CHEM 103: Chemistry in Context

Unit 3

Energy, Chemistry and Society

Unit 3.2

Alternative Energy

Reading: CC Chapters 7.4, 7.6, 4.9, 11.3, 11.9, 8.7, and G&R 7,8

Colorado State University

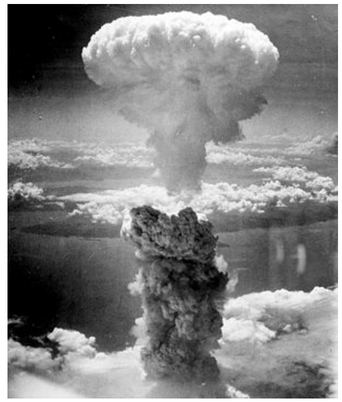
Nuclear Option

Reading: Chapter 7 (CC & G&R)
1. How nuclear reactors produce electricity

2. How fission produces energy

3. Radioactivity

4. Costs, risks and benefits of nuclear power



http://en.wikipedia.org/wiki/Nuclear_weapon

"Fat Man"
atomic bomb
20 kiloton
TNT (84 TJ)

Fukushima Dai-ichi nuclear complex, 3/15/11

http://www.cbsnews.com/2300-202_162-10007053.html

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

Byron Nuclear Power Plant (Illinois)

© Associated Press/AP

~20% of our (US) electricity comes from nuclear fission

Nuclear-Powered Electricity (Ch. 7.3)

$$\text{efficiency} = 1 - \frac{T_{low}}{T_{high}}$$

(T in Kelvin = 273 + T (deg C))

Cooling towers

Containment Structures

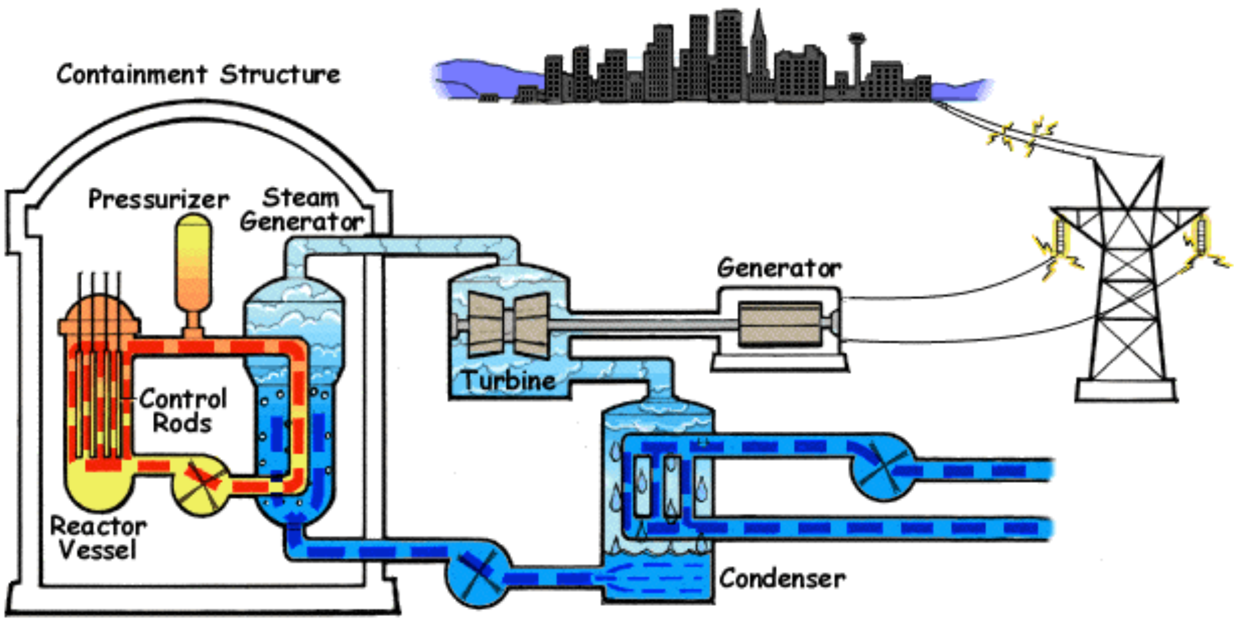
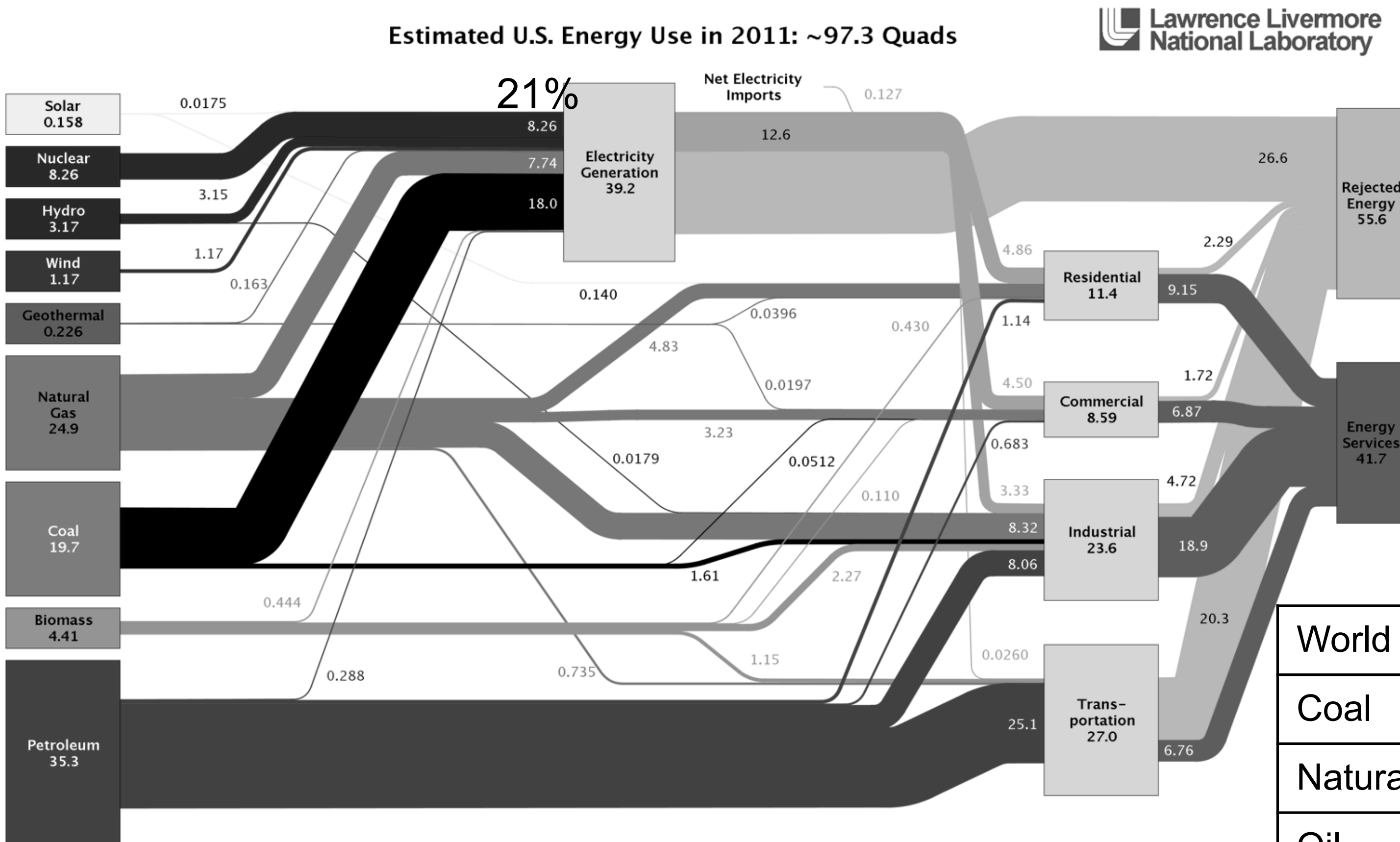


