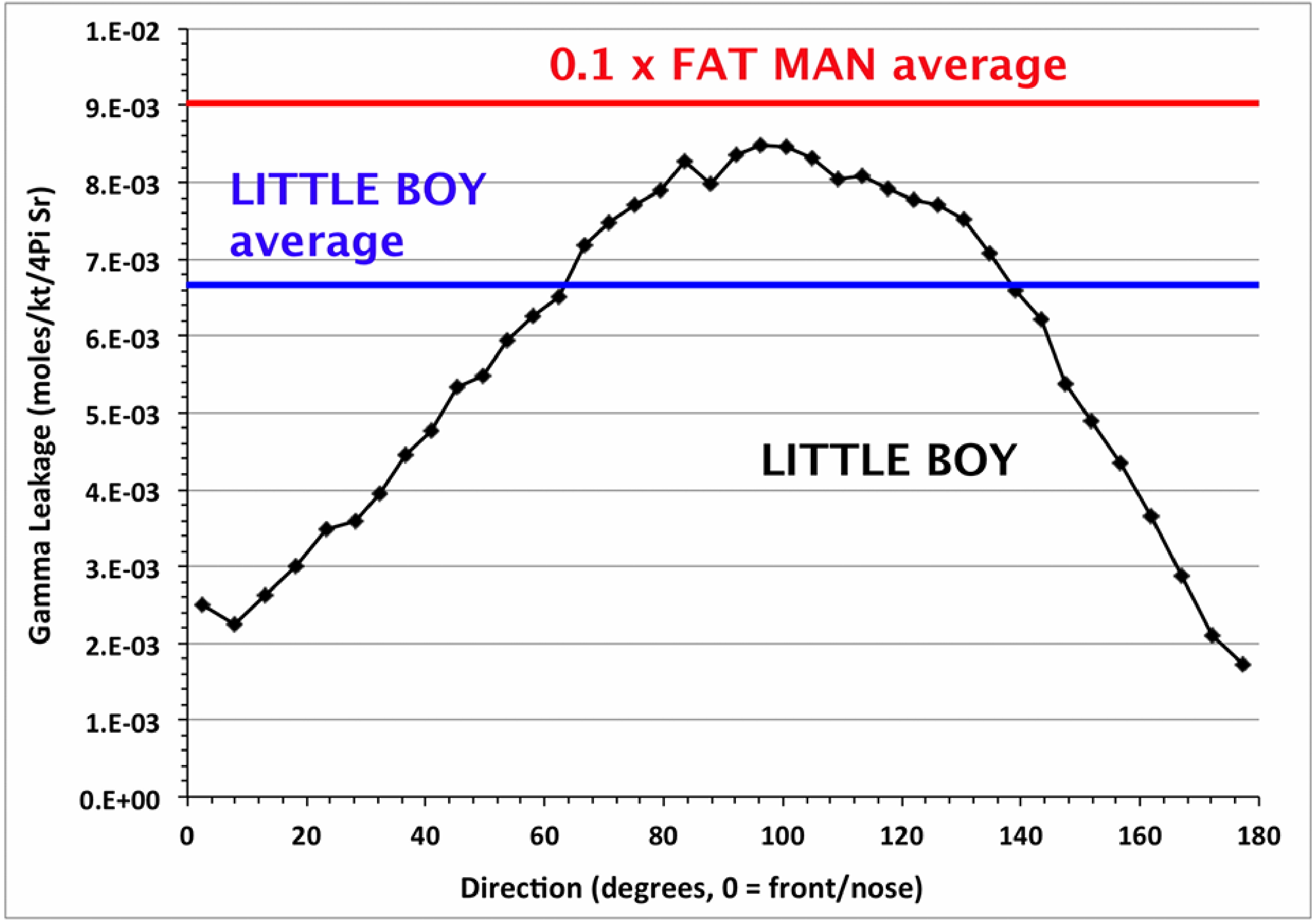


Figure 5: Gamma output variation with angle. Segment tallies have been scaled up to the full sphere. Note that the Fat Man value has been reduced by a factor of 10. As with neutrons, the output is suppressed toward the nose (0°) and tail (180°), though these directions represent a small solid angle and the average is heavily weighted toward the values near the waist (90°).

