Nuclear Power

IB PHYSICS | ENERGY PRODUCTION

Remember Binding Energy per Nucleon?

Nuclide	# of p	# of n	Nucleus Mass
Iodine-**127**	**53**	**74**	**126.87544u**

m_e	0.000549u
m_p	1.007276u
m_n	1.008665u
1u	931.5 MeV c^{-2}

53 × 1.007276 u
74 × 1.008665 u

128.026838u – 126.87544u = 1.15140u

Mass Defect

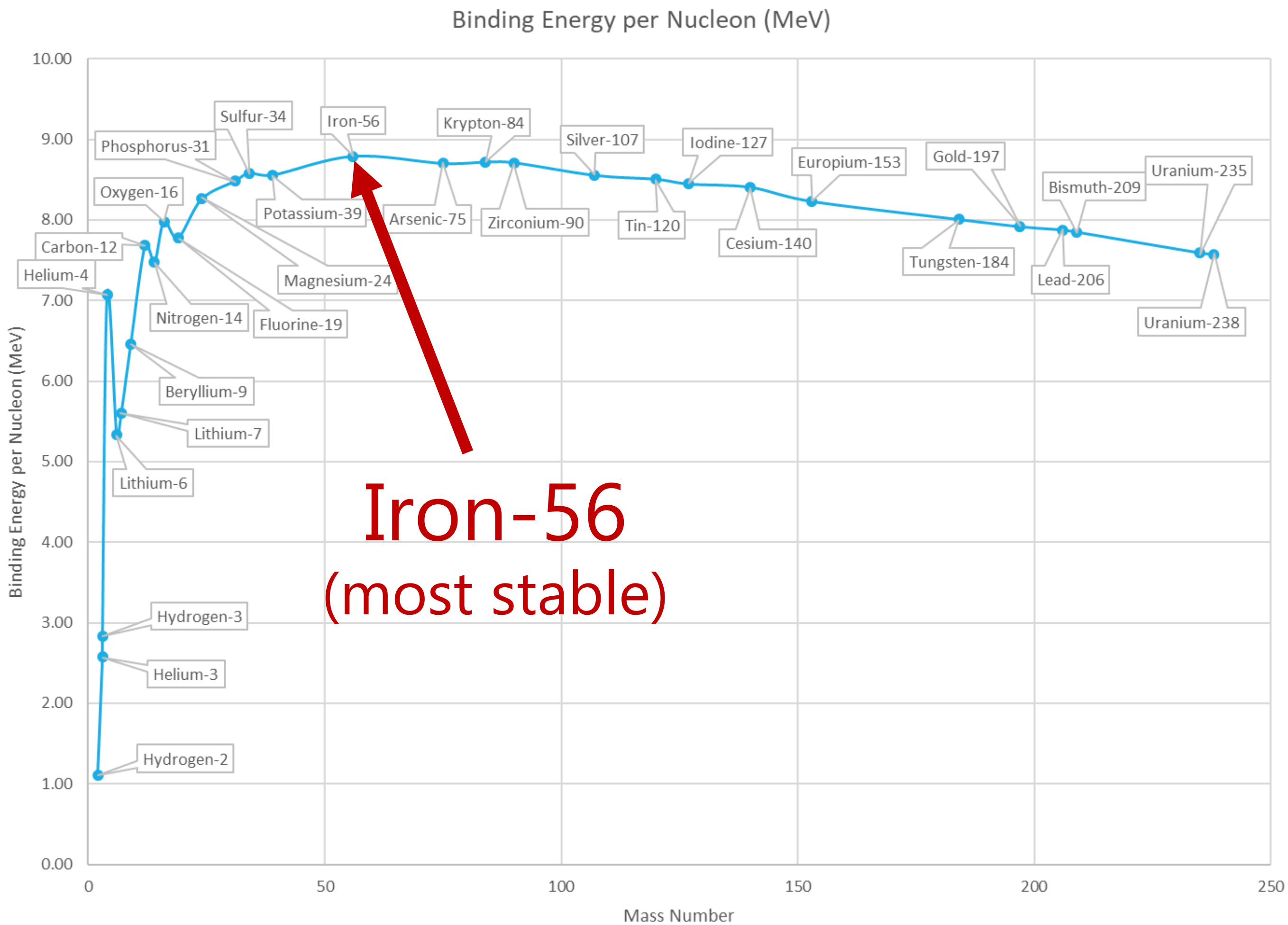
$$1.15140\ u \times \frac{931.5\ MeV\ c^{-2}}{1\ u} = 1072.53\ MeV\ c^{-2}$$

Convert mass to MeV c^{-2}

$$E = mc^2 = (1072.53\ MeV\ \cancel{c^{-2}})\cancel{c^2} = 1072.53\ MeV$$

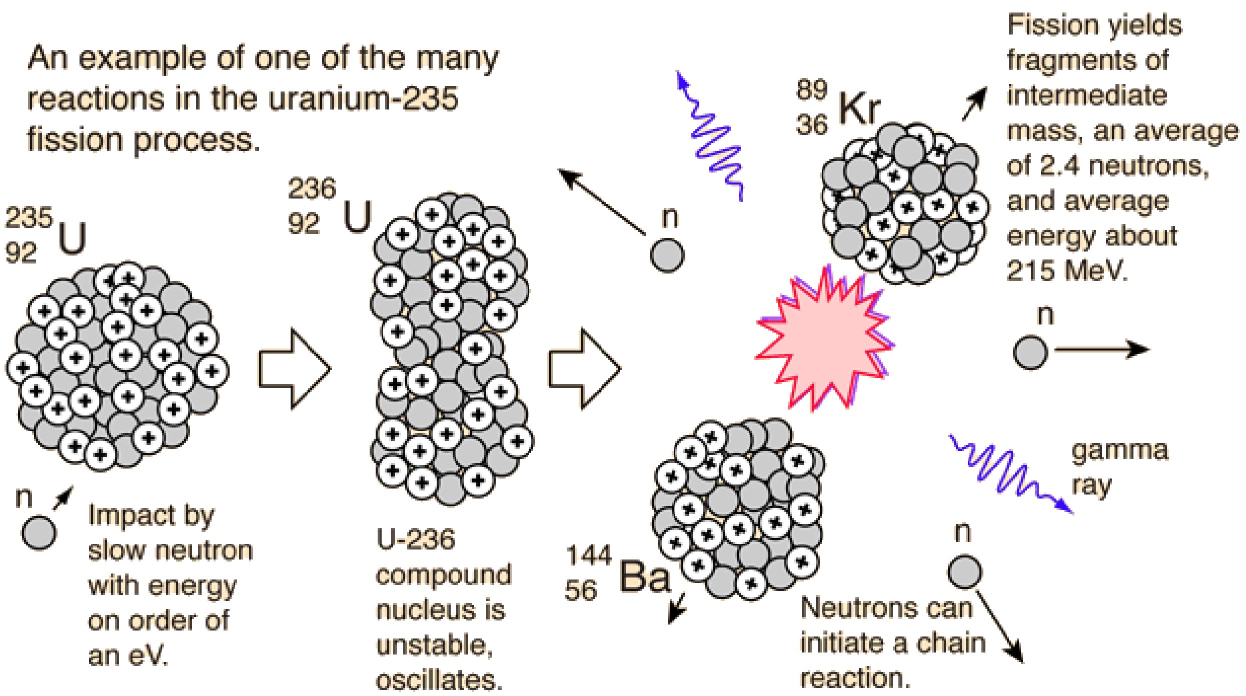
$$1072.53\ MeV / 127 = \boxed{\mathbf{8.45\ MeV\ per\ Nucleon}}$$

