SAND2016-7682PE

An Introduction to Nuclear Materials (aka 'Nuke 101')

(or: Why is this stuff radioactive and how do we get energy out of it?)

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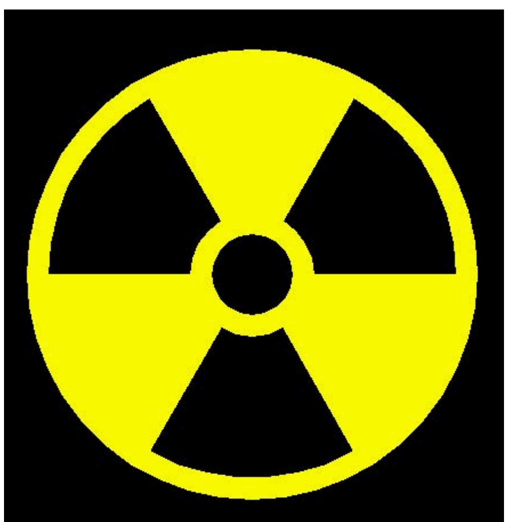
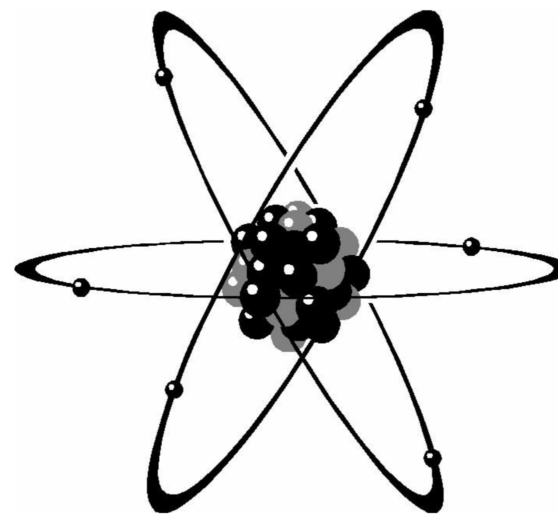
The George Washington University



September 12, 2015



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Some terms:

Fission: Splitting of an atom into smaller parts- accompanied by *serious* energy release.

Fissile: Capable of sustaining a chain reaction of nuclear fission.

Radioactivity: process in which an unstable atomic nucleus spontaneously loses energy by emitting ionizing* particles and radiation.

Chain reaction: I'll show you.

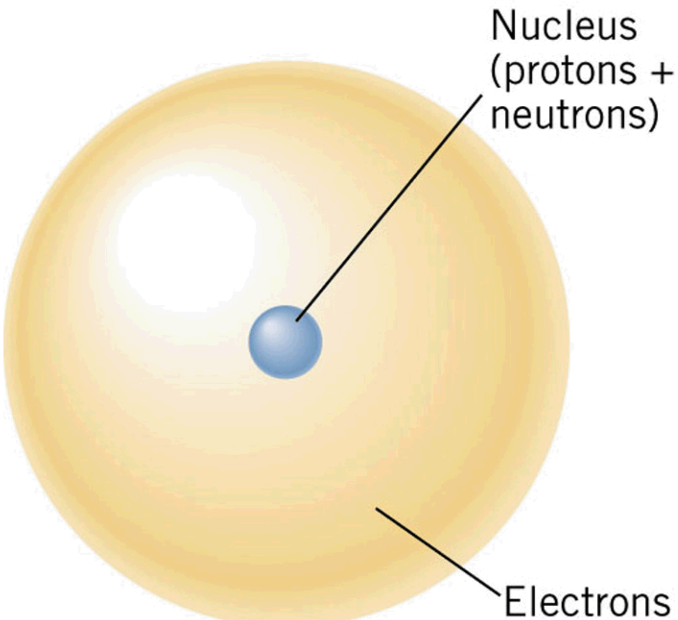
Fertile: Can be converted to fissile material- usually in a reactor or accelerator.

Path forward for today: Fission independent of application- Weapon vs. Reactor

In order to appreciate any of this, one needs to know the structure of an atom.

*Ionizing: induces emission of an electron in another substance.

A *very* simplified view.



Chemistry:

Physics:

- Atoms are comprised of **subatomic particles**
- There are three principal kinds of subatomic particles:
    - Proton – carries a positive charge, found in the nucleus
    - Electron – carries a negative charge, found outside the nucleus
    - Neutron – carries no charge, found in the nucleus

A closer look at the *nucleus*.

Positively charged, contains protons AND neutrons.
The *number* of protons defines the element!

Isotope: an atom with the same number of protons, but a different number of neutrons.

Table 7.1 Fundamental subatomic particles

Particle	Symbol(s)	Rest Mass		Charge
		amu	g	
Proton	${}_{1}^{1}p^{+}$, ${}^{1}H^{+}$	1.00728	1.673×10^{-24}	+1
Neutron	${}_{0}^{1}n$	1.00867	1.675×10^{-24}	0
Electron	e^{-}, β^{-}	0.000549	9.110×10^{-28}	−1
Positron	β^{+}	0.000549	9.110×10^{-28}	+1
Pion	$\pi^{+/0/-}$	0.15	2.5×10^{-25}	+1, 0, −1
Neutrino	ν	$<2 \times 10^{-8}$	0	0
Antineutrino	$\bar{\nu}$	$<2 \times 10^{-8}$	0	0

Table from Bowser, “Inorganic Chemistry.”

The Periodic Table of the Elements

1 **H** Hydrogen 1.00794																	2 **He** Helium 4.003
3 **Li** Lithium 6.941	4 **Be** Beryllium 9.012182											5 **B** Boron 10.811	6 **C** Carbon 12.0107	7 **N** Nitrogen 14.00674	8 **O** Oxygen 15.9994	9 **F** Fluorine 18.9984032	10 **Ne** Neon 20.1797
11 **Na** Sodium 22.989770	12 **Mg** Magnesium 24.3050											13 **Al** Aluminum 26.981538	14 **Si** Silicon 28.0855	15 **P** Phosphorus 30.973761	16 **S** Sulfur 32.066	17 **Cl** Chlorine 35.4527	18 **Ar** Argon 39.948
19 **K** Potassium 39.0983	20 **Ca** Calcium 40.078	21 **Sc** Scandium 44.955910	22 **Ti** Titanium 47.867	23 **V** Vanadium 50.9415	24 **Cr** Chromium 51.9961	25 **Mn** Manganese 54.938049	26 **Fe** Iron 55.845	27 **Co** Cobalt 58.933200	28 **Ni** Nickel 58.6934	29 **Cu** Copper 63.546	30 **Zn** Zinc 65.39	31 **Ga** Gallium 69.723	32 **Ge** Germanium 72.61	33 **As** Arsenic 74.92160	34 **Se** Selenium 78.96	35 **Br** Bromine 79.904	36 **Kr** Krypton 83.80
37 **Rb** Rubidium 85.4678	38 **Sr** Strontium 87.62	39 **Y** Yttrium 88.90585	40 **Zr** Zirconium 91.224	41 **Nb** Niobium 92.90638	42 **Mo** Molybdenum 95.94	43 **Tc** Technetium (98)	44 **Ru** Ruthenium 101.07	45 **Rh** Rhodium 102.90550	46 **Pd** Palladium 106.42	47 **Ag** Silver 107.8682	48 **Cd** Cadmium 112.411	49 **In** Indium 114.818	50 **Sn** Tin 118.710	51 **Sb** Antimony 121.760	52 **Te** Tellurium 127.60	53 **I** Iodine 126.90447	54 **Xe** Xenon 131.29
55 **Cs** Cesium 132.90545	56 **Ba** Barium 137.327	57 **La** Lanthanum 138.9055	72 **Hf** Hafnium 178.49	73 **Ta** Tantalum 180.9479	74 **W** Tungsten 183.84	75 **Re** Rhenium 186.207	76 **Os** Osmium 190.23	77 **Ir** Iridium 192.217	78 **Pt** Platinum 195.078	79 **Au** Gold 196.96655	80 **Hg** Mercury 200.59	81 **Tl** Thallium 204.3833	82 **Pb** Lead 207.2	83 **Bi** Bismuth 208.98038	84 **Po** Polonium (209)	85 **At** Astatine (210)	86 **Rn** Radon (222)
87 **Fr** Francium (223)	88 **Ra** Radium (226)	89 **Ac** Actinium (227)	104 **Rf** Rutherfordium (261)	105 **Db** Dubnium (262)	106 **Sg** Seaborgium (263)	107 **Bh** Bohrium (262)	108 **Hs** Hassium (265)	109 **Mt** Meitnerium (266)	110 (269)	111 (272)	112 (277)	113	114				

58 **Ce** Cerium 140.116	59 **Pr** Praseodymium 140.90765	60 **Nd** Neodymium 144.24	61 **Pm** Promethium (145)	62 **Sm** Samarium 150.36	63 **Eu** Europium 151.964	64 **Gd** Gadolinium 157.25	65 **Tb** Terbium 158.92534	66 **Dy** Dysprosium 162.50	67 **Ho** Holmium 164.93032	68 **Er** Erbium 167.26	69 **Tm** Thulium 168.93421	70 **Yb** Ytterbium 173.04	71 **Lu** Lutetium 174.967
90 **Th** Thorium 232.0381	91 **Pa** Protactinium 231.03588	92 **U** Uranium 238.0289	93 **Np** Neptunium (237)	94 **Pu** Plutonium (244)	95 **Am** Americium (243)	96 **Cm** Curium (247)	97 **Bk** Berkelium (247)	98 **Cf** Californium (251)	99 **Es** Einsteinium (252)	100 **Fm** Fermium (257)	101 **Md** Mendelevium (258)	102 **No** Nobelium (259)	103 **Lr** Lawrencium (262)

| Not naturally occurring. →

Atomic Numbers, Mass Numbers and Isotopes

Mass Number. Equal to number of protons AND neutrons

$$^{235}_{92}U$$

Symbol

Atomic Number or 'Z'. Equal to # Protons OR Electrons

92
U
238.0829

Atomic weight in amu.

All atoms of the same element have the same number of <u>protons.</u>

Naturally occurring elements are found as mixture of isotopes

Uranium	Iron
U-238: 99.284%	Fe-54: 5.80%
U-235: 0.711%	Fe-56: 91.72%
U-234: 0.0058%	Fe-57: 2.2%
	Fe-58: 0.28%

How can nuclei change?