Thermonuclear N Spectra (per KT yield) Outside Weapon - DTRA 2017

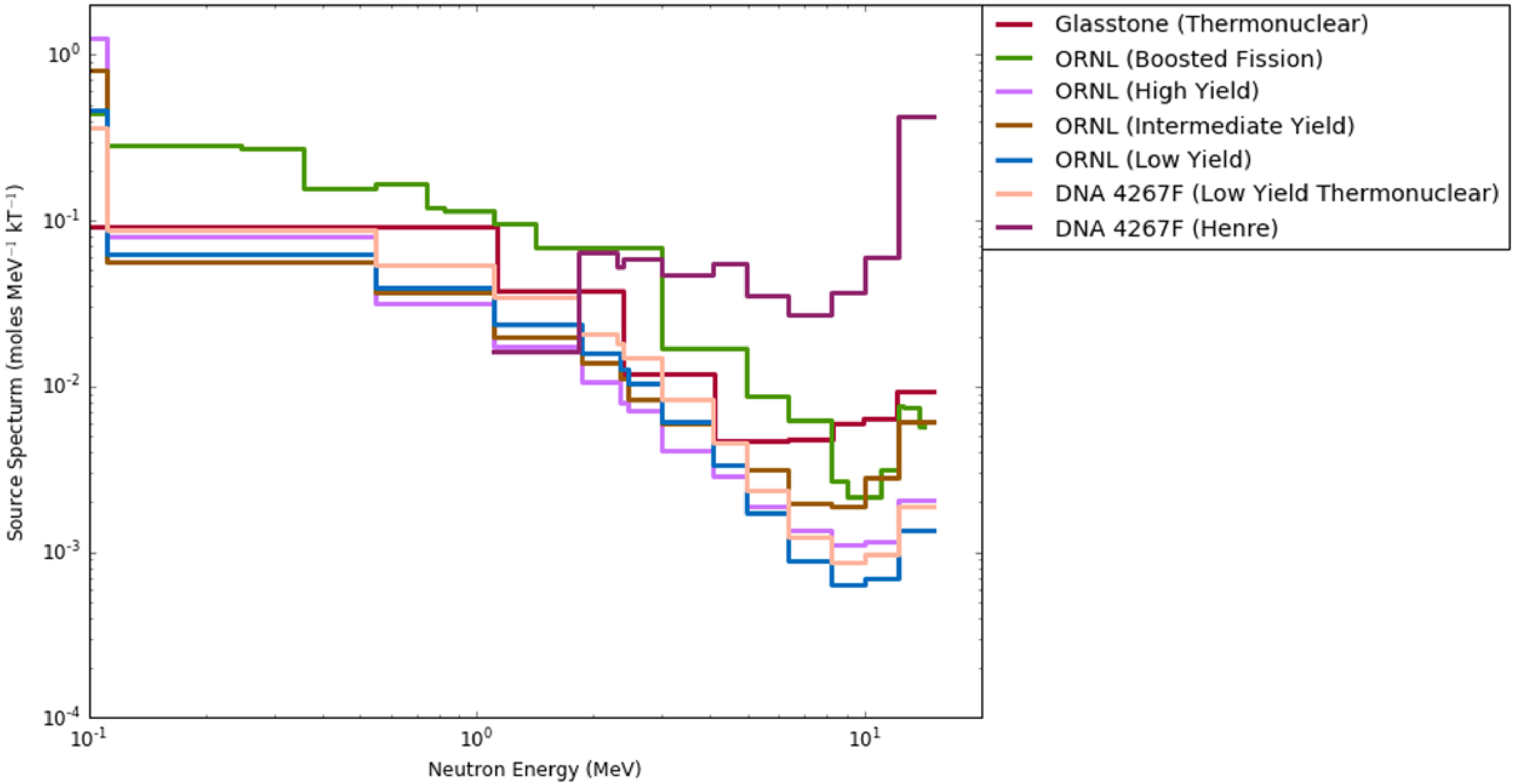


Figure 4. Thermonuclear neutron spectra with energies greater than 0.1 MeV

Thermonuclear Gamma Spectra (per KT yield)
Outside Weapon - DTRA 2017

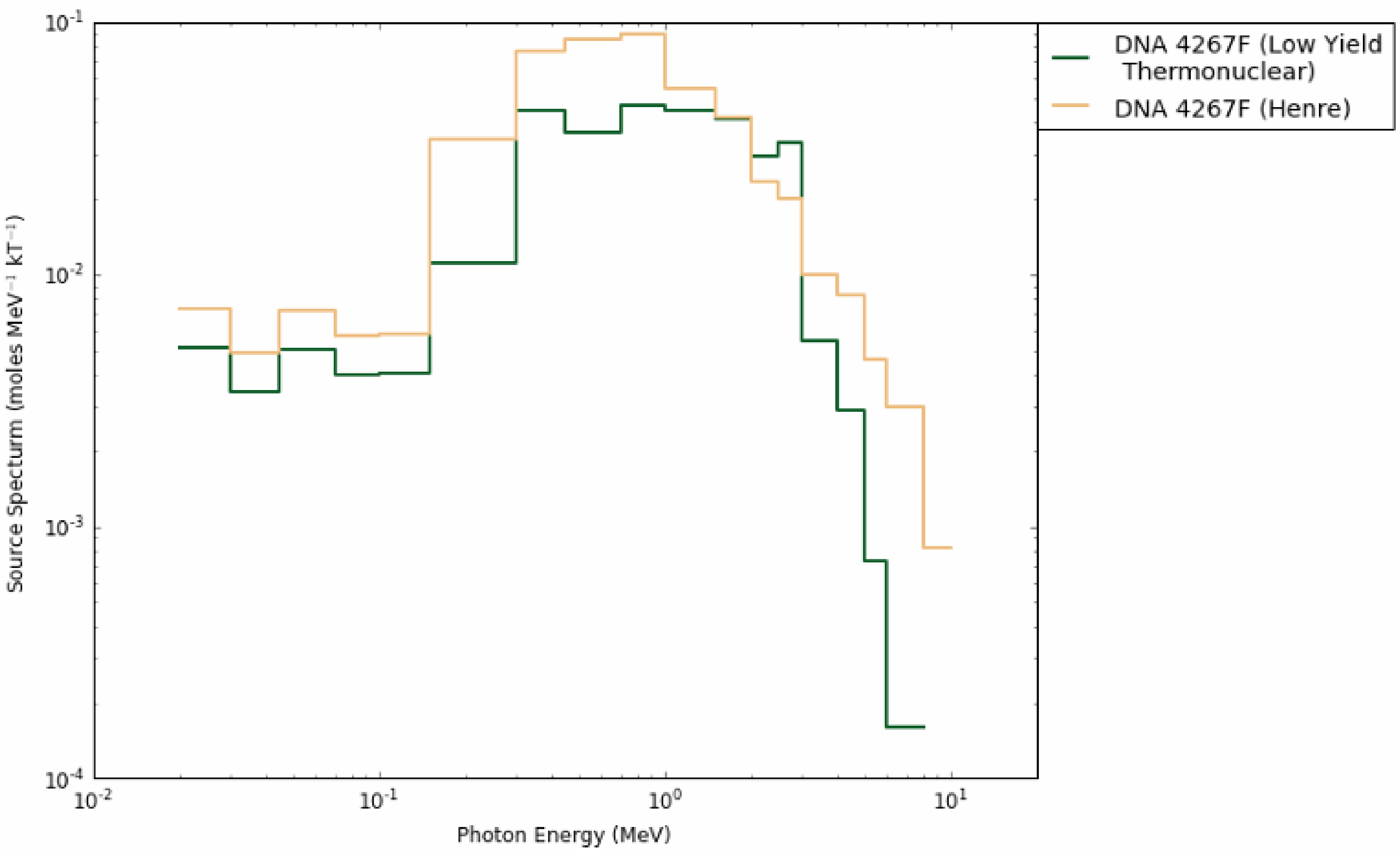


Figure 6. Photon spectra from thermonuclear sources

Gammas from Weapon

- “Instantaneous” Gamma’s are produced within the weapon and almost entirely absorbed by the dense nuclear material during the fission and fusion process. Most do not leave the weapon
- Prompt Gamma’s peak at about 10-100 ns after detonation
- Delayed Gammas come as the weapon expands into the air/ground/vacuum as the vaporized (plasma) weapon material density rapidly decreases
- In addition to the gammas from the weapon, there is also neutron capture in the air (Nitrogen primarily) that emits a radiative capture (of n) and produces more gammas
- If the detonation is near the ground, the neutrons induced radioactivity in the ground (and air) that can produce gammas.

