Relative abundances of carbon isotopes in our atmosphere are:
- C-12 (stable) - C-13 (stable)
- C-14 (radioactive) 0.0000000001%

The C-14 is incorporated into compounds such as CO₂. This gets photosynthesized into plant material, then eaten by animals. The C-14 is constantly decaying by beta emission.

An equilibrium is established as long as the plant or animal ________
(The C-14 is being replaced at the same rate it is going away.)

After death: C-14 levels drop.

**LP#11.** If live plant material has C-14 at a level that generates 15.3 dpm (per g C)
How old is an artifact if the measured activity of C-14 is 11.8 dpm?
The half-life of C-14 is 5715 yrs.

Problems asking for the amount of time are better solved with the form of the equation: \[ \ln \left( \frac{\text{rate}_t}{\text{rate}_0} \right) = -kt \]

Rearranging, \[ t = \frac{\ln (\text{rate}/\text{rate}_0)}{-k} \]

Limitations:

**Good for > ______________**
(less and we don’t see enough of a change)

**Good for < ______________**
(more and there isn’t enough C-14 left to measure accurately)
- Assumes baseline C-14 levels have been constant for all time.
- WWII and above ground atomic bomb testing actually changed current baseline!
**Dating Older Items**
Several techniques exist.
One of the most dependable relies on the decomposition of U-238 to Pb 206 in volcanic rock.
There are many decay steps involved, but the overall half-life is $4.5 \times 10^9$ years.
It assumes that there was no Pb-206 in the rock at the time it formed.
All of the Pb was originally U at time=0
So the starting amount of **MOLES** of U would be the sum of the current **MOLES** of Pb & U currently present.

**LP#12.** A meteor contains 0.556 g of Pb-206 to every 1.00g U-238. Determine the age of the meteor.

Step 1: Calculate the moles of each nuclide present.

Step 2: Calculate the total amount of U-238 present at time=0.

Step 3: Calculate fraction remaining.

Step 4: Calculate the rate constant for the decay process.

Step 5: Plug into $t = \frac{\ln (N_t/N_0)}{-k}$
7. Nuclear Energy Reactions

Mass/Energy Relationships

**Law of Conservation of Mass Plus Energy**

In nuclear reactions, we must combine the laws of conservation of mass and energy.

**Conversion Between Mass and Energy**

\[ E = mc^2 \]

energy (J) \quad mass (kg) \quad (speed of light = 2.998 \times 10^8 \text{ m/s})

Very small amounts of mass convert to very large amounts of energy.

**Atomic Mass Units**

1 amu = 1/12 the mass of one C-12 atom

1 amu = 1.66054 \times 10^{-24} \text{ g}

\[ 6.02214 \times 10^{23} \text{ amu} = 1 \text{g} \]

**Rest Mass of Particles**

<table>
<thead>
<tr>
<th>Particle</th>
<th>amu/atom OR g/mol</th>
<th>amu/atom OR g/mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron</td>
<td>5.486 \times 10^{-4}</td>
<td>p + e-</td>
</tr>
<tr>
<td>proton</td>
<td>1.00728</td>
<td></td>
</tr>
<tr>
<td>neutron</td>
<td>1.00866</td>
<td></td>
</tr>
</tbody>
</table>

**Binding Energy**

- The energy that holds nucleons together
- The higher the binding energy,

**Mass defect** - the loss in mass (that is converted to energy) that occurs when protons and neutrons combine to form a nucleus.

1. Lost mass is converted into energy.
   **Binding Energy** is usually expressed on a __________
   using the electron volts as the energy unit
   (1 eV = 1.60 \times 10^{-19} \text{ J}) OR (1 \text{ MeV} = 1.60 \times 10^{-13} \text{ J})
EXAMPLE: (shortened process)
Calculate the nuclear binding energy in MeV/nucleon for $^{194}_{77}$Ir, atomic mass = 193.965 0784 amu.

