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Radiochemistry Webinars

Nuclear Radiation Safety

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Meet the Presenter… *Dr. David Roelant*

FLORIDA INTERNATIONAL UNIVERSITY

Dr. David Roelant is the Director of the Florida International University (FIU) Interdisciplinary Nuclear Research Program (INRP) at the Applied Research Center, whose mission is to develop a $10M+/yr, multidisciplinary nuclear R&D program. He has performed, led, or managed over 440 projects and over $200M of environmental, defense technology, energy, and nuclear research since 1978. Dr. Roelant holds a B.S. degree in Applied Math, a M.S. in Mechanical Engineering, and a PhD in Nuclear Engineering from the University of Michigan. His experience includes positions at the Argonne and Lawrence Livermore National labs, Harry Diamond labs, the Naval Research lab, Carderock Naval Surface Warfare Center, HM Technologies, BDM, TRW, PAI, and the University of Michigan. In the areas of environmental, energy and nuclear research, Dr. Roelant specializes in radiation and chemical sensors development; soil, groundwater, building and radioactive waste characterization; MARSSIMS; imaging modalities such as radar, sonar, electrical resistance tomography; radiation detection and measurement; modeling radiation transport; health physics; nuclear chemistry, nuclear engineering and nuclear medicine; radiology (PET, SPRINT, MRI, CAT); modeling of high intensity, laser radiation interaction with matter with coupled radiation transport, ionization dynamics, and plasma hydrodynamics models. Since coming to FIU in 1999, Dr. Roelant has been Principal Investigator on over $50M of research from the U.S. Department of Energy and Department of Defense, the EPA, and the U.S. Nuclear Regulatory Commission. He has led research groups including Sensors, Military Technology, Environmental Science and Technology, and Nuclear. He is supported by an external board of 16 world class nuclear experts from industry, academia, government and national labs.

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DEPARTMENT OF ENERGY • UNITED STATES OF AMERICA

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Nuclear Radiation Safety

David Roelant, PhD

FIU FLORIDA INTERNATIONAL UNIVERSITY

National Analytical Management Program (NAMP)

TRAINING AND EDUCATION SUBCOMMITTEE

Outline

Nuclear radiation and radioactivity

- Types and sources of nuclear radiation
- Definitions, units, constants and equations
- Radioactivity of some dangerous radionuclides
- Interaction of radiation with matter
- Radiation dose
- Background sources and exposure

Biological Effects

- Cellular effect
- Short-term effects
- Long-term effects

Radiological Hazards

- External exposure
- Internal exposure, contamination

Detection and Measurement

- Detector efficiency
- Counting statistics
- Principles of Geiger-Mueller tubes
- Gas proportional detectors
- Scintillators and solid-state detectors
- Dose and dose rate measurements
- Contamination measurements
- Health physics portable and fixed lab instruments

Outline (cont.)

Radiation Safety Programs

- ALARA, procedures, trainings
- Surveys, posting, and labeling
- Dosimetry principles and exposure-dose relationship
- Principles of internal and external radiation protection
- Leak testing and instrument calibration
- Waste disposal
- Record keeping
- How to set up and evaluate protective measures

Regulatory Agencies and Regulations (ICRP, IAEA,...)

Online Resources for Radiation Safety

Questions and Answers

Types of Radiation Safety Training/ Webinar Goal

- Radiation trainings can vary from an hour long General Radiation Training to several years for Health Physics PhDs
- The goal of this webinar is to provide nuclear workers/ researchers with a comprehensive review of the many facets involved in safety related to ionizing radiation (per Outline) while summarizing important principles and “big picture” consequences and issues
- This is not a trainings for nuclear experts, RSOs, managers, equipment operators, or other specialized workers
- The approach is to provide a broad coverage of the science, hazards, and instrumentation in order to lay the foundation for radiation safety
- Much of this will be a review for many users of radioactive materials and those that work in radiation areas and yet I expect all will learn from this webinar

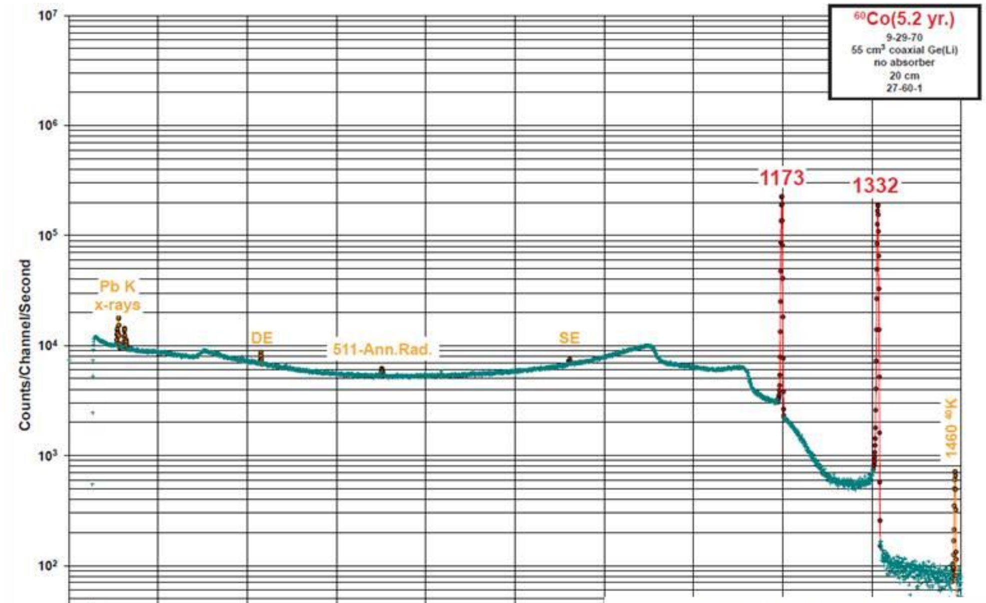
Types of Nuclear Radiation

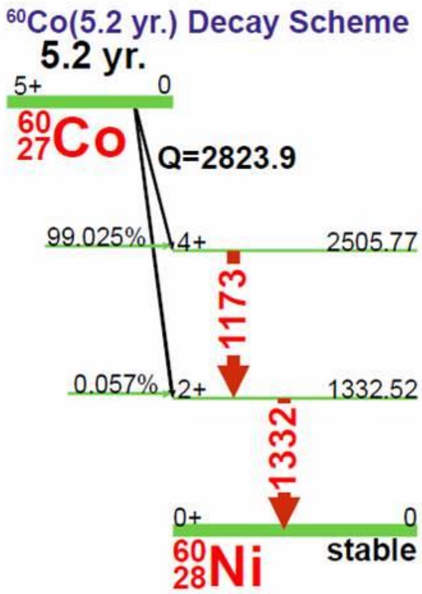
- Nuclear radiation originates from the nucleus of atoms (tunneling & energy transitions)
- Types of nuclear radiation (α, β, γ, n)
  - **Alpha particles**, mostly Z>82 but as small as Te(Z=52). α tunnels from nucleus (Coulomb repulsion vs Strong force)
  - **β particles** (electrons) are emitted from the nucleus of radionuclides with excess neutrons; a neutron changes to a proton and an electron; the electron is emitted from the nucleus;
  - β positron emission from nuclei with excess protons, a proton is converted to a neutron and a positron;
  - β decay involves neutrinos and is a 3-body reaction
  - **Gamma rays** are photons that travel relatively long pathways until they interact with electrons
  - **Neutrons**: important around nuclear reactors, cyclotrons, accelerators, radionuclide generators, spontaneous fission material. Not present in contamination.
  - Prompt neutrons ~ 10^{-14} sec. Delayed neutrons after fission (0.65% of neutrons have times from milliseconds to a few minutes due to Beta decay that proceeds it)
  - ~650 radionuclides with half lives over 1 hour; > 2400 radionuclides have half lives < 1 hr
  - Other nuclear reactions: internal conversion electron, isomeric transition, Bremsstrahlung radiation, Cherenkov radiation (non-ionizing), characteristic x-rays