Image by US Nuclear Regulatory Commission

Figure 7.1 – Schematic of a nuclear power plant

Nuclear Energy Flows to Electricity



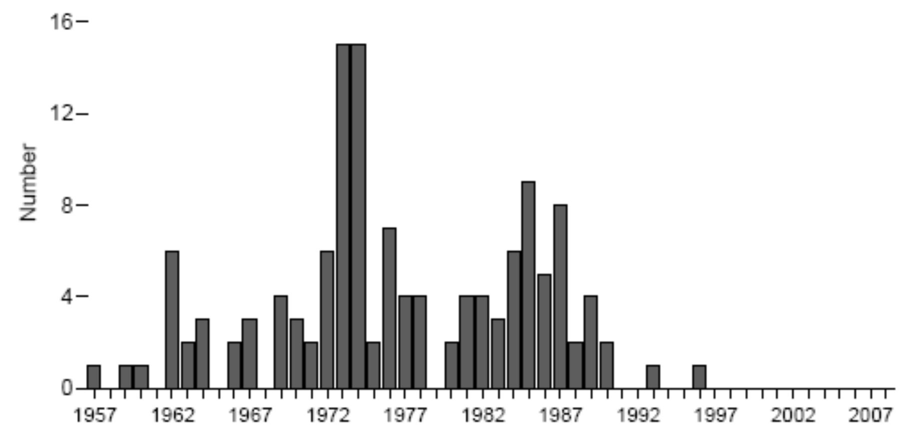
Source: LLNL 2012. Data is based on DOE/EIA-0384(2011), October, 2012. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports flows for non-thermal resources (i.e., hydro, wind and solar) in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 80% for the residential, commercial and industrial sectors, and as 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

World Reserves	
Coal	20,200 EJ
Natural Gas	7,170 EJ
Oil	10,200 EJ
US use:	
Coal	20.8 EJ
Natural Gas	26.3 EJ
Oil	37.2 EJ
Nuclear	8.7 EJ

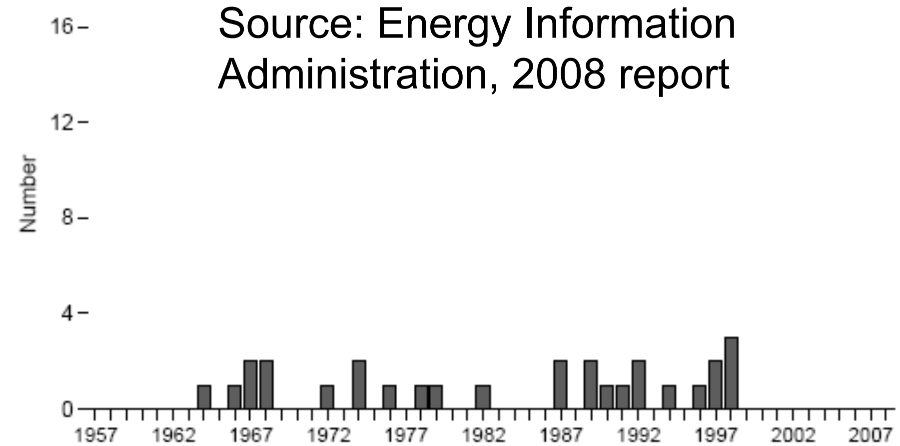
Nuclear Energy Contribution (US)

- Facts (www.nrc.gov)
  - 104 licensed nuclear power plants in US (2011)
  - ~3 EJ per year total output
  - all in the form of electricity (~1/5 of electricity used in US annually)
  - 17 applications for new power plants (2007-9)
  - 0 new applications 2010-11
  - 7 applications expected in near future (2012-6)
- Positives
  - no carbon dioxide emissions
  - can operate at any time
- Negatives
  - expensive setup
  - radioactive waste
  - security concerns
  - only produces electricity

Full-Power Operating Licenses Issued,[2] 1957-2008



Permanent Shutdowns by Year, 1957-2008



Source: Energy Information Administration, 2008 report

Note: Data are at end of year.
Source: Table 9.1.