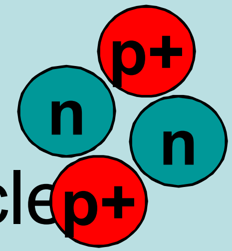
- Three ways a nucleus can change:
  - Radioactive decay (spontaneous splitting)
  - Fusion (induced joining)
  - Fission (spontaneous or induced splitting)

Radiation Types

Alpha (α)

2 protons, 2 neutrons

positively charged particle



Beta (β)

like an electron

negatively charged particle

Gamma (γ)

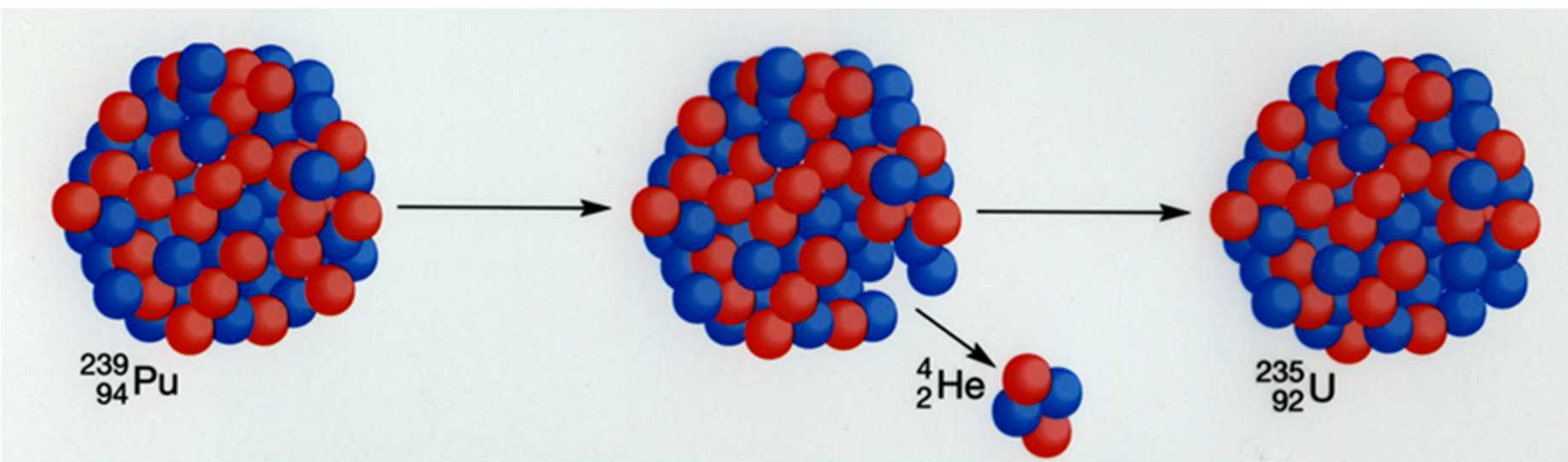
Wave energy (*not* a particle)

Radioactive α-decay

α- particle

$$^{239}_{94}Pu \longrightarrow\ ^{235}_{92}U + \ ^{4}_{2}He^{2+}$$

94 p^+	92 p^+	2 p^+
145 n	143 n	2 n



alpha particle

There is a large amount of energy associated with this!

End result: Z *decreases* by 2

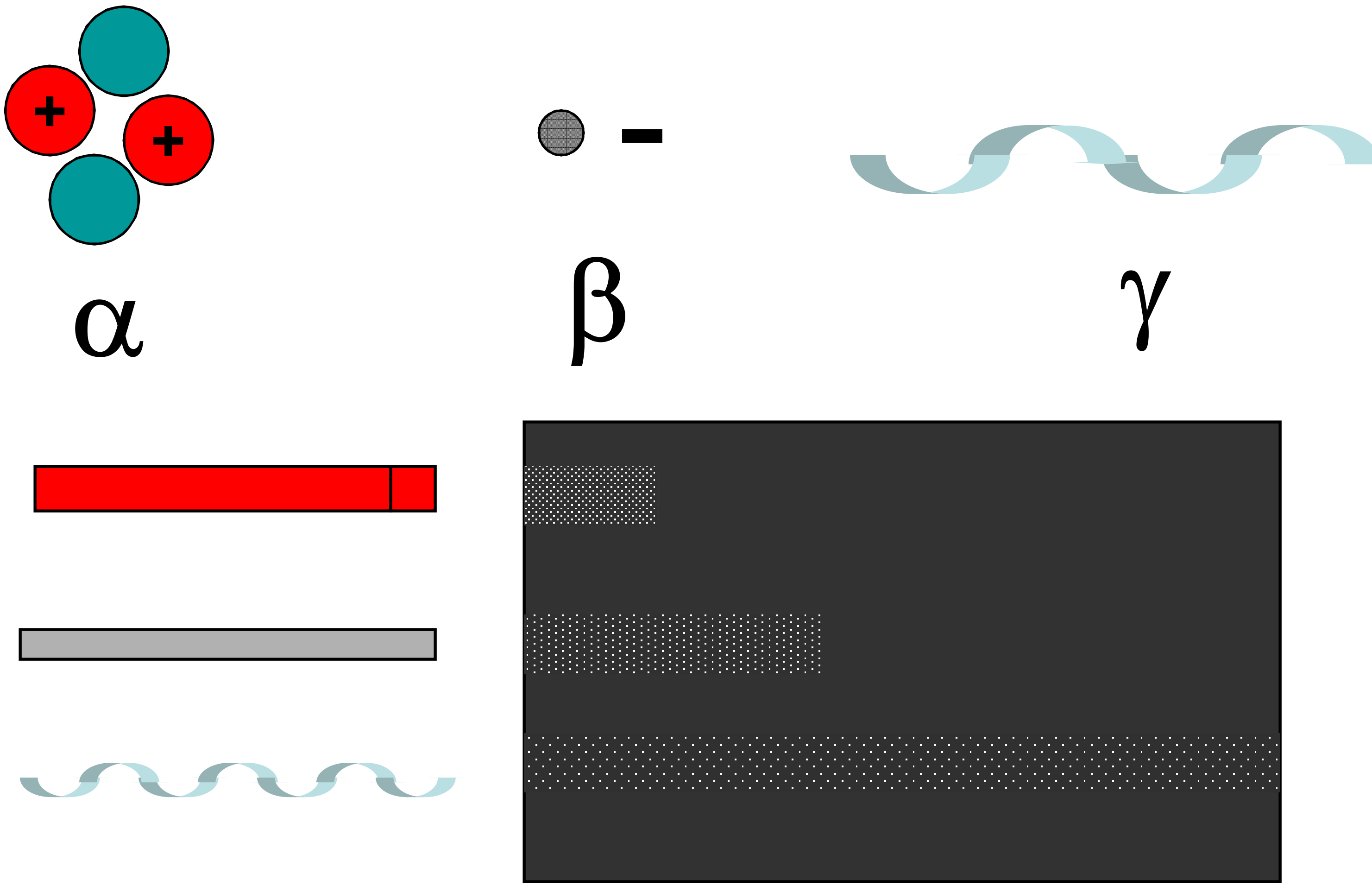
Radioactive β-decay example

$$^{131}_{53}I \rightarrow ^{131}_{54}Xe + ^{0}_{-1}e$$

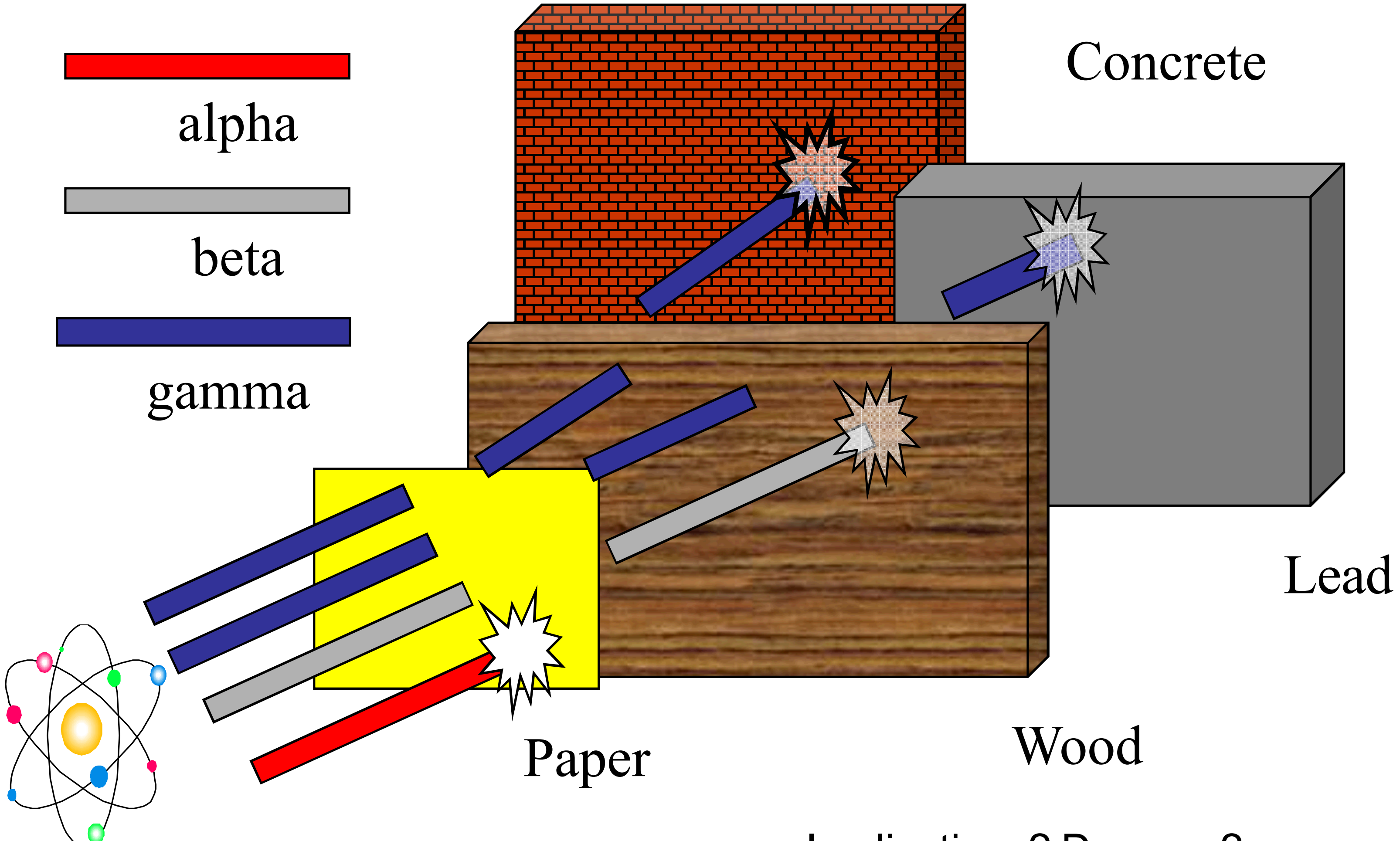
In reverse:

$$^{81}_{37}Rb + ^{0}_{-1}e \rightarrow ^{81}_{36}Kr$$

PENETRATING ABILITY



SHIELDING



Implications? Damage?

$t_{1/2}$ or half-life: time required for any given substance to react (or decay) to half of its original amount.

Nuclear decays are UNAFFECTED by external conditions such as temperature, pressure, environment, etc.

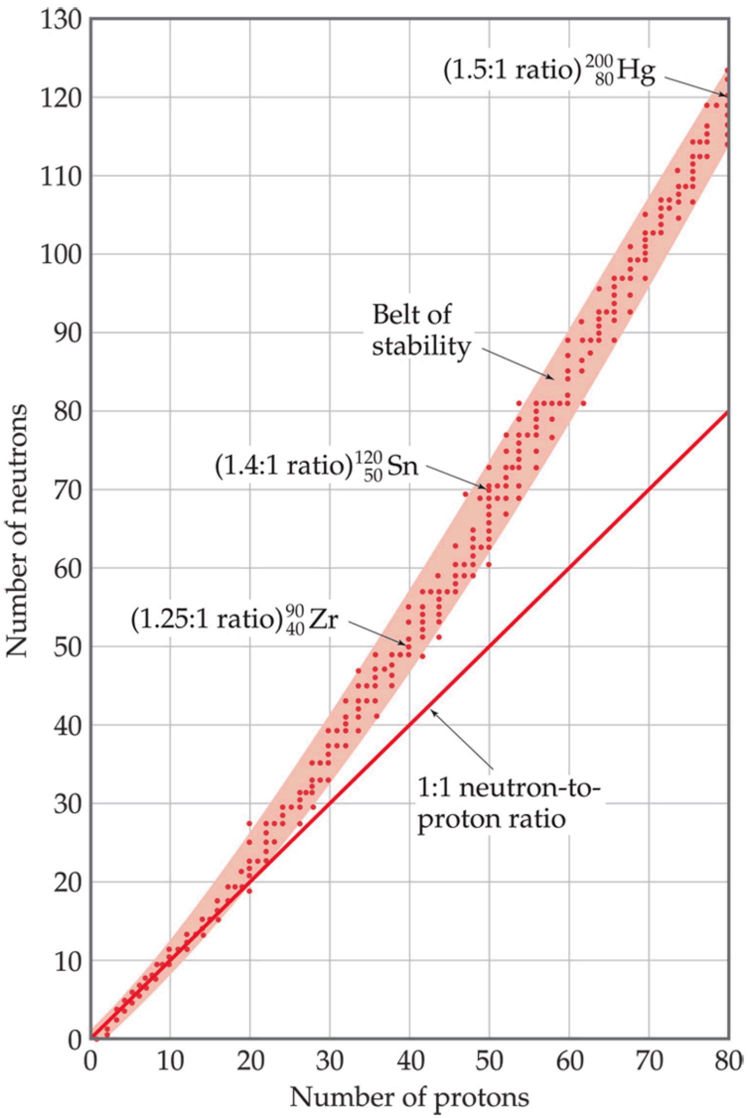
TABLE 21.4 ▪ The Half-lives and Type of Decay for Several Radioisotopes

	Isotope	Half-life (yr)	Type of Decay
Natural radioisotopes	$^{238}_{92}U$	4.5×10^9	Alpha
	$^{235}_{92}U$	7.0×10^8	Alpha
	$^{232}_{90}Th$	1.4×10^{10}	Alpha
	$^{40}_{19}K$	1.3×10^9	Beta
	$^{14}_{6}C$	5715	Beta
Synthetic radioisotopes	$^{239}_{94}Pu$	24,000	Alpha
	$^{137}_{55}Cs$	30	Beta
	$^{90}_{38}Sr$	28.8	Beta
	$^{131}_{53}I$	0.022	Beta

^{99}Tc ($t_{1/2}$=2.13×10^5 years)
^{129}I ($t_{1/2}$=1.57×10^7 years)

^{137}Cs ($t_{1/2}$=30 years)
^{90}Sr ($t_{1/2}$=28 years) ← Fission products

So, what is with all this ‘decay’ business? Why does an atom do this? The nucleus is unstable. Not enough neutrons.