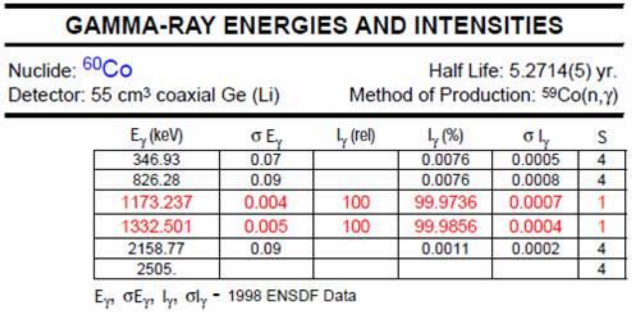
Half-Life

The time required for the amount of radioactive material to decrease by one-half

Decay Scheme of ^{60}Co







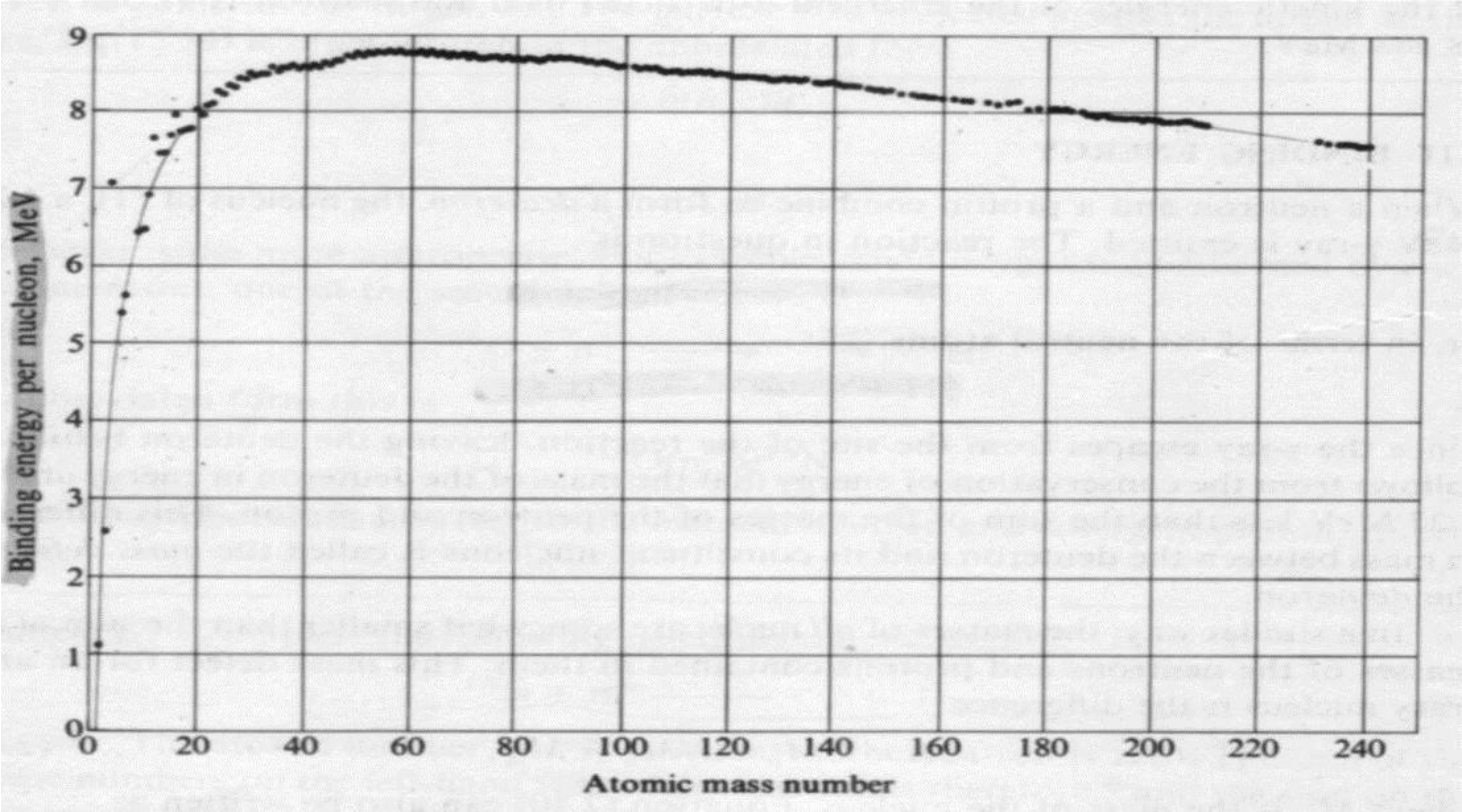
GAMMA-RAY ENERGIES AND INTENSITIES

Nuclide: ^{60}Co
Half Life: 5.2714(5) yr.
Detector: 55 cm³ coaxial Ge (Li)
Method of Production: ^{59}Co(n,γ)

E_γ (keV)	σE_γ	I_γ (rel)	I_γ (%)	σI_γ	S
346.93	0.07		0.0076	0.0005	4
826.28	0.09		0.0076	0.0008	4
1173.237	0.004	100	99.9736	0.0007	1
1332.501	0.005	100	99.9856	0.0004	1
2158.77	0.09		0.0011	0.0002	4
2505.					4

E_γ, σE_γ, I_γ, σI_γ - 1998 ENSDF Data

Binding Energy per Nucleon as a Function of Atomic Mass Number



J.R. Lamarsh, Introduction to Nuclear Engineering

Sources of Nuclear Radiation

Sources of terrestrial radionuclides:

- Supernova seeding galaxies
  - 99.9%+ of radionuclides
  - Earth's age is 4.6 billion years old, formed from material available then in galaxy
  - 34 primordial radionuclides. Pu-244 shortest half-life of those measured, 8x10^7 years, 57 half-lives or 10^{17} reduction. 28 of these 3X to 160 trillion X the age of the universe (13.8 B years). ^{128}Te undergoes double beta decay with half-live of 2.2×10^{24} years, the longest half-life of all nuclides proven to be radioactive.
  - U-238, U-235, K-40, Th-232, Sm-146, Pu-244 half-lives = or < the age of the universe
  - U-238, U-235, Th-232 decay chains have 45 radionuclide daughters including radon, before ending as Pb-207, Pb-208
- Cosmic radiation, 99% H-1, He-4, mostly solar origin but measurable supernova accelerated galactic origin, most radionuclides generated in the atmosphere where 22 radionuclides are formed from spallation neutrons inducing further spallations (e.g., of Ar). Examples of such cosmogenic nuclide: H-3, C-14, P-32
- Human-made from nuclear reactors, accelerators (nuclear medicine, science), radionuclide generators

Spontaneous and Induced Fission

- Spontaneous fission (SF) is due to tunneling (radioactive decay) and has no incident neutron (as contrasted with induced fission)
- SF is observable for mass numbers 232 and above (U-235, U-238, Pu-239, Pu-240, Cm-250, Cf-252)
- Fissionable radionuclides: able to fission upon absorption of a neutron
- Fissile radionuclides: fissionable nuclides that can be induced to fission with a high probability with thermal neutrons. Fissile Rule: 2 X Z – N = 41, 45
- Nuclear fuel with fissile isotopes: U-233, U-235, Pu-239, Pu-241
- Breeder reactors generate more fuel than they burn, require small initial fissile material; U-238 (99%+) and Th-232 (99%+) are fertile nuclides able to be used in fast reactors

Definitions, Units, Constants, Equations

- Atomic number, Z, number of protons in nucleus
- Mass number, A, number of protons + neutrons in the nucleus ${}_{92}U^{235}$
- Isotopes: radionuclides with same Z but different A, e.g., Pb has 33 known isotopes from Pb-182-Pb-214 with only Pb-204, -206, -207, -208 being stable
- Isobars: radionuclides with same A, e.g., Cl-40, Ar-40, K-40, Ca-40
- Isotones: radionuclides with the same number of neutrons
- Ionizing radiation: photons or particles capable of removing an electron from an atom
- Atomic mass units, amu or u. 1 amu = 1/12 of C-12 atom = 931.5 MeV
- Neutron = 1.0086654 u; proton = 1.0072765 u; electron = 0.00054858 u
- Mass of proton = Mass of electron * 1836
- Erg = energy to lift 1/980 gm a distance of 1 cm = 625 billion eV (electron volts)
- Conservation of energy, charge and total number of neutrons + protons (B4 vs after)
- Becquerel (Bq) = 1 disintegration/s; 1 Curie (Ci) = 37 billion Bq
- Decay constant, λ = Ln(2)/(half-life), from exponential decay
- Radioactivity = $A = Ao * \exp(-\lambda t) = d(N)/dt = -\lambda * N$ $N = No * \exp(-\lambda t)$

Radioactivity of Some Dangerous Radionuclides

- 12.3 year – **Tritium**, incorporates into water and into body
- 8 days – **Iodine-131** (nuclear fallout), thyroid accumulation
- 30.17 years – **Cesium-137**, major source of radioactivity after 40 years of nuclear fuel with fission fragments decaying (high-level radioactive waste (HLW)), water soluble, distributed throughout body
- 28.8 years – **Strontium-90**, pure beta emitter, similar to calcium and incorporated in bones. Detectable in teeth of those born after 1963, in surface soil across the Earth, also significant source in old spent fuel and HLW
- 3.8 days – **Radon-222**, colorless, odorless, tasteless radioactive gas, the primary source for human exposure and risks from naturally occurring background radiation. From U and Th decay chains. 2nd to smoking for causing lung cancer (21,000 per year), 2 alpha decays and 2 beta decays within 1 hour of original alpha decay

Uranium (kidney damage); **radium** (bone); **Po-210** (lung and bladder cancers)

Nuclear waste = 93% U+1.3% Pu+0.14% other actinides +5.2% fission products

Calculating Radioactivity Decay

- Jan. 1st you receive a radioactive sample with 10.0 mCi of P-32 (half-life 14.262 days). The radioactivity 45 days later is?

- P-32 decays by beta emission to S-32 100% of the time

- $\lambda = \mathrm{Ln}(2)/T_{1/2} = 0.693147/14.262$ days $= 0.0486$ per day

- A = 10 mCi * exp(-0.0486/day*(45 days)) = 1.12 mCi

Decay Chain Radioactivity

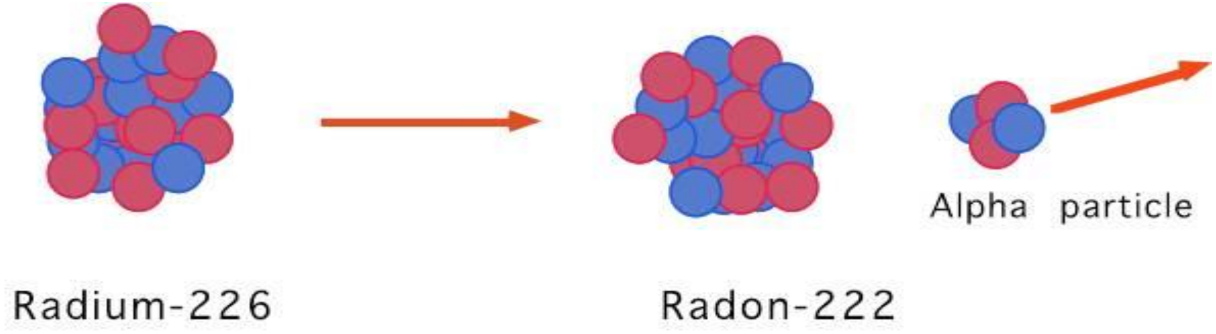
$$A \rightarrow B \rightarrow C \rightarrow$$

$$\alpha_B = \alpha_{B_o} e^{-\lambda_B t} + \frac{\alpha_{A_o} \lambda_B}{\lambda_B - \lambda_A} \left(e^{-\lambda_A t} - e^{-\lambda_B t} \right)$$

Where Radionuclide A decays into B which in turn decays into C
λs are the decay constants and t is time