Binding Energy per Nucleon



Fission

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{236}_{92}U \rightarrow ^{144}_{56}Ba + ^{89}_{36}Kr + \underline{\ 3\ }\ ^{1}_{0}n$$



IB Physics Data Booklet

Fundamental constants

Quantity	Symbol	Approximate value
Speed of light in vacuum	c	$3.00 \times 10^{8}\ \mathrm{m\ s^{-1}}$
Planck's constant	h	$6.63 \times 10^{-34}\ \mathrm{J\ s}$
Elementary charge	e	$1.60 \times 10^{-19}\ \mathrm{C}$
Electron rest mass	m_e	$9.110 \times 10^{-31}\ \mathrm{kg} = 0.000549\ \mathrm{u} = 0.511\ \mathrm{MeV\ c^{-2}}$
Proton rest mass	m_p	$1.673 \times 10^{-27}\ \mathrm{kg} = 1.007276\ \mathrm{u} = 938\ \mathrm{MeV\ c^{-2}}$
Neutron rest mass	m_n	$1.675 \times 10^{-27}\ \mathrm{kg} = 1.008665\ \mathrm{u} = 940\ \mathrm{MeV\ c^{-2}}$
Unified atomic mass unit	u	$1.661 \times 10^{-27}\ \mathrm{kg} = 931.5\ \mathrm{MeV\ c^{-2}}$
Solar constant	S	$1.36 \times 10^{3}\ \mathrm{W\ m^{-2}}$
Fermi radius	R_0	$1.20 \times 10^{-15}\ \mathrm{m}$

Fission

$$ {}^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{93}_{37}\mathrm{Rb} + {}^{141}_{55}\mathrm{Cs} + 2\,{}^{1}_{0}\mathrm{n} + {}^{0}_{0}\gamma $$

1.675 $\times 10^{-27}$ kg	390.173 $\times 10^{-27}$ kg	154.248 $\times 10^{-27}$ kg	233.927 $\times 10^{-27}$ kg	2 × 1.675 $\times 10^{-27}$ kg

391.848 $\times 10^{-27}$ kg > 391.525 $\times 10^{-27}$ kg

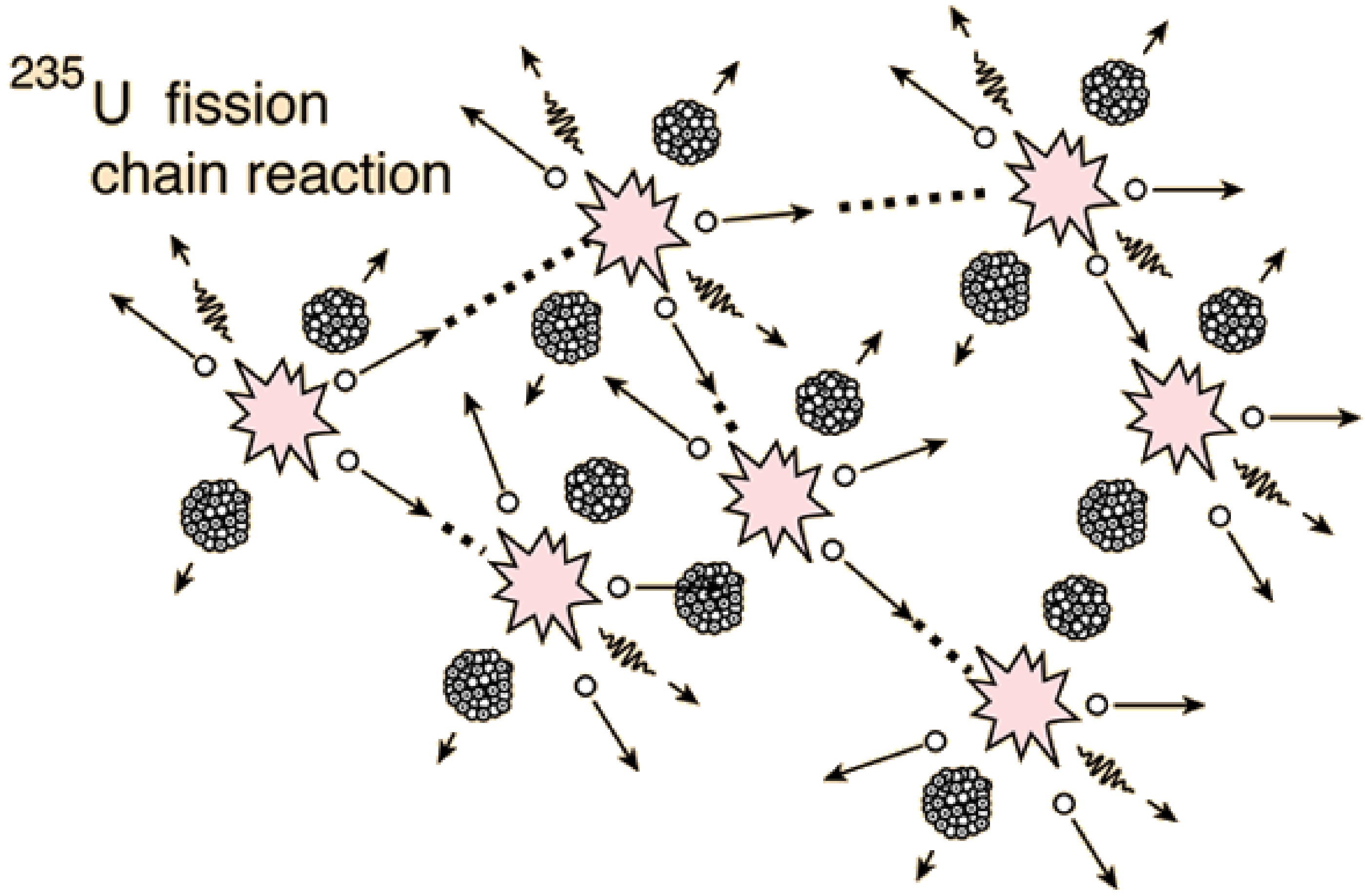
391.848 $\times 10^{-27}$ kg - 391.525 $\times 10^{-27}$ kg = 0.323 $\times 10^{-27}$ kg

$$0.323 \times 10^{-27}\ kg \times \frac{1\ u}{1.661 \times 10^{-27}\ kg} = \mathbf{0.19446\ u}$$