Time Dependence of Gamma Radiation

Glasstone and Dolan – Chap 8

Nuclear Isomer is a nuclear metastable state – usually short lived which then decays usually emitting gamma radiation ("isomeric decays")

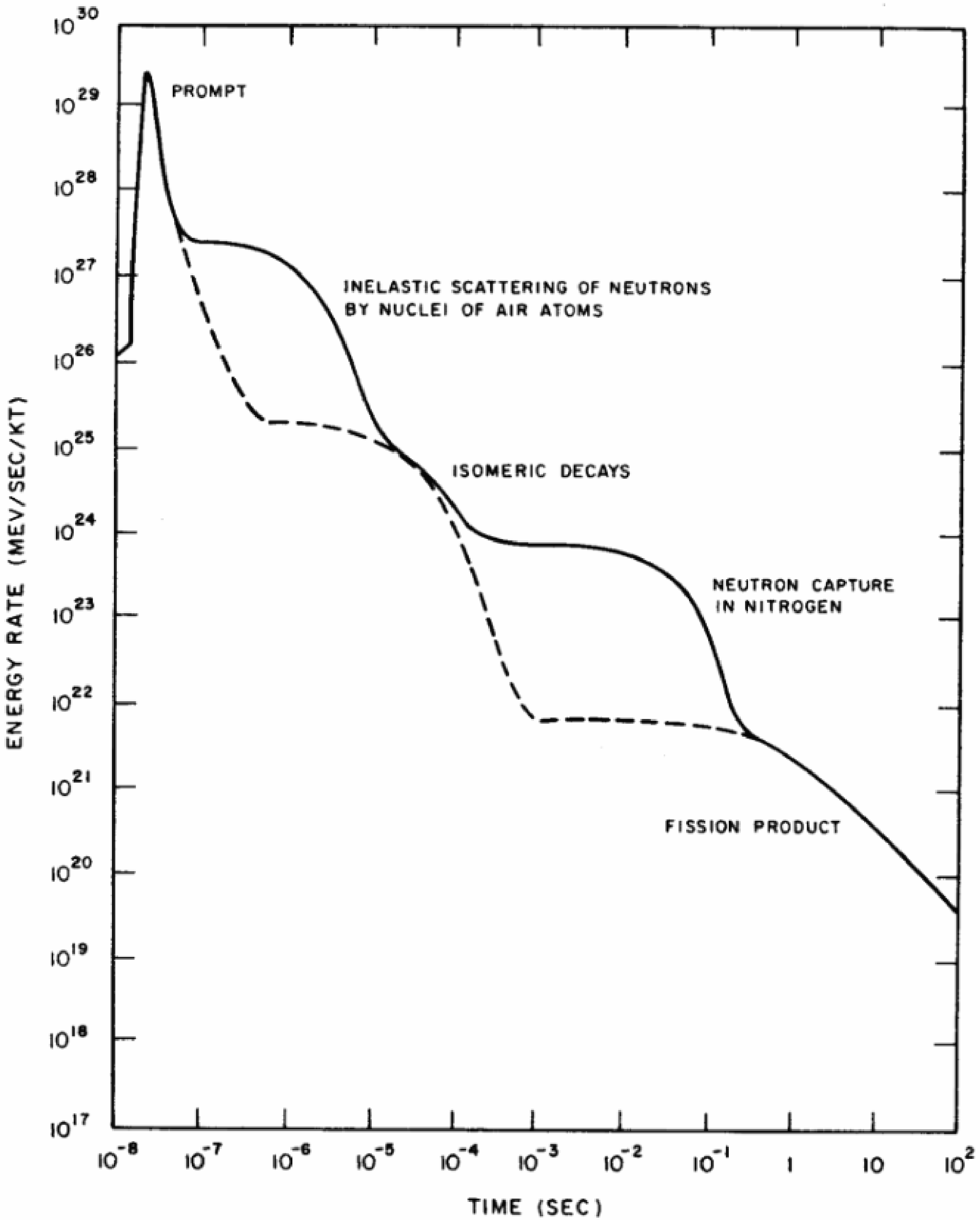


Figure 8.14. Calculated time dependence of the gamma-ray energy output per kiloton energy yield from a hypothetical nuclear explosion. The dashed line refers to an explosion at very high altitude.