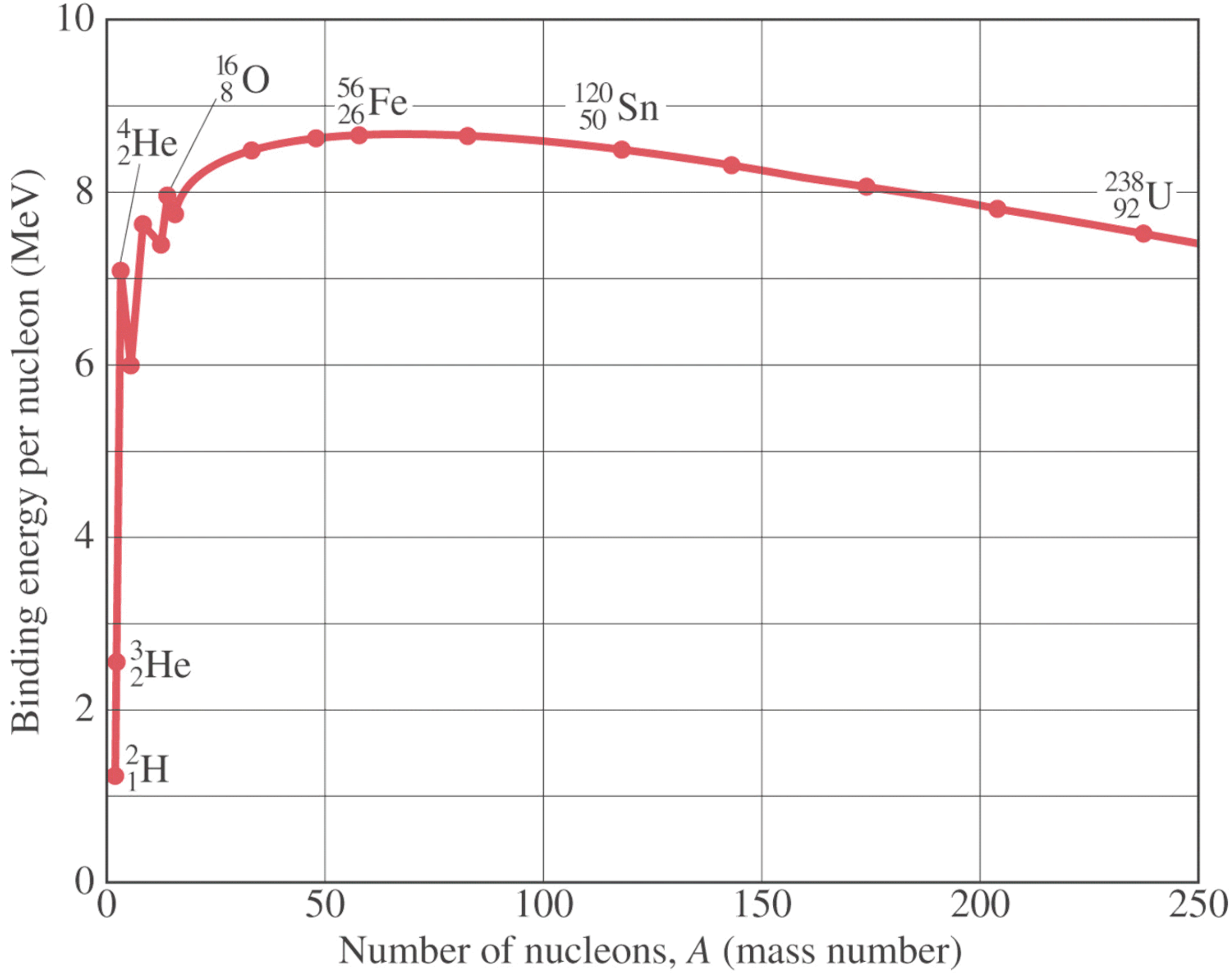
More protons require more neutrons to provide a compensating nuclear strong force and to dilute the electrostatic proton-proton repulsions. The plot stops at element 83 (bismuth) because no element above this has a *stable* isotope.

- Isotopes with atomic number greater than 83 tend to be **alpha emitters**.

- Isotopes occurring above and to the left of the band of stability tend to be **beta emitters.**

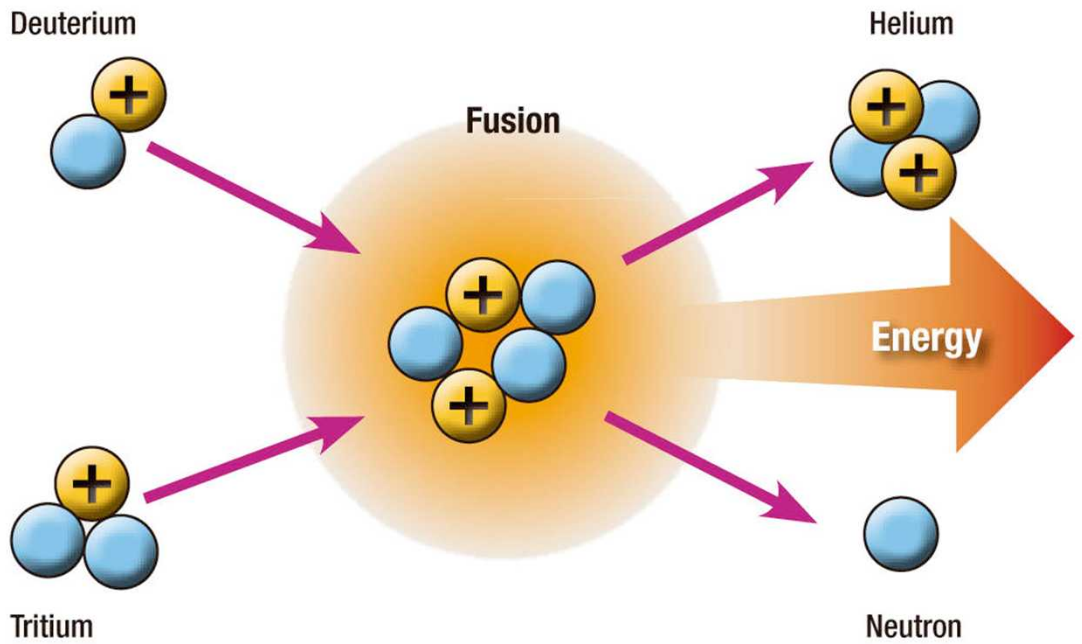
- Isotopes lying below and to the right of the band are positron emitters.

