Radiation Effects of a Nuclear Bomb

Beside shock, blast, and heat a nuclear bomb generates high intensity flux of radiation in form of $\gamma$-rays, x-rays, and neutrons as well as large abundances of short and long-lived radioactive nuclei which contaminate the entire area of the explosion and is distributed by atmospheric winds worldwide.

$T_{1/2} = 5730\text{y}$

Effective half-life $\sim 5-10\text{ y}$ (photosynthesis)
$^{14}\text{C}$ distribution

+ nuclear test related $^{14}\text{C}$ production

Cosmic ray produced neutrons

$^{14}\text{N} \rightarrow ^{14}\text{C} + ^{14}\text{P}$

[7.5 kg $^{14}\text{C}$ created in the atmosphere per annum]

$^{14}\text{C} \rightarrow ^{14}\text{N} + \text{B-}$
The units rad (rem) are a measure of radiation exposure!
Monitoring radiation intensity

Classical Unit: 1 Curie [Ci] \[ 1 \text{[Ci]} = \frac{dN}{dt} = 3.7 \times 10^{10} \text{[decays/s]} \]

Modern Unit: 1 Becquerel [Bq] \[ 1 \text{[Bq]} = \frac{dN}{dt} = 1 \text{[decay/s]} \]

The so-called dosimetry units (rad, rem) determine the amount of damage radioactive radiation can do to the human body. They depend on the kind and nature of the incident radiation (X-rays, \(\gamma\)-rays, \(\alpha\)-particles, \(\beta\)-particle, or neutrons). It also depends on the energy loss of the particular radiation and the associated ionisation effects in the human body material.
Radiation Detection
Radiation Exposure & Dosimetry

Dose: \[ D = \frac{E}{m} \]

Amount of energy \( E \) deposited by radiation into body part of mass \( m \).

unit Rad or Gray

Equivalent Dose: \[ H = Q \cdot D \]

Radiation independent dose \( Q \) is normalization factor which accesses the individual body damage done by the particular kind of radiation

Unit Rem or Sievert

- Photons: \( Q=1 \)
- Neutrons: \( E<10\text{keV} \quad Q=5 \)
- Neutrons: \( E>10\text{keV} \quad Q=15 \)
- Protons: \( Q=5 \)
- Alphas: \( Q=20 \)
UNITS OF RADIATION MEASUREMENT

Dosage units:

The Sievert (Gray) is a measure of biological effect.

1 Gray (Gy) = 1 Joule/kg (Energy/mass)

1 Sievert (Sv) = Gray x Q, where Q is a "quality factor" based on the type of particle.

- Q for electrons, positrons, and x-rays = 1
- Q = 3 to 10 for neutrons, protons dependent upon the energy transferred by these heavier particles.
- Q = 20 for alpha particles and fission fragments.

Converting older units:

- 1 rad = 1 centigray = 10 milligrays (1 rad = 1cGy = 10 mGy)
- 1 rem = 1 centisievert = 10 millisieverts (1 rem = 1cSv = 10 mSv)

Nominal background radiation absorbed dose of 100 mrad/year = 1 mGy/yr.
Nominal background radiation dose biological equivalent of 100 mrem/year = 1 mSv/yr.
Occupational whole body limit is 5 rem/yr = 50 mSv/yr.
2.5 mrem/hr or 25 uSv/hr is maximum average working level in industry.

Exposure rate from Naturally Occurring Radioactive Material; an empirically derived conversion factor for Ra-226 decay series: 1.82 microR/hour = 1 picoCurie/gram.
Exposure to Natural and Man-made Radioactivity

Total average annual dose:
H ≈ 250-300 mrem

Tobacco contains $\alpha$-emitter $^{210}$Po with $T_{1/2}=138.4$ days. Through absorption in the bronchial system smoking adds 280 mrem/year to the annual dose of US population.

Average annual dose from nuclear bomb test fallout $H_{fo} \approx 0.06$ mrem.
Sources of Natural and Radioactivity
Cosmic Ray Bombardment

Cosmic Rays origin from:
- solar flares;
- distant supernovae;

Spectrum of CR

Fluxes of Cosmic Rays

Low energy CR

High energy CR
Cosmic Rays in High Altitude

Earth is relatively protected from cosmic rays through atmosphere shield; typical exposure is H=3.2 mrem/h. Mountain climbers and airline crews and passengers are exposed to higher doses of radiation. Dose doubles every 1500 m in height. At 10 km height dose is about 100 times sea-level dose H=0.32mrem/h.

$$D(h_n=n \cdot 1500m) = 2^n \cdot D(h_0=1500m)$$

Example: Total dose H:
• after 10h of flight:
  H=3.2 mrem,
• for round trip:
  H=6.4 mrem
• Frequent flyer with about 10 transatlantic flights/year
  H=64 mrem/year.

Compare to natural dose (~200 mrem/y)!
Observable Effects!

Wife’s ring with ground level dose!

Husband’s ring with transatlantic high altitude dose ⇝ 8 times more dose

Au $\gamma$-activity
Natural Radioactivity in the US

Uranium Concentrations

Long lived $^{40}$K Radioactivity

$^{40}$K has a half-life of $T_{1/2}=1.28 \cdot 10^9$ years.
its natural abundance is 0.021 %.