Gamma glow from Atmosphere Backscatter

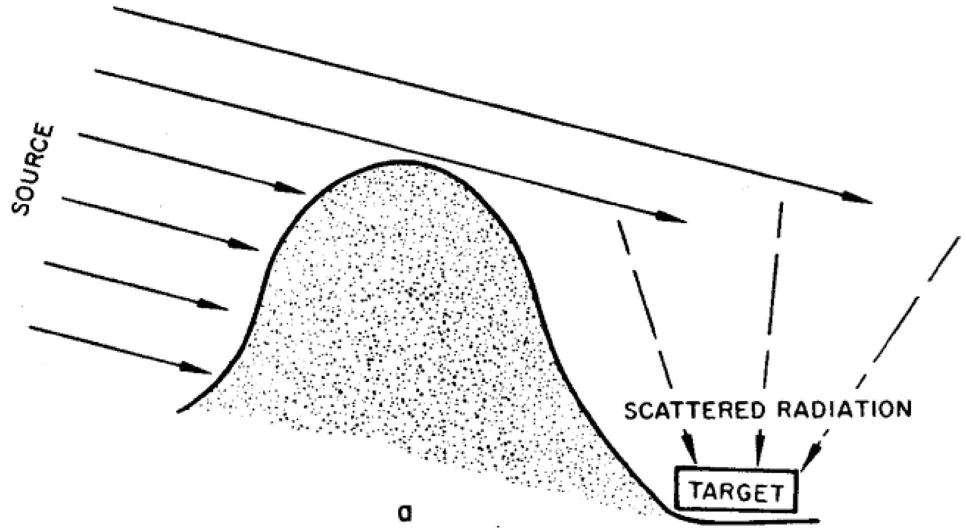
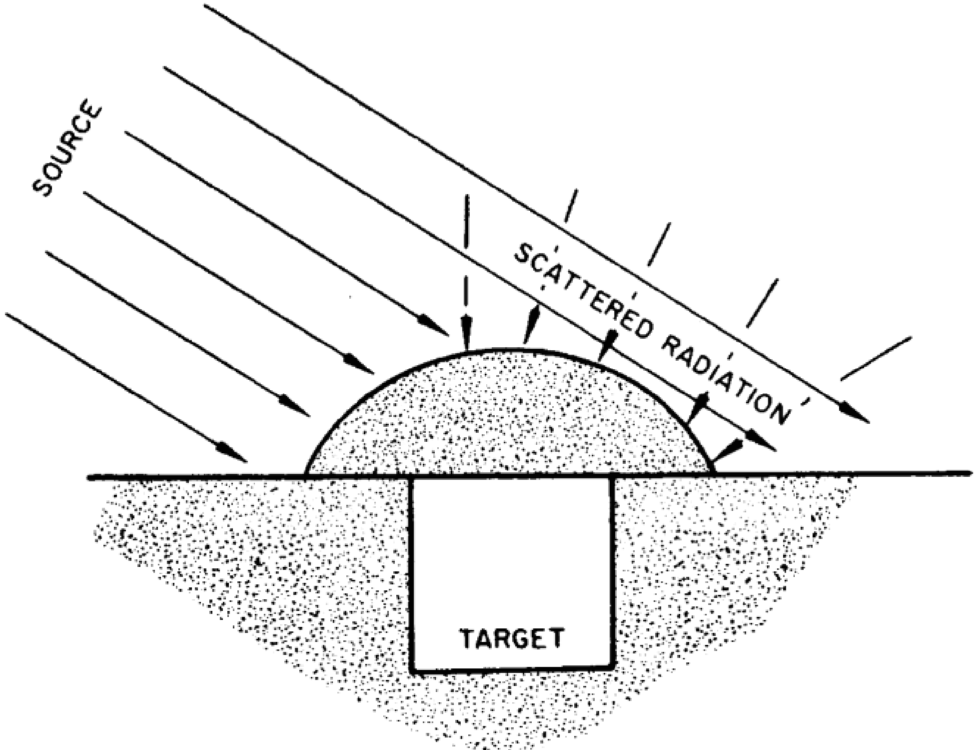


Figure 8.45a. Target exposed to scattered gamma radiation.