Interaction of α Radiation with Matter

- α particles plow straight through atomic electrons, slowly giving up energy via Coulomb collisions until they slow enough to pick up an orbital electron and then quickly stop
- Penetrate 10s of microns into solids and centimeters into gases
- Stopped by skin
- Dangerous when inhaled, ingested, enter blood via open wound (internal)
- Energies typically 4-8 MeVs



88 protons, 138 neutrons

86 protons, 136 neutrons

Interaction of β Radiation with Matter

- β particles interact via collisions with atomic electrons, random walk (tortuous) path
- Have kinetic energy from 3-body radioactive decay of 0 to a maximum endpoint energy. Endpoint energies can be keVs to 5 MeVs
- MeV electrons are relativistic and also yield Bremsstrahlung. For energies below 3 MeVs (i.e., most βs) Coulomb energy losses dominate over radiative
- Attenuated exponentially with distance through a material: I = Io * exp(-nt)

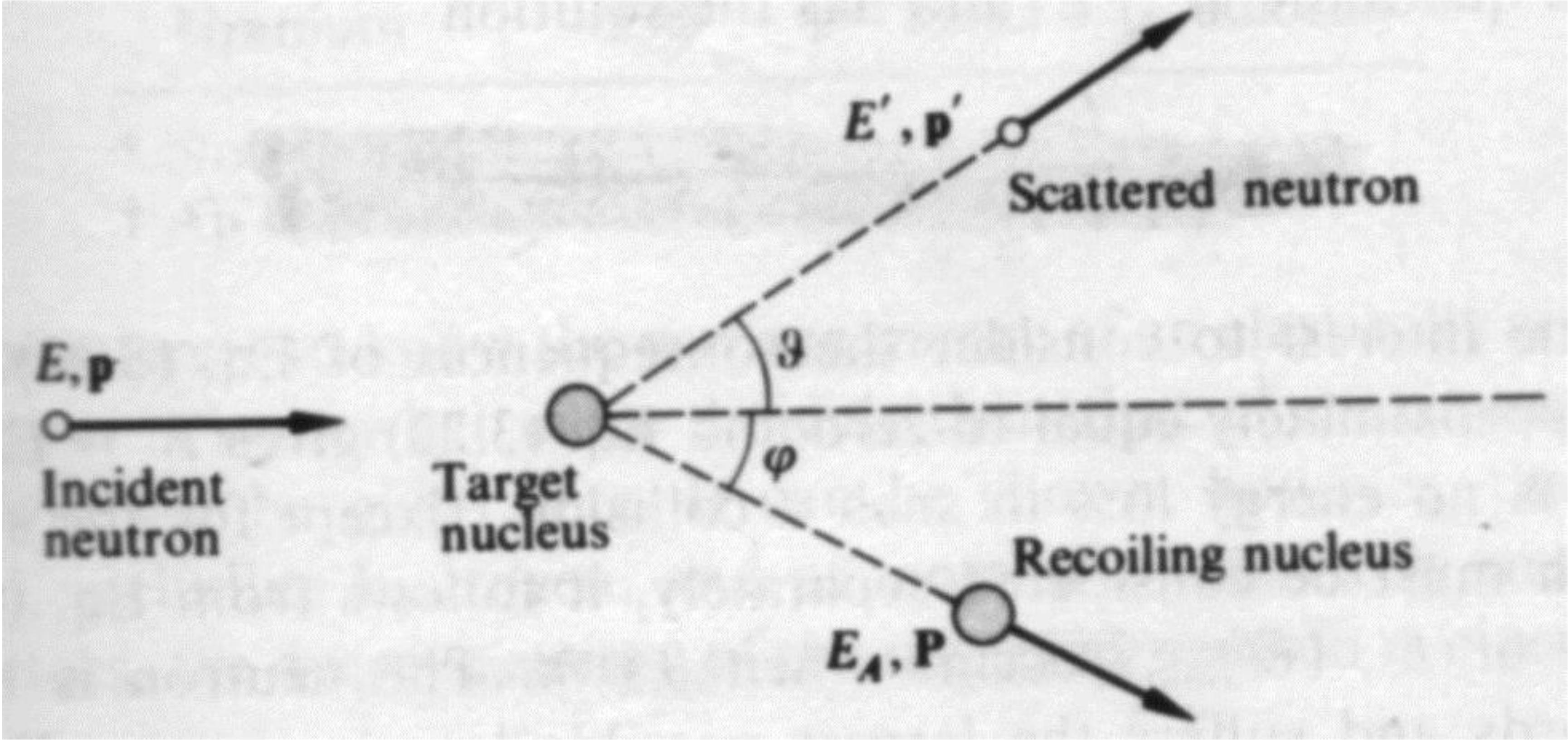
  where I and Io are transmitted and incident intensities, respectively. t = material thickness, and n is an energy dependent total linear absorption coefficient
- Materials with the same mass thickness (density*thickness) have comparable ranges for electrons (mm in most solids for ~1 MeV, high-energy electrons
- Positron slows down similar to electron until at low speeds it forms positronium with an electron and both spiral into each other, annihilating and giving two 0.511MeV photons in exact opposite directions
- Double beta decay is the simultaneous emission of 2 β particles & 2 antineutrinos (ν)

$${}_1H^3 \rightarrow {}_2He^3 + \beta + \nu \qquad {}_6C^{14} \rightarrow {}_7N^{14} + \beta + \nu$$

Interaction of Neutrons with Matter

- Neutrons are not charged and interact with atomic nuclei
- At high energies they can spallate n, p from struck nuclei (secondary cosmic rays)
- Arise on Earth from spontaneous and induced fission (also from nuclear fusion Deuterium-Tritium, (α, n) sources, (n, 2n) reactions)
- Slow from over 100 MeVs to 0.025 eV thermal energy via collisions with hydrogen (water) with same mass
- Certain nuclei such as fissile and fissionable nuclei have large resonances or cross sections for reacting with incumbent neutrons

Energy Loss in Scattering Collisions

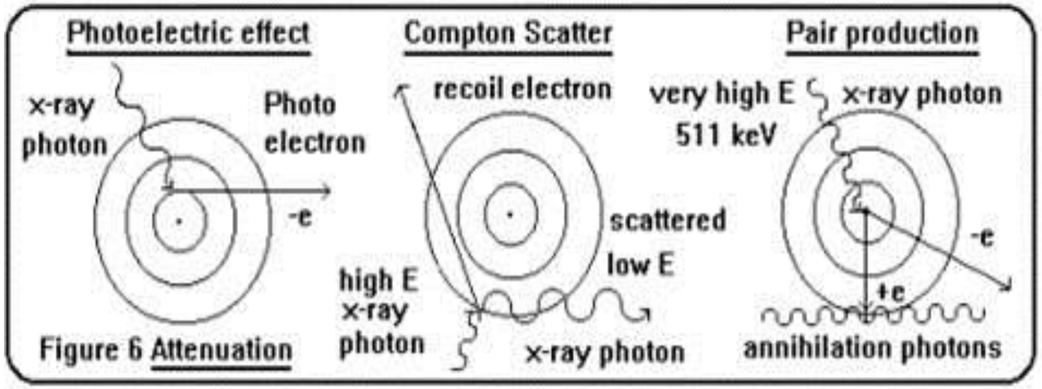


Elastic Scattering of a Neutron by a Nucleus

John R. Lamarsh, Introduction to Nuclear Engineering

γ-Ray Interactions with Matter

- 3 processes account for how γ-rays interact with matter:
  - Photoelectric Effect
  - Compton Effect
  - Pair Production



Photoelectric Effect

- Incident γ-ray interacts with an entire atom, the γ-ray disappears, and one of the atomic electrons is ejected from the atom

- The hole in the electronic structure is later filled by a transition of one of the outer electrons into the vacant position

- The electronic transition is accompanied by the emission of x-rays characteristic of the atom, or by the ejection of an Auger electron

Dependence of Photoelectric Cross Section on Z

$$\sigma_c \sim Z^n/E^3$$

where n is a function of E (see figure)

- The cross section is the probability of the photoelectric effect offering (units = area)
- Because of the strong dependence of σ_{pe} on Z and E, the photoelectric effect is of greatest importance for the heavier atoms such as lead, especially at lower energies

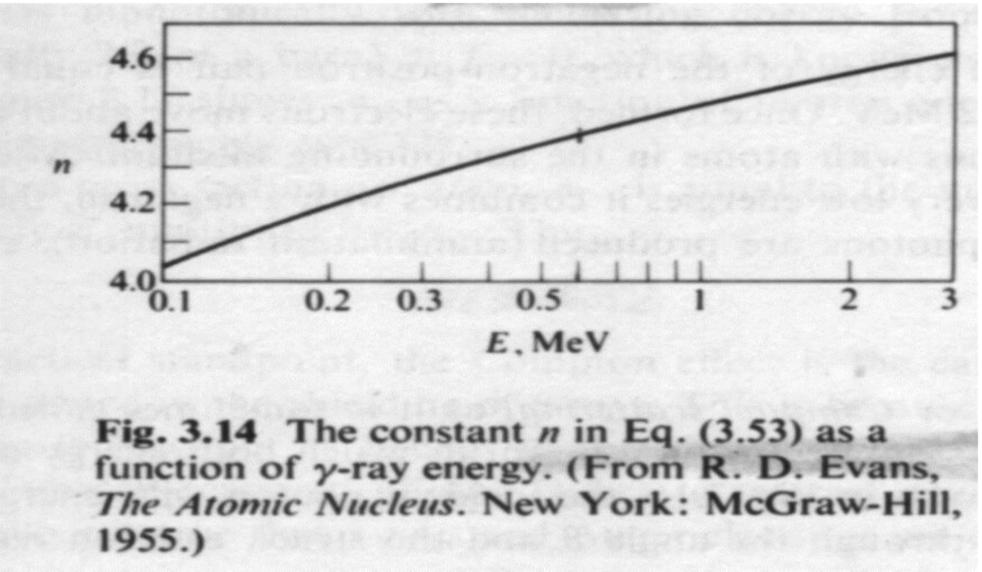


Fig. 3.14 The constant *n* in Eq. (3.53) as a function of γ-ray energy. (From R. D. Evans, *The Atomic Nucleus*. New York: McGraw-Hill, 1955.)

