Lecture 35: Health Physics
(From Flux to Biological Risk)

CBE 30235: Introduction to Nuclear Engineering — D. T. Leighton

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Introduction: The Unit Conversion Nightmare

The field of Health Physics is notorious for having two sets of units for everything (SI vs. Conventional). We must master the "Pipeline of Dose"—the sequence of converting a source term into a biological risk.

1. Source	$\xrightarrow{\text{Geometry}}$	**2. Field**	$\xrightarrow{\text{Interaction}}$	**3. Absorbed Dose**
Activity		Flux		Energy Dep.
(Ci, Bq)		(ϕ)		(Rad, Gy)

Figure 1: The physical chain of events.

1 1. The Four Tiers of Radiation Units

1.1 Tier 1: Activity (The Source)

How many atoms decay per second? This tells you nothing about danger until you know type, energy, distance and shielding.

- **Curie (Ci):** 3.7×10^{10} decays/s (Based on 1 gram of Ra-226).
- **Becquerel (Bq):** 1 decay/s (The SI unit).
- **Analogy:** The rate at which a pitcher throws baseballs.

1.2 Tier 2: Exposure (The Air)

Historically easier to measure than tissue dose. Defined by the ionization of dry air.

- **Roentgen (R):** Amount of X-ray/Gamma radiation that creates 1 esu of charge in 1 cc of dry air.
- **Analogy:** How many baseballs are flying through the air near you and how fast they are moving.

1.3 Tier 3: Absorbed Dose (The Physics)

Energy deposited per unit mass of material.

- **Rad:** 100 erg/g.
- **Gray (Gy):** 1 J/kg.
- **Conversion:** 1 Gy = 100 Rad.
- **Analogy:** How hard the baseballs hit you over time (Kinetic Energy absorbed).

1.4 Tier 4: Equivalent Dose (The Biology)

Not all energy is equal. A 1 MeV neutron does far more biological damage than a 1 MeV gamma ray.

- **Rem:** Roentgen Equivalent Man.
- **Sievert (Sv):** The SI unit.
- **Conversion:** 1 Sv = 100 Rem.

$$H(\text{Rem}) = D(\text{Rad}) \times Q$$

Where Q is the **Quality Factor** (or Radiation Weighting Factor, w_R).

2 2. Calculating Dose from Flux

How do we turn the Flux $\phi(E)$ we calculated in shielding (Lectures 33-34) into Dose rate $\dot{D}$?

2.1 The Fundamental Equation

The energy deposition rate is simply the intensity ($I = \phi E$) times the mass absorption coefficient.

$$\dot{D} = \phi \cdot E \cdot \left(\frac{\mu_{en}}{\rho}\right) \cdot C$$

Where:

- ϕ: Flux (#/cm^{2}s).
- E: Energy per particle (Joules or MeV).
- μ_{en}/ρ: Mass Energy-Absorption Coefficient (cm^2/g). This is a material property (Tissue/Water).
- C: Unit conversion constant.

2.2 Quality Factors (Q): The "LET" Concept

Why is a neutron worse than a gamma?

- **LET (Linear Energy Transfer):** dE/dx. How densely the particle deposits energy along its track.
- **Low LET (γ, β):** Sparse ionization. DNA breaks are single-strand and easily repaired by the cell. $Q = 1$.
- **High LET (α, n):** Dense ionization "furrow." Causes **Double Strand Breaks** (DSBs) in DNA. Hard to repair; leads to mutations.

Radiation Type	**Quality Factor (Q)**
X-Rays, Gamma, Electrons	1
Thermal Neutrons	2–5
Fast Neutrons	10–20
Alpha Particles	20

3 3. Biological Case Studies: The "Bad Actors"

In a reactor accident, we worry about specific isotopes based on their chemistry (Bio-accumulation).

3.1 Case A: Iodine-131 (The Thyroid)

- **Chemistry:** The body cannot distinguish I-131 from stable I-127. The thyroid gland concentrates Iodine by a factor of $\approx 500\times$.
- **Hazard:** Beta emitter. Concentrates in a small gland (high dose per gram). Causes thyroid cancer (especially in children).
- **The Countermeasure (KI Pills):** Potassium Iodide.
- **Mechanism: Isotopic Dilution / Competitive Inhibition**. By flooding the blood with stable Iodine (KI) *before* exposure, you saturate the thyroid's uptake channels. Any radioactive iodine inhaled is rejected and excreted by the kidneys.

3.2 Case B: Strontium-90 (The Bones)

- **Chemistry:** Group 2 element, chemically analogous to **Calcium**.
- **Hazard:** The body builds Sr-90 into bone matrix. It has a long biological half-life.
- **Result:** Chronic irradiation of the **Bone Marrow**. Primary cause of Leukemia in high-dose scenarios.

3.3 Case C: Cesium-137 (The Whole Body)

- **Chemistry:** Group 1 element, chemically analogous to **Potassium**.
- **Hazard:** Distributes uniformly in muscle/soft tissue. Gamma emitter. Delivers "Whole Body Dose."

4 4. Acute Radiation Syndrome (ARS)

If the dose is high enough (Deterministic Effect), cells die faster than they can reproduce.

4.1 The "Dosimeter" of the Body: White Blood Cells

The first cells to vanish are the ones with the highest turnover rate: Lymphocytes.

- A drop in lymphocyte count is the standard clinical method to estimate dose immediately after an accident.