Binding energy per nucleon



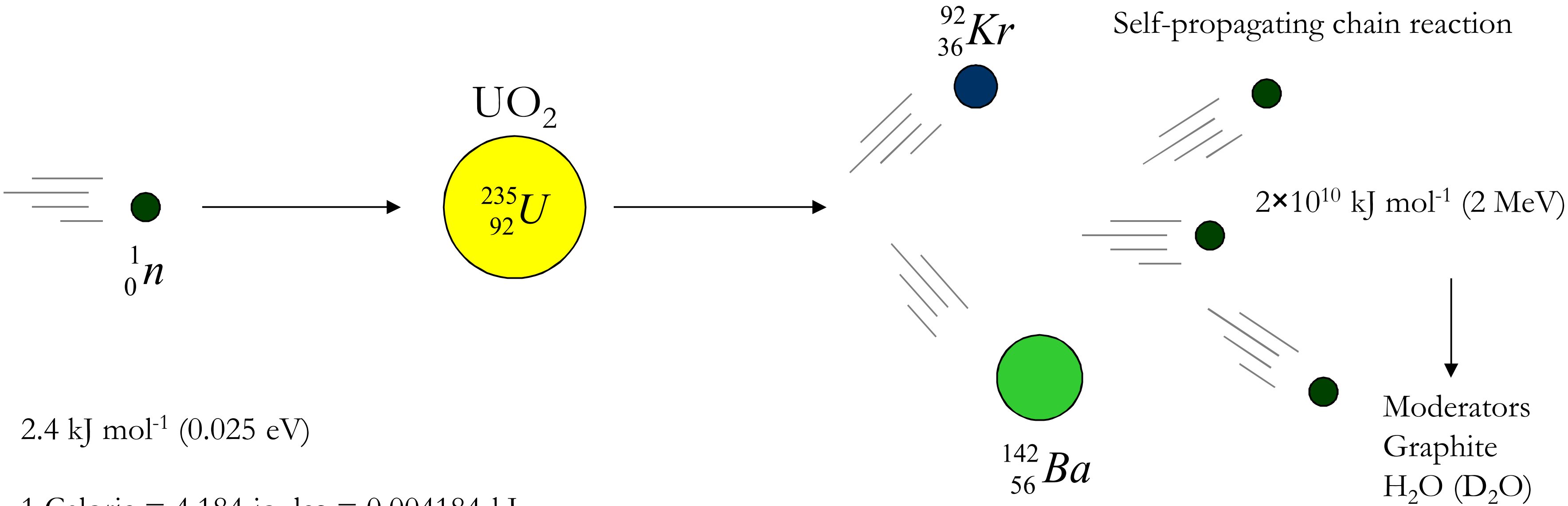
Fusion in a nutshell

- Take two light elements and smoosh them together



Taken from http://nuclear-energy.net/what-is-nuclear-energy/nuclear-fusion

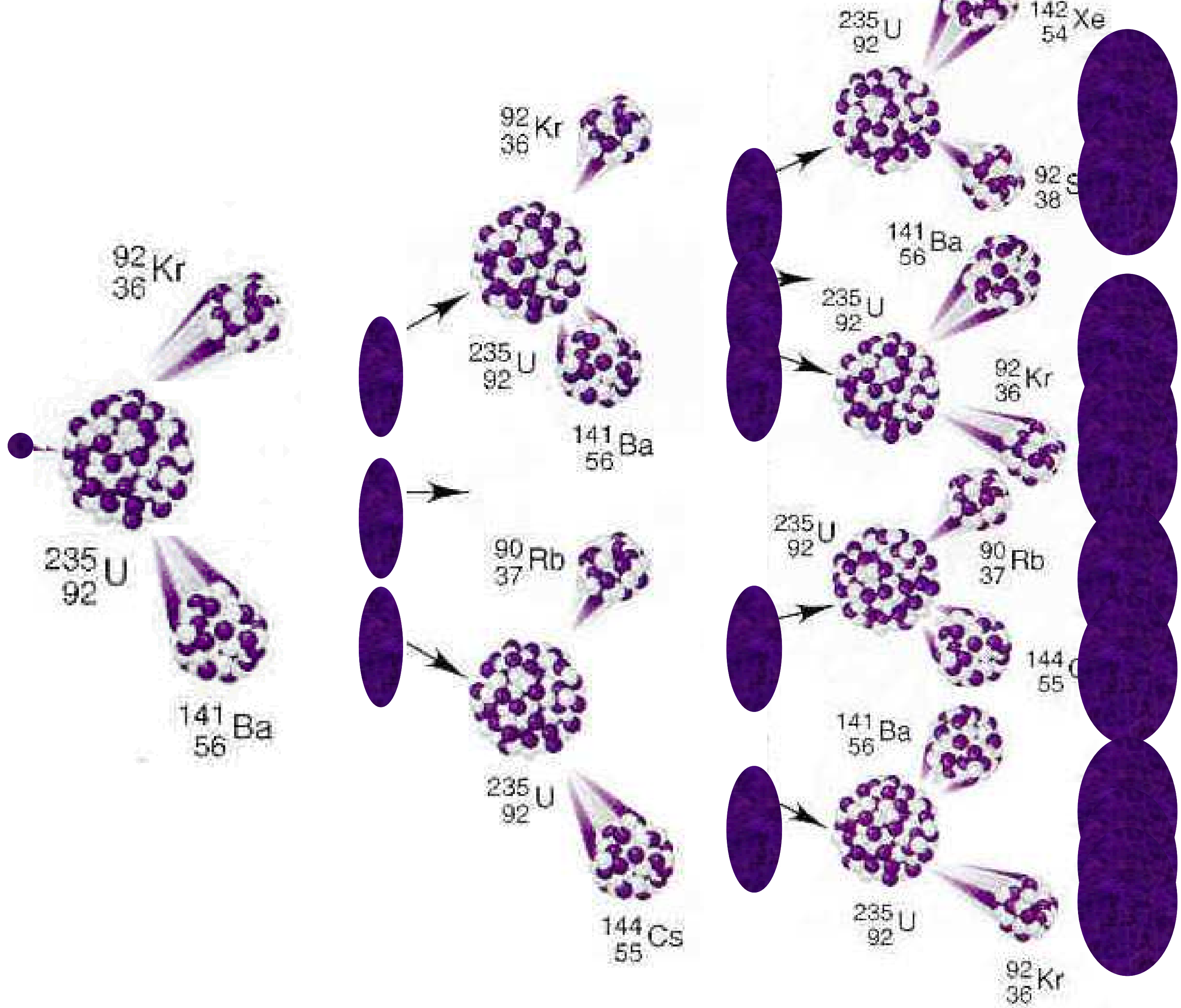
Nuclear Fission in a Nutshell



2.4 kJ mol^{-1} (0.025 eV)

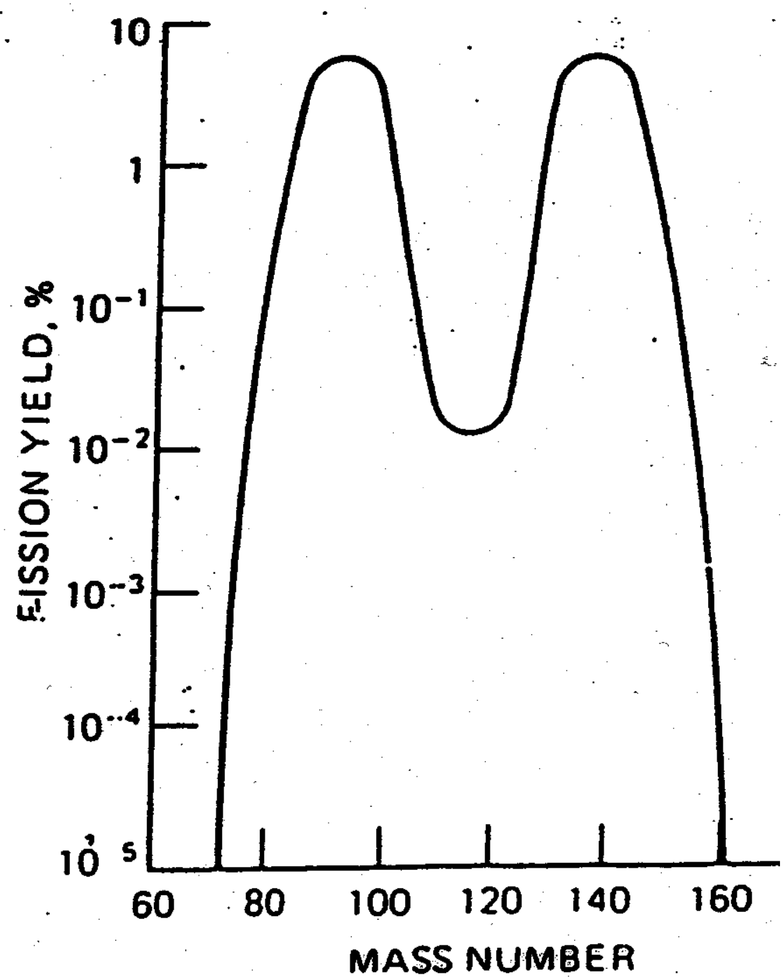
1 Calorie = 4.184 joules = 0.004184 kJ

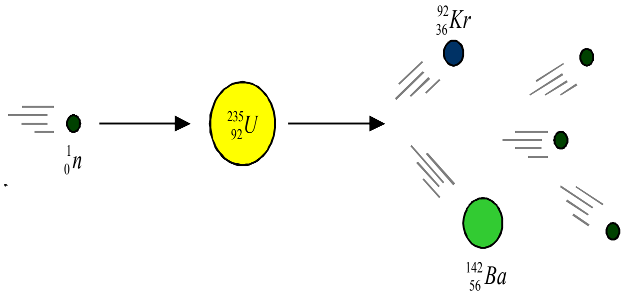
Nuclear Fission: Chain Reaction



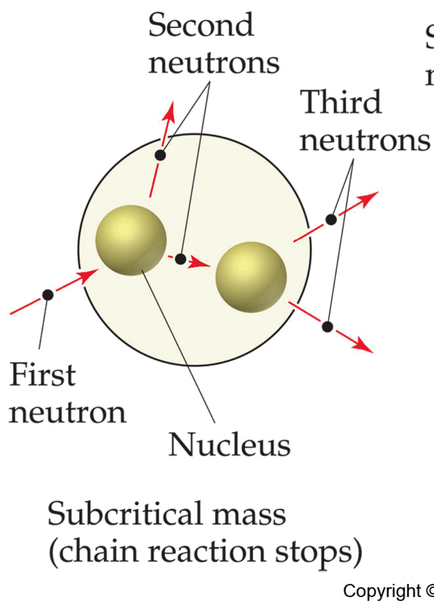
http://www.dailymotion.com/video/xi1njm_nuclear-fission-chain-reaction-ping-pong-balls-and-mousetraps_tech

Identity of Fission Fragments





Critical Mass: the smallest amount of fissile material needed to sustain a nuclear reaction.



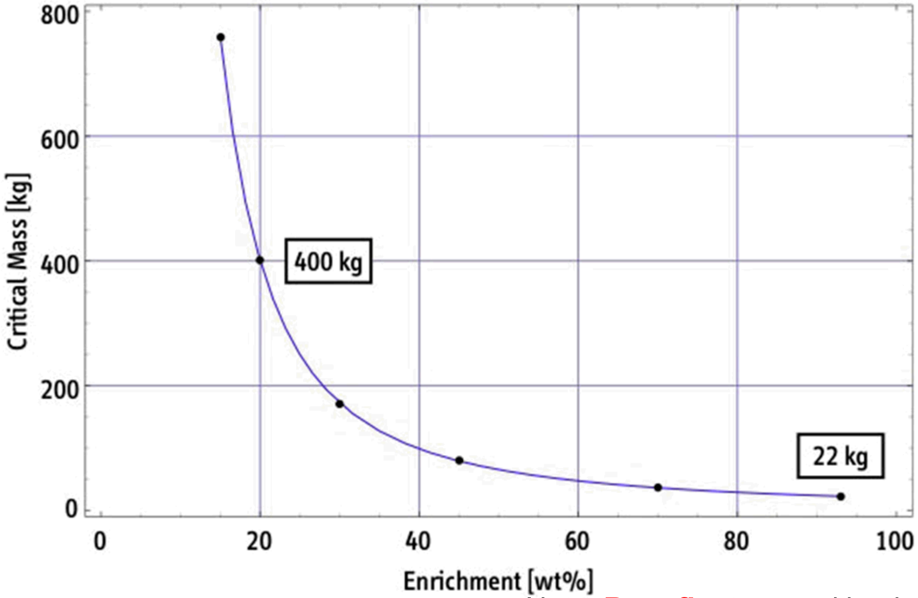
One neutron in, but then those produced induce further reaction.

Natural uranium: 0.7% U-235

SEU- Slightly Enriched uranium: 0.9 to 2% U-235

LEU- Low enriched uranium: <20% U-235

HEU- Highly enriched uranium: >20% U-235



Take home message: know the level of enrichment when reading policy, news, whatever.

Note: **Be reflector** used in above graph.

Source: Alexander Glaser and Frank N. von Hippel, "Global Cleanout: Reducing the Threat of HEU-Fueled Nuclear Terrorism," *Arms Control Today, January/February 2006,* *available online at: http://www.armscontrol.org/act/2006_01-02/JANFEB-heuFeature.asp.* ***Key term: downblending***

Figure itself from http://nti.org/db/heu/critical_mass_figure.html

Nabbed: Two of the alleged uranium dealers are arrested by police

Three held over 'dirty bomb' plot

THREE people, including two former policemen, have been arrested in Moldova on suspicion of selling uranium that could have been used in a 'dirty bomb', it emerged yesterday. They were trying to sell 1.8kg (4lb) of uranium-238, which officials claimed had a value of £7.3million, on the international black market. It can be enriched to use in nuclear warheads – but that requires much more of the material than the amount seized.

It may have been used with conventional explosives to create a 'dirty bomb', which spreads radioactive material over a small area. 'This could be very dangerous if set off in an enclosed public space like the Metro,' said Greenpeace. Traffickers were allegedly trying to sell the uranium, kept, along with guns and grenades, in the garage of one former policeman, when they were arrested by undercover officers posing as buyers.

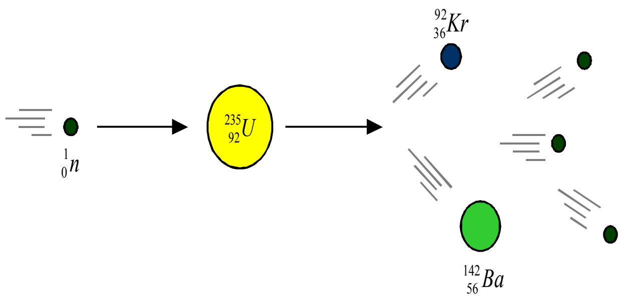
London 'freebie' August 2010.

Other things that can happen besides fission: neutron capture

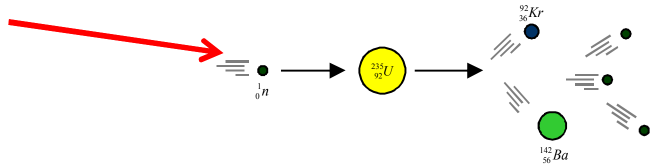
Not every neutron that hits a nucleus induces fission

Incoming neutron has to have the right energy, or ‘speed.’