John R. Lamarsh, Introduction to Nuclear Engineering

Compton Effect

- Elastic scattering of a photon by an electron, in which both energy and momentum are conserved

- A Compton cross section per electron (${}_{e}\sigma_{C}$) decreases monotonically with increasing energy from a maximum value 0.665 b (essentially 2/3 of a barn) at E = 0, which is known as the *Thompson cross section*, σ_T

$$\boldsymbol{\sigma_c \sim Z/E}$$

Pair Production

- Photon disappears and an *electron pair* – a positron and a negatron – is created
- This effect does not occur unless the photon has at least 1.022 MeV of energy
- Cross section for pair production (σ_{pp}) increases steadily with increasing energy
- Pair production can take place only in vicinity of a Coulomb field

$$\sigma_{pp} \sim Z^2$$

Attenuation Coefficients

- Macroscopic γ-ray cross sections are called attenuation coefficients $\mu = N_\sigma = \mu_{pe} + \mu_{pp} + \mu_C$

- Mass attenuation coefficient (μ/ρ)

$$\frac{\mu}{\rho} = \frac{\mu_{pe}}{\rho} + \frac{\mu_{pp}}{\rho} + \frac{\mu_C}{\rho}$$

Gamma rays are attenuated exponentially with distance through a material:

$$I = Io * \exp(-\mu t)$$

where I and Io are transmitted and incident intensities, respectively. t = material thickness, and μ is an energy dependent total attenuation coefficient

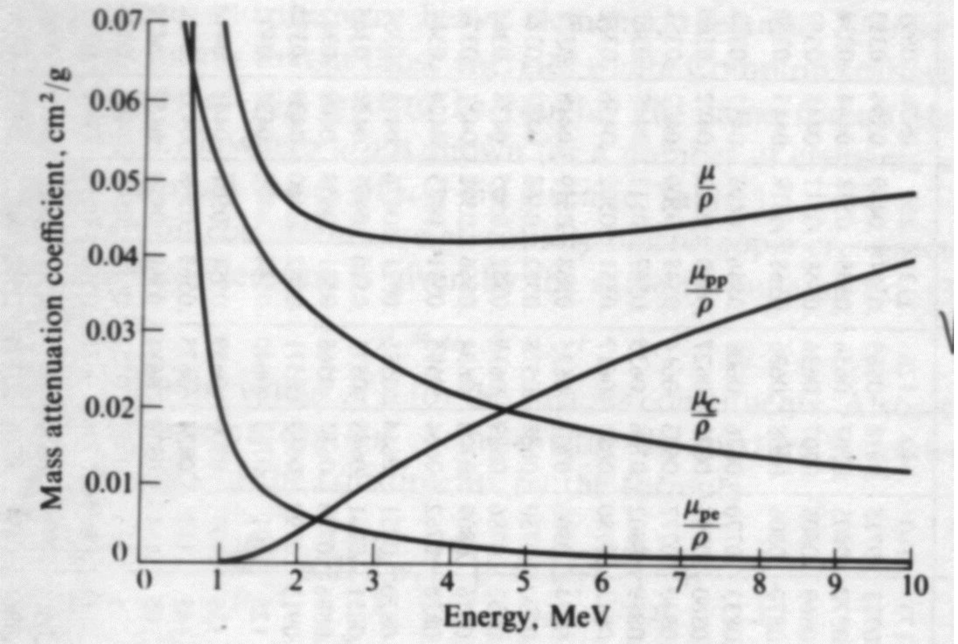


Fig. 3.18 The mass attenuation coefficients of lead as a function of γ-ray energy.

John R. Lamarsh, Introduction to Nuclear Engineering

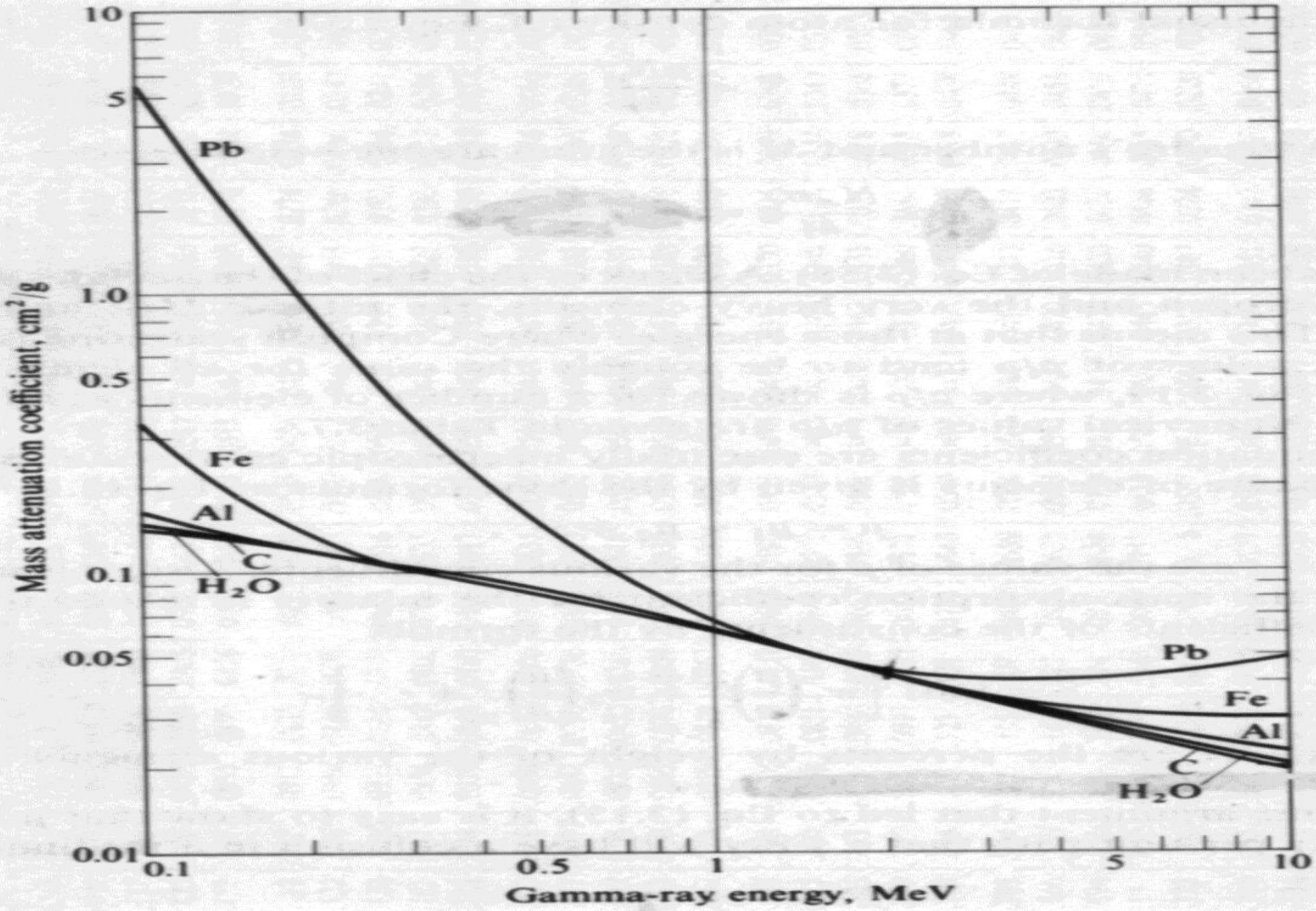
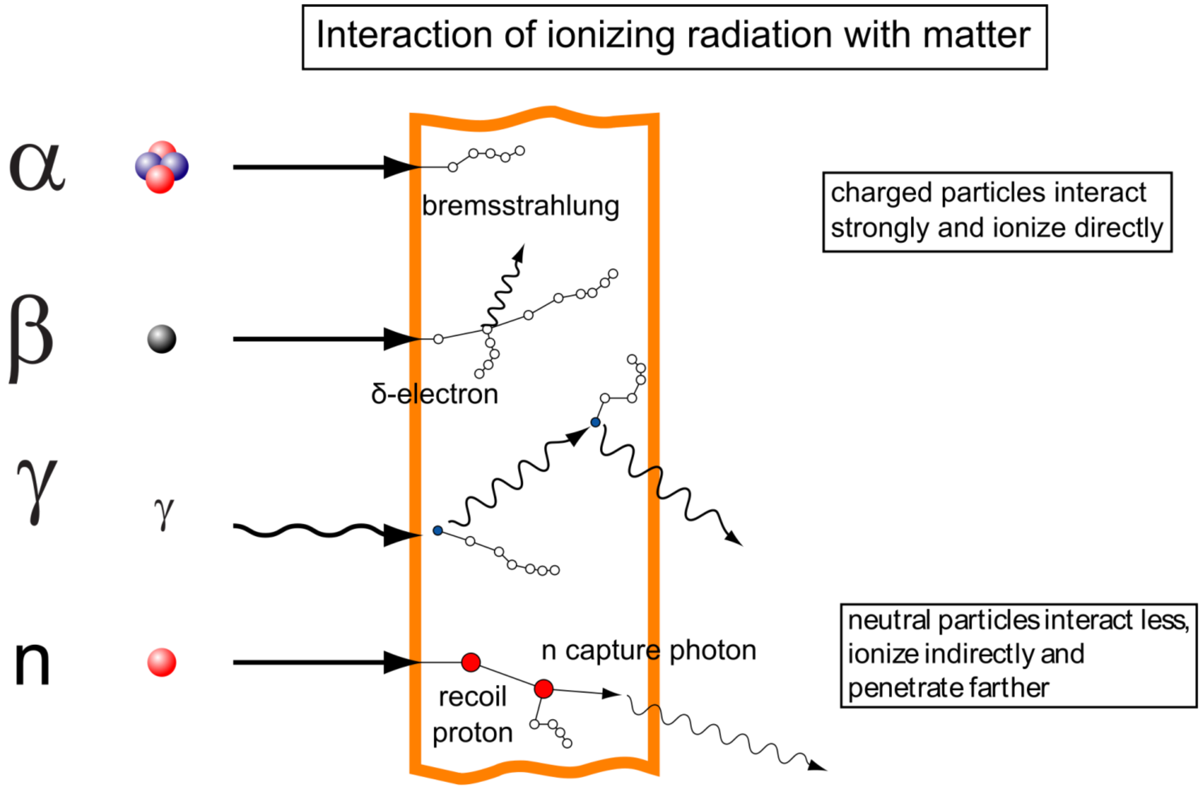


Fig. 3.19 The mass attenuation coefficients of several elements. (From S. Glasstone and A. Sesonske, *Nuclear Reactor Engineering*. New York: Van Nostrand, 1967; by permission, USAEC.)