4.2 The Progression

1. **Prodromal Phase (0-48 hrs):** Nausea, vomiting. The severity/speed of onset correlates with dose.
2. **Latent Phase (The "Walking Ghost"):**
   - Patient feels better. Nausea subsides.
   - **Physiology:** The stem cells in the marrow/gut are dead, but the mature cells (RBCs, WBCs) are still circulating. The patient is "running on fumes."
   - As the mature cells die off naturally over days/weeks, they are not replaced.
3. **Manifest Illness:**
   - **Hematopoietic** (>1 **Gy):** Infection, bleeding (no platelets). Survivable with care.
   - **Gastrointestinal** (>10 **Gy):** Gut lining sloughs off. Electrolyte imbalance, sepsis. Nearly always fatal.
   - **CNS** (>50 **Gy):** Immediate nervous system collapse.

5 5. Regulatory Limits (10CFR20)

The Nuclear Regulatory Commission (NRC) sets limits based on the **LNT (Linear No-Threshold)** hypothesis.

5.1 The Numbers

Category	Limit (Rem/yr)	Notes
Average Background	0.300–0.600	Includes Radon, Cosmic, Medical.
General Public	0.100	**ADDITIONAL** dose above background. (e.g., limit for a plant's neighbor).
Occupational (Worker)	5.000	(5000 mRem). Federal Legal Limit.
Declared Pregnant	0.500	For the gestation period (protects fetus).
LD 50/30	≈ 400.000	Lethal Dose to 50% in 30 days (Acute).

5.2 Dose Context: Where you Live Matters

Background radiation is not constant. It varies wildly by location and lifestyle.

Case Study: The Background Radiation Variable

1. Sea Level vs. Altitude (Cosmic Dose):
People in **Denver, CO** (1 mile high) receive ≈ 50 mrem/yr from cosmic rays, nearly double the dose of someone at sea level (≈ 26 mrem/yr).
2. Indoor vs. Outdoor (Radon Dose):
Surprisingly, being **Indoors** usually results in a higher dose than being outdoors.

- **Outdoors:** Radon gas dilutes into the atmosphere.
- **Indoors:** Radon seeps from the ground and accumulates in basements.
- **Result:** A person staying inside a poorly ventilated basement can receive > 1000 mrem/yr, far exceeding the limit for a nuclear plant neighbor.

5.3 ALARA (As Low As Reasonably Achievable)

It is not enough to stay below the 5 Rem limit. If you can do a job for 100 mrem, but you get sloppy and take 200 mrem, you are in violation of ALARA, even though you are legally "safe" below 5000.

6 Case Study: The "Perfect" Poison (The Litvinenko Assasination)

In November 2006, Alexander Litvinenko, a former Russian security officer, was assassinated in London using **Polonium-210**. This event serves as a grim but definitive case study in the engineering distinction between **External Hazard** and **Internal Dose**.

6.1 The Physics of the Weapon: Polonium-210

Polonium-210 (^{210}Po) is a nearly pure alpha emitter produced by neutron bombardment of Bismuth-209 in a high-flux nuclear reactor.

- **Decay Mode:** Alpha decay to stable Lead-206 (^{206}Pb).
- **Alpha Energy:** 5.3 MeV.
- **Gamma Emission:** Negligible ($< 0.001\%$ of decays).
- **Half-Life:** 138 days (High specific activity, meaning a tiny mass yields a massive dose).

6.2 The Engineering Failure: Why Detection Was Missed

Litvinenko presented with symptoms of severe radiation sickness (hair loss, immune failure), yet he was not diagnosed for weeks. Why?

6.2.1 1. The Shielding Paradox (External Detection)

Standard security measures failed because of the alpha particle's short range.

- **The Container:** The poison was likely transported in a simple glass vial or commercial beverage container.
- **The Physics:** A 5.3 MeV alpha particle travels less than 40 μm in glass. The container walls ($> 1000\,\mu$m) absorbed 100% of the radiation.
- **The Survey:** A standard Geiger-Müller counter held inches from the assassin's bag would read **Background levels**. Without gamma rays to penetrate the container, the source was invisible.

6.2.2 2. The Biological Catastrophe (Internal LET)

While harmless outside the body (stopped by the dead layer of the epidermis), alpha particles are the most destructive type of radiation once ingested.

- **High LET (Linear Energy Transfer):** Alpha particles are heavy (^{4}He nuclei) and doubly charged (+2). They plow through tissue like a bulldozer, depositing all their energy in a very short distance ($\sim 50\,\mu$m, or about 5 cell diameters).
- **The Quality Factor (Q):** In calculating dose equivalent (Sieverts), alpha particles are assigned a Weighting Factor (w_R) of **20**.

$$\text{Dose (Sv)} = \text{Absorbed Dose (Gy)} \times 20 \tag{1}$$

  This means 1 Joule of alpha energy does **20 times the biological damage** of 1 Joule of gamma or beta energy. The massive double-strand DNA breaks are almost impossible for cells to repair.

6.3 The Forensic Trace

The assassination was ultimately uncovered not by a Geiger counter, but by **Alpha Spectroscopy** on biological samples (urine). Once identified, investigators could trace the path of the poison (teapots, hotel rooms, airplane seats) because minute traces of Po-210 had escaped the container or been excreted by the assassins.

> **Engineering Lesson:** "Non-detectable" does not mean "Safe." A survey meter only tells you what is penetrating the probe wall. If you suspect an alpha hazard, you must use an open-window probe (Pancake) or take swipe samples for laboratory analysis.

References

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4. **Beir VII Report**: "Health Risks from Exposure to Low Levels of Ionizing Radiation" (National Academies).
   `https://nap.nationalacademies.org/resource/11340/beir_vii_final.pdf`