Likelihood of fission (or capture) represented by a cross-section



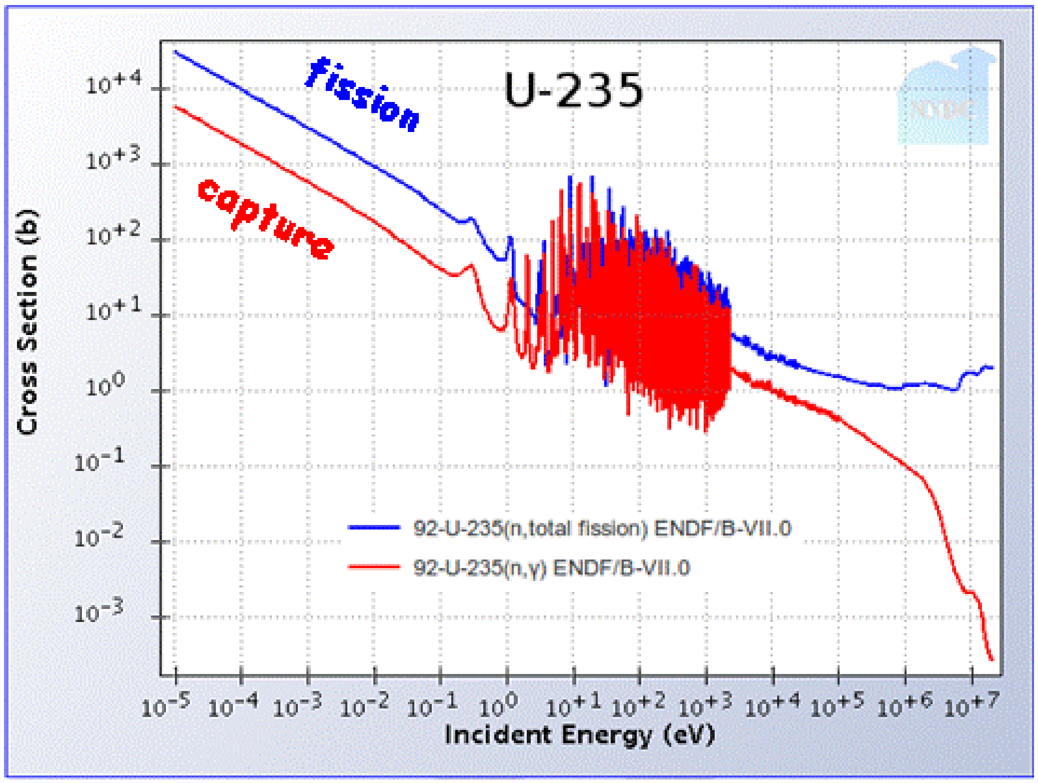
What the heck is a neutron cross section?



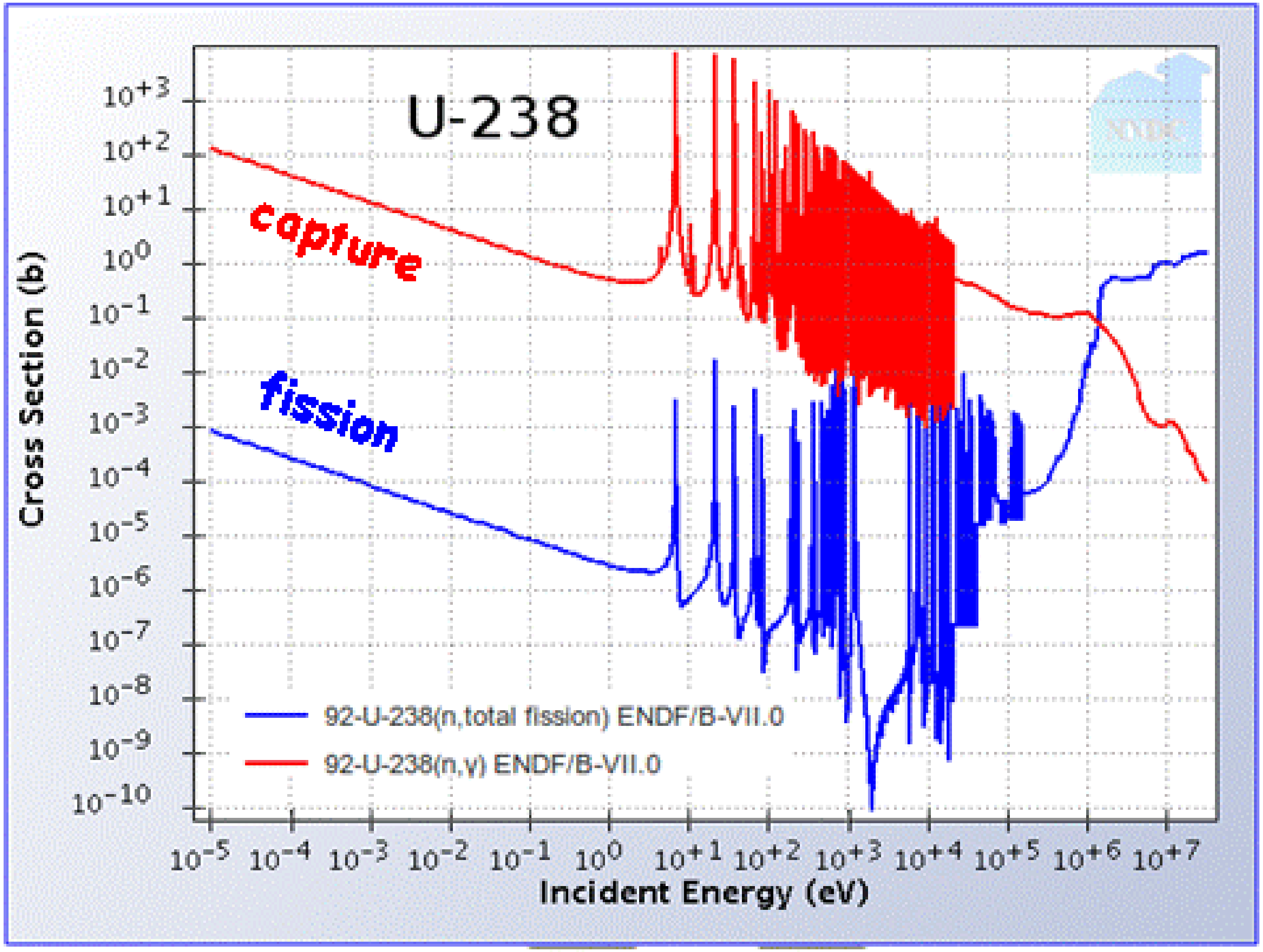
Used to express the likelihood of interaction between an incident neutron and a target nucleus. σ in barns where 1 barn = 1 x 10^{-24} cm^2.

We need to know the ENERGY of the incident neutron. Wikipedia has a great page:

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



U-238, on the other hand, more likely to undergo capture,

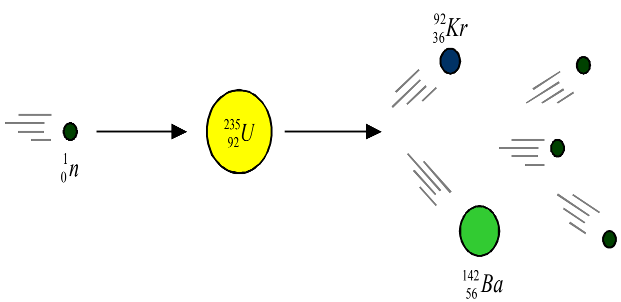


Typical Chemical Reaction:

$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l)$

1.0 gram CH_4 yields 55.36 kJ or 1 PowerBar

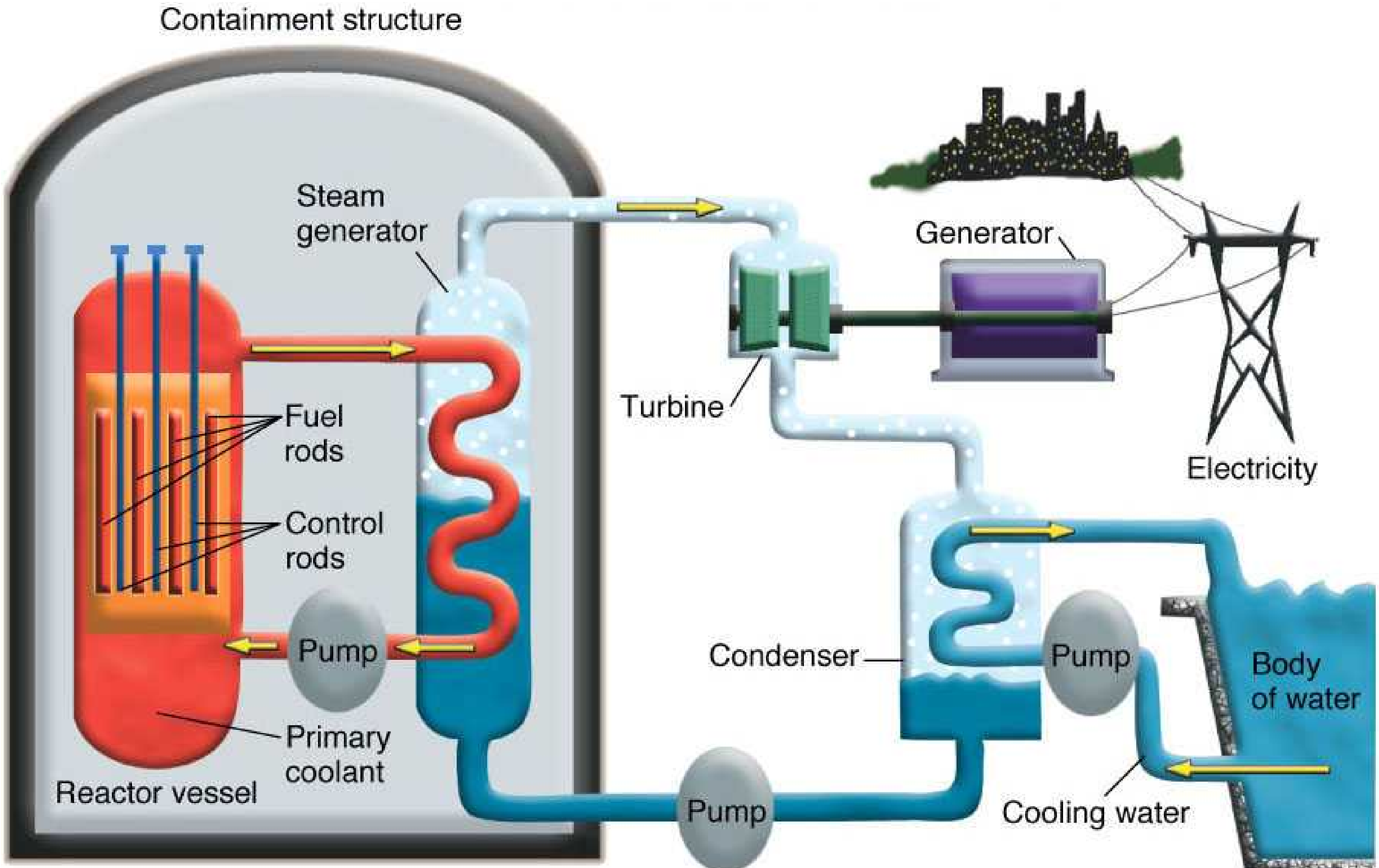
Typical Fission Reaction:
1.0 gram U-235; assume 10% completeness