J.R. Lamarsh, Introduction to Nuclear Engineering

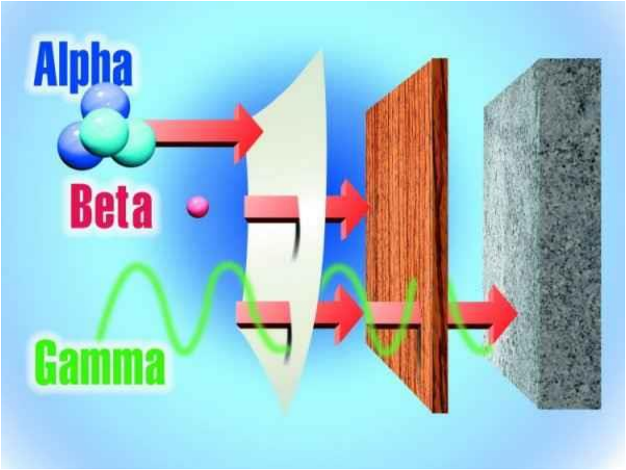
Penetration Depth of Nuclear Radiation



Interaction of ionizing radiation with matter

charged particles interact strongly and ionize directly

neutral particles interact less, ionize indirectly and penetrate farther

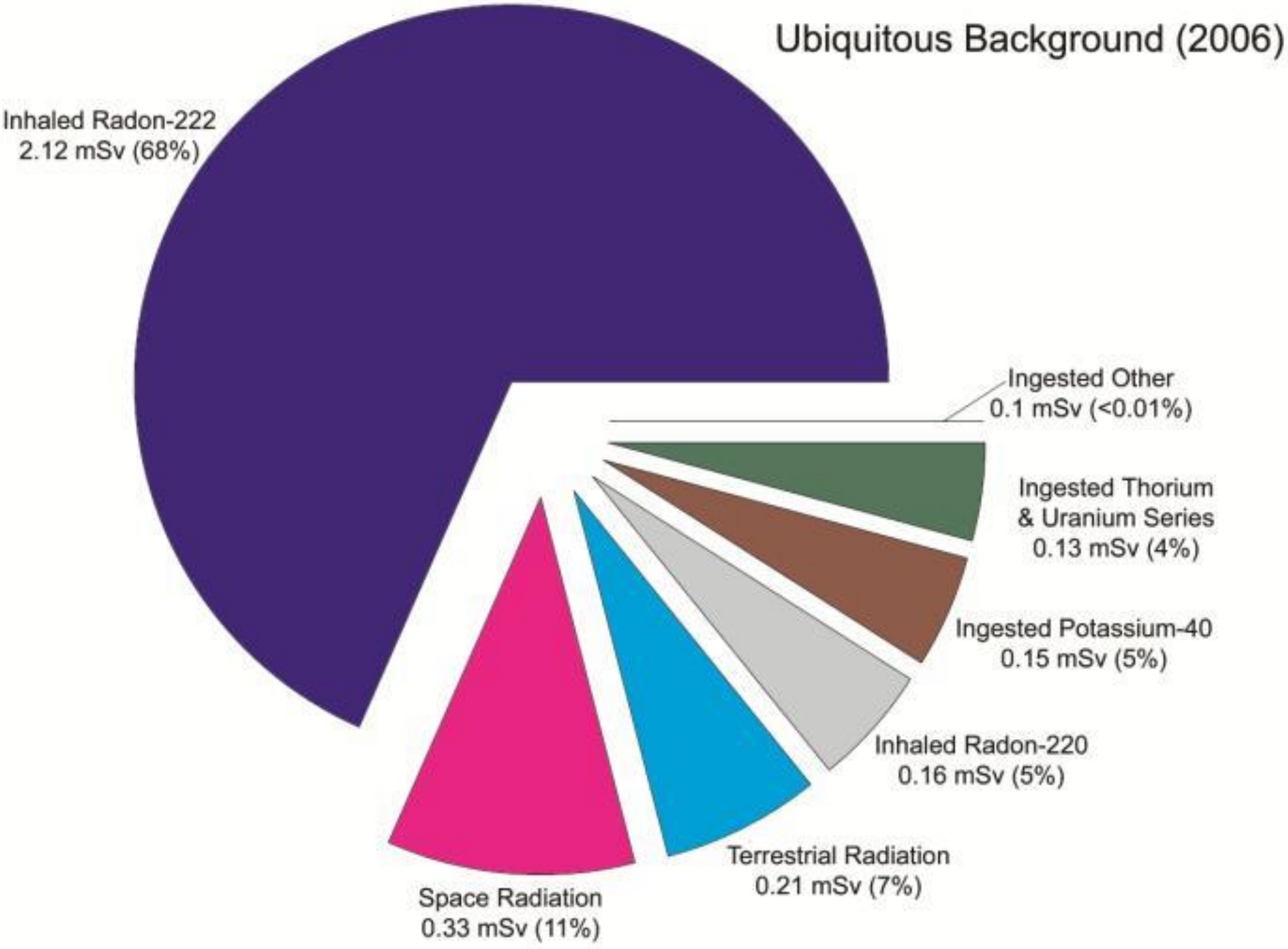


Problem – is Steel Container Safe for Storage?

- It is proposed to store liquid radioactive waste in a steel container.
- If the intensity of γ-rays incident on the interior surface of the tank is estimated to be $3 \text{ x } 10^{11}$ γ-rays/$\text{cm}^2 \bullet \text{sec}$ and the average γ-ray energy is 0.8 MeV, then at what rate is energy deposited at the outer surface of the container?
- Steel is a mixture of mostly iron and elements such as nickel and chromium that have about the same atomic number as iron. So, as far as γ-ray absorption is concerned, steel is essentially all iron.
- From table 3.8, μ_o/ρ for iron at 0.8 MeV is 0.0274 cm^2/g.
  The rate of energy deposition is then:

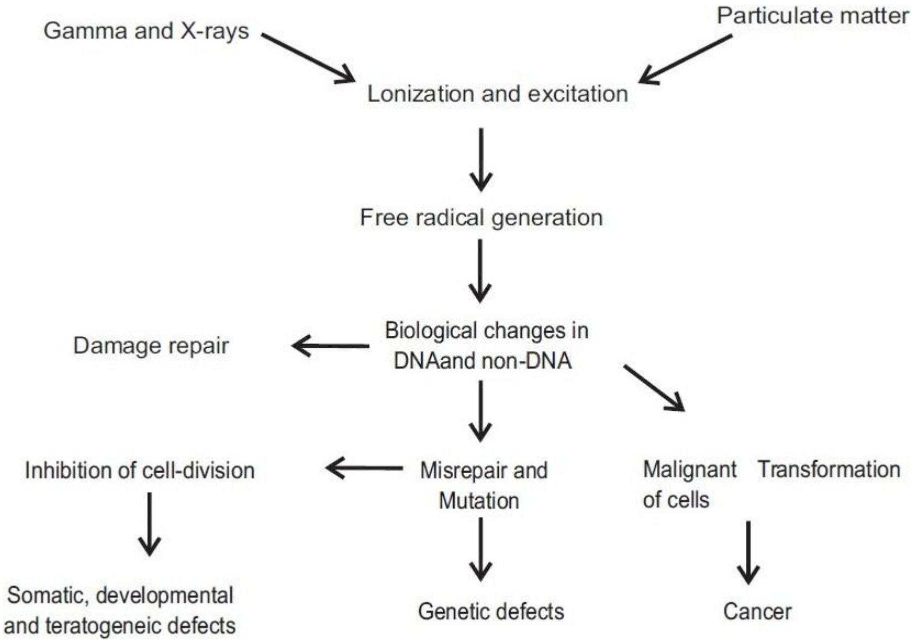
$$0.8 \bullet 3\, x\, 10^{11} \bullet 0.0274 = 6.58\, x\, 10^{9}\ {\text{MeV}}\Big/_{g \bullet \sec} = 2.52\, x\, 10^{-4}\ {\text{cal}}\Big/_{g \bullet \sec}$$