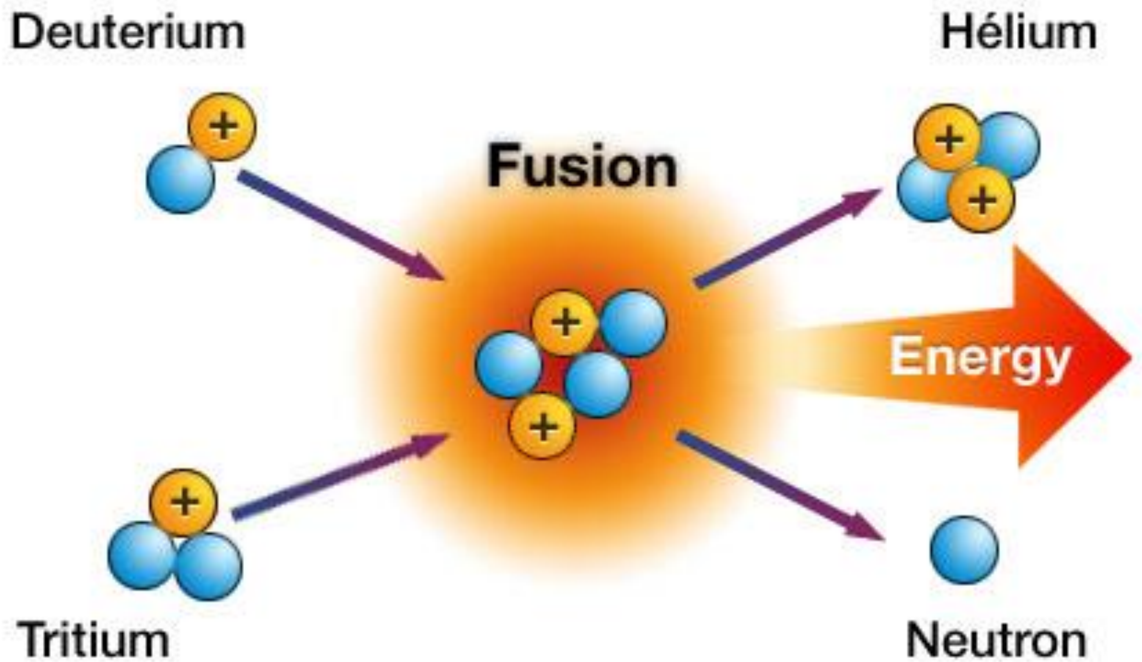
$$0.19446\ u \times 931.5 = \mathbf{181.14\ MeV}$$

Mass Defect	0.19446 u	Energy Released	181.14 MeV

Chain Reaction



Fusion



Fusion

Hydrogen-2	2.0141 u
Helium-3	3.0161 u
Neutron	1.0087 u

$$^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n}$$

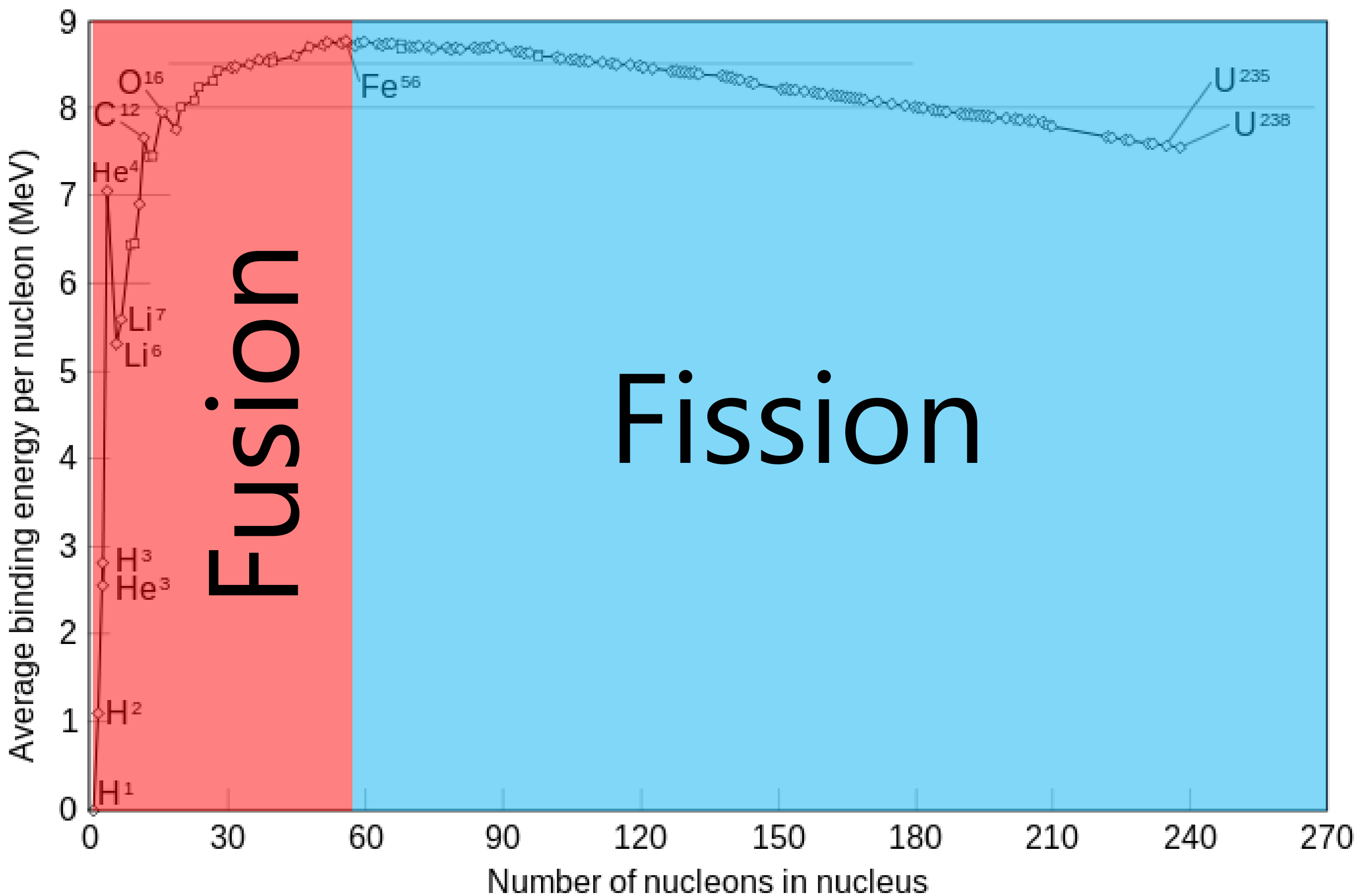
(2.0141 u + 2.0141 u) – (3.0161 u + 1.0087 u) = 0.0034 u