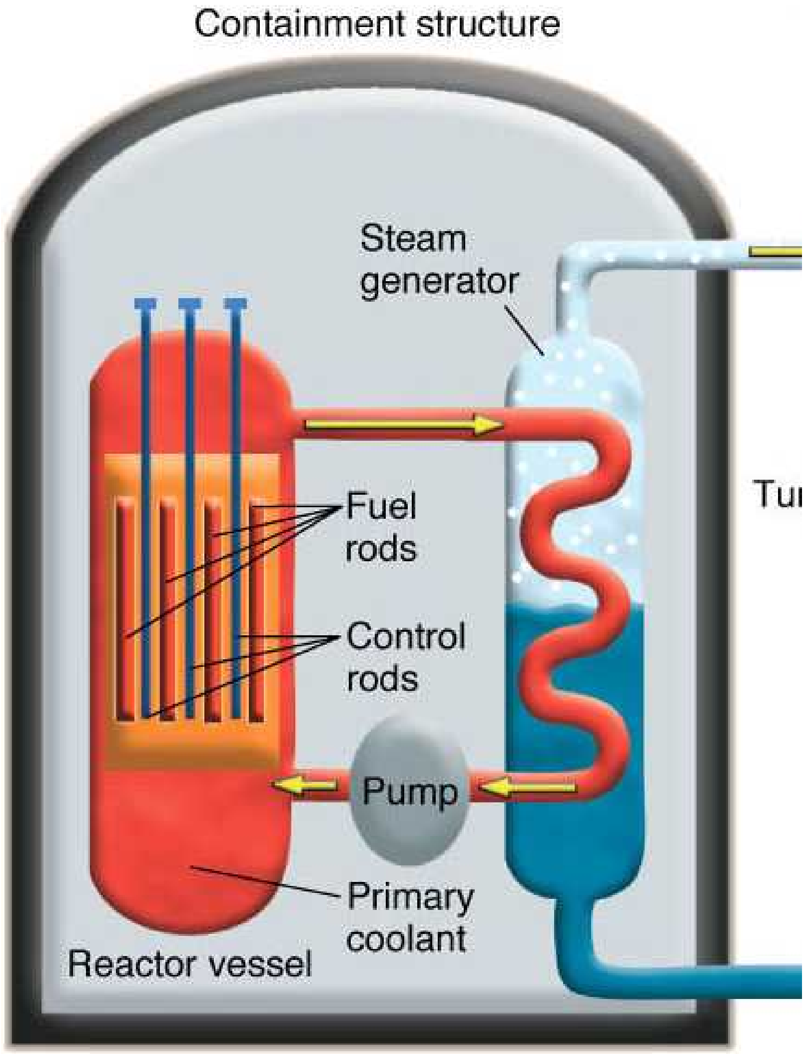
7.17×10^6 kJ or 7500 PowerBars

1 Fuel Pellet (once through) = 3 barrels of oil, 1 ton of coal or 17,000 ft^3 natural gas

Diagram of a nuclear power plant



A nuclear reactor, shown here schematically, produces heat that converts water to steam. The steam powers a turbine, just as in a conventional coal-burning plant.



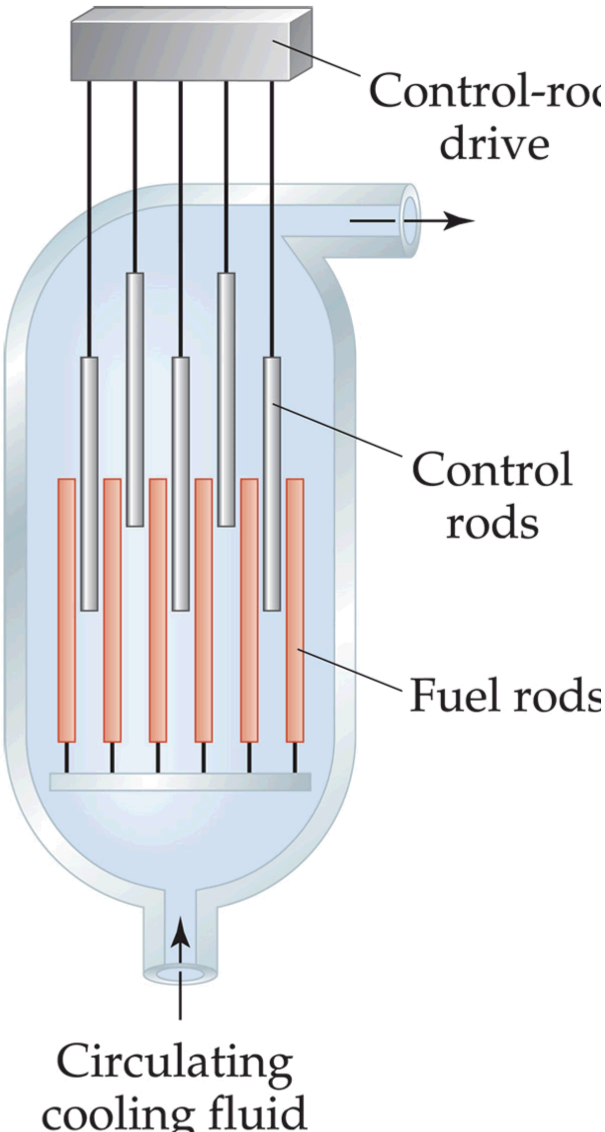
Closer look at just the reactor:

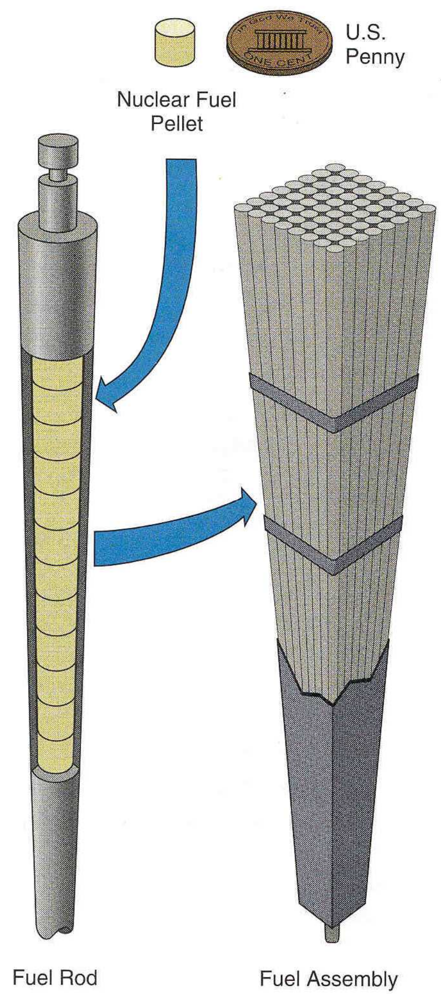
This is a BWR

AKA ‘LWR’

Other flavors of LWR include PWR

Control Rods and Fuel Rods





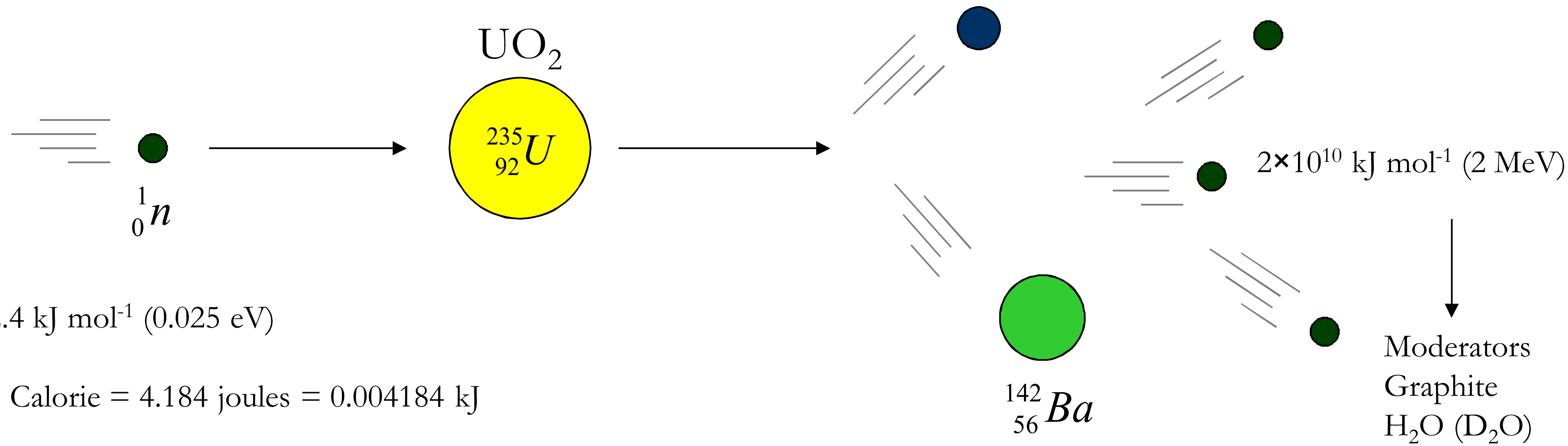
- Nuclear reactors use only 3-5 % of fissionable U-235, in the form of uranium dioxide (UO_2).

- Neutrons given off during the fission of U-235 are absorbed by atoms of U-238, cadmium and boron: no build up of a neutron stream.

- No critical mass of U-235.

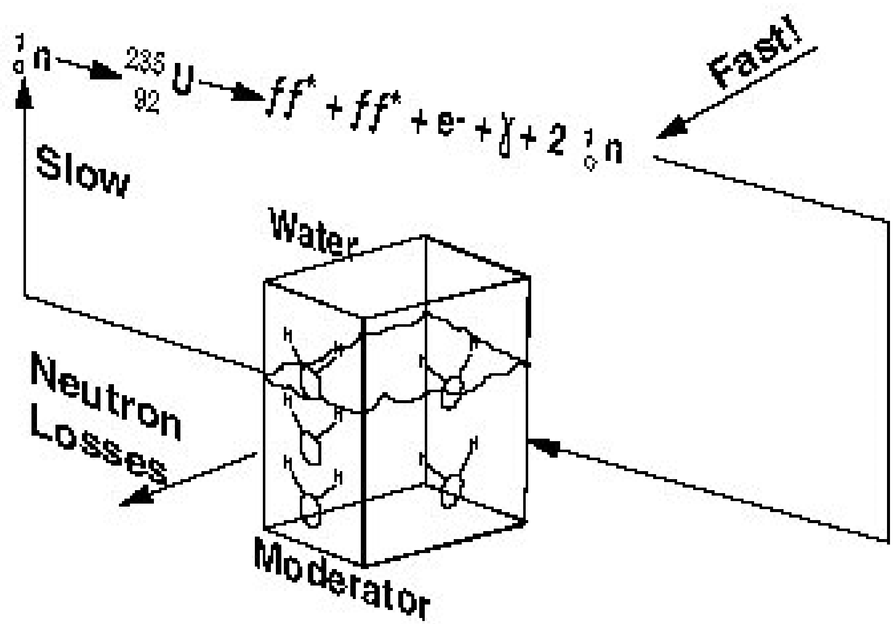
One more thing about nuclear reactors: Moderators.

2.3 neutrons per fission



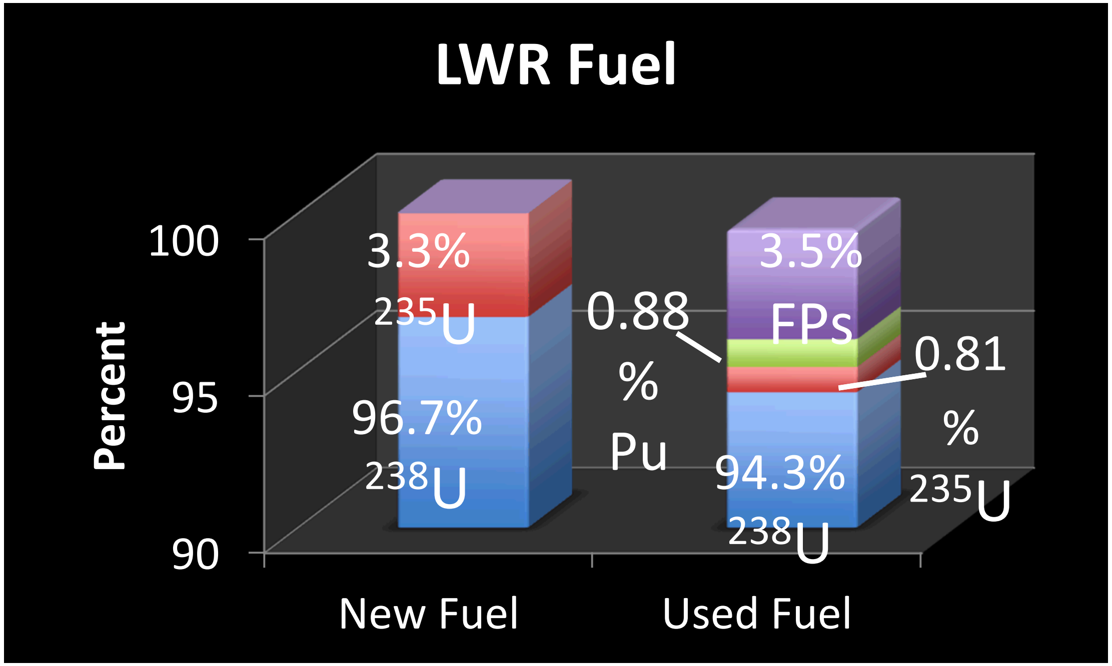
2.4 kJ mol^{-1} (0.025 eV)

1 Calorie = 4.184 joules = 0.004184 kJ



Water is the moderator- hence the term “Light Water Reactor”

Look at how the composition of fuel *evolves*.