Background Sources and Exposure

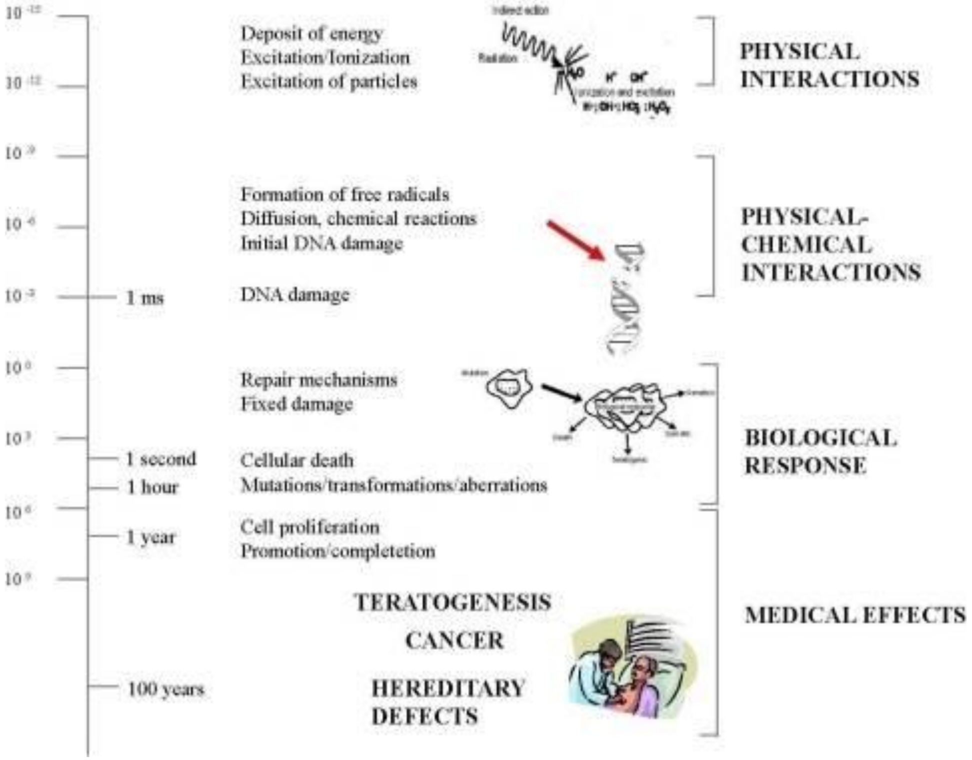


2006 NCRP Report 160

Biological Effects



Sudha Rana, Raj Kumar, Sarwat Sultana, Rakesh Kumar Sharma, Journal of Pharmacy and Bioallied Sciences (2010)



Foffa I, Cresci M, Andreassi MG, International Journal of Environmental Research and Public Health (2009)

Cellular Effects

- Damage from direct breakage of molecular bonds and damage from highly reactive O and OH radicals created indirectly from the radiation
- Blood system is one of most sensitive to radiation. Drop in white cell count (few Sv)
- Radiation sensitive cells are: high dividing rate; long dividing future; unspecialized
- Crypt cells in small intestine die, leading to organ death
- Cell nucleus is most susceptible to radiation. At 500-1000 rads lysosomes rupture, plasma membranes start to leak, ATP, DNA and RNA production is halted until cell repair
- Linear Energy Transfer (LET): ion pairs created per cm; High LET causes greater biological harm and is assigned a higher quality factor (QF)
- Gamma, beta, x-rays QF=1; alpha QF=20; thermal neutrons QF=3; fast protons and neutrons QF=10; larger ionizing particles QF>20
- α particles can deposit most of their energy in a single cell (4000-9000 ion pairs/mm) and are an internal hazard, range is <10 cm in air and 60 μm in tissue
- β particles can create 6 - 8 ion pairs per mm and is a skin and internal hazard; range is 30 cm in air and few mm in tissue for 1 MeV
- Hard X-rays, gamma rays; range km in air; m in tissue; shielded by Pb or concrete

Short-term (Acute) Effects

Dose in Rads	Effect
0 – 25	No detectable clinical effects
25-100	Slight reduction in lymphocytes and neutrophils, serious effects improbable
100 – 200	Nausea and fatigue, possible vomiting over 125 rads, delayed effects, may shorten life ~1%
200-300	Epilation; nausea and vomiting on first day. Latent period 2 weeks, loss of appetite, malaise, sore throat, pallor, petechia, diarrhea, recovery 3 months
300-600	Radiation dermatitis and erythema; nausea and vomiting first few hours, latent period of no symptoms, epilation, malaise, fever, hemorrhage, petechia, purpura, inflammation of throat, rapid emaciation and death (50% for 450 rads)
600 or more	Nausea, vomiting, diarrhea in few hours; 1 week latent period; same as above, death as early as 2nd week; 100% eventual death
1000-2000	Transepidermal injury
>2000	Radionecrosis
>5000 (over time)	Chronic dermatitis

E.L. Saenger, Ed. Medical Aspects of Radiation Accidents, p. 9 US AEC, 1963.

Long-term Effects

- Genetic: Effects passed on from generation to generation due to mutation in genetic material
- Somatic: Effects manifested as cancer; cataracts; abnormal fetus; growth retardation
- Normal rate of genetic disorders of live births is 45 of 1000
- 1 rem *in utero* adds 0.005-0.075 more to this
- Normal rate of cancer deaths in a lifetime for 10,000 people is 2500; 4 more deaths expected from exposure of 10,000 people to 1 rad
- Loss of days of life (risk) for: smoking 20 cigarette per day 2370 days; overweight 777 days; auto accidents 207 days; drowning 24 days; all natural disasters 4.8 days; 1 rem occupational dose 1.5 days; 1 rem/yr from 18-65 years old 51 days

Radiological Hazards

External Exposure

- External radiation protection principles: time, distance, shielding
- Minimize time exposed to radiation
- Maximize distance: dose drop as $1/r^2$ for localized sources; double distance = ¼ dose
- Shield the rad source; α, and charged particles are quickly attenuated by air or piece of paper; mm Al for β; cm Pb for gamma and cm of plastic, paraffin or water (H atoms) for neutrons
- Shield with material of appropriate composition and thickness; multiple half value layers. 30-40 inches of concrete provides 5 orders of magnitude reduction in most γ-rays of concern
- Dose rate X exposure time = total dose

Internal Exposure

- Hazard when radionuclides enter body via inhalation, ingestion, open wounds, through skin
- Internal doses are difficult to calculate
- α particles the highest dose and damage but β still important
- Primary protection is by containment of the radioactive source; control measures to prevent contamination and monitoring to identify it quickly
- Particular radionuclides accumulate in sensitive organs (I in thyroid; actinides in bones leading to increased damage and increased probability the body retains the radionuclides)
- Body may release contaminants over time, leading to a biological half-life

Isotope	Radiological half-life	Biological half-life
H-3	4500 d	11.9 d
I-131/Xe-131	8 d	138 d
U-235	260 billion d	300 d

Contamination

- Ensure contamination control is maintained
- Ensure contamination is not transferred to non-radioactive areas
- Provide feedback on the effectiveness of contamination control measures
- Prevent unnecessary personnel exposure resulting from intake of contamination
- Contamination can be removed or fixed in place
- Removable contamination is more hazardous; detection methods should distinguish between fixed and non-fixed contamination
- Frequency and thoroughness of monitoring depends on many factors
- Workers should monitor themselves and their hands, wrists, clothes, work surfaces during and after each exposure
- Monitor all processing and storage areas regularly per safety plan requirements
- Base procedures, instrumentation and controls by the quantity and characteristics of the emitted radiation

Detection and Measurement

Detector Efficiency

- Geometric efficiency – % of decay particles that are emitted isotopically from a point source that impinge on the detector surface = $\Omega/4\pi$ where Ω is solid angle subtended by the detector face
- Intrinsic peak efficiency, ε, is the % of particles that impinge upon the detector that are detected; this is measured experimentally
- $N = S*T*\varepsilon*\Omega/4\pi$ where N is # counts; S: source in Bq, and T: time interval counted

Intrinsic γ Detection Efficiency	**Detector Type**	**Primary Charge Carriers per 1 MeV Deposited (Energy Resolution)**
>90% 5-100keV 15% 1 MeV	Ge solid state	330,000
1%	Gas detectors	33,000
1%	GM tubes	10,000,000,000 (no E resolution)
100% below 200 keV; 30% at 1 MeV	NaI inorganic scintillator	6,000 (limited by # photoelectrons)

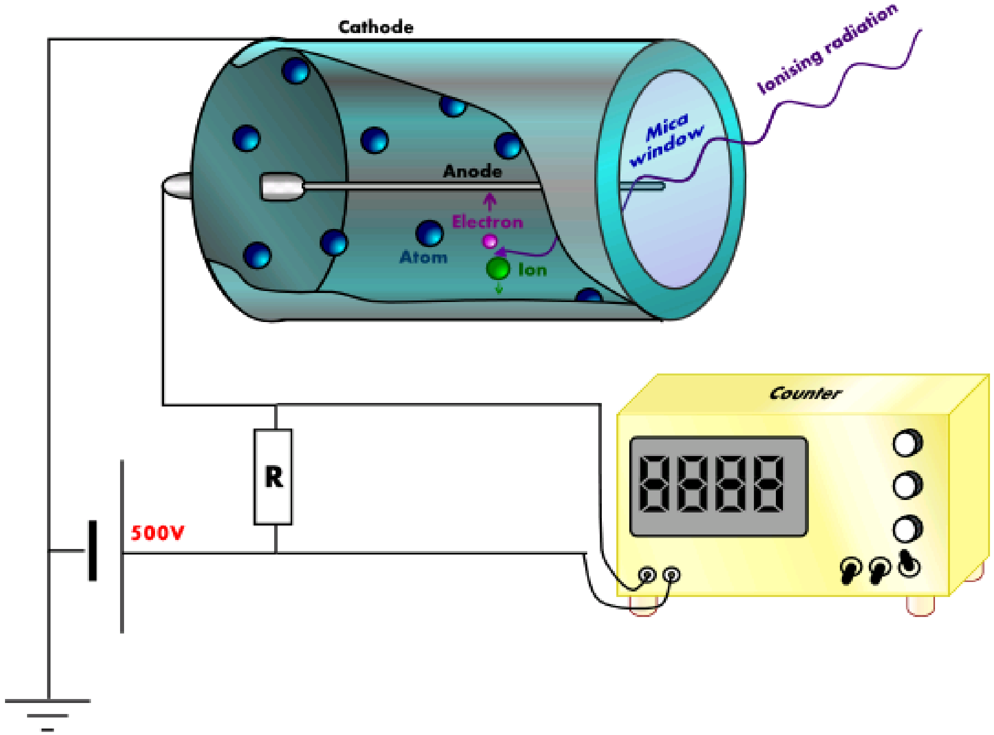
Counting Statistics

- Binomial distribution is exact but has factorials that are often difficult to calculate
- Counting samples with radioactivity involves large numbers of radionuclides with small probability ($p<<1$) for decaying during the counting period – binomial simplifies to Poisson distribution. Accurate for all radioactivity measurements except very short half-life radionuclides
- Sample variance s^2 and mean are directly measured from data
- The Poisson predicted variance = σ^2 = mean;   standard deviation σ = sqrt (mean)
- Hence any single count has an accuracy of the square root of that count
- If the mean is large (>25), then Poisson simplifies to the Gaussian (normal) distribution
- Chi-squared is closely related to s^2 and therefore one can test measurements to see if there are more fluctuations in data than predicted $s^2 = \sigma^2$
- Minimum detectable amount (MDA): for sample counts <<background, $N_D = 4.65 \text{ sqrt}(N_B) + 2.71$ [Currie Eqn]
- N_D minimum mean of counts from source to ensure false positives < 5%