4.0282 u   4.0248 u

0.0034 u × 931.5 = 3.1671 MeV

Mass Defect	0.0034 u	Energy Released	3.1671 MeV

Fusion vs. Fission



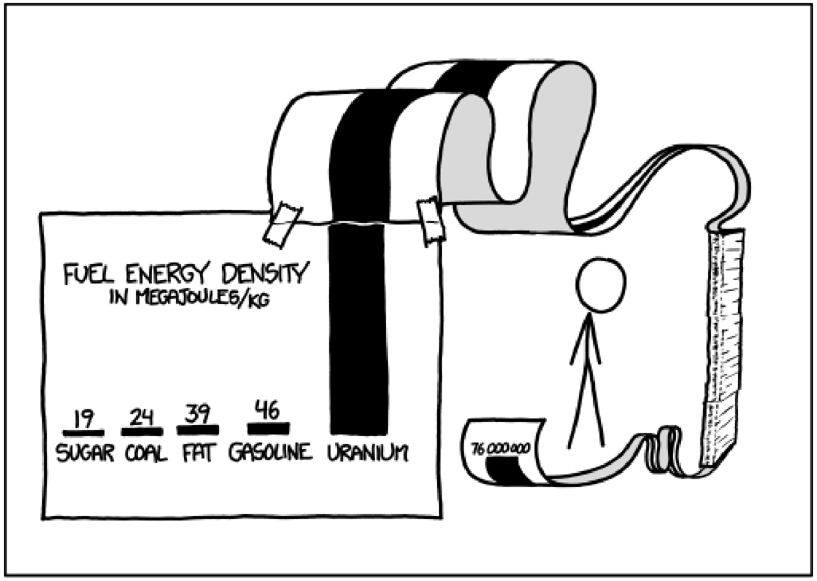
Energy Density

Specific Energy = Energy per Unit Mass [J kg^{-1}]

Energy Density = Energy per Unit Volume [J m^{-3}]

$$E_S = \frac{E}{m}$$

$$E_D = \frac{E}{V}$$



SCIENCE TIP: LOG SCALES ARE FOR QUITTERS WHO CAN'T FIND ENOUGH PAPER TO MAKE THEIR POINT *PROPERLY*.

Uranium

Uranium found in the earth's crust is primarily comprised of two different isotopes of Uranium

$^{238}_{92}U$	$^{235}_{92}U$
Uranium-238	Uranium-235
99.3%	0.7%

Where does the uranium used by the US come from?

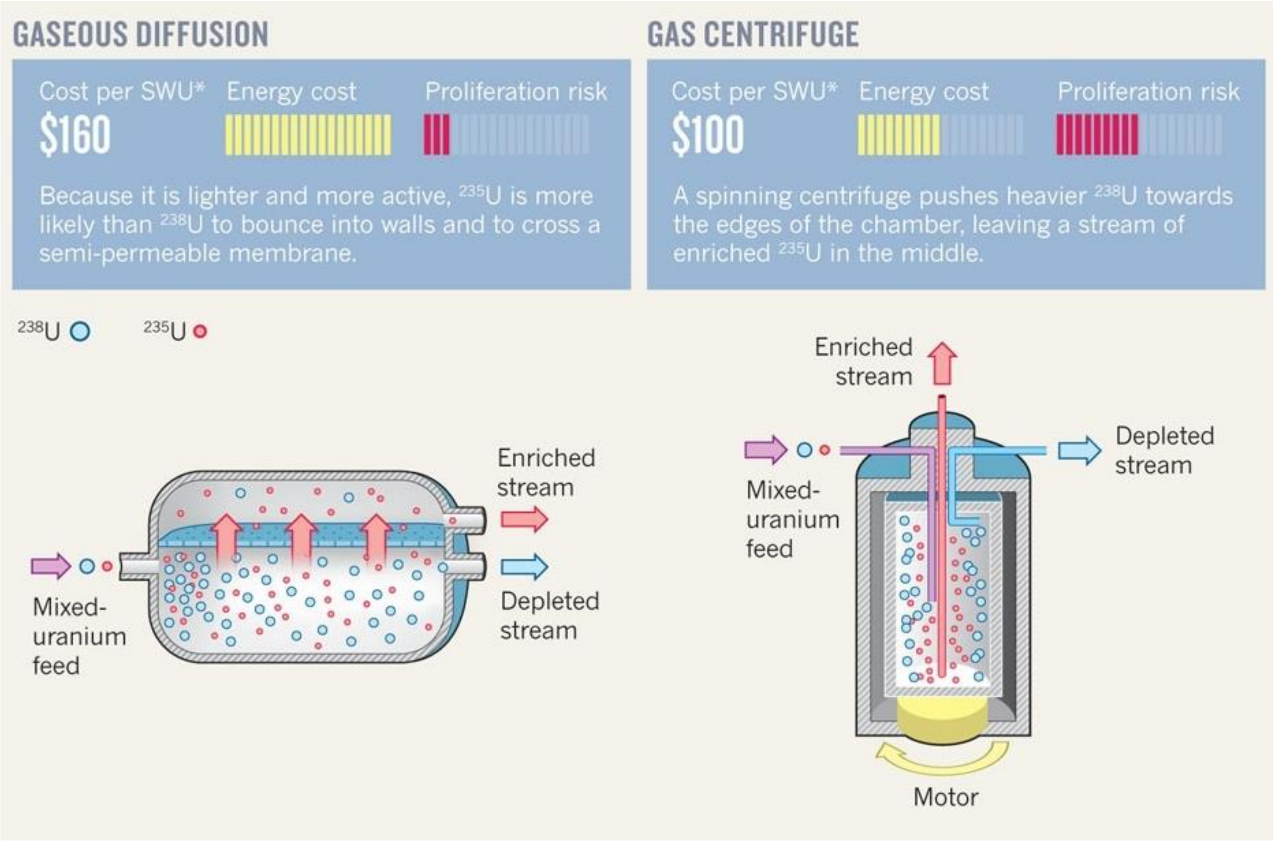
37%	Kazakhstan, Russia, and Uzbekistan
30%	Canada
17%	Australia
10%	Malawi, Namibia, Niger, and South Africa
6%	United States