Most nuclear fuel (spent or not) is ^{238}U:

$${}^{238}_{92}U + {}^{1}_{0}n \rightarrow {}^{239}_{92}U$$

Note the neutron *capture*!

$${}^{239}_{92}U \rightarrow {}^{239}_{93}Np + \beta^{-} (t_{1/2} = 24\,\text{min})$$

$${}^{239}_{93}Np \rightarrow {}^{239}_{94}Pu + \beta^{-} \quad (t_{1/2}=2.36\text{ days})$$

$${}^{237}_{93}Np \rightarrow {}^{233}_{91}Pa + {}^{4}_{2}\text{He} \quad (t_{1/2}=2.14 \times 10^{6}\text{y})$$

One man's trash is another man's treasure. This is how you make Pu (albeit in a different reactor type).

Segue to Radiation, Half-Lives and Stability.

Other concepts: self-protecting, ‘too hot to handle’, detection, screening, etc.

Waste implications?

Back to waste for a second…

Spent Fuel Composition
95.6 % Uranium (<1% ^{235}U)
0.9% Plutonium
0.3 % major fission products (^{137}Cs, ^{90}Sr, HLW)
0.1% long-lives fission products (I, Tc)
0.1% long-lived minor actinides (Np, Am, Cm)
3% stable or short-lived fission products (no disposal problem)

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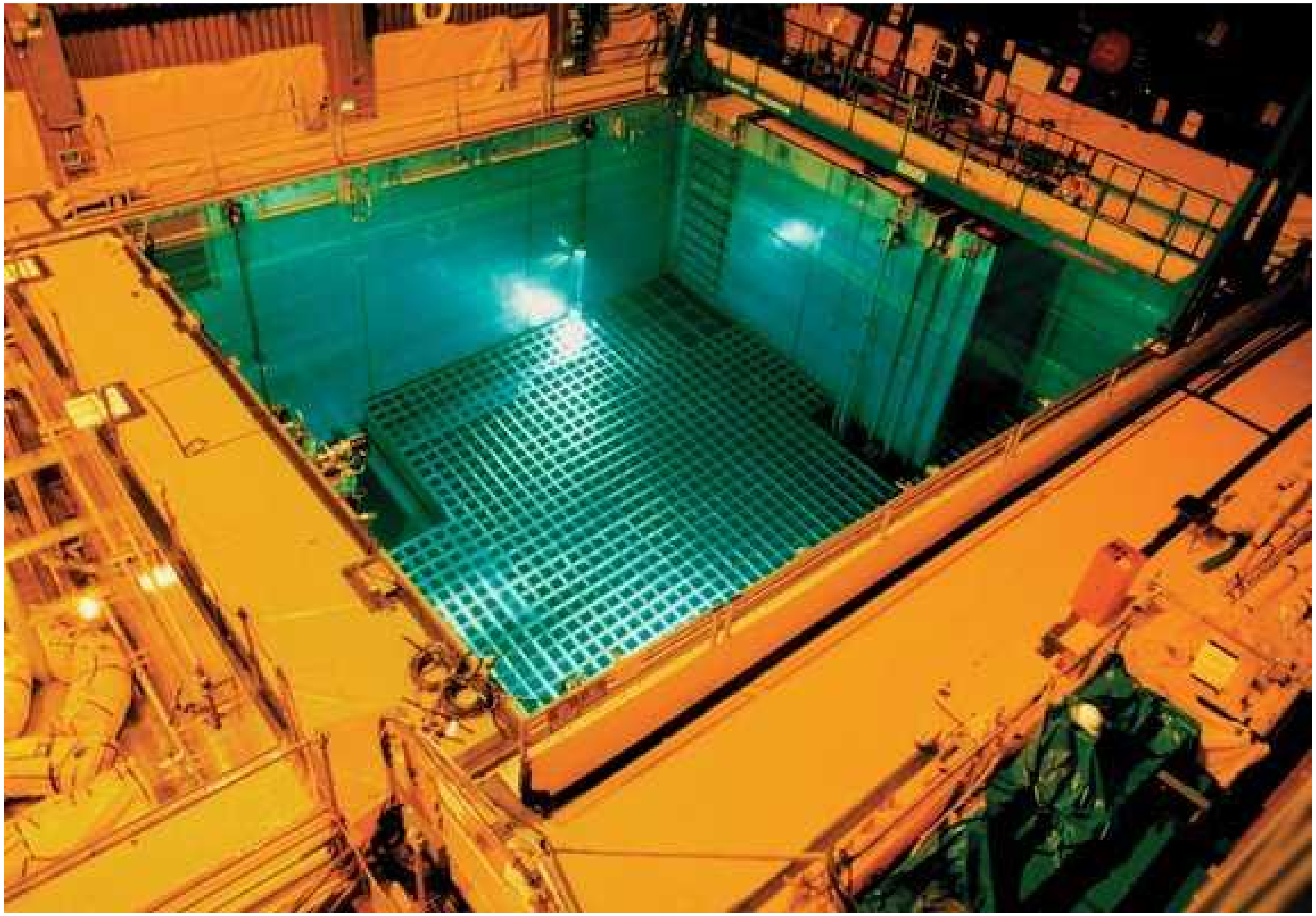
^{99}Tc ($t_{1/2}=2.13\times10^{5}$ years) ^{137}Cs ($t_{1/2}=30$ years)
^{129}I ($t_{1/2}=1.57\times10^{7}$ years) ^{90}Sr ($t_{1/2}=28$ years)

Storage Pools- Quickie.
Fuel assemblies ‘cool’ here for 10-20 years*
Non linear cooling rate.



Blue Glow?
Cherenkov Radiation

*Wikipedia- Spent Fuel Pool

Photo: Earth Magazine

The need for a long term repository- why?

TABLE 8.1 Fission Products Requiring Long-Term Isolation

Fission Product	*Half-Life (years)*	*Activity Discharged Annually from a 1000 MW PWR Reactor (Ci/y)*
Sr-90	28	2.1×10^6
Cs-137	30	2.9×10^6
Se-79	6×10^4	11
Sn-126	1×10^5	15
Tc-99	2.1×10^5	390
Zr-93	1.5×10^6	50
Cs-135	3.0×10^6	8
Pd-107	7×10^6	3
I-129	1.7×10^7	1.0

TABLE 8.2 Most Important Actinides Requiring Long-Term Isolation

Actinide	*Half-Life (years)*
Np-237	2.1×10^6
Pu-239	2.4×10^4
Pu-240	6.6×10^3
Pu-242	3.6×10^5
Am-241	4.6×10^2
Am-243	8.0×10^3

BB&NE.

$t_{1/2}$ or half-life: time required for any given substance to react (or decay) to half of its original amount.

Nuclear decays are UNAFFECTED by external conditions such as temperature, pressure, environment, etc.

TABLE 21.4 ■ The Half-lives and Type of Decay for Several Radioisotopes

	Isotope	Half-life (yr)	Type of Decay
Natural radioisotopes	$^{238}_{92}U$	4.5×10^9	Alpha
	$^{235}_{92}U$	7.0×10^8	Alpha
	$^{232}_{90}Th$	1.4×10^{10}	Alpha
	$^{40}_{19}K$	1.3×10^9	Beta
	$^{14}_{6}C$	5715	Beta
Synthetic radioisotopes	$^{239}_{94}Pu$	24,000	Alpha
	$^{137}_{55}Cs$	30	Beta
	$^{90}_{38}Sr$	28.8	Beta
	$^{131}_{53}I$	0.022	Beta

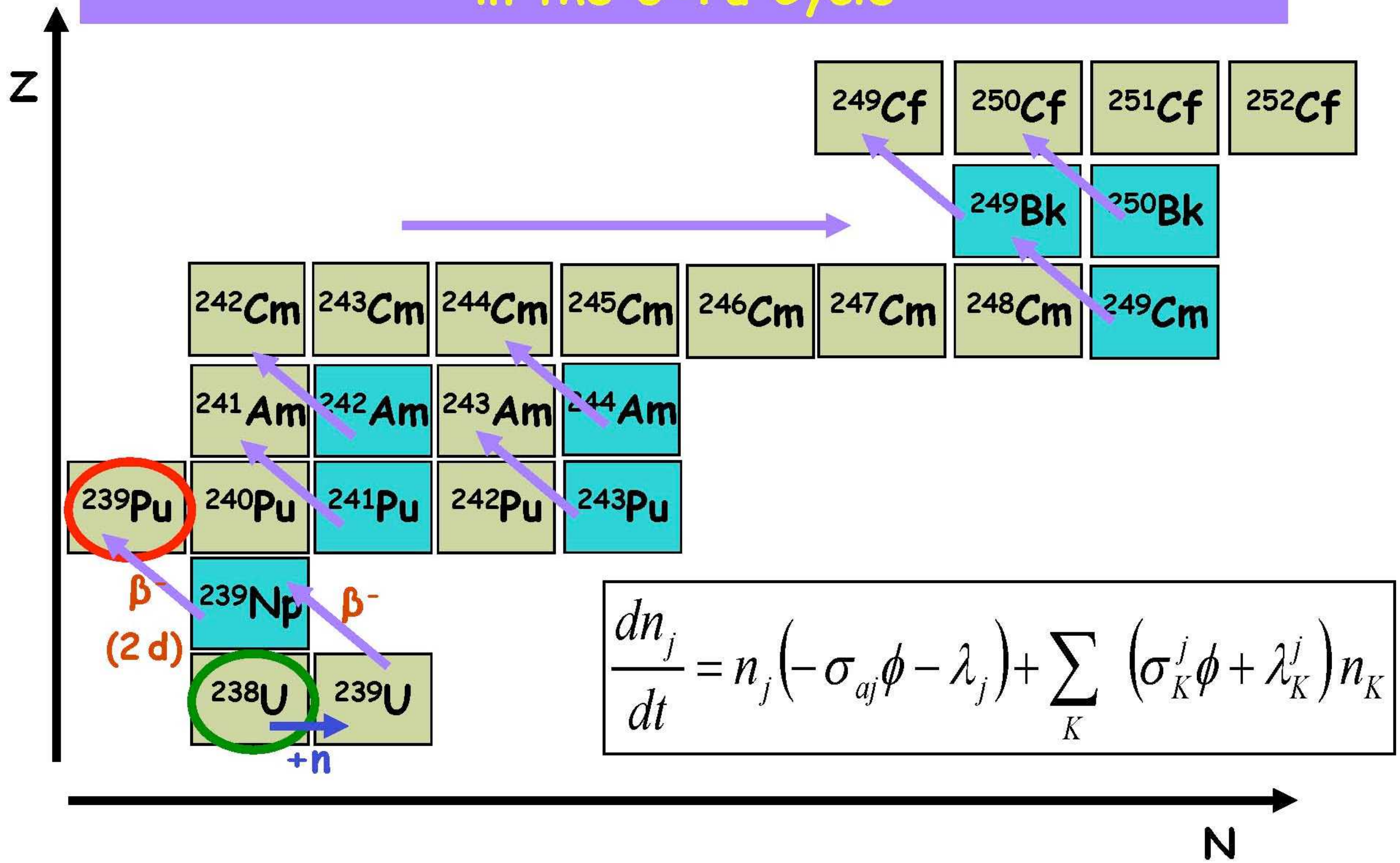
Short term Storage Issues
Heat load

Long-term Storage Issues
Heat load vs. radiation

^{99}Tc ($t_{1/2}$=2.13×10^5 years)
^{129}I ($t_{1/2}$=1.57×10^7 years)