(Mass of $e^- + p = 1.00783$ amu; $n = 1.00866$ amu)

SOLUTION: First calculate the total mass of the individual particles

\[
\begin{align*}
\text{Mass of 77 (p) + (e^-)} &= \\
\text{Mass of 117 (n)} &= \\
\hline
\text{Mass of individual particles combined} &= \\
\end{align*}
\]

Next, solve for the mass defect by subtracting the mass of the $^{194}$Ir nucleus from the rest mass of the individual free particles.

\[
\text{Mass defect} = \text{mass of particles} - \text{mass of atom}
\]

We could use Einstein’s $E=mc^2$ to calculate the energy associated with this mass (converted to kg).

OR

We can use the convenient factor that 1 amu = 931.5 MeV

We now convert to MeV/nucleon
**Fission & Fusion**

The greater the binding energy/nucleon the more ___________ the nucleus.

The most stable nucleus is __________

1. Heavy nuclei - gain stability and release energy if they fragment to yield mid-mass elements.
2. Light nuclei can gain stability and release energy if they fuse together.

**Fission**

The fragmentation of heavy nuclei.

1. Nuclei break into fragments when struck by neutrons.
2. Doesn't occur in exactly the same way each time.
3. Uranium-235 - more than 100 different fission pathways.
   
   a. One frequently occurring pathway is
   
   b. three neutrons released induce nine more fissions → 27 neutrons
**Chain Reactions**

- a reaction that continues to occur even if the supply of neutrons from outside is cut off
- a sufficient amount of radioactive nuclide that allows the chain reaction to become self-sustaining

**Limitations:**

*Small sample size* - many of the neutrons escape before initiating additional fission events

*The density of particle packing* affects amount needed to achieve critical mass

*Container material* (if it reflects some neutrons back inward, it reduces amount necessary to reach critical mass.)

Enormous amounts of heat are generated during nuclear fission.

a. Fission of 1.0g of U-235 can produce...

b. Some countries generate as much as of their power through nuclear fission

c. Products of fission reaction are themselves still radioactive with very long half-lives.

**LP#13.** According to the following reaction, what other isotope besides tellurium-137 is produced by nuclear fission of uranium-235

\[
\frac{238}{92}U + \frac{1}{0}n \rightarrow \frac{137}{52}Te + 2\frac{1}{0}n + ?
\]
Uses of Fission Technology

Nuclear Reactors

Fuel: U-238 enriched with 3%

The concentration of U-235 is too low to go supercritical.
Fuel is in the form of UO$_2$ encased in Zr or steel rods

Heat from the decay reaction is used to heat water to steam to drive turbines.
Steam must be cooled before being released, so usually located

Control rods: made of Cd or B are used to slow down the reaction because they can

Nuclear Reactor Schematic

Heat produced in the reactor core is transferred by coolant circulating in a closed loop to a steam generator.

The steam then drives a turbine To generate electricity
**Atomic Bomb**

Subcritical uranium-235 masses

Chemical explosive

---

**Nuclear Fusion**

The joining together of light nuclei.

1. Release enormous amounts of energy.

2. This is how the sun produces energy.

   The sun contains 73% H, and 26% He, 10% of other

   \[ ^{1}\text{H} + ^{1}\text{H} \rightarrow ^{2}\text{H} + ^{0}\text{e} \]

   \[ ^{1}\text{H} + ^{2}\text{H} \rightarrow ^{3}_{2}\text{He} \]

   \[ ^{3}_{2}\text{He} + ^{3}_{2}\text{He} \rightarrow ^{4}_{2}\text{He} + ^{2}_{1}\text{H} \]

   \[ ^{3}_{2}\text{He} + ^{1}_{1}\text{H} \rightarrow ^{4}_{2}\text{He} + ^{0}_{1}\text{e} \]

3. Fusion of hydrogen nuclei - a potential power source.
   
   a. hydrogen isotopes are cheap and plentiful
   
   b. fusion products are non-radioactive and nonpolluting (helium)
4. Technical problems to achieving a practical and controllable fusion.
   a. to initiate the process,

   Hence the name

   b. What type of container do you do it in?