Yellowcake Uranium

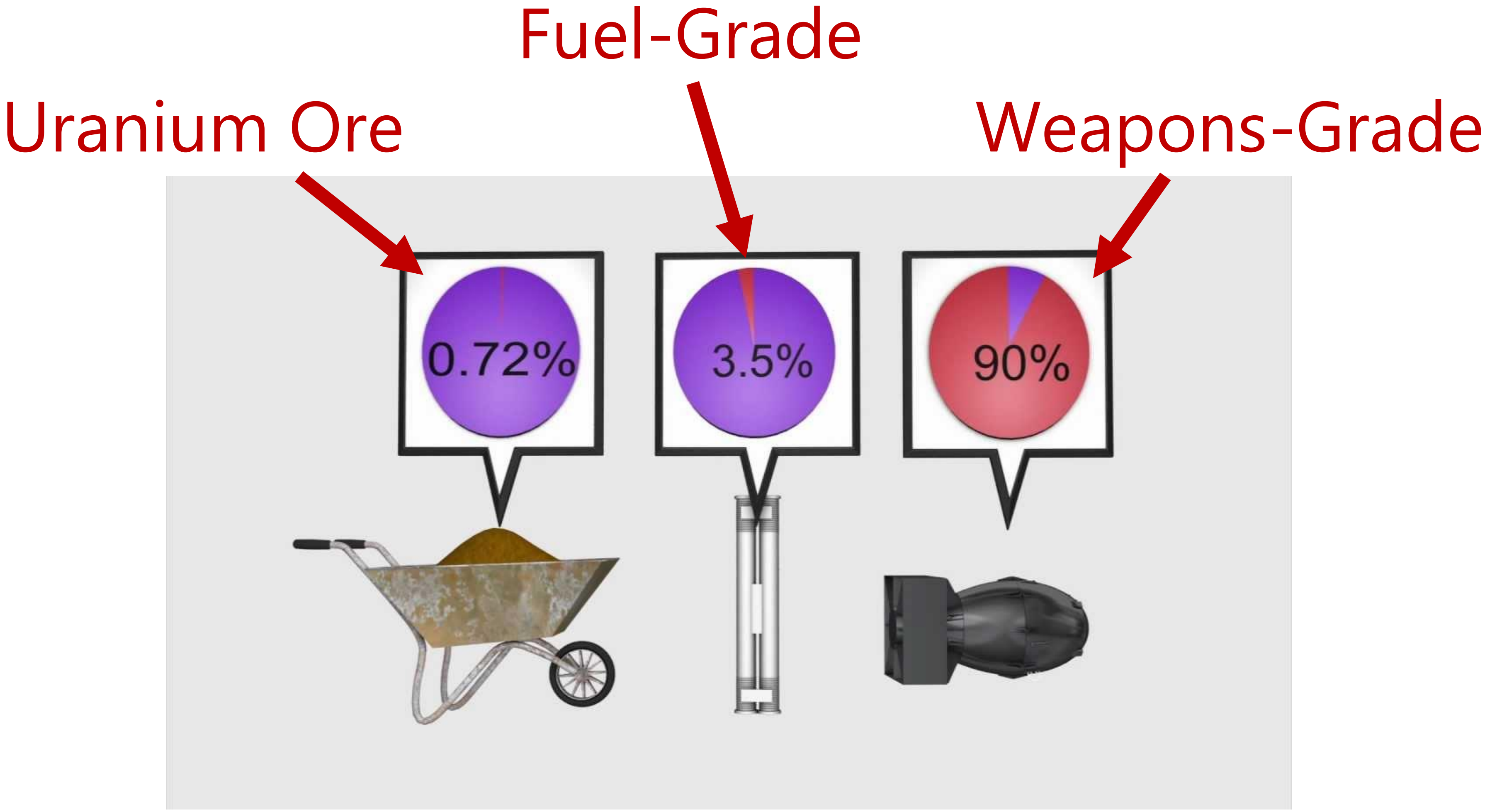
Uranium ore is milled into a U_3O_8 powder known as **yellowcake**

