Question

1. Name two long-lived radioactive materials chemically embedded in your body material

2. What is the difference between the dosimetry units “rad” and “rem”?

3. What is the origin of the primary and what is the origin of the secondary gamma radiation associated with a nuclear bomb explosion?
Radiation Effects of a Nuclear Bomb

Radiation can have severe effects on the human body by generating chemical and biological damage to the molecular structure and composition of the body material.
Neutron capture induced activity

Released neutrons are captured on all nuclei in the bomb environment.

Radioactive dust in a New York leaf, 36 h after Nevada explosion

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Half-life (years)</th>
<th>Formation reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{26}$Al</td>
<td>$7.3 \times 10^5$</td>
<td>$^{27}$Al(n, 2n)</td>
</tr>
<tr>
<td>$^{36}$Cl</td>
<td>$3.01 \times 10^3$</td>
<td>$^{35}$Cl(n, $\gamma$)</td>
</tr>
<tr>
<td>$^{41}$Ca</td>
<td>$1.03 \times 10^5$</td>
<td>$^{40}$Ca(n, $\gamma$)</td>
</tr>
<tr>
<td>$^{59}$Ni</td>
<td>$7.6 \times 10^4$</td>
<td>$^{58}$Ni(n, $\gamma$)</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>5.24</td>
<td>$^{59}$Co(n, $\gamma$)</td>
</tr>
<tr>
<td>$^{63}$Ni</td>
<td>100</td>
<td>$^{62}$Ni(n, $\gamma$)</td>
</tr>
<tr>
<td>$^{79}$Se</td>
<td>$6.0 \times 10^4$</td>
<td>$^{78}$Se(n, $\gamma$)</td>
</tr>
<tr>
<td>$^{93m}$Zr</td>
<td>$1.1 \times 10^6$</td>
<td>$^{93}$Nb(n, n')</td>
</tr>
<tr>
<td>$^{93}$Nb</td>
<td>12</td>
<td>$^{93}$Nb(n, $\gamma$)</td>
</tr>
<tr>
<td>$^{94}$Nb</td>
<td>$2 \times 10^4$</td>
<td>$^{92}$Mo(n, $\gamma$)</td>
</tr>
<tr>
<td>$^{93}$Mo</td>
<td>3500</td>
<td>$^{120}$Sn(n, $\gamma$)</td>
</tr>
<tr>
<td>$^{121m}$Sn</td>
<td>5</td>
<td>$^{150}$Sm(n, $\gamma$)</td>
</tr>
<tr>
<td>$^{151}$Sm</td>
<td>80</td>
<td>$^{151}$Eu(n, 2n)</td>
</tr>
<tr>
<td>$^{150}$Eu</td>
<td>36</td>
<td>$^{151}$Eu(n, $\gamma$)</td>
</tr>
<tr>
<td>$^{152}$Eu</td>
<td>13.5</td>
<td>$^{153}$Eu(n, 2n)</td>
</tr>
<tr>
<td>$^{154}$Eu</td>
<td>16</td>
<td>$^{153}$Eu(n, $\gamma$)</td>
</tr>
<tr>
<td>$^{166m}$Ho</td>
<td>1200</td>
<td>$^{165}$Ho(n, $\gamma$)</td>
</tr>
<tr>
<td>$^{178m}$Hf</td>
<td>31</td>
<td>$^{177}$Hf(n, $\gamma$)</td>
</tr>
<tr>
<td>$^{186m}$Re</td>
<td>$2 \times 10^5$</td>
<td>$^{185}$Re(n, $\gamma$)</td>
</tr>
<tr>
<td>$^{192m}$Ir</td>
<td>240</td>
<td>$^{191}$Ir(n, $\gamma$)</td>
</tr>
<tr>
<td>$^{193}$Pt</td>
<td>60</td>
<td>$^{192}$Pt(n, $\gamma$)</td>
</tr>
<tr>
<td>$^{205}$Pb</td>
<td>$1.5 \times 10^7$</td>
<td>$^{204}$Pb(n, $\gamma$)</td>
</tr>
</tbody>
</table>
Decline by the “rule of seven”

This rule states that for every seven-fold increase in time following a fission detonation (starting at or after 1 hour), the radiation intensity decreases by a factor of 10. Thus after 7 hours, the residual fission radioactivity declines 90%, to one-tenth its level of 1 hour. After $7 \cdot 7$ hours (49 hours, approx. 2 days), the level drops again by 90%. After $7 \cdot 2$ days (2 weeks) it drops a further 90%; and so on for 14 weeks.