We have not yet overcome these limitations to put fusion technology to work on the positive front.
Unfortunately, we have overcome the limitations on the military front.

This is the technology of the ___________________________________________________________________

Where does the required temperature of reaction come from?
Fusion Bomb Design

- High-Explosive lenses
- Uranium-238 (tamper)
- Vacuum ("levitation")
- Tritium gas ("boosting")
- Plutonium/ Uranium-235 (hollow core)
- Polystyrene foam
- Uranium-238 (tamper)
- Lithium-6 deuteride (fusion fuel)
- Plutonium (sparkplug)
- Reflective casing
The very first test of a fusion H-bomb was known as ___________________________ in ___________________________.

The largest H-bomb ever detonated was the ___________________________ in ___________________________ by the Soviet Union.

As of Jan 2014

<table>
<thead>
<tr>
<th>Country</th>
<th>Date of First Test</th>
<th>Date of Last Test</th>
<th>Number of Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>1945</td>
<td>1992</td>
<td>1,032</td>
</tr>
<tr>
<td>Soviet Union (Russia)</td>
<td>1949</td>
<td>1990</td>
<td>715</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>1952</td>
<td>1991</td>
<td>45</td>
</tr>
<tr>
<td>France</td>
<td>1960</td>
<td>1996</td>
<td>210</td>
</tr>
<tr>
<td>China</td>
<td>1964</td>
<td>1996</td>
<td>45</td>
</tr>
<tr>
<td>India</td>
<td>1974 (1)</td>
<td>1998 (2)</td>
<td>3</td>
</tr>
<tr>
<td>Pakistan</td>
<td>1998</td>
<td>1998</td>
<td>2</td>
</tr>
<tr>
<td>North Korea</td>
<td>2006 and 2009</td>
<td>2013</td>
<td>3</td>
</tr>
<tr>
<td>Israel</td>
<td>1979?</td>
<td>1979?</td>
<td>Maybe 1?</td>
</tr>
<tr>
<td>South Africa</td>
<td>1979?</td>
<td>1979?</td>
<td>Maybe 1?</td>
</tr>
</tbody>
</table>

Since then 2 more in 2016 and 1 in 2017 by North Korea.
1963 Partial Nuclear Test Ban Treaty prohibited ________________
France & China did not sign initially

1996 Comprehensive Nuclear Test Ban Treaty prohibits ________________
China, Egypt, Iran, Israel, & USA have signed but not ratified the treaty.
India, North Korea, & Pakistan have not even signed it yet.

**Units of Measure for Ionizing Radiation**

Depend on what is being measured.

**Decay Events / Decay Rate**

1. **Becquerel (Bq)** - 1 Bq = 1 disintegration/s
2. **Curie (Ci)** - 1 Ci = $3.7 	imes 10^{10}$ disintegrations/s
   (This is the decay rate for 1 g of radium.)

**Energy Absorbed**

1. **Gray (Gy)** - SI unit measures the amount of energy absorbed per kilogram of tissue exposed to a radiation source.
   
   $1 \text{ Gy} = 1 \text{ J/kg}$

2. **Rad** - (radiation absorbed dose) measures energy absorbed per gram of tissue exposed to a radiation source.

   $1 \text{ Rad} = 1 \times 10^{-5} \text{ J/g}$  \( 100 \text{ Rad} = 1 \text{ Gy} \)

**Ionizing Intensity**

1. **Roentgen** - is a unit for measuring ionizing radiation intensity. It measures the capacity of radiation to affect matter in general.