Fission Weapon Gamma Dose vs Slant Range Low Alt Airburst

Glasstone and Dolan – Chap 8

Recall 500 REM = 50% lethality

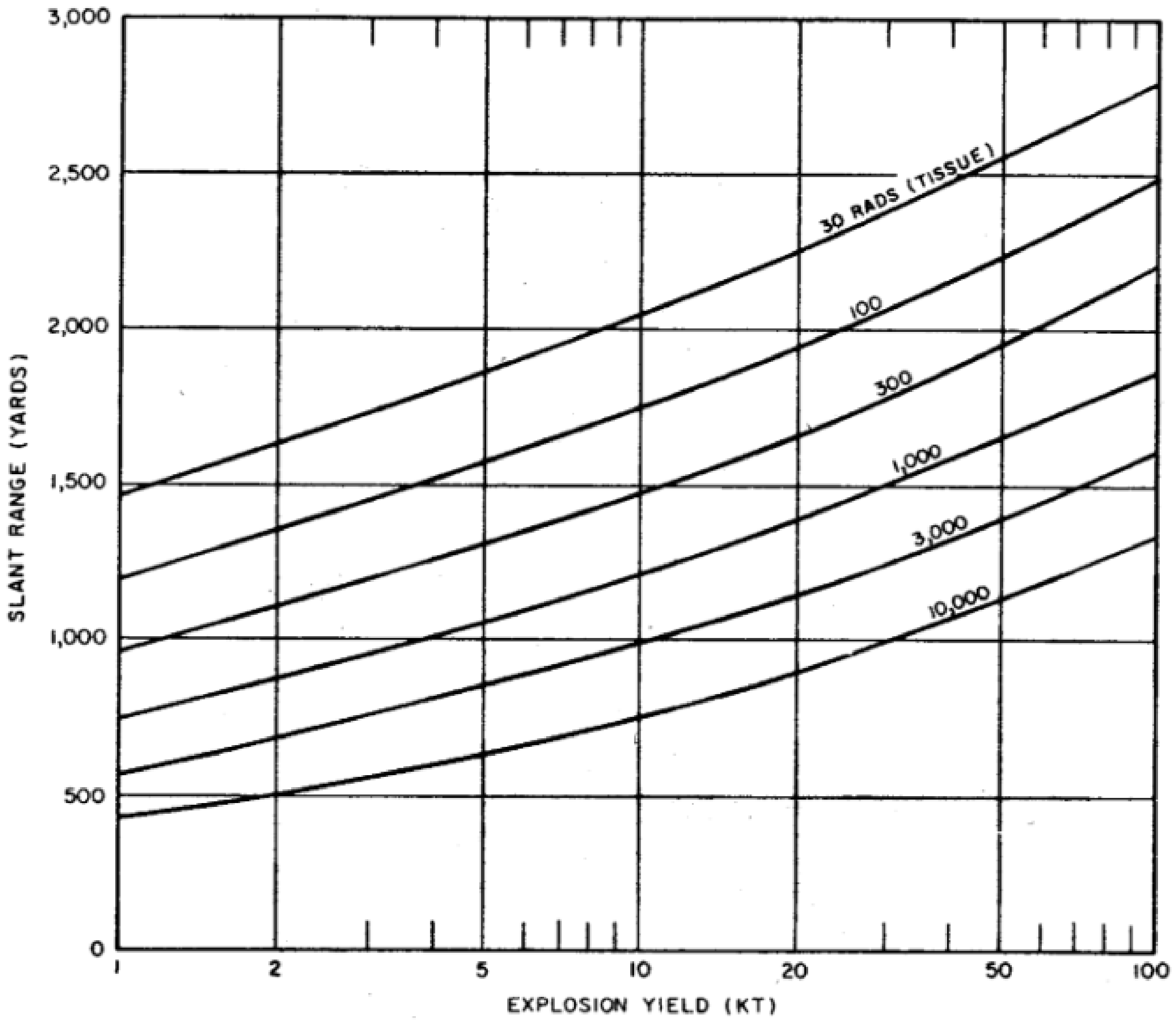


Figure 8.33a. Slant ranges for specified gamma-ray doses for targets near the ground as a function of energy yield of air-burst fission weapons based on 0.9 sea-level air density. (Reliability factor from 0.5 to 2 for most fission weapons.)

TN Weapon Gamma Dose vs Slant Range Low Alt Airburst

Glasstone and Dolan – Chap 8

Recall 500 REM = 50% lethality

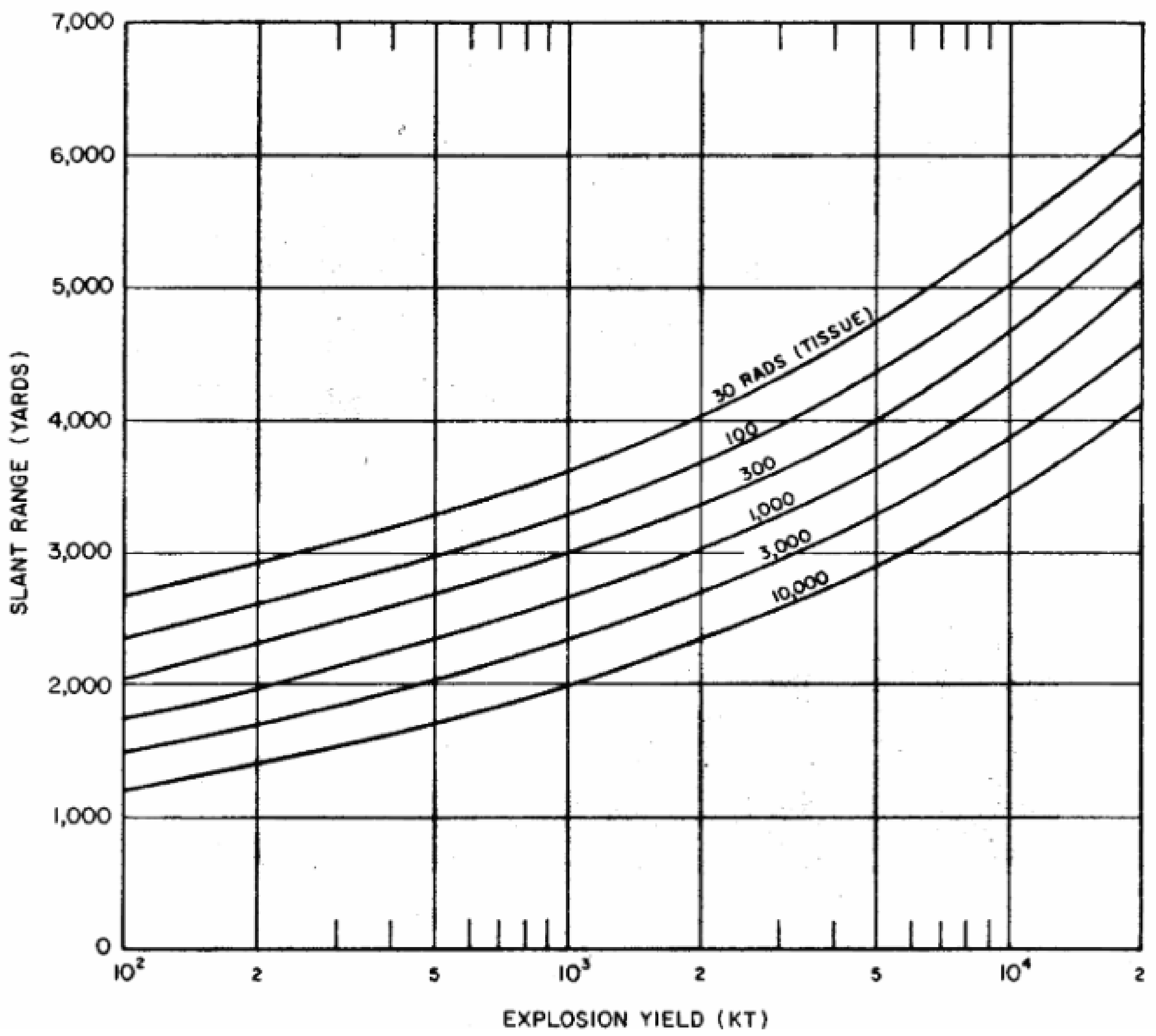


Figure 8.33b. Slant ranges for specified gamma-ray doses for targets near the ground as a function of energy yield of air-burst thermonuclear weapons with 50 percent fission yield, based on 0.9 sea-level air density. (Reliability factor from 0.5 to 1.5 for most thermonuclear weapons.)