Principles of Geiger-Mueller Tubes

- Particle counting instruments are often used by HPs (friskers, portal monitors), respond to a single ionizing particle, and are typically based upon GM tubes
- Gas tube detectors transition from ionization chamber to proportional counters to GM tubes with increasing applied potential (high voltage)
- Electrons are accelerated with high electric field (1/r field) around the wire anode, causing an avalanche of secondary electrons; these avalanches cascade (Geiger discharge) to surround the entire anode wire in GM tube, losing energy dependence but greatly increasing amplification
- The time it takes for positive ions to drift from anode wire where created to the outer wall determines the resolving time of the detector (sum of dead time and recovery time), typically 200-400 μs
- Advantages: a) relatively inexpensive; b) durable and easily portable; detects all types of radiation
- Disadvantages: a) cannot differentiate type of radiation; b) no energy resolution; c) very low efficiency; d) poor γ-ray counting and lower energy α counting

- Many GM tubes are specialized for various radiation monitoring applications including mini-tubes, ultrathin end window, neutron monitoring, etc.
- Pancake detectors work on the GM tube principle



Scintillators

- Solid: organic and inorganic scintillators; liquid scintillators

- Organic scintillators are inexpensive, can be made large, have great time resolution under a nanosecond, used in high-energy physics, electron spectroscopy, neutron detection

- Inorganic scintillators, e.g., NaI and CsI, have much higher Z, more electrons, better efficiency for gamma ray spectroscopy

- Liquid scintillation analyzers and counters require the sample to be dissolved into a clear scintillation cocktail; ideal for alpha and low-energy beta emitters that cannot penetrate other detectors except for GM detectors with thin (4-9μ) mica end windows (pancakes, GM tubes)

Solid-state Detectors

- Semiconductor detectors: intrinsic; n-type; p-type; compensated; heavy doped
- Surface barrier detectors and ion implanted diodes are widely used for alpha and shorter range radiations, not adaptable to more penetrating gamma rays since active volume is limited to 2-3 mm for normal purity Ge and Si
- High purity (intrinsic) Ge has impurities less than 1:10^{12}
- HPGe has a high thermal leakage current at room temperature, requiring cooling by liquid nitrogen or mechanical coolers
- HPGe has greater energy resolution allowing for identification of gamma rays from multiple transitions of multiple radionuclides simultaneously, but with photopeak efficiencies 10X less than NaI scintillators
- HPGe is ~25X as costly as NaI
- Niche application is for measurements involving multiple lines from multiple radionuclides

Radiation Dosimetry

R	1 Roentgen = 2.58 Coul./kg (exposure and exposure rate refer only to γ)
rad	1 Radiation Absorbed Dose = 100 ergs per γ absorbing material = .01 J/kg
Gray	= 1 joule of absorbed energy per kg
RBE	Relative Biological Effectiveness or Effective Dose Equivalent RBE = dose of 250 kV x-rays/(dose of other rad with same effects)
rem	Roentgen Equivalent Man = unit of dose of ionizing radiation with same bio effect as X-rays rem = rad * Quality Factor (QF)
Sievert	= 1 Gray X QF
RBE/EDE	Dose-weighted by probability of specific biological end effects such as cancer and genetic damage. Units rems or Sieverts

Dose Equivalent Rate = Dose Rate * QF

Gamma, beta, x-rays QF=1; alpha QF=20; thermal neutrons QF=3; fast protons and neutrons QF=10; larger ionizing particles QF>20

Radiation Dosimetry (cont.)

- Annual Limit on Intake (ALI): derived limit of rad material taken into adult worker by inhalation or ingestion per year
- Maximum Permissible Concentration

Muscle tissue: sp. gravity 1; per gram .172E22 N atoms; .602E22 C; 5.98E22 H; 2.75E22 O; 3.28E23 electrons

1 R leads to 95 ergs/g which is close to 1 rad = 100 ergs/g, hence R and rad are sometimes interchanged in literature

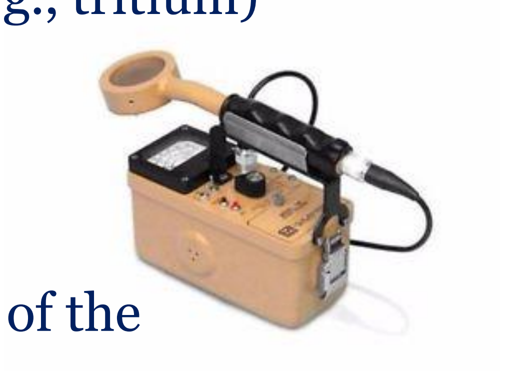
Kerma analyzes effect of indirectly ionizing radiation (x-rays, g-rays, and fast neutrons) transferred to ionizing particles (photoelectrons, Compton electrons, positron-negatron pairs, and nuclei struck by neutrons). Units J/kg is same as dose, but quite different.

Contamination Measurements

- Bring probe to within ½ inch of the surface, making sure not to contaminate the probe or break the thin mica end window (GM tubes/ pancake detectors)
- Move at 3-4 inches/sec
- Test for removable contamination with a 1-inch dia. smear or wipe
- Wear gloves
- Wiping a set distance each time allows for a constant surface area to be covered each time for comparisons (e.g., 100 cm^2)
- Express contamination levels as dpm or mCi/100 cm^2

Portable Radiation Detectors

- For low energy β, there are no portable instruments (e.g., tritium)
- Medium energy β, GM probe with thin window
- High energy β, GM probe or NaI probe
- α emitters are detectable when probe is within an inch of the contamination



- Low-high energy γ-rays, detect with GM probe or NaI probe
- Many new portable instruments (dirty bomb, environmental contamination, identifies isotopes simply)
- Fully portable spectroscopy systems are available but not designed for rapid, rugged, easy to use, HP requirements
- Wipes are often kept with dedicated, portable radiation instruments for non-fixed contamination measurements

Lab-based Radiation Detectors

- For low-high energy β, liquid scintillation analyzers
- α emitters, liquid scintillation analyzers
- Low-high energy γ-rays, liquid scintillation analyzers
- Med-high energy γ-rays, Gamma counters also practical
- Many specialized instruments such as multiple urine samplers; whole body counters; in situ waste and contamination; on-line process monitors, air sample collection systems, monitors for Homeland Security applications; windowless counters in which samples are inserted, etc.

Combination HPGe (Lung and GI Tract) and NaI (Thyroid) System.

Radiation Safety Programs

ALARA, Controls, Procedures, and Training

- ALARA: **A**s **L**ow **A**s **R**easonable **A**chievable
- Means making every reasonable effort to maintain exposures to ionizing radiation as far below the dose limits as practical, consistent with the purpose for which the licensed activity is undertaken, taking into account the state of technology, the economics of improvements in relation to state of technology, the economics of improvements in relation to benefits to the public health and safety, and other societal and socioeconomic considerations, and in relation to utilization of nuclear technology and licensed materials in the public interest
- Process or Engineering Controls: Containments; ventilation with HEPA filters; decontaminating or fixing surface contamination; limiting access to select personnel; limit time workers stay in rad areas
- Respiratory protective devices are a last resort since they limit communication, comfort, worker efficiency to 25%, visibility AND medical screening, fit testing and more must be in place prior to use

Passive Engineered Controls

Installed shielding
Walls, gates, or locked doors
Labyrinths

Active Engineered Controls

Key controls
Interlocked monitoring instruments
Warning indicators or status displays
Ventilation systems

Surveys, Posting, and Labeling

- Radiation contamination **surveys**: identify unknown radiation sources, measure dose rate, identify and localize surface contamination and measure atmospheric contamination
- Monitors should be used during and after every use of radioactive sources
- For liquid and loose solid sources extra care must be taken to prevent the spread of contamination outside radiation zones
- **Postings**: NRC 10CFR20.1902 Posting requirements
- The appropriate placards should communicate the danger, i.e., GRAVE DANGER, VERY HIGH RADIATION AREA; DANGER, HIGH RADIATION AREA; CAUTION, AIRBORNE RADIOACTIVITY AREA; CAUTION, RADIOACTIVE MATERIALS
- **Labeling**: All containers with radioactivity should be labeled with radioactive symbol, isotope, quantity, date measured, chemical form (under 1 µCi might be exempt)

MSWS01

MSWS02

MSWS03

Leak Testing and Instrument Calibration

- **Leak Testing**: Every 6 months it is recommended to leak test sealed sources by using a wet filter paper or a cotton swab. If $\alpha<200$ Bq or $\beta<2000$ Bq, then the source is considered free of leaks.

- **Calibration**
  - γ-ray calibration is often done with a point source located at several distances, all greater than 10 cm from the detector. The variation in the 1/r2 can account for scattering. Sometimes a second instrument is used to take the same measurements. When calibrated, a γ–ray survey meter should measure +/- 10% for >95% of measurements.
  - For β particles, dose response of most portable HP instruments is strongly energy-dependent and hence is used to detect the presence and relative quantity but not the dose. Calibration to NIST traceable sources is possible by measuring dose at the surface and several distances above the surface. β particles with less than 70 keV cannot penetrate to target cells in the skin and are not important for external dosimetry.
  - α emitter monitors read count rate. Sources for calibration are metal plates with source material electroplated. Monitor must be within an inch of the source surface.