**Tissue Damage**

1. **Rem** - (roentgen equivalent for man) measures the amount of tissue damage caused by radiation. It takes into account the differences in biological effects for different types of radiation

   a. $.1 \text{ Rem} =$ the amount of radiation that produces the same effect as 1 rad of x-rays.
   
   b. $(\text{dose in rads}) \times (\text{biological effectiveness factor}) = \text{dose in rems}$

---

**Sources of Exposure to Radiation**

<table>
<thead>
<tr>
<th>Source</th>
<th>Average annual exposure (mrem)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radation</td>
<td>296 mrem (22%)</td>
</tr>
<tr>
<td>Cosmic Rays</td>
<td>96 mrem (7%)</td>
</tr>
<tr>
<td>Background</td>
<td>39 mrem (11%)</td>
</tr>
<tr>
<td>Medical X-rays</td>
<td>60 mrem (11%)</td>
</tr>
<tr>
<td>Nuclear Medicine</td>
<td>14 mrem (4%)</td>
</tr>
<tr>
<td>Consumer Products</td>
<td>11 mrem (3%)</td>
</tr>
</tbody>
</table>

---

20 - 27
Estimate Your Personal Annual Radiation Dose

We live in a radioactive world – humans always have. Radiation is part of our natural environment. We are exposed to radiation from materials in the earth itself, from naturally occurring radon in the air, from outer space, and from inside our own bodies (as a result of the food and water we consume). This radiation is measured in units called millirems (mrems). The average dose per person from all sources is about 620 mrems per year. It is not, however, uncommon for any of us to receive less or more than that in a given year (largely due to medical procedures we may undergo). Standards allow exposure to as much as 5,000 mrems in a year for those who work with and around radioactive material. 1