Potassium decay to Argon
On average, 0.27% of the mass of the human body is potassium K of which 0.021% is radioactive $^{40}\text{K}$ with a half-life of $T_{1/2}=1.25\cdot10^9$ [y]. Each decay releases an average of $E_{avg}=0.5$ MeV $\beta$- and $\gamma$-radiation, which is mostly absorbed by the body but a small fraction escapes the body.

Calculate, how many radioactive $^{40}\text{K}$ atoms are in your body system!
**Some Mass and Number Considerations**

* mass of the body: \( m_{\text{body}} \)

* mass of potassium K in the body: \( m_K = 0.0027 \cdot m_{\text{body}} \)

* mass of radioactive \(^{40}\text{K}\) in the body: \( m_{^{40}\text{K}} = 0.00021 \cdot m_K = 5.67 \cdot 10^{-7} \cdot m_{\text{body}} \)

\[ 40 \text{g of } ^{40}\text{K} \equiv 6.023 \cdot 10^{23} \text{ atoms} \]

\[ m_{^{40}\text{K}} = 5.67 \cdot 10^{-7} \cdot m_{\text{body}} [g] = \frac{6.023 \cdot 10^{23} \cdot 5.67 \cdot 10^{-7} \cdot m_{\text{body}}}{40} [\text{particles}] = N_{^{40}\text{K}} \]

\[ \frac{N_{^{40}\text{K}}}{m_{\text{body}}} = 8.54 \cdot 10^{15} \text{ [particles / g]} \]

to calculate \( N_{^{40}\text{K}} \), you need the body mass \( m_{\text{body}} \) in gramm.

for 80 kg body: \( N_{^{40}\text{K}} = 6.83 \cdot 10^{20} \text{ [particles]} \)
Example: \(^{40}\text{K}\)

Calculate the absorbed body dose over an average human lifetime of \(t = 70\ \text{y}\) for this source of internal exposure.

\[
D = \frac{E_{\text{absorbed}}}{m_{\text{body}}} = t \cdot A\left(^{40}\text{K}\right) \cdot \frac{E_{\text{avg}}}{m_{\text{body}}}
\]

\[
A\left(^{40}\text{K}\right) = \lambda \cdot N_{^{40}\text{K}} = \ln \frac{2}{T_{1/2}} \cdot N_{^{40}\text{K}}
\]

\[
D = 70\ [\text{y}] \cdot \frac{\ln 2}{1.25 \cdot 10^9 \ [\text{y}]} \cdot (8.54 \cdot 10^{15} \ [\text{g}^{-1}] \cdot m_{\text{body}}) \cdot \frac{0.5 \ [\text{MeV}]}{m_{\text{body}}}
\]

\[
D = 1.66 \cdot 10^{11} \ [\text{MeV/kg}] = 2.63 \cdot 10^{-2} \ [\text{J/kg}] = 2.63 \cdot 10^{-2} \ [\text{Gy}] = 2.63 \ [\text{rad}]
\]

with: \(1\ [\text{eV}] = 1.602 \cdot 10^{-19} \ [\text{J}]\)
Radon is a radioactive inert gas.

Radon progenies build up in confined space – are breathed in, stick to surface of airways and emit α-particles.

Basal cells in bronchial epithelium are believed to be target cells for cancer.
### Annual Average Total Effective Dose Equivalent to the U.S. Population

<table>
<thead>
<tr>
<th>Source</th>
<th>Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Background, Radon</td>
<td>200 mrems</td>
</tr>
<tr>
<td>Cosmic and Terrestrial source</td>
<td>56</td>
</tr>
<tr>
<td>Medical and Dental X-Rays</td>
<td>54</td>
</tr>
<tr>
<td>Internal Source, $^{40}$K</td>
<td>40</td>
</tr>
<tr>
<td>Tobacco Smoking</td>
<td>280</td>
</tr>
<tr>
<td>Other Consumer Products</td>
<td>10</td>
</tr>
<tr>
<td><strong>Total, All Population</strong></td>
<td>640</td>
</tr>
<tr>
<td><strong>Total, Non-Smokers</strong></td>
<td>360</td>
</tr>
</tbody>
</table>
### Comparing the Risks: Radiation, Smoking, and Driving

A full set of dental X-rays using a high energy X-ray machine and E-speed film has a relative cancer risk equivalent to that of smoking ~2-3 cigarettes.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Dose</th>
<th>Chance of Death</th>
<th>Equivalent to</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone Marrow</td>
<td>From Leukemia</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{131}$I treatments for thyrotoxicosis</td>
<td>15 rem</td>
<td>$3 \times 10^{-4}$</td>
<td>2200</td>
</tr>
<tr>
<td>Chest radiograph</td>
<td>10 mrem</td>
<td>$2 \times 10^{-7}$</td>
<td>1.5</td>
</tr>
<tr>
<td>Skull examination</td>
<td>78 mrem</td>
<td>$1.6 \times 10^{-6}$</td>
<td>11.4</td>
</tr>
<tr>
<td>Barium enema</td>
<td>875 mrem</td>
<td>$17.5 \times 10^{-6}$</td>
<td>128</td>
</tr>
</tbody>
</table>
Release of Radiation by Nuclear Bomb