Shielding Thickness for Fission Products and Nitrogen Neutron Capture Gamma Emission

Glasstone and Dolan – Chap 8

Table 8.41

APPROXIMATE EFFECTIVE TENTH-VALUE THICKNESSES FOR FISSION PRODUCT AND NITROGEN CAPTURE GAMMA RAYS

		Fission Product		Nitrogen Capture	
Material	Density (lb/cu ft)	Tenth-Value Thickness (inches)	D × T (lb/sq ft)	Tenth-Value Thickness (inches)	D × T (lb/sq ft)
Steel (Iron)	490	3.3	135	4.3	176
Concrete	146	11	134	16	194
Earth	100	16	133	24	200
Water	62.4	24	125	39	201
Wood	40	38	127	63	210

Percent of Initial Gamma Dose vs Time 20 KT and 5 MT

Glasstone and Dolan – Chap 8

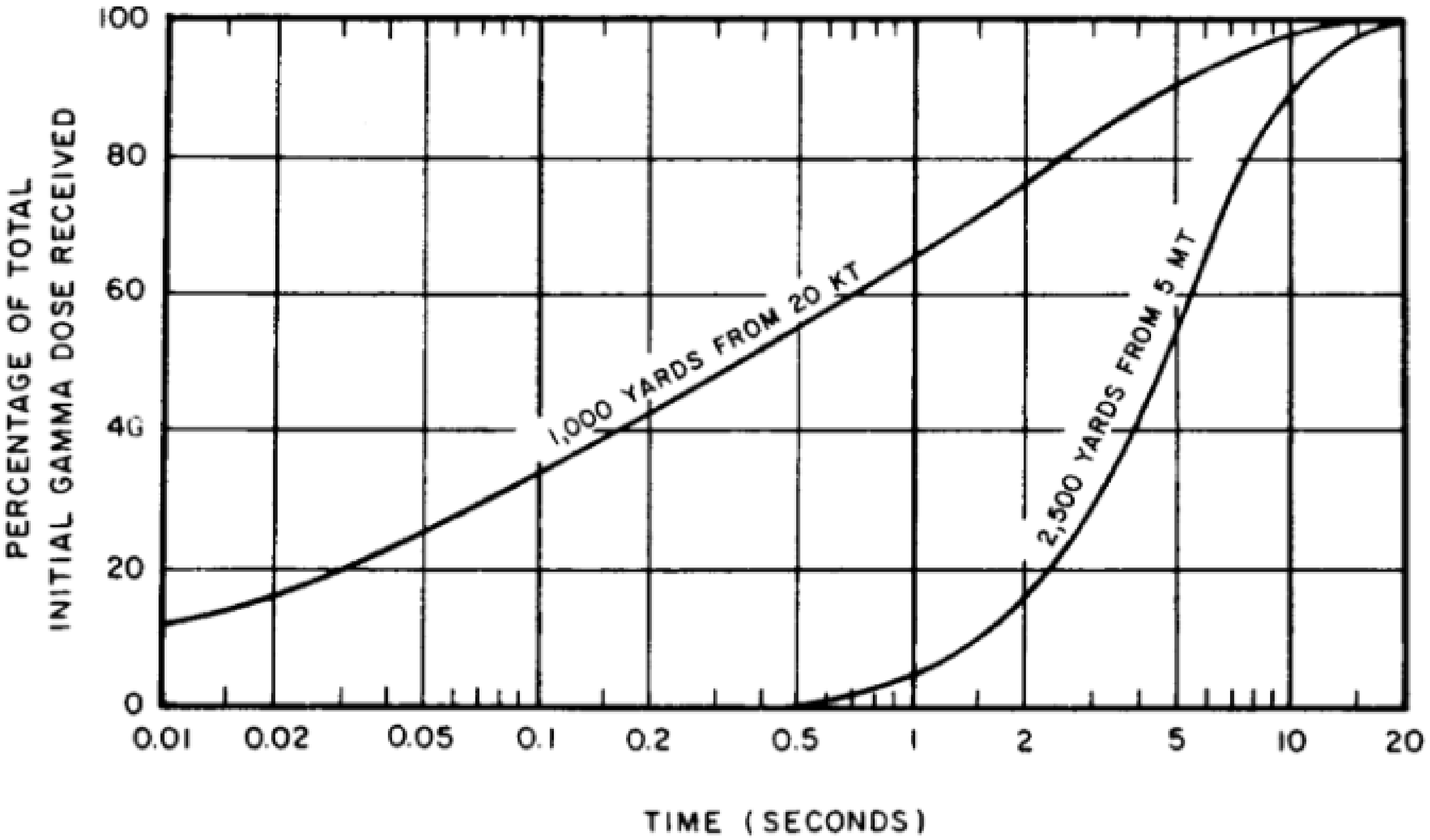


Figure 8.47. Percentage of initial gamma-radiation dose received as a function of time for 20-kiloton and 5-megaton air bursts.

Neutrons from Weapons

- Neutrons carry a relatively small fraction of weapon yield
  - Typ ~1%
- Prompt Neutrons Come within 1 μs after detonation
  - Neutrons come from both fission and fusion process
- Delayed Neutrons come from Fission products
  - Delayed Neutrons are < 1% of total neutrons
  - **However the delayed neutron dose is "enhanced" by "hydrodynamic effects" from the blast wave (less air as it is "pushed out of the way"). For distances > ~1km from high yield weapon (MT range) the dose from delayed neutrons can exceed the dose from prompt neutrons**
  - **Majority of delayed neutrons come within 1 minute**
- Due to scattering on weapons materials, casing, air the neutron spectrum (# vs energy) at observer is quite different (softer spectrum) than inside the weapon (at moment of detonation/ creation)
- Neutron from fission are typ ~ 1 Mev while those from fusion are typ ~ 12-14 MeV (peak of spectrum outside weapon)