Uranium Enrichment

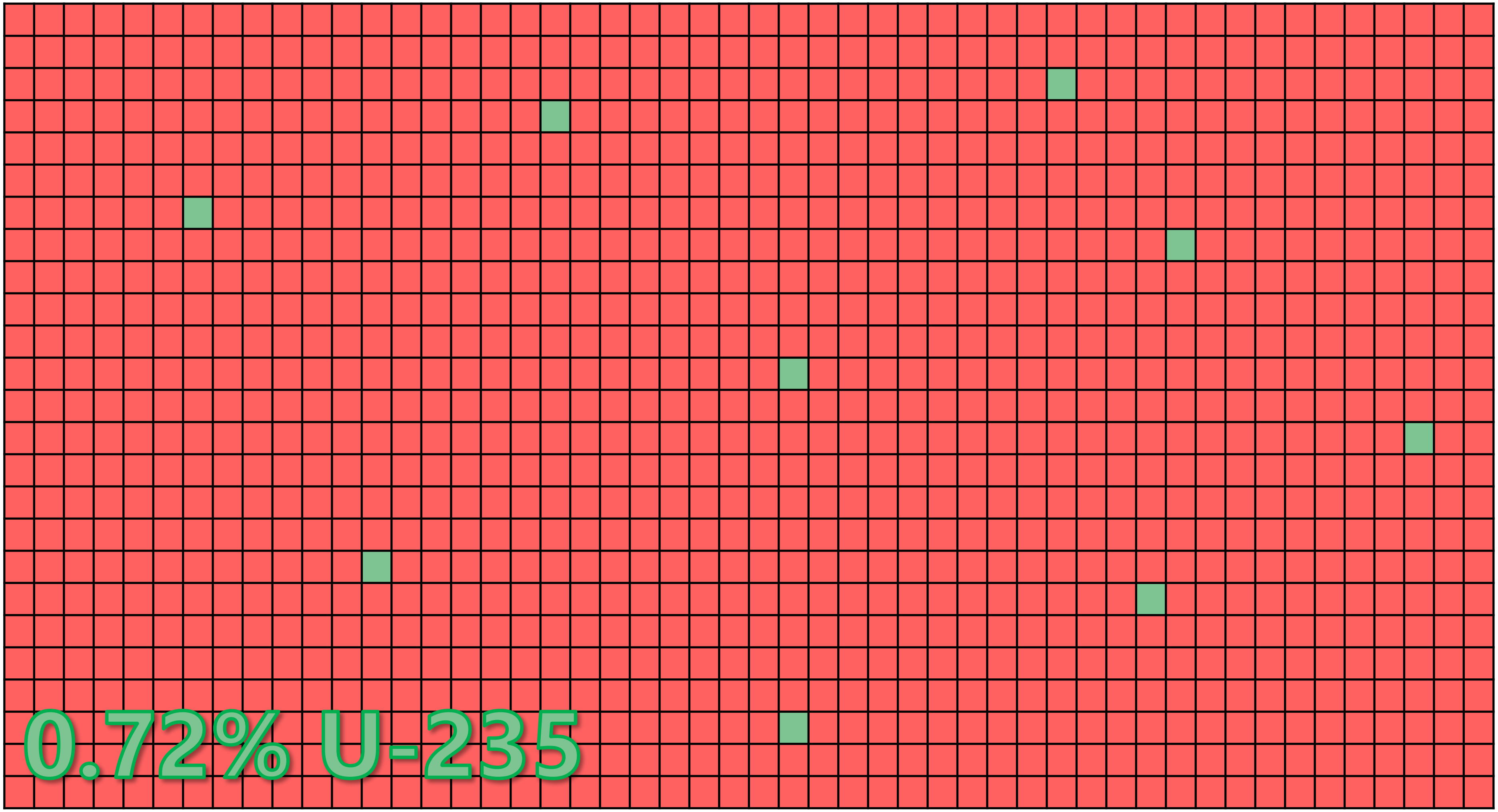
The yellowcake is converted into Uranium Hexafluoride gas and enriched to create a mixture with a higher percentage of U-235 nuclides