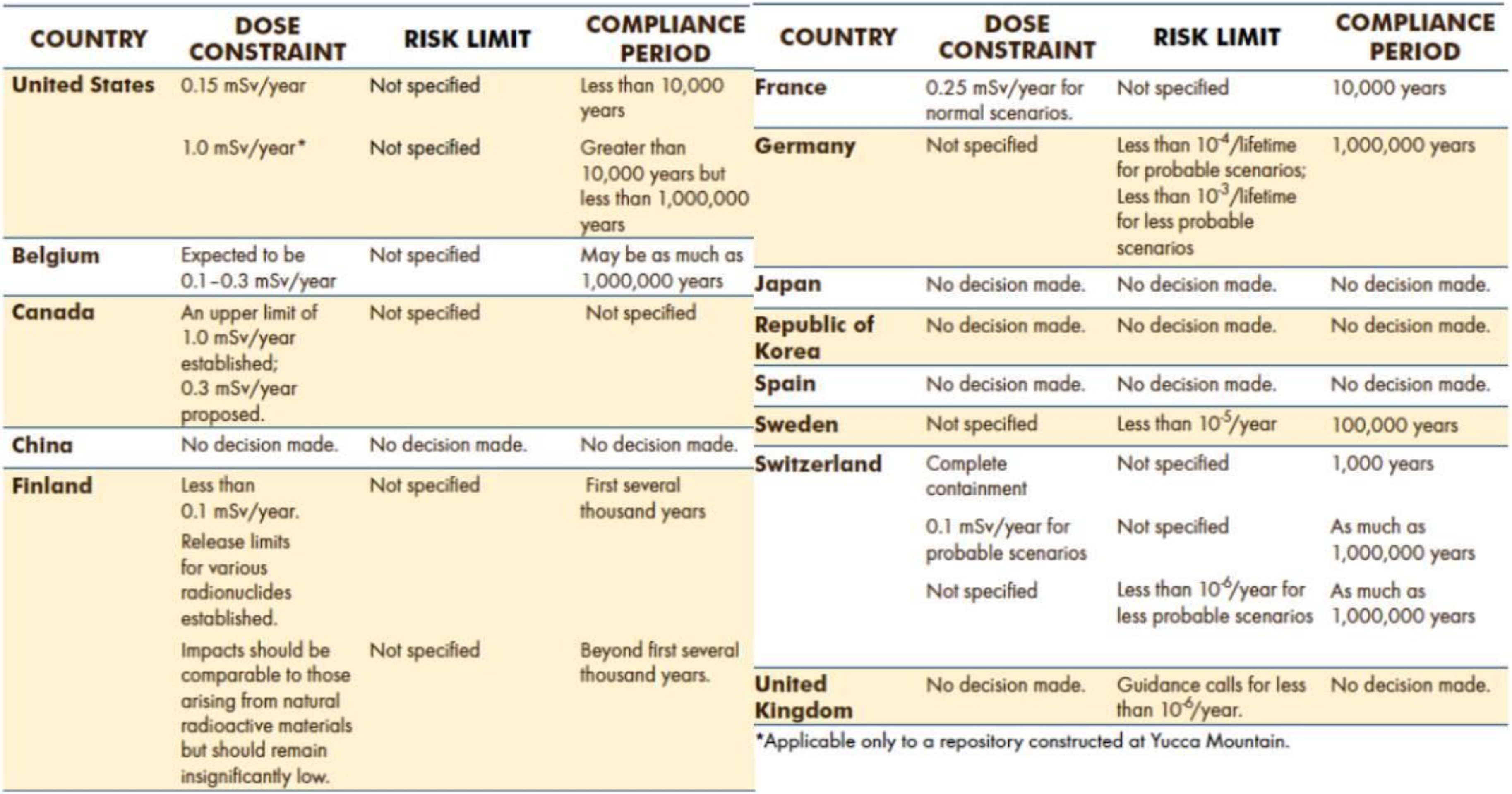
Waste Disposal

- The NRC regulates the management, storage and disposal of radioactive waste produced as a result of NRC-licensed activities. The agency has entered into agreements with 37 states, called Agreement States, to allow these states to regulate the management, storage and disposal of certain nuclear waste.

- For low-level waste, three commercial land disposal facilities are available, but they accept waste only from certain states or accept only limited types of low-level wastes. The remainder of the low-level waste is stored primarily at the site where it was produced, such as at hospitals, research facilities, clinics and nuclear power plants.

- The collection, storage, and ultimate disposal of radioactive waste is under the authority of an RSO

Health and Safety Requirements for Disposal of HLW and SNF



COUNTRY	DOSE CONSTRAINT	RISK LIMIT	COMPLIANCE PERIOD
United States	0.15 mSv/year	Not specified	Less than 10,000 years
	1.0 mSv/year*	Not specified	Greater than 10,000 years but less than 1,000,000 years
Belgium	Expected to be 0.1–0.3 mSv/year	Not specified	May be as much as 1,000,000 years
Canada	An upper limit of 1.0 mSv/year established; 0.3 mSv/year proposed.	Not specified	Not specified
China	No decision made.	No decision made.	No decision made.
Finland	Less than 0.1 mSv/year. Release limits for various radionuclides established.	Not specified	First several thousand years
	Impacts should be comparable to those arising from natural radioactive materials but should remain insignificantly low.	Not specified	Beyond first several thousand years.

COUNTRY	DOSE CONSTRAINT	RISK LIMIT	COMPLIANCE PERIOD
France	0.25 mSv/year for normal scenarios.	Not specified	10,000 years
Germany	Not specified	Less than 10^{-4}/lifetime for probable scenarios; Less than 10^{-3}/lifetime for less probable scenarios	1,000,000 years
Japan	No decision made.	No decision made.	No decision made.
Republic of Korea	No decision made.	No decision made.	No decision made.
Spain	No decision made.	No decision made.	No decision made.
Sweden	Not specified	Less than 10^{-5}/year	100,000 years
Switzerland	Complete containment	Not specified	1,000 years
	0.1 mSv/year for probable scenarios	Not specified	As much as 1,000,000 years
	Not specified	Less than 10^{-6}/year for less probable scenarios	As much as 1,000,000 years
United Kingdom	No decision made.	Guidance calls for less than 10^{-6}/year.	No decision made.

*Applicable only to a repository constructed at Yucca Mountain.

Record Keeping

- **RSOs have been fined, sued and sent to jail.**
- **Detailed Guidance for OSHA's Injury and Illness Recordkeeping Rule**

https://www.osha.gov/recordkeeping/entryfaq.html

NRC: 10CFR36.81 Records and retention periods

All record-keeping and reporting requirements are specified in regulations. Document the applicable requirements and commitments to compliance. The facility must also maintain all records of the Radiation Protection Program, including annual program audits and program content review. The following items should also be identified:

1. The person responsible for maintaining all required records.
2. Where the records will be maintained.
3. The format for maintenance of records and documentation.
4. Procedures for record keeping regarding additional authorized sites (mobile providers).

Regulatory Agencies and Regulations (USA)

- U.S. Nuclear Regulatory Commission (commercial and government nuclear programs)
- U.S. Department of Energy (self-regulated for nuclear safety)
- Occupational Health and Safety Administration (Dept. Labor)/Radiation Safety: U.S. Dept. of Transportation
- SDWA, Safe Drinking Water Act (and amendments)
- CAA, Clean Air Act (and amendments)
- CWA NPDES, Clean Water Act, National Pollutant Discharge Elimination System permits
- World Nuclear Association: http://www.world-nuclear.org/Information-Library/
- Nuclear Quality Assurance Level 1 (NQA-1): established by the American Society of Mechanical Engineers (ASME) and endorsed by NRC to ensure compliance with the requirements of the nuclear industry as established by federal regulations
- In most states, all radiation sources, either radiation (X-ray) machines or radioactive material, are subject to state laws and regulations. Many opt for a broad radiation license from their state regulator

Online Sources of Information

- Radiation Answers: http://www.RadiationAnswers.org
- Ask an Expert, Health Physics Society: http://hps.org/publicinformation/ate/ask.cfm
- American Academy of Health Physics: http://www.hps1.org/aahp/wp_links.htm
- National Council on Radiation Protection and Measurements, http://NCRPonline.org
- EPA Office of Air and Radiation/Radiation Protection Library: http://www2.epa.gov/radiation
- Nuclear Education Online http://www.nuclearonline.org/curriculum/RadiationSafety.asp
- Recommendations of International Commission on Radiological Protection (ICRP) http://www.icrp.org/docs/ICRP_Publication_103-Annals_of_the_ICRP_37(2-4)-Free_extract.pdf
- International Atomic Energy Agency's Radiation Protection and Safety of Radiation Sources www-pub.iaea.org/MTCD/publications/PDF/Pub1578_web-57265295.pdf & www-nds.iaea.org

Online Sources of Information (cont.)

- US Nuclear Regulatory Commission (NRC) Safety Requirements http://www.nrc.gov/reactors/operating/ops-experience/tritium/safety-requirements.html#require
- Radioactivity Regulatory Agencies: EPA,FDA, NRC and State Governments http://www.nrc.gov/about-nrc/radiation/protects-you/reg-matls.html
- Nuclear Regulators around the world (World Nuclear Association): http://www.world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Appendices/Nuclear-regulation---regulators/
- National Nuclear Data Center www.nndc.bnl.gov
- Gamma Spectroscopy Center, INL (sample NaI and Ge spectra for selected isotopes) *www4vip.inl.gov/**gammaray**/catalogs/ge/catalog_ge.shtml*
- NIST Physical Reference Data (tables and graphs of ionization energy loss & absorption coefficients) *www.**nist**.gov/pml/**data**/*

Upcoming Webinars

- The Diverse Geologic Environments of Natural Uranium Resources
- Introduction to Nuclear Forensics
- Nuclear Fission/Nuclear Devices

NAMP website: www.wipp.energy.gov/namp