Fission Weapon Neutron Dose vs Slant Range Low Alt Airburst

Glasstone and Dolan – Chap 8

Recall 500 REM = 50% lethality

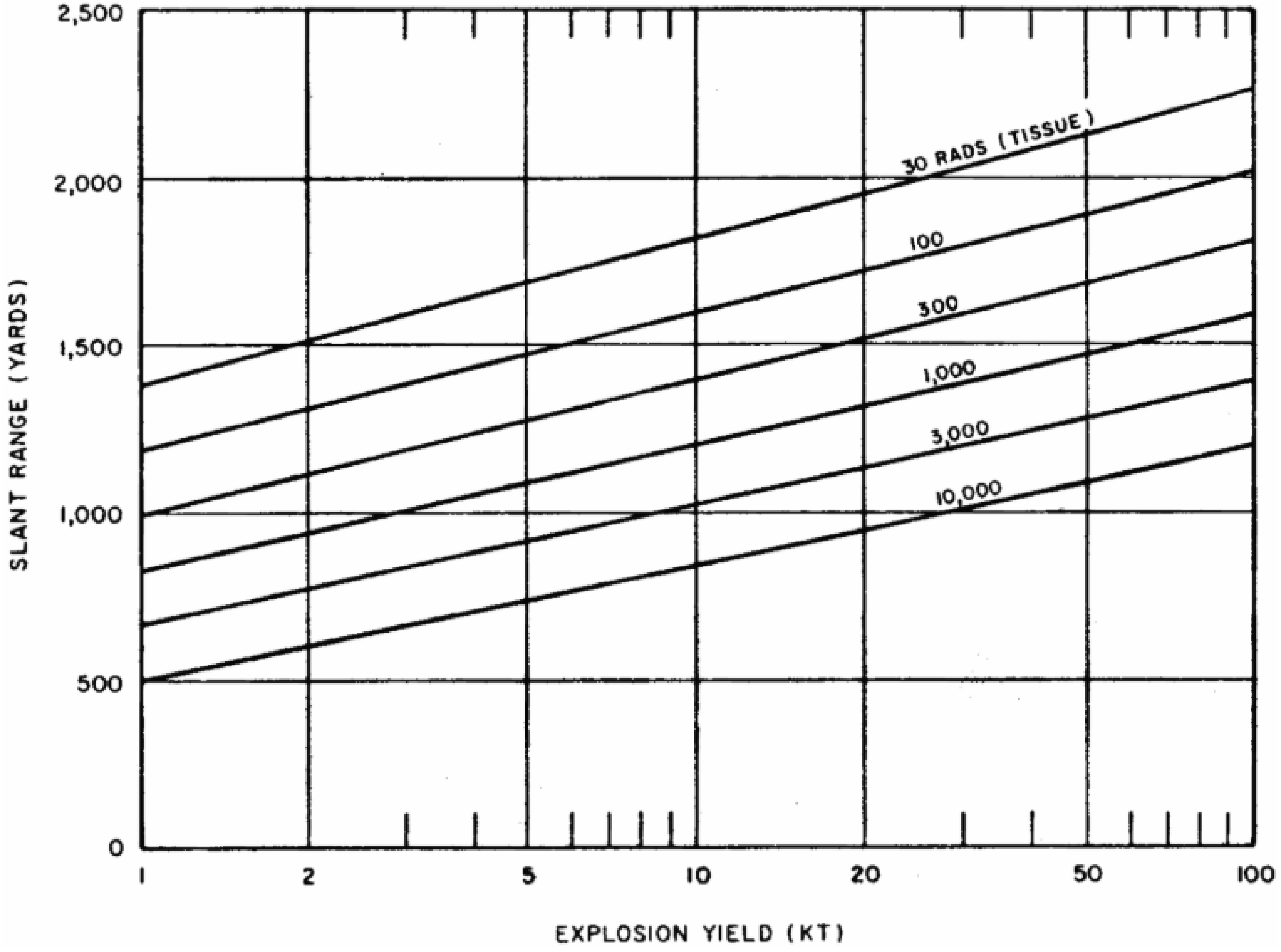


Figure 8.64a. Slant ranges for specified neutron doses for targets near the ground as a function of energy yield of air-burst fission weapons based on 0.9 sea-level air density. (Reliability factor from 0.5 to 2 for most fission weapons.)