The rule is accurate to 25% for the first two weeks, and is accurate to a factor of two for the first six months. After 6 months, the rate of decline becomes much more rapid.

\[
A_{t_n} = 7^n A_{t_0} = 10^{-n} A_{t_0}
\]

![Graph showing the decline over time with a logarithmic scale for activity (in %) and days.](image)
<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Half-life (^a)</th>
<th>NTS Fallout</th>
<th></th>
<th>Global Fallout</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>External Dose (^b)</td>
<td>Thyroid Internal Dose</td>
<td>Red Bone Marrow Internal Dose</td>
<td>External Dose (^b)</td>
</tr>
<tr>
<td>Tritium</td>
<td>12.3 y</td>
<td>0.0001</td>
<td>0.07</td>
<td></td>
<td>0.07</td>
</tr>
<tr>
<td>Carbon-14</td>
<td>5730 y</td>
<td>0.1</td>
<td>0.04</td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>Manganese-54</td>
<td>313 d</td>
<td>0.02</td>
<td>0.2</td>
<td></td>
<td>[0.002]</td>
</tr>
<tr>
<td>Strontium-89</td>
<td>52 d</td>
<td>0.001</td>
<td>0.07</td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>Strontium-90</td>
<td>28.5 y</td>
<td>0.02</td>
<td>0.04</td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>Zirconium/Niobium-95</td>
<td>64 d</td>
<td>0.02</td>
<td>0.2</td>
<td></td>
<td>[0.5]</td>
</tr>
<tr>
<td>Zirconium/Niobium-97</td>
<td>17 h</td>
<td>0.02</td>
<td>0.2</td>
<td></td>
<td>[0.5]</td>
</tr>
<tr>
<td>Ruthenium-103</td>
<td>39 d</td>
<td>0.03</td>
<td>0.2</td>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td>Ruthenium-106</td>
<td>368 d</td>
<td>0.001</td>
<td>0.02</td>
<td></td>
<td>0.02</td>
</tr>
<tr>
<td>Antimony-125</td>
<td>2.7 y</td>
<td>0.02</td>
<td>0.04</td>
<td></td>
<td>0.04</td>
</tr>
<tr>
<td>Iodine-131</td>
<td>8 d</td>
<td>0.02</td>
<td>0.2</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>TeLlurium/Iodine-132</td>
<td>3.3 d</td>
<td>0.02</td>
<td>0.04</td>
<td></td>
<td>[0.002]</td>
</tr>
<tr>
<td>Iodine-133</td>
<td>0.9 d</td>
<td>0.02</td>
<td>0.04</td>
<td></td>
<td>[0.002]</td>
</tr>
<tr>
<td>Cesium-136</td>
<td>13 d</td>
<td>0.002</td>
<td>0.04</td>
<td></td>
<td>0.04</td>
</tr>
<tr>
<td>Cesium-137</td>
<td>30 y</td>
<td>0.009</td>
<td>0.04</td>
<td></td>
<td>0.04</td>
</tr>
<tr>
<td>Barium/Lanthanum-140</td>
<td>13 d</td>
<td>0.006</td>
<td>0.04</td>
<td></td>
<td>0.04</td>
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<tr>
<td>Cerium-144</td>
<td>284 d</td>
<td>0.02</td>
<td>0.04</td>
<td></td>
<td>0.04</td>
</tr>
<tr>
<td>Neptunium-239</td>
<td>2.4 d</td>
<td>0.02</td>
<td>0.04</td>
<td></td>
<td>0.04</td>
</tr>
</tbody>
</table>

Rounded totals:
- Adults: 0.5
- Child born 1 January 1951: [30] \(^c\)

\(^a\) y=years; d=days; h=hours.
\(^b\) The external dose is equal for all organs of the body.
\(^c\) Values in brackets are for a child born 1 January 1951.
Studies of impact of ionizing radiation on the human body - Hiroshima -

US-Japanese teams medical tests, autopsies, human organ analysis, on-site radioactivity measurements …
Radiation Exposure Types