^{137}Cs ($t_{1/2}$=30 years)
^{90}Sr ($t_{1/2}$=28 years)

Paths of Minor actinide formation in the U-Pu Cycle



$$\frac{dn_j}{dt} = n_j\left(-\sigma_{aj}\phi - \lambda_j\right) + \sum_K \left(\sigma_K^j\phi + \lambda_K^j\right)n_K$$

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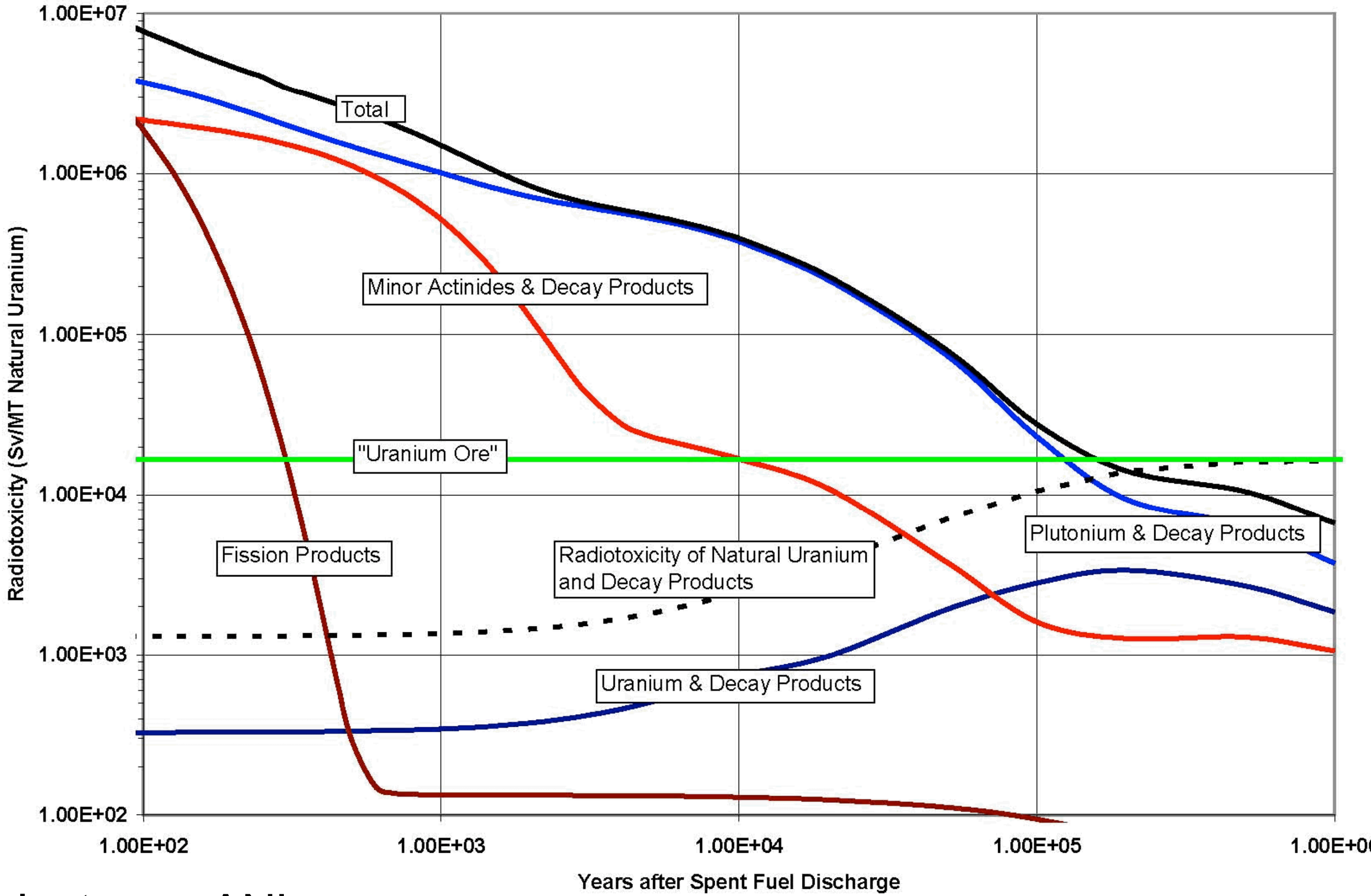
Minor actinides come from decay of U or Pu. Pu came from neutron capture(s).

Spent fuel and radiotoxicity 3/3

The dynamic nature of SNF

Evolution of the radiotoxic inventory, expressed in sievert per tonne of initial heavy metal (uranium) (Sv/ihmt) of UOX spent fuel unloaded at 60 GW d/t, versus time (years).



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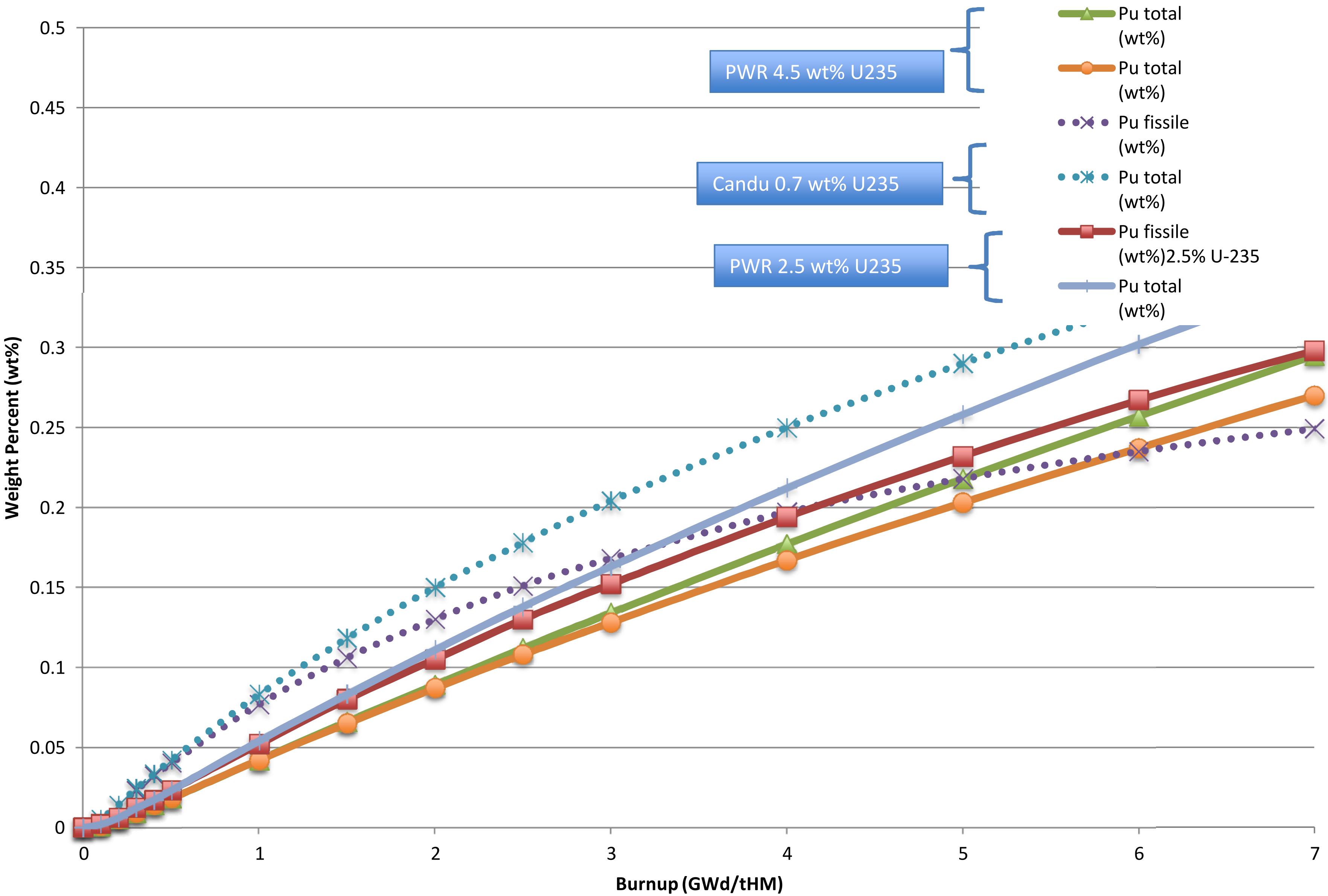
Back-up Slides



Pu total (wt%)
Pu total (wt%)
Pu fissile (wt%)
Pu total (wt%)
Pu fissile (wt%)2.5% U-235
Pu total (wt%)
PWR 4.5 wt% U235
Candu 0.7 wt% U235
PWR 2.5 wt% U235
Weight Percent (wt%)
Burnup (GWd/tHM)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0
1
2
3
4
5
6
7

1 Power Bar = 230 calories

labels are kcal!

$CH_4 + O_2 \longrightarrow CO_2 + 2H_2O \qquad \Delta H = -890 \text{ kJ}$

$1\text{g } CH_4 \times \frac{1 \text{ mol}}{16.06 \text{ g}} = .0622 \text{ moles}$

3.75×10^{22} molecules, BTW

$\frac{890 \text{ kJ}}{1 \text{ mol } CH_4} \times .0622 \text{ mole } CO_2$ 230 kcal

55.36 kJ

$55.36 \text{ kJ} \times \frac{1000 \text{ J}}{1 \text{ kJ}} \times \frac{4.184 \text{ J}}{1 \text{ calorie}}$

$= 2.32 \times 10^5$ cal

$= 2.32 \times 10^2$ kcal

~ 1 Powerbar!

$1\text{g U-235} \times \frac{1 \text{ mol}}{235} = .0043 \text{ moles}$ × 10% efficiency .00043 moles

2.58×10^{21} atoms × 10% " 2.58×10^{20} atoms

For 1 atom:

92 protons × 1.00728 amu

143 n × 1.00866 amu

236.90814

Measured Mass wikipedia

235.04393

$1.8642 \text{ amu} \times \frac{1.66054 \times 10^{-24} \text{ g}}{1 \text{ amu}} \times \frac{1 \text{ kg}}{1000 \text{ g}} = 3.0956 \times 10^{-27} \text{ kg}$

Bad calc under here

nucleus

atoms

0000551

Revised 8/29/14

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3\,^{1}_{0}n$$

using observed masses from Wiki

$$235.043930 + 1.00866 = 236.05259$$

$$140.91441 + 91.92615 + 3(1.00866) = 235.86654$$

$$236.05259 \longrightarrow 235.86654$$

$$\Delta M = 0.18605 \text{ amu}$$

$$= 3.08943 \times 10^{-28} \text{ kg}$$

$$\Delta E = \Delta M c^2 = 3.08943 \times 10^{-28} \text{ kg} \cdot (3.0 \times 10^8 \text{ m/s})^2$$

$$= 2.7805 \times 10^{-11} \text{ J/atom}$$

w/ above: 1.0 g U-235 @ 10% fission

$$2.7805 \times 10^{-11} \text{ J/atom} \times 2.58 \times 10^{20} \text{ atoms}$$

$$= 7.174 \times 10^{9} \text{ J} \times \frac{1 \text{ calorie}}{4.184 \text{ J}} \times \frac{1 \text{ kcal}}{1000 \text{ cal}} \times \frac{1 \text{ PB}}{230 \text{ kcal}}$$

7.455×10^{3} Power bars