Nuclear Power Usage Worldwide

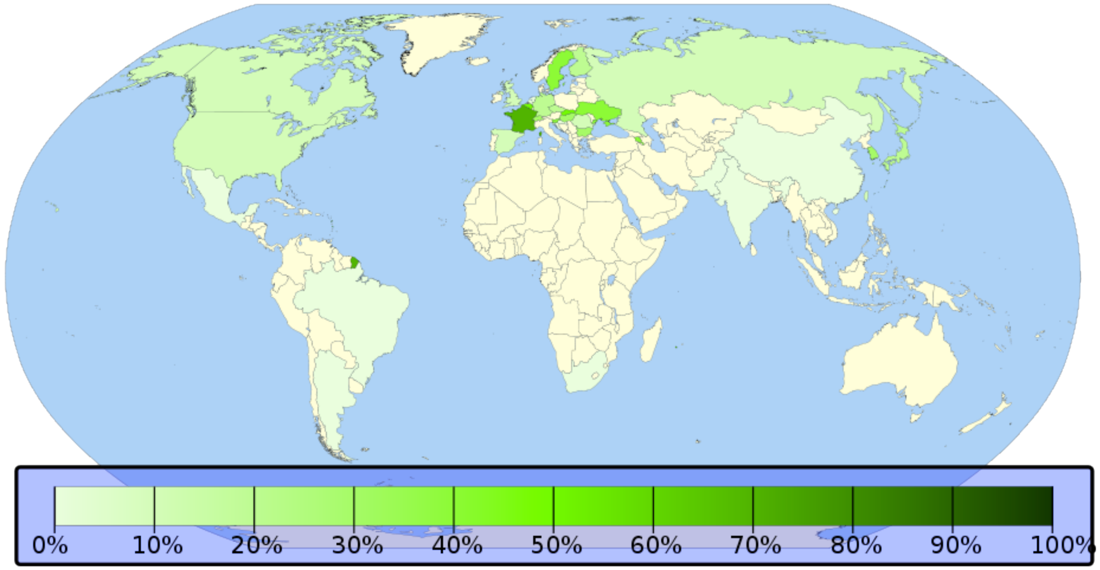


Image by NuclearVacuum/CC BY-SA 3.0

Figure 7.3 – Percentage of electricity generated by nuclear power by country

Country	% of electricity from nuclear power
France	80%
Slovakia, Belgium	
Ukraine, Hungary	50%
Sweden, Slovenia	
Switzerland, Czech Republic	30-40%
Finland, Bulgaria, South Korea.	
Japan	29% (Prior to the Fukuyama-Daichi disaster in 2011)
US	19%
Russia	18%
China	2%

Where U^{238} reserves are in US

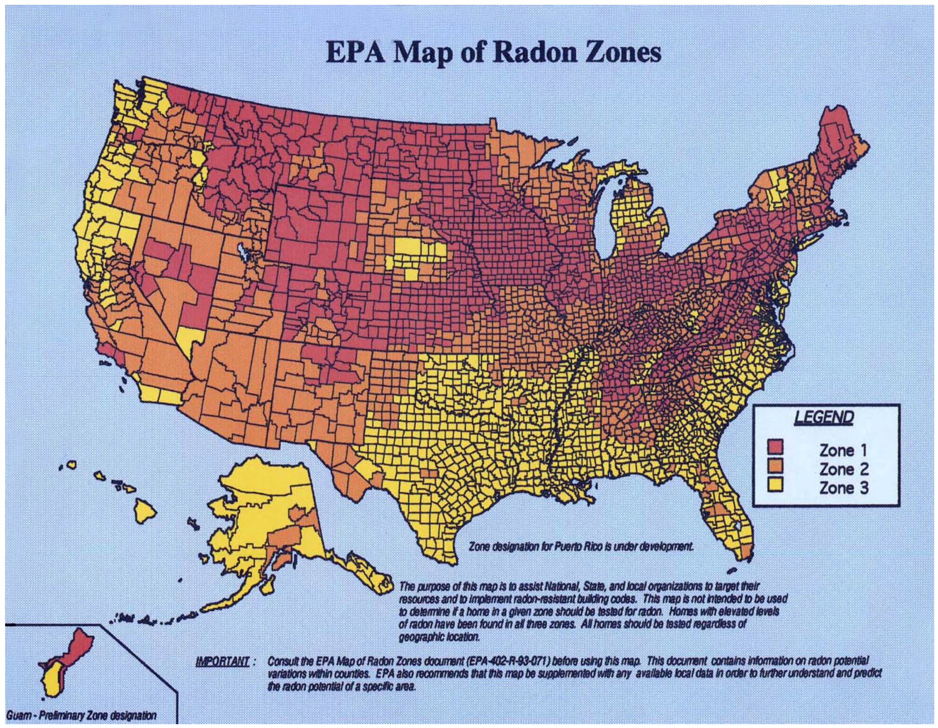


Image from US Geological Survey/EPA

Figure 7.4 – Radon levels in the United States. Zone 1 (red) indicates high levels; zone 3 (yellow), low levels. Radon levels also are an indicator of uranium.

Reducing CO_2 Emissions with Nuclear Power (?)

How many new nuclear power plants would have to be built to replace the US electricity generated by fossil fuel combustion?

In 2011, 66.4% of energy for electricity came from fossil fuels (energy flow chart)

12.6 Quad total useful electrical energy generated in 2011 = 13.3 EJ

$$0.664 \times 13.3 \text{ EJ} = 8.8 \text{ EJ}$$

Reasonable assumption: each nuclear power plant generates 1 GW of power

$$1 \text{ GW} = \frac{1 \text{ GJ}}{\text{sec}} = \frac{10^9 \text{ J}}{\text{sec}}$$

power x time = energy

$$\frac{10^9 \text{ J}}{\text{sec}} \times \frac{60 \text{ sec}}{\text{min}} \times \frac{60 \text{ min}}{\text{hr}} \times \frac{24 \text{ hr}}{\text{day}} \times \frac{365 \text{ day}}{\text{yr}} = \frac{3.154 \times 10^{16} \text{ J}}{\text{yr}}$$

~ 0.0315 EJ / year per power plant

$$8.8 \text{ EJ} \times \frac{1 \text{ power plant}}{0.0315 \text{ EJ}} = 279 \text{ NEW nuclear power plants required}$$

(We have 104 operating in the US today.)

Energy Payback for Nuclear Power (updated 2011)

Cost of nuclear power plant:
Construction \$3,500 / kW
Production: \$0.0168 / kW•hr
Decommissioning costs: \$300M up to 10% of the construction cost

1 GW PP construction cost: $\frac{\$3,500}{1\text{ kW}} \times \frac{10^6\text{ kW}}{1\text{ GW}} = \$3.5\text{x}10^9$

1 GW PP operation cost: $\frac{\$1.68\text{x}10^{-2}}{\text{kWhr}} \times \frac{10^6\text{kWhr}}{1\text{GWhr}} \times \frac{8{,}760\text{hr}}{\text{year}} = \$1.5\text{x}10^8\text{/year}$

http://nuclearinfo.net/Nuclearpower updated June 2010

Let's pretend that labor is free (it worked for the pyramids). How much **energy** is required to build and operate a nuclear power plant?