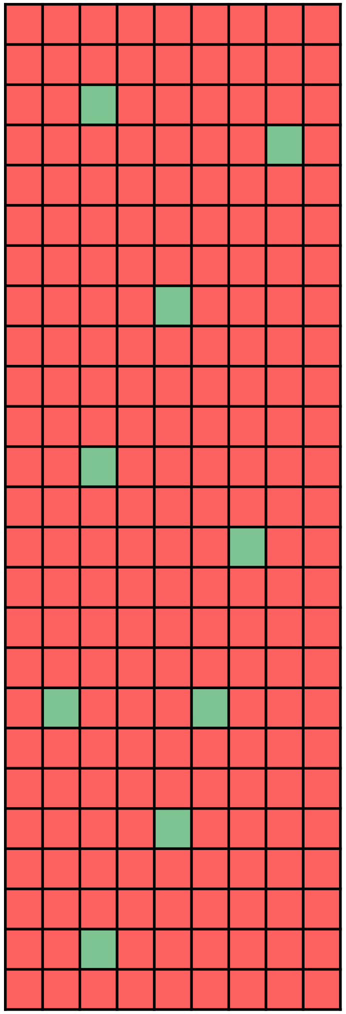
Uranium Enrichment



Uranium Enrichment



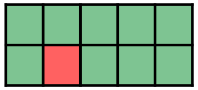
Uranium Enrichment



4% U-235

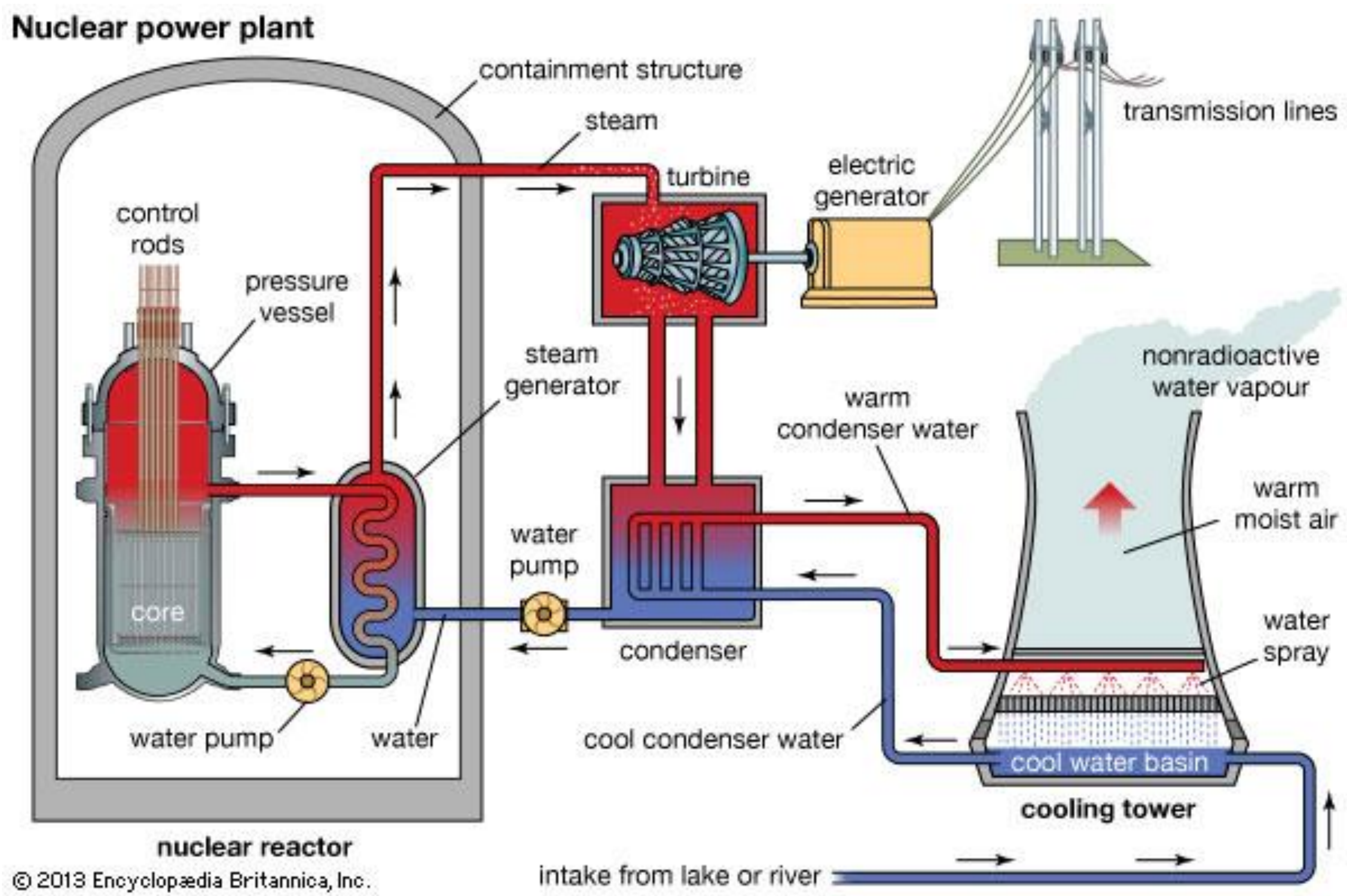
Uranium Enrichment

90% U-235



Uranium Fuel Rods

Nuclear Power Plant

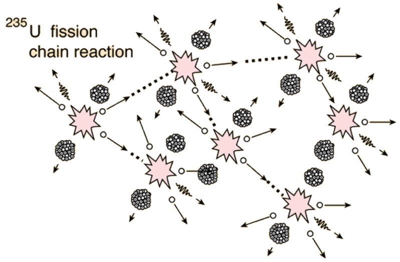


Chain Reaction

For a controlled chain reaction, each reaction should trigger one other reaction

Important Factors

- Only about 4% of the fuel is actually comprised of fissionable U-235 atoms
- Neutrons have to traveling relatively slowly to be captured by a U-235 atom