<table>
<thead>
<tr>
<th>Factors</th>
<th>Common Sources of Radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Where You Live</td>
<td></td>
</tr>
<tr>
<td>Cosmic Radiation (from outer space)</td>
<td></td>
</tr>
<tr>
<td>Exposure depends on your elevation (how much air is above you to block radiation)</td>
<td></td>
</tr>
<tr>
<td>Amounts are listed in mrem (per year)</td>
<td></td>
</tr>
<tr>
<td>At sea level</td>
<td>26 mrem</td>
</tr>
<tr>
<td>0 – 1000 ft</td>
<td>28 mrem</td>
</tr>
<tr>
<td>1 – 2000 ft</td>
<td>31 mrem</td>
</tr>
<tr>
<td>2 - 3000 ft</td>
<td>35 mrem</td>
</tr>
<tr>
<td>3 – 4000 ft</td>
<td>41 mrem</td>
</tr>
<tr>
<td>4 – 5000 ft</td>
<td>47 mrem</td>
</tr>
<tr>
<td>5 – 6000 ft</td>
<td>52 mrem</td>
</tr>
<tr>
<td>[Elevation of cities (in feet); Atlanta 1050; Chicago 595; Dallas 435; Denver 5280; Las Vegas 2000, Minneapolis 815; Pittsburgh 1200; St Louis 455; Spokane 1890; Salt Lake City 4400; Sacramento 43.]</td>
<td></td>
</tr>
<tr>
<td>Terrestrial (from the ground)</td>
<td></td>
</tr>
<tr>
<td>If you live in a state that borders the Gulf or Atlantic Coasts, add 16 mrem</td>
<td></td>
</tr>
<tr>
<td>If you live in the Colorado Plateau area, add 63 mrem</td>
<td></td>
</tr>
<tr>
<td>If you live anywhere else in the continental US, add 30 mrem</td>
<td></td>
</tr>
<tr>
<td>House Construction</td>
<td></td>
</tr>
<tr>
<td>If you live in a stone, adobe, brick, or concrete building, add 7 mrem</td>
<td></td>
</tr>
<tr>
<td>Power Plants</td>
<td></td>
</tr>
<tr>
<td>If you live within 50 miles of a nuclear power plant, add 0.01 mrem</td>
<td></td>
</tr>
<tr>
<td>If you live within 50 miles of a coal-fired power plant, add 0.03 mrem</td>
<td></td>
</tr>
<tr>
<td>Food, Water, Air</td>
<td></td>
</tr>
<tr>
<td>Internal Radiation²</td>
<td></td>
</tr>
<tr>
<td>From food (Carbon-14 and Potassium-40) &amp; water (radon dissolved in water)</td>
<td>40 mrem</td>
</tr>
<tr>
<td>From air (radon)</td>
<td>228 mrem</td>
</tr>
<tr>
<td>How You Live</td>
<td></td>
</tr>
<tr>
<td>Jet Plane Travel</td>
<td>0.5 mrem per hour in the air</td>
</tr>
<tr>
<td>If you have porcelain crowns or false teeth³,</td>
<td>0.07 mrem</td>
</tr>
<tr>
<td>If you go past luggage x-ray inspection at airport,</td>
<td>0.002 mrem</td>
</tr>
<tr>
<td>If you view TV or computer screen with CRT tech.⁴,</td>
<td>1 mrem</td>
</tr>
<tr>
<td>If you smoke ½ pack of cigarettes every day,</td>
<td>18 mrem</td>
</tr>
<tr>
<td>If you have a smoke detector,</td>
<td>0.008 mrem</td>
</tr>
<tr>
<td>If you use a gas camping lantern,</td>
<td>0.2 mrem</td>
</tr>
<tr>
<td>If you wear a plutonium powered pacemaker,</td>
<td>100 mrem</td>
</tr>
<tr>
<td>Medical Tests</td>
<td></td>
</tr>
<tr>
<td>Medical Diagnostic Tests –Number of millirems per procedure⁵</td>
<td></td>
</tr>
<tr>
<td>X-Rays:</td>
<td></td>
</tr>
<tr>
<td>Chest-10 mrem, Mammography (2 views)-72, Skull-10, Upper GI-600,</td>
<td></td>
</tr>
<tr>
<td>Cervical Spine-20, Lumbar Spine-600, Abdomen (kidney/bladder)-700,</td>
<td></td>
</tr>
<tr>
<td>Barium Enema-800, Pelvis-60, Hip-70, Dental Bitewing/Image-0.5,</td>
<td></td>
</tr>
<tr>
<td>Extremity (hand/foot)-0.5</td>
<td></td>
</tr>
<tr>
<td>CT Scans:</td>
<td></td>
</tr>
<tr>
<td>Head-200 mrem, Chest-700, Abdomen/Pelvis-1000, Extremity-10,</td>
<td></td>
</tr>
<tr>
<td>Angiography (heart)-2000, Angiography (head)-500, Spine-1000,</td>
<td></td>
</tr>
<tr>
<td>Whole Body-1000, Cardiac-2000</td>
<td></td>
</tr>
<tr>
<td>Tobacco Products (for each daily cigarette) 500 (bronchial epithelial dose)</td>
<td></td>
</tr>
<tr>
<td>Your Estimated Annual Radiation Dose</td>
<td></td>
</tr>
</tbody>
</table>

2. Average values.
3. Some of the radiation sources listed in this chart result in an exposure to only part of the body. For example, false teeth or crowns result in a radiation dose to the mouth. The annual dose numbers given here represent the “effective dose” to the whole body.
4. The value is less than 1, but adding a value of 1 would be reasonable.
5. Exposures for medical tests vary depending upon equipment and the patient. The doses listed are an average for an actual exposure.

Primary sources for this information are National Council on Radiation Protection and Measurements Reports: #92 Public Radiation Exposure from Nuclear Power Generation in the United States (1987); #93 Ionizing Radiation Exposure of the Population of the United States (1987); #94 Exposure of the Population in the United States and Canada from Natural Background Radiation (1987); #95 Radiation Exposure of the U.S. Population from Consumer Products and Miscellaneous Sources (1987); #100 Exposure of the U.S. Population from Diagnostic Medical Radiation (1989); and #160 Ionizing Radiation Exposure of the Population of the United States (2009).

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