Assume construction cost is 25% energy & oil is \$100/barrel

$$0.25 \text{ x } \left(\$3.85\text{x}10^9 \text{ x } \frac{\text{barrel}}{\$100} \times \frac{6.12\text{x}10^9\text{J}}{1\text{ barrel}} \right) = 0.059 \text{ x } 10^{18}\text{ J} = 0.059\text{ EJ}$$

Assume operation cost is 25% energy & oil is \$100/barrel

$$0.25 \text{ x } \left(\$1.5\text{x}10^8 \times \frac{1\text{ barrel}}{\$100} \times \frac{6.12\text{x}10^9\text{J}}{1\text{ barrel}} \right) = 2.3 \text{ x } 10^{15}\text{ J} = 0.0023\text{ EJ (per year)}$$

Yearly production (from previous slide)

$$1\text{ GW} \times \frac{8{,}760\text{hr}}{\text{year}} \times \frac{3.6\text{x}10^6\text{J}}{1\text{ kWhr}} \times \frac{10^6\text{ kWhr}}{1\text{ GWhr}} = 3.2\text{x}10^{16}\text{ J} = 0.032\text{ EJ}$$

Net yearly production:
0.032 – 0.0023 EJ = 0.0297 EJ

~2 years of continuous operation to repay just the **energy** involved in the plant's construction

Radioactivity

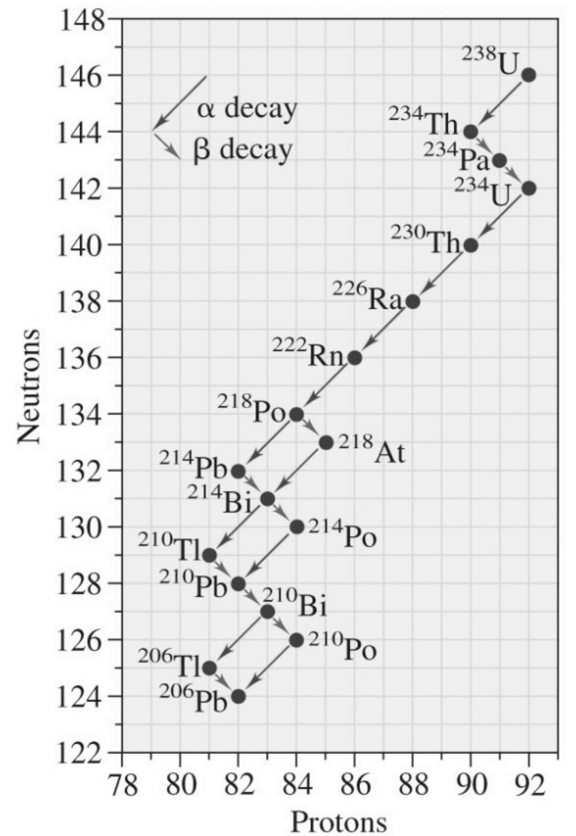
Radioactivity is the *spontaneous* emission of radiation

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

Table 7.2 Types of Nuclear Radiation

Type	Symbol	Composition	Charge	Change to the Nucleus That Emits It
Alpha	${}^{4}_{2}He$	2 protons 2 neutrons	2+	Mass number decreases by 4. Atomic number decreases by 2.
Beta	${}^{0}_{-1}e$	an electron	1−	Mass number does not change. Atomic number increases by 1.
Gamma	${}^{0}_{0}\gamma$	a photon	0	No change in either the mass number or the atomic number.

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.



$${}^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$$

$${}^{234}_{90}Th \rightarrow {}^{234}_{91}Pa + {}^{0}_{-1}e \quad \left({}^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e\right)$$

All elements with atomic # 84 & higher are radioactive

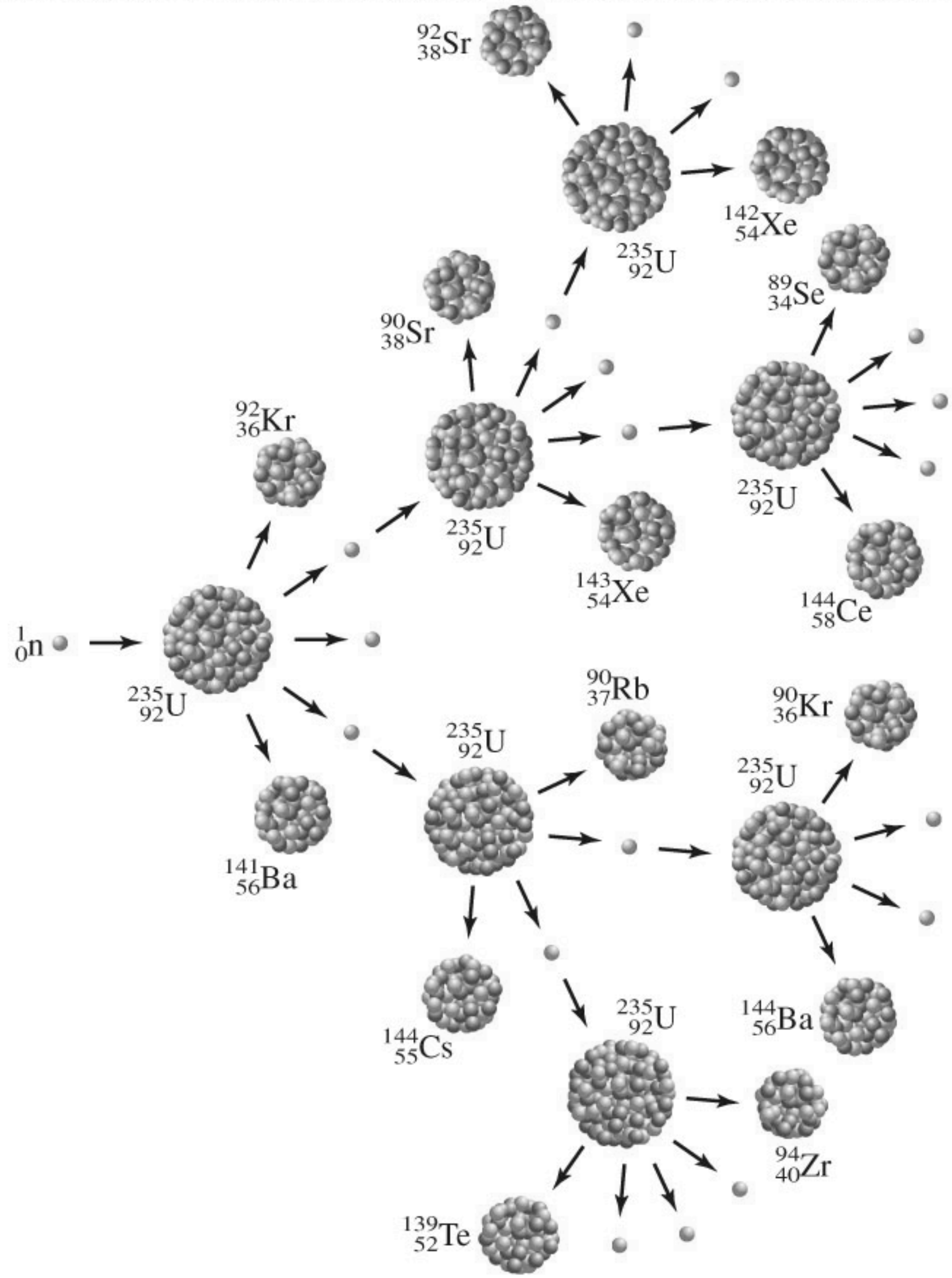
Examples of lighter radioactive isotopes: ${}^{3}_{1}H$, ${}^{14}_{6}C$, ${}^{40}_{19}K$, ${}^{98}_{43}Tc$

Chain Reaction

U-235 + 1 neutron may make several fission products…

When balancing fission reactions, make sure the mass numbers and # of protons are conserved on both sides of the equation

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.