Irradiation

External Contamination

Internal Contamination
Schematic Model of Radionuclide Uptake

**Intake:**
- Ingestion
- Inhalation
- Surface

**Uptake:**
- Gastro-Intestinal GI Tract
- Lymph Nodes
- Lung

**Excretion:**
- Feces
- Urine

**Deposition Sites:**
1. Whole Body
2. Bone
3. Liver
4. Muscle
5. Thyroid

Deposition depends on chemical characteristics of isotopes

- $^{90}$Sr
- $^{232}$Th
- $^{137}$Cs
- $^{131}$I
Radiation interacting with cell molecules
Sequence of Events in Indirect Action

\[ T_{1/2} \text{ in sec} \]

- Incident X-ray photons
  \[ \downarrow \]
  - Fast electrons
    \[ \downarrow \]
    - Ion radicals
      \[ \downarrow \]
      - Free radicals
        \[ \downarrow \]
        - Macromolecular changes from breakage of chemical bonds
          \[ \downarrow \]
          - Biological effects

- days - cell killing
- generation - mutation
- years - carcinogenesis
Energy dependence of radiation damage

Linear energy transfer (LET): amount of energy deposited per unit track length
Acute Radiation Syndrome

- Signs and symptoms experienced by individuals exposed to acute whole body irradiation.
- Data collected largely through Japanese atomic bomb survivors at Hiroshima and Nagasaki.
- Limited number of accidents at nuclear installations.
- Clinical radiotherapy.
- Well-characterized animal data base.
- LD$_{50}$ dose of human is $\sim$4.5 Gy = 450 rad.
- Lethal Dose is $\geq$ 8 Gy = 800 rad
A 50% lethality is reached with an accumulated dose of 450 cGy = 450 rad = 4.5 Gy. A dose of 100 rad dose is survivable. A 800 rad dose is lethal.
Alexander Litvinenko

Litvinenko died on radiation poisoning by a small amount of $^{210}$Po after 22 days. $^{210}$Po is an alpha emitter that has a half-life of 138.4 days; it decays directly to its stable daughter isotope, $^{206}$Pb. The alpha particles have an energy of 5.307 MeV. Calculate the minimum amount of $^{210}$Po Litvinenko must have eaten.

$(1 \text{ MeV} = 1.6 \cdot 10^{-13} \text{ Joule})$

\[
A = \lambda \cdot N = \frac{\ln 2}{T_{1/2}} \cdot N = 5 \cdot 10^{-3} \cdot N \left[ \text{d}^{-1} \right]
\]

\[
210 \text{ g} = 6.022 \cdot 10^{23} \text{ particles} \quad x \text{ g} = x \cdot 2.87 \cdot 10^{21} \text{ particles}
\]

\[
D = \frac{E}{m} \cdot A \cdot t = \frac{5.307 \text{MeV}}{80 \text{kg}} \cdot A \cdot t = \frac{4.25 \cdot 10^{-15} \text{J}}{80 \text{kg}} \cdot N \cdot t
\]

\[
D = 1.17 \cdot 10^{-15} \text{Gy} \cdot N = 3.35 \cdot 10^{6} \cdot x \text{ Gy}
\]

\[
x = \frac{8 \text{ Gy}}{3.35 \cdot 10^{6}} = 2.4 \cdot 10^{-6} \text{ g} \quad A = 3.43 \cdot 10^{13} \text{ d}^{-1} = 4 \cdot 10^{8} \text{ s}^{-1} = 4 \cdot 10^{8} \text{ Bq}
\]
Prodromal Radiation Syndrome

• Early symptoms that appear after exposure to whole body radiation:
  – gastrointestinal: nausea, vomiting, diarrhea, anorexia
  – neuromuscular: easy fatigability

• Effect is dose dependent:
  – Varies in time of onset
  – Severity
  – Duration
Survival Chance

For people who died within 2 days to 2 months after bomb explosion

As function of distance (exposure)

Remaining lifespan as function of dose

Probability of death as a function of distance from the hypocenter

Time of occurrence of death from acute radiation effects.
Radiation Side Effects

Radiation sickness

- 100% death within several days to weeks with modern medical interventions
- Vomiting, nausea
- Decrease of lymphocyte counts
- Cumulative dose of residual radiation beyond the first day
- Gastric fluoroscopy (skin dose)
- Annual background dose
- Chest X-ray photograph

![Graph showing the relationship between distance from hypocenter and air dose for gamma rays and neutrons in Hiroshima and Nagasaki.](image-url)
Nagasaki Effects

[Image of a sign in Chinese and English]

NAGASAKI INFECTION HOSPITAL
Early Lethal Effects

**Hematopoietic syndrome:**
- Cause of death at doses <8 Gy.
- Peak incidence of death occurs at about 30 days post-irradiation, and continues for up to 60 days.
- Suppresses normal bone marrow and spleen functions.
- Symptoms associated with hematopoietic syndrome are: chill, fatigue, hemorrhages, ulceration, infection and anemia. Death usually result unless receive bone marrow transplant.