TN Weapon Neutron Dose vs Slant Range Low Alt Airburst

Glasstone and Dolan – Chap 8

Recall 500 REM = 50% lethality

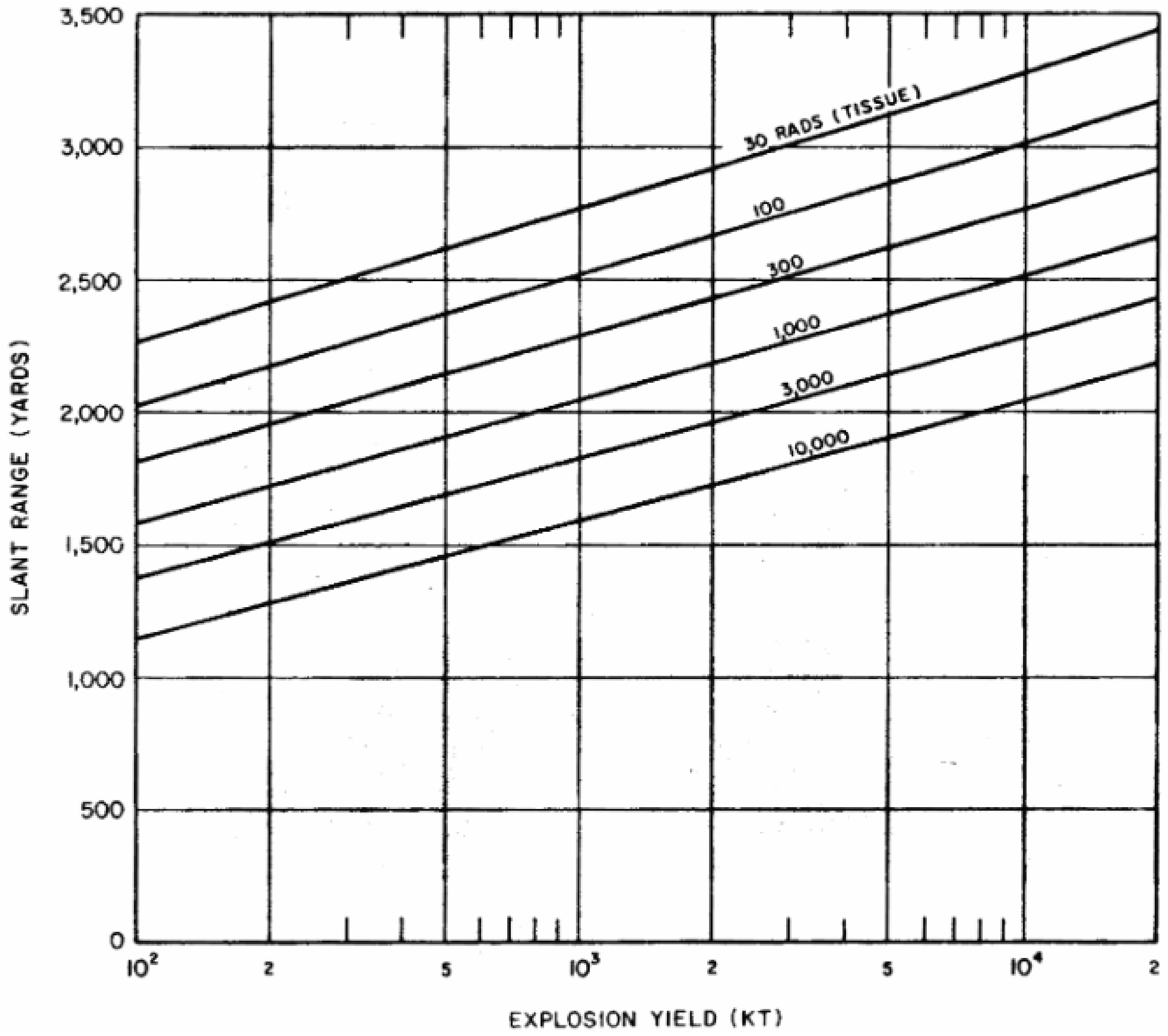


Figure 8.64b. Slant ranges for specified neutron doses for targets near the ground as a function of energy yield of air-burst thermonuclear weapons with 50 percent fission yield, based on 0.9 sea-level air density. (Reliability factor from 0.25 to 1.5 for most thermonuclear weapons.)

Clinical – Medical Response to various Radiation Loads Glasstone and Dolan 1977 – Chapter 12

For consistency, the data in Table 12.108 are the doses (in rems) equivalent to the absorbed doses (in rads) in tissue at the surface of the individual. For gamma rays, these absorbed doses are essentially equal to the exposures in roentgens (§ 8.18). For nuclear weapon radiation, the midline tissue doses for average size adults would be approximately 70 percent of the doses in the table.

Summary of Clinical Effects of Acute Radiation – Table 12.108 GD 1977

Range	0 to 100 rems Subclinical range	100 to 1,00 rems Therapeutic range			Over 1,000 rems Lethal range	
		100 to 200 rems	200 to 600 rems	600 to 1,000 rems	1,000 to 5,000 rems	Over 5,000 rems
		Clinical surveillance	Therapy effective	Therapy promising	Therapy palliative	
Incidence of vomiting	None	100 rems: infrequent 200 rems: common	300 rems: 100%	100%	100%	
Initial Phase Onset Duration	 — —	 3 to 6 hours ≤ 1 day	 ½ to 6 hours 1 to 2 days	 ¼ to ½ hour ≤ 2 days	 5 to 30 minutes ≤ 1 day	Almost immediately[**]
Latent Phase Onset Duration	 — —	 ≤ 1 day ≤ 2 weeks	 1 to 2 days 1 to 4 weeks	 ≤ 2 days 5 to 10 days	 ≤ 1 day[*] 0 to 7 days[*]	Almost immediately[**]
Final Phase Onset Duration	 — —	 10 to 14 days 4 weeks	 1 to 4 weeks 1 to 8 weeks	 5 to 10 days 1 to 4 weeks	 0 to 10 days 2 to 10 days	Almost immediately[**]
Leading organ	Hematopoietic tissue				Gastrointestinal tract	Central nervous system
Characteristic signs	None below 50 rems	Moderate leukopenia	Severe leukopenia; purpura; hemorrhage; infection. Epilation above 300 rems.		Diarrhea; fever; disturbance of electrolyte balance.	Convulsions; tremor; ataxia; lethargy.
Critical period post-exposure	—	—	1 to 6 weeks		2 to 14 days	1 to 48 hours
Therapy	Reassurance	Reassurance; hematologic surveillance.	Blood transfusion; antibiotics.	Consider bone marrow transplantation.	Maintenance of electrolyte balance.	Sedatives
Prognosis	Excellent	Excellent	Guarded	Guarded	Hopeless	
Convalescent period	None	Several weeks	1 to 12 months	Long	—	
Incidence of death	None	None	0 to 90%	90 to 100%	100%	
Death occurs within	—	—	2 to 12 weeks	1 to 6 weeks	2 to 14 days	< 1 day to 2 days
Cause of death	—	—	Hemorrhage; infection		Circulatory collapse	Respiratory failure; brain edema.

Shielding Thickness for Gamma and Neutrons

Glasstone and Dolan – Chap 8

Table 8.72

DOSE TRANSMISSION FACTORS FOR VARIOUS STRUCTURES

Structure	Initial Gamma Rays	Neutrons
Three feet underground	0.002-0.004	0.002-0.01
Frame House	0.8-1.0	0.3-0.8
Basement	0.1-0.6	0.1-0.8
Multistory building (apartment type):		
Upper stories	0.8-0.9	0.9-1.0
Lower stories	0.3-0.6	0.3-0.8
Concrete blockhouse shelter:		
9-in. walls	0.1-0.2	0.3-0.5
12-in walls	0.05-0.1	0.2-0.4
24-in walls	0.007-0.02	0.1-0.2
Shelter, partly above grade:		
With 2 ft earth cover	0.03-0.07	0.02-0.08
With 3 ft earth cover	0.007-0.02	0.01-0.05

Functional Fits to Nuclear Effects

- See Class website for the fits and 1960-1980 "circular slide rule of weapons effects" – a classic!
- PDF file of below is on our class website
- **Nuclear Bomb Effects Circular Slide Rule Design and Functional Fits – Fletcher et all 1963 (used in Glasstone and Dolan – Effects of Nuclear Weapons book including 1977 edition)**
- https://apps.dtic.mil/sti/tr/pdf/ADA384998.pdf