Energy from Fission: Breaking up Nuclei

$E = mc^2$ $c = 3\text{x}10^8$ m/s ➔ $c^2 = 9\text{x}10^{16}$ m^2/s^2

$${}^{1}_{0}\text{n} + {}^{235}_{92}\text{U} \rightarrow \left[{}^{236}_{92}\text{U}\right] \rightarrow {}^{141}_{56}\text{Ba} + {}^{92}_{36}\text{Kr} + 3\,{}^{1}_{0}\text{n}$$

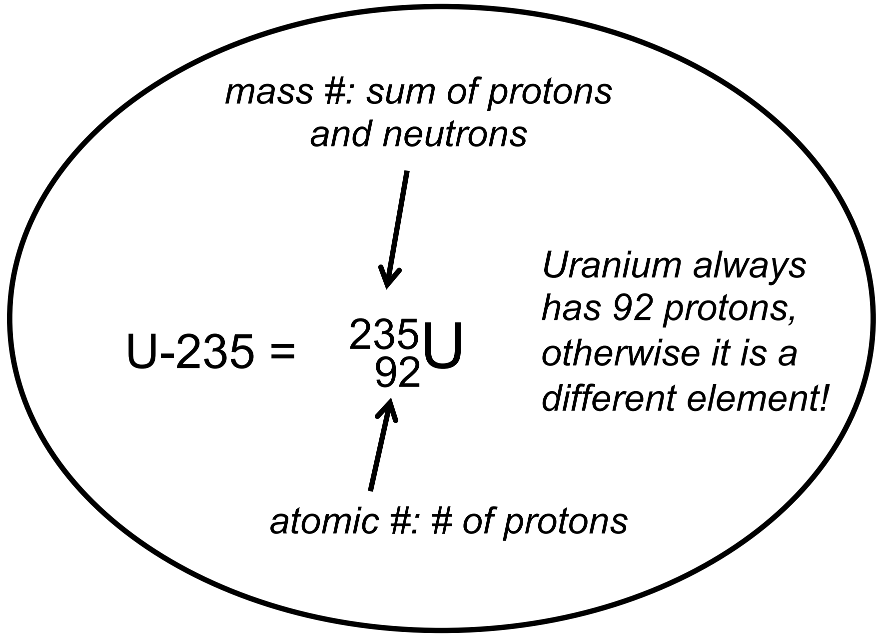
${}^{235}_{92}$U mass=235.0439299

${}^{1}_{0}$n mass=1.008665

${}^{141}_{56}$Ba mass=140.916453

${}^{92}_{36}$Kr mass=91.926156

Δmass=-0.1839909



For 1 mole of ${}^{235}_{92}$U Δmass=-0.1839909 g

$$\Delta E = \Delta mc^2 = 0.184 \times 9\text{x}10^{16}\text{g m}^2/\text{s}^2 = 1.66\text{ x}10^{16}\text{g m}^2/\text{s}^2 \quad \left(1\text{ J}=1\text{kg m}^2/\text{s}^2\right)$$

$$\text{so } \Delta E = 1.66\text{ x}10^{16}\text{g m}^2/\text{s}^2 \times \frac{1\text{ kg}}{1000\text{ g}} \times \frac{1\text{ J}}{1\text{kg m}^2/\text{s}^2} = 1.66\text{ x}10^{13}\text{ J}=1.66\text{ x}10^{10}\text{ kJ}$$

$$\text{or an energy content of } 1.66\text{ x}10^{10}\text{ kJ/mol} \times \frac{1\text{ mole}}{235.0\text{g}} = 7.1\text{x}10^{7}\text{ kJ/g}$$

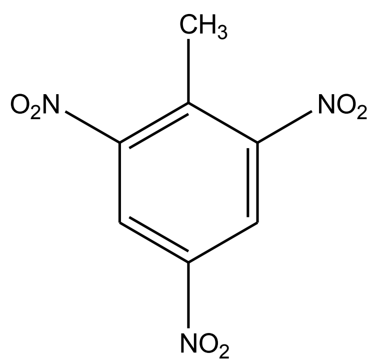
Actual: ~8.8x10^7 kJ/g

i.e. a lot of energy!

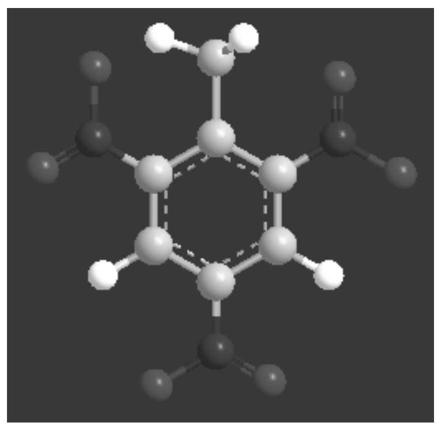
5 train cars of coal   Energy density=70.5 GJ/g (natural gas is 50 kJ/g)

Dynamite vs Fission… (Ch. 7.2)

TNT, or trinitrotoluene (discovered in 1863 by Alfred Nobel) became the standard of explosive power. The power of emerging nuclear weapons was therefore compared to TNT…



TNT



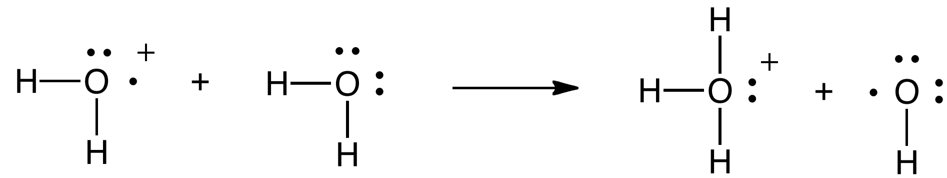
2 moles of (unstable) TNT rearrange to form 15 moles of hot gas (3 mol N_2, 7 mol CO, 5 mol H_2O) plus some carbon. **About 1 g of TNT will produce about 1 L of hot gas – a 1000 times increase in volume +4.2kJ energy.**

Fission of 1 g of U-235, where only about 0.1% of its mass is converted to energy, is equivalent to the detonation (explosive combustion) of 33 tons of TNT.