**Gastrointestinal syndrome:**
- Occurs at dose >10 Gy of gamma-rays or its equivalence.
- Death usually occurs within 3 to 10 days.
- Symptoms due largely to depopulation of the epithelial lining of the GI tract by radiation.
- No human has survived radiation dose >10 Gy.
- Clinical symptoms include nausea, vomiting, and prolong diarrhea, dehydration, loss of weight, complete exhaustion, and eventually death.
Epilation – severe loss of hair

Hair loss is a common sign of radiation exposure & sickness. Severe epilation (2/3 hair loss) occurs at doses of >2 Gy=200 rad.

2km from hypocenter
Purpura, or bleeding under the skin, is one of the symptoms of acute radiation sickness. The heavily exposed survivors experienced fever, nausea, vomiting, lack of appetite, bloody diarrhea, epilation, purpura, sores in their throat or mouth (nasopharyngeal ulcers), and decay and ulceration of the gums about the teeth (necrotic gingivitis). The time of onset of these symptoms depends on the exposure level.
Early Lethal Effects

_Central nervous syndrome or cerebrovascular syndrome:

• Identified at doses >100 Gy of gamma-rays.
• Death occurs within hours from cardiovascular and neuromuscular complications.
• Clinical manifestations include severe nausea, vomiting within minutes of exposure, disorientation, loss of muscular co-ordination, respiratory distress, seizures, coma and death.
Time course of clinical symptoms

Waselenko J K et al. Ann Intern Med 2004;140:1037-1051
Long term effects - blindness

Radiation damage to epithelial Cells. Damaged cells move to the back of the eye and cause lens opacity by blocking light. Occurs with 50% chance for people with dose of ~500 rad.
Mutation and Fiction
Radiation-induced Mutagenesis

- Radiation *DOES NOT* produce new, unique mutations, but increases the incidence of the same mutations that occur spontaneously.
- Mutation incidence in humans is *DOSE* and *DOSE-RATE* dependent.
- A dose of 1 rem (10 mSv) per generation increases background mutation rate by 1%.
- Information on the genetic effects of radiation comes almost entirely from animal and *IN VITRO* studies.
- Children of A-bomb survivors from Hiroshima and Nagasaki fail to show any significant genetic effects of radiation.
Tumor evolution in animal tests
Radiation Carcinogenesis

- A stochastic late effect.
- No threshold, an all or none effect.
- Severity is not dose related.
- Probability of carcinogenesis is dose dependent.
- Leukemia has the shortest latency period of ~5 years. Solid tumors have a latency period of ~20 to 30 years.
- Total cancer risk for whole body irradiation is one death per $10^4$ individuals exposed to 1 rem.
Radiation impact on bone marrow

100 rad = 1 Gy ≈ 1 Sv

Radiation >2 Gy suppresses normal bone marrow functions and causes long term mutation of red or white blood cells

![Graph showing linear decrease with distance and logarithmic increase with dose.]

- Linear decrease with distance!
- Logarithmic increase with dose

- Number of mutant red blood cells per million vs. bone marrow dose in sieverts
- Dose vs. mortality rate (%)

- Mutation vs. bone marrow dose
- Mortality vs. bone marrow dose

Bone marrow dose versus distance from hypocenter in the Hiroshima survey group.

Percent mortality versus bone marrow dose in the Hiroshima survey.
Hemogram

blood impact of 300 rad exposure
Leukemia

When leukemia develops, the body produces large numbers of abnormal blood cells. In most types of leukemia, the abnormal cells are white blood cells.

An increase in the number of leukemia cases was first noted in the late 1940s. As of 1990, there were 176 leukemia deaths among 50,113 survivors with significant exposures (>0.5Gy). It is estimated that about 90 of these deaths are associated with radiation exposure.

Leukemia Latency and Time at Risk Periods
Leukemia – case of Sadako
Long range genetic effects

Chromosomes observed during cell division. Abnormal ones are marked by grey arrow.

Observed increase with dose indicates long term genetic effects.
Welcome to the Individual Dose & Risk Calculator for the Nevada test side fall out: $^{131}I$ exposure.

http://ntsi131.nci.nih.gov/