Nuclear bomb causes sudden release of a high flux on:

- **γ-rays** $E=\hbar\nu \approx 1-10$ MeV electromagnetic waves
- **x-rays** $E=\hbar\nu \approx 1-100$ keV electromagnetic waves
- **α-radiation** $^4\text{He}$ nuclei
- **β-radiation** electrons and positrons
- **neutrons** neutrons
- **heavy radioactive species** (cause for delayed radiation)

The prompt radiation is absorbed in the surrounding atmosphere according to exponential absorption law

$$I(d) = I_0 \cdot e^{-\mu \cdot d}$$

$I_0$ is the initial intensity and $\mu$ is the attenuation coefficient determined by the interaction probability of radiation with molecules and atoms in air.
Hiroshima radiation spread data

Primary $\gamma$ ray originated low dose of $<100$ rad near the hypocenter, secondary $\gamma$-ray originated dose of $>100$ rad within 1500 m radius.

*Keima* versus distance for the various components of the radiation in Hiroshima (data from Kerr et al.\textsuperscript{10}). Doses are in grays ($1$ Gy = 100 rad).
Absorption probability

Attenuation coefficient $\mu$ depends on energy and nature of particle, medium, and interaction probability. High Coulomb scattering probability for charged particles, causes high absorption probability, results in short range!

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Range ($\alpha$) (cm)</th>
<th>Range ($\beta$) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.01</td>
<td>0.2</td>
</tr>
<tr>
<td>100</td>
<td>0.10</td>
<td>16.0</td>
</tr>
<tr>
<td>1000</td>
<td>0.50</td>
<td>330.0</td>
</tr>
<tr>
<td>10000</td>
<td>10.50</td>
<td>4100.0</td>
</tr>
</tbody>
</table>

Main component gammas & neutrons

1 m Concrete
Neutrons originated secondary $\gamma$ radiation by inelastic neutron scattering as well as by neutron capture on nitrogen isotopes in the surrounding air. Secondary $\gamma$-production enhances radiation flux and radiation extension.

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.
Fission products

Production of neutron-rich radioactive isotopes in the mass 80-130 range which decay by $\beta^-$ decay or by $\beta^-$ delayed neutron emission. Back to stable isotopes. Decay time scale depends on the associated half-lives which determine the flux and time scale for delayed radiation exposure.

e.g. $^{126}\text{Ag}(\beta^-, n)^{125}\text{Cd}$ vs $^{126}\text{Ag}(\beta^-)^{126}\text{Cd}$
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 7·7 hours (49 hours, approx. 2 days), the level drops again by 90%. After 7·2 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.

\[ A_{t_n = 7^n \cdot t_0} = 10^{-n} A_{t_0} \]
<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>Tritiu$m$</td>
<td>12.3 y</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>Carbon-14</td>
<td>5730 y</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Manganese-54</td>
<td>313 d</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Strontiu$m$-89</td>
<td>52 d</td>
<td>0.001</td>
<td>0.03</td>
<td>0.0009</td>
<td>0.2</td>
</tr>
<tr>
<td>Strontiu$m$-90</td>
<td>28.5 y</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Zirconium/Niobium-95</td>
<td>64 d</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Zirconium/Niobium-97</td>
<td>17 h</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Rutheni$m$um-103</td>
<td>39 d</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Rutheni$m$um-106</td>
<td>368 d</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Antimi$m$num-125</td>
<td>2.7 y</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Iodine-131</td>
<td>8 d</td>
<td>5</td>
<td>0.001</td>
<td>0.001</td>
<td>0.4</td>
</tr>
<tr>
<td>Tellurium/Iodine-132</td>
<td>3.3 d</td>
<td>0.1</td>
<td>0.06</td>
<td>0.001</td>
<td>[2]</td>
</tr>
<tr>
<td>Iodine-133</td>
<td>0.9 d</td>
<td>0.02</td>
<td>0.04</td>
<td>0.001</td>
<td>0.0009</td>
</tr>
<tr>
<td>Cesium-136</td>
<td>13 d</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.3</td>
</tr>
<tr>
<td>Cesium-137</td>
<td>30 y</td>
<td>0.01</td>
<td>0.009</td>
<td>0.009</td>
<td>0.1</td>
</tr>
<tr>
<td>Barium/Lanthanum-140</td>
<td>13 d</td>
<td>0.2</td>
<td>0.006</td>
<td>0.006</td>
<td>0.1</td>
</tr>
<tr>
<td>Ceriu$m$um-144</td>
<td>284 d</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Neptuni$m$um-239</td>
<td>2.4 d</td>
<td>0.5</td>
<td>0.1</td>
<td>0.7</td>
<td>0.7</td>
</tr>
</tbody>
</table>

\(^{a}\) 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.
Dose received from bomb tests

Welcome to the Individual Dose & Risk Calculator for the Nevada test side fall out: $^{131}$I exposure

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