Radioactivity and You

$$H_2O \xrightarrow{^{0}_{0}\gamma\text{, x-ray}} H_2O^{\bullet +} + e^-$$

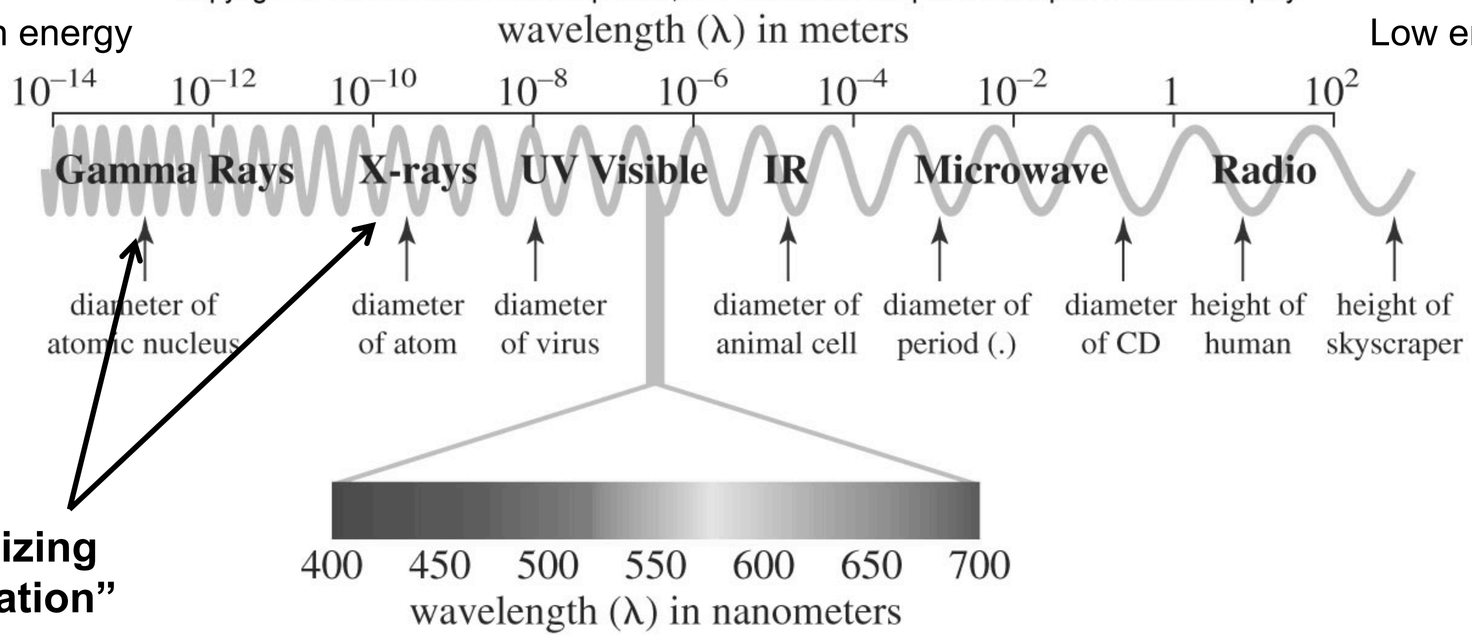
radical + a cation
will react with other molecules, including DNA



Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

High energy

Low energy



"ionizing radiation"

rapidly dividing cells particularly susceptible
+ for cancer treatment
– for bone marrow, skin, intestinal linings, other healthy cells that divide rapidly

Radiation Exposures and Doses

Exposure to ionizing radiation is measured in rads—0.01 J per kg tissue

Dose takes into account the total energy of the absorbed radiation, what tissues are absorbing it, as well as the type of radiation

Units of dose are rem and Sieverts (Sv):
rem = (#rads) x Q (range 1-20)
1 mrem = 10 μSv

Typical US **background radiation** dose = 360 mrem (but somewhat higher in CO)

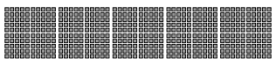
ref 1: www.ocrwm.doe.gov/factsheets/doeymp0403.shtml

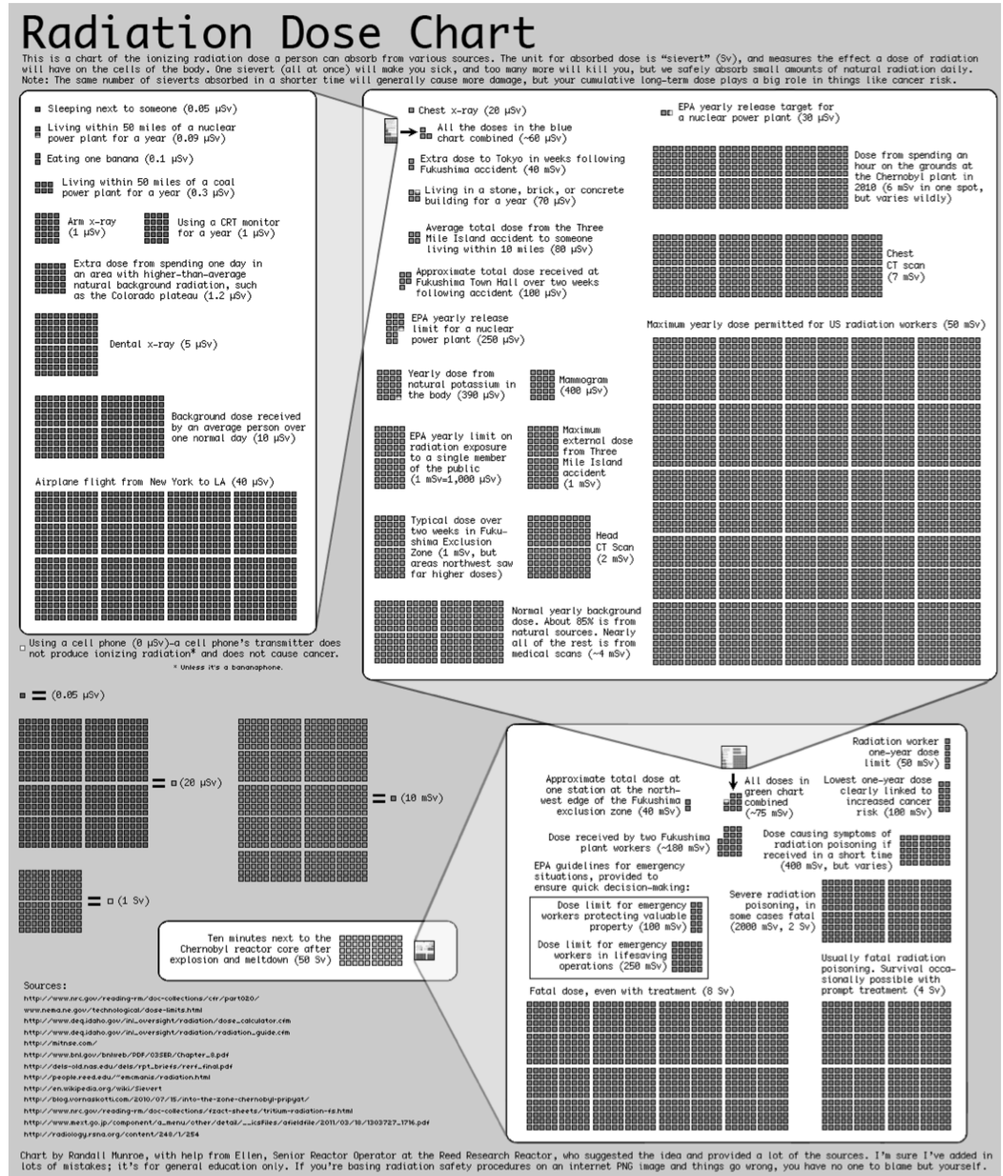
Activity	Radiation dose per year (mrem)	Ref.
Living in Ft. Collins (5000 ft elevation, lots of U in soil)	140	1
Food, water, air	240	Text
Nuke fallout	1	Text
Live near nuclear power plant	0.009	Text
Live near coal fired power plant	0.03	Text
Watch TV	1	Text
Smoke 1 pk/day	1000	Text
Airplane flight (roundtrip)	2-5	1
Dental X-rays	10-39	1
Chest X-ray	10	Text
Computer use	0.1	Text