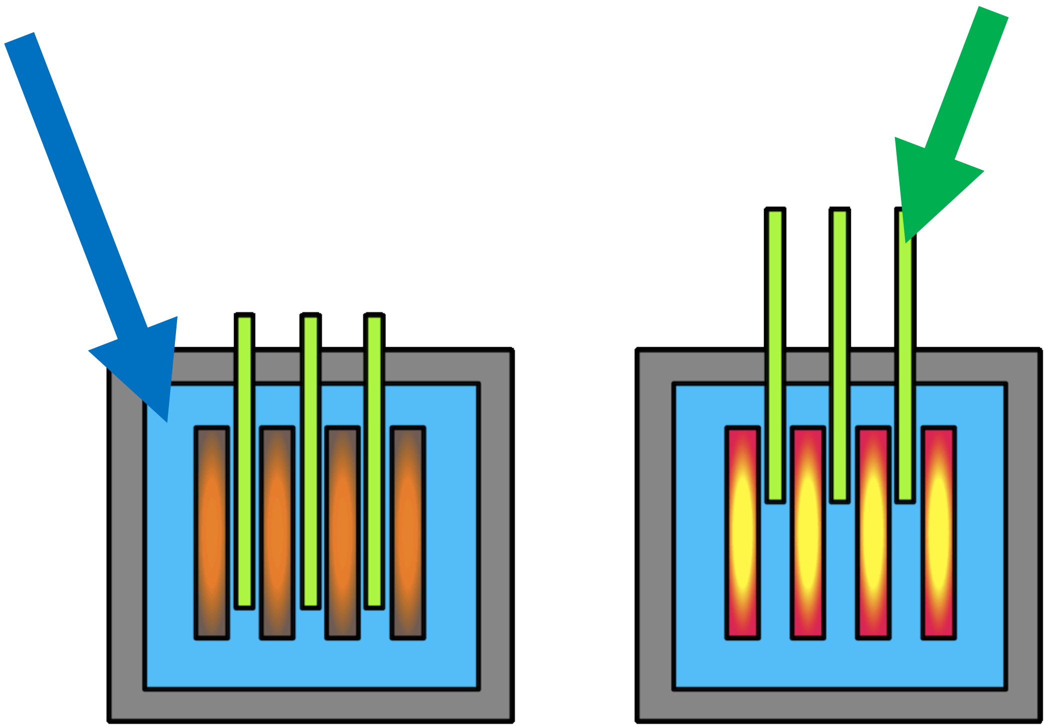
Chain Reaction

Moderator - water or graphite

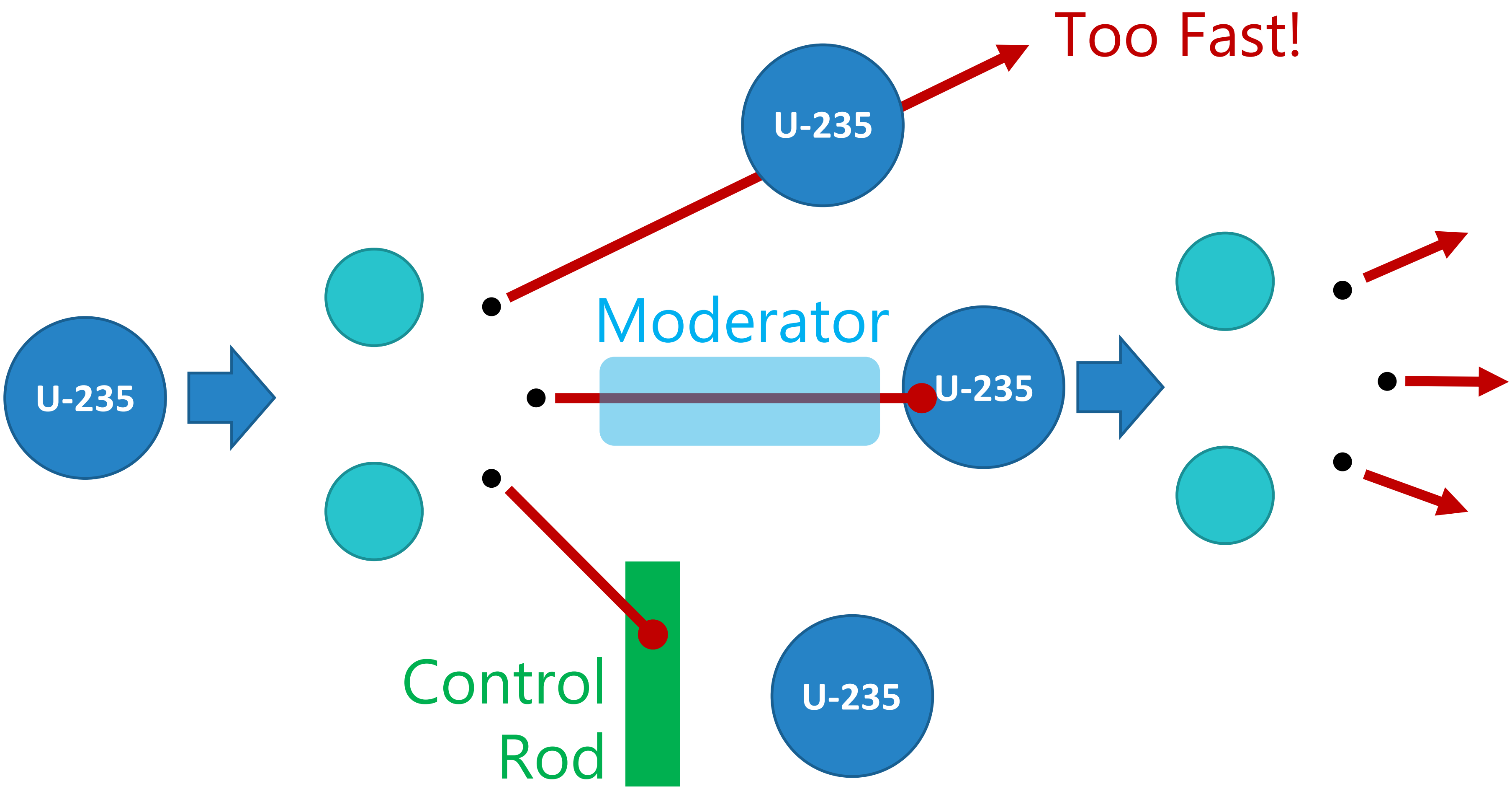
Slows down neutrons

Control Rods - boron

Absorbs neutrons

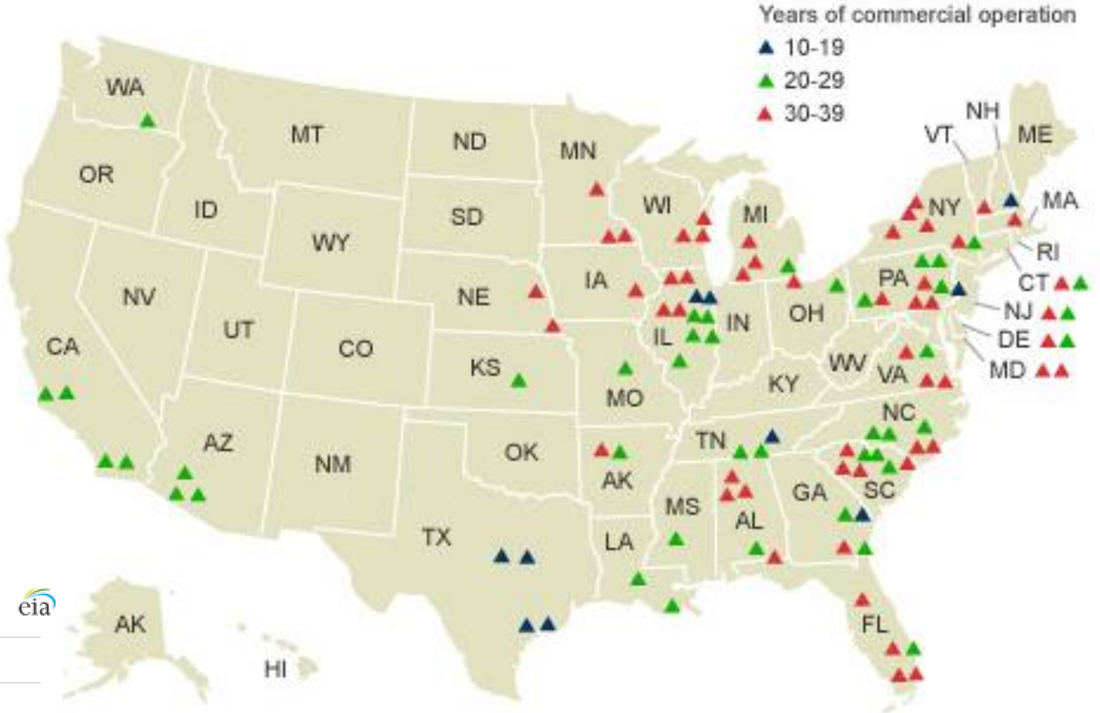


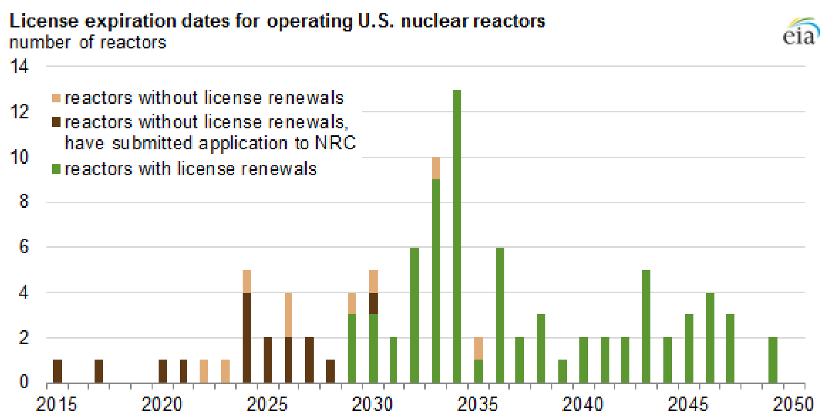
Chain Reaction



Nuclear Power Plants

The US currently has about 100 nuclear power plants in operation representing about 20% of the total generated electricity

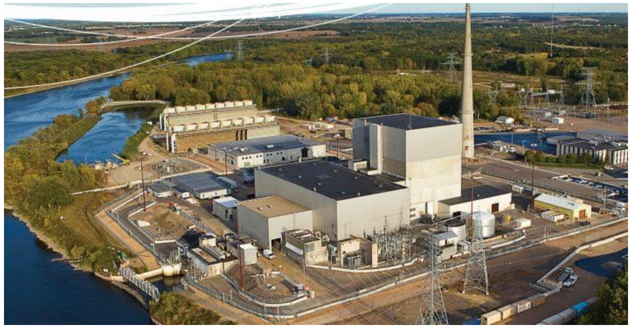




Nuclear Power