Visual

Living in Ft. Collins (5000 ft elevation, lots of U in soil (1400 μS)

Smoke 1 pk/day 10,000 μS)

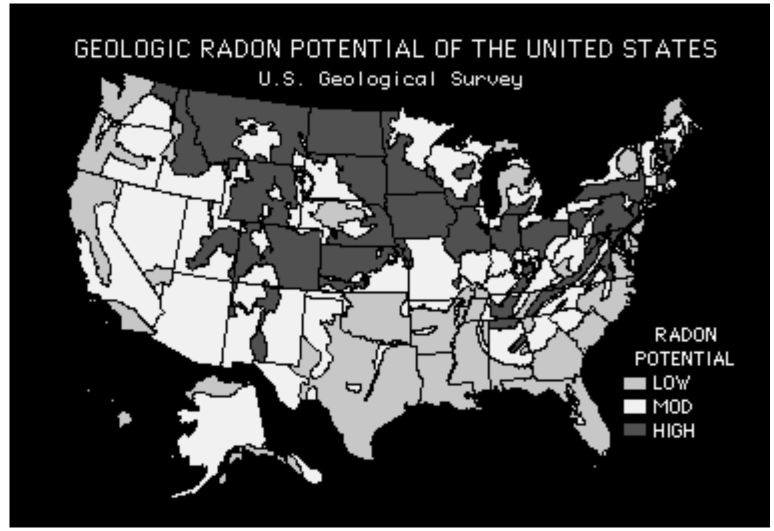




http://xkcd.com/radiation/ (provided by Ellen Werle)

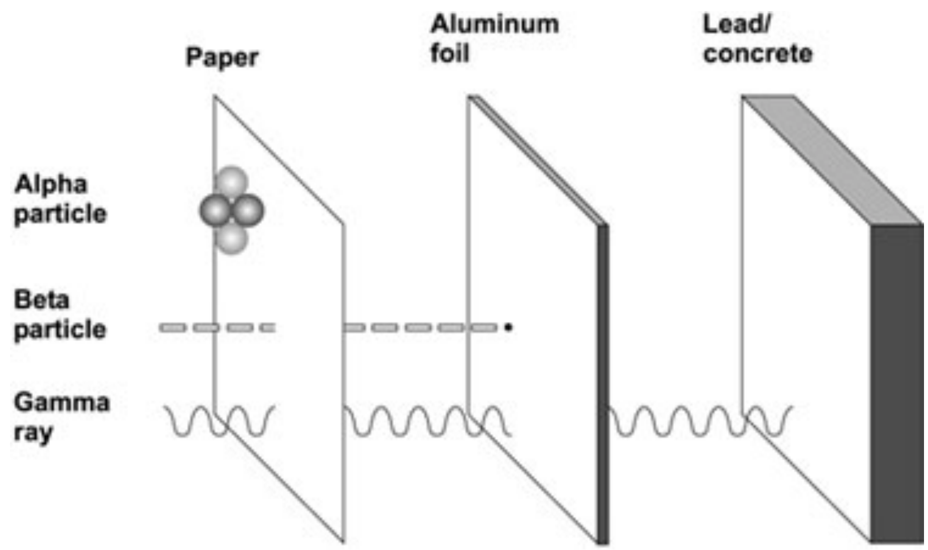
Radiation

- Why is background radiation higher in CO?
  - higher altitude (less atmosphere to block cosmic rays)
  - more rocks (granite)
    - higher U content
    - higher Rn content from U radioactive decay



http://energy.cr.usgs.gov/radon/rnus.html

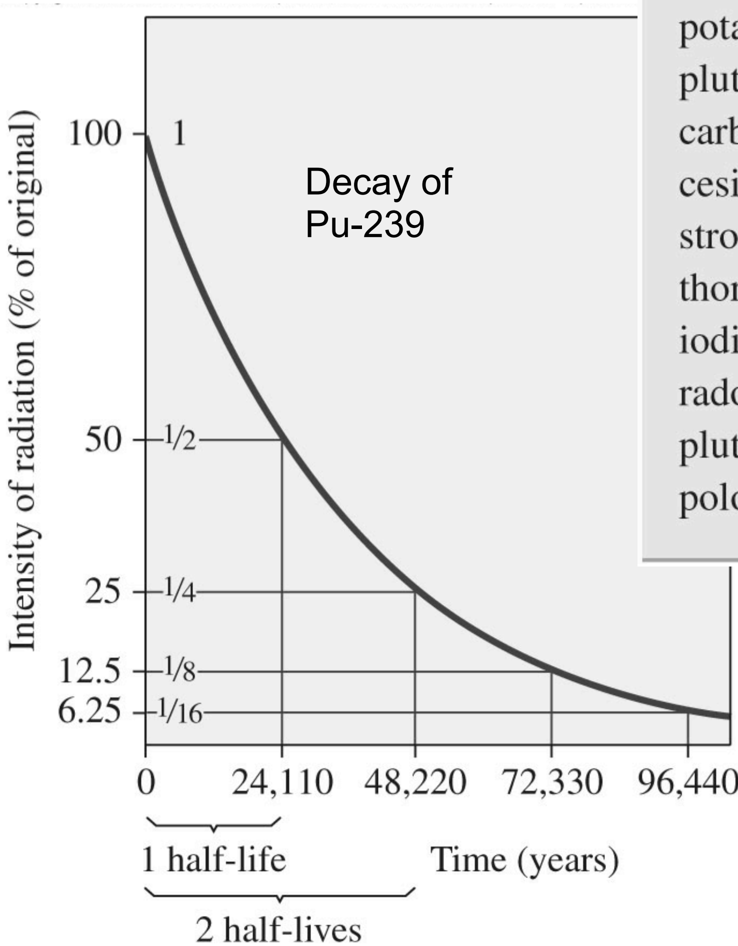
- Blocking sources of radioactivity
  - alpha particles blocked by dead skin layer—only dangerous if ingested
  - beta particles blocked by Plexiglas and distance
  - gamma particles require lead, concrete, or other dense materials



www.ocrwm.doe.gov/factsheets/doeymp0403.shtml

Nuclear Waste: Here Today, Here Tomorrow

Half-life: the time required for the level of radioactivity to fall to one-half of its initial value.



Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or

Table 7.5 Half-Lives for Selected Radioisotopes

Radioisotope	Half-life ($t_{1/2}$)
uranium-238	4.5×10^9 years
potassium-40	1.3×10^9 years
plutonium-239	24,110 years
carbon-14	5715 years
cesium-137	30.2 years
strontium-90	29.1 years
thorium-234	24.1 days
iodine-131	8.04 days
radon-222	3.82 days
plutonium-231	8.5 minutes
polonium-214	0.00016 seconds

High level radioactive waste includes spent nuclear fuel and other things with long half lives —must be permanently separated from life. **Low level radioactive waste** represents ~90% of the radioactive waste generated.

Dealing with Radioactive Materials

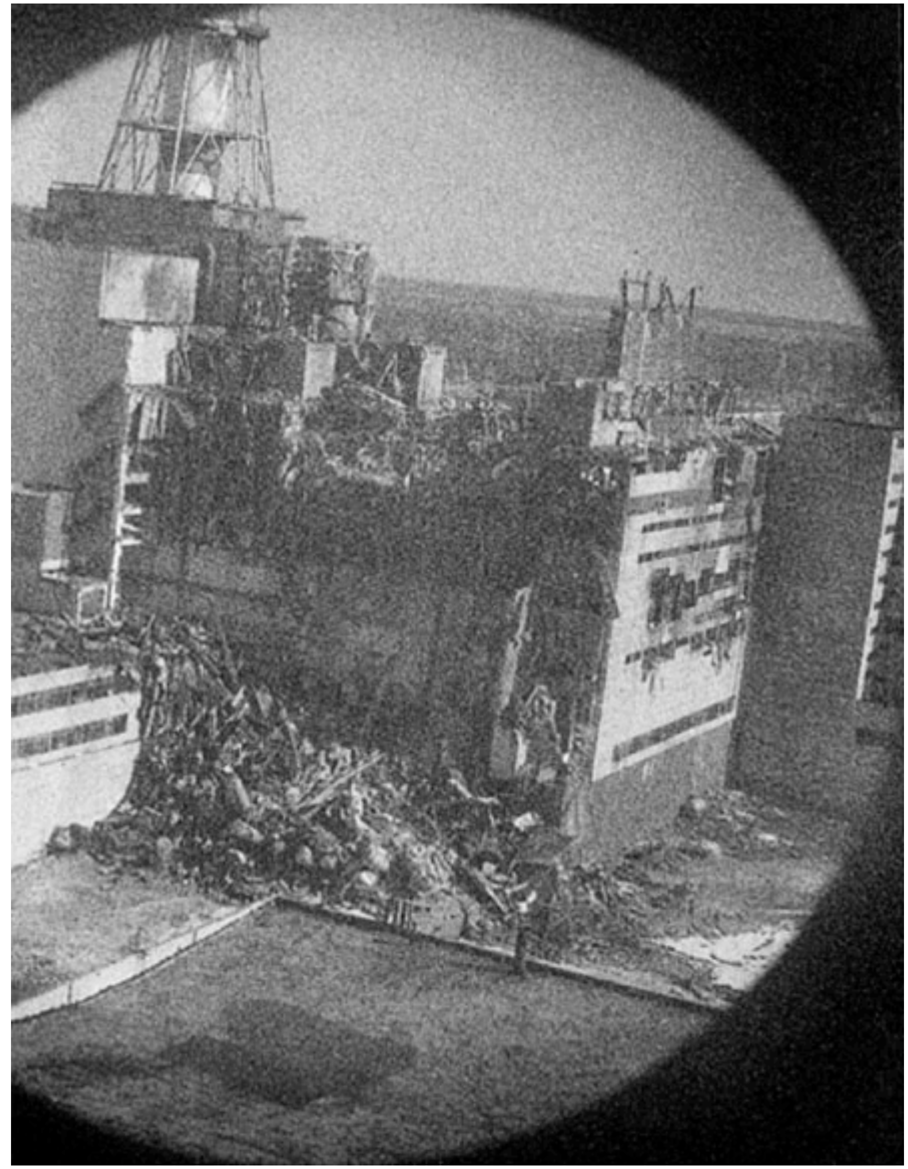
- Reprocessing
  - extract useful fuel from spent fuel
- Breeder reactors
  - *n* + U-238 ➔ Pu-239 + energy
  - Pu-239 ➔ fission products + energy
- Storage of fuel rods
  - storage pools (e.g. @ Fukushima AND every reactor in the US)
- Vitrification and storage, but where?
  - Yucca Mountain, NV?
  - Scandinavia?

- Nuclear weapons vs fuel
  - naturally mined uranium: ~0.7% U-235
  - fuel: 3-5% enriched in U-235
  - weapons: 90% U-235
  - depleted uranium: ~99.8% U-238
    - radioactive but not fissile
  - critical mass for U-235: 55 kg
  - critical mass for Pu-239: 10 kg
    - according to Wikipedia
- Uranium centrifuges
  - U-238 heavier than U-235
  - $UF_4 + F_2$ ➔ UF_6 (gas)
- Dirty bombs
  - conventional bombs + radioactive material

Chernobyl (1986)

The Chernobyl disaster was not a nuclear explosion:

- tremendous heat caused a pressure spike, ruptured fuel elements & released nuclear fuel particles which exploded when they contacted coolant water
- graphite (carbon) used to slow neutrons caught on fire
  - graphite control rods not used in US
- graphite & water (water gas chemistry) reacted to produce H_2 which explosively reacted with O_2 in the air
- 9 tons radioactive material emitted
  - equivalent to 100 Hiroshima bombs



Nuclear Summary

- Fission vs fusion
- Balancing fission equations
- How nuclear energy is converted to electricity (it's all about steam production)
  - $E = mc^2$
  - 20% of our electricity comes from nuclear sources
- Radioactivity
  - health effects
  - exposure and dose (rem)
  - how to block radiation
- Issues with using nuclear power
  - radiation (and public fear of radiation), nuclear waste, nuclear weapons, upfront costs, only electricity is produced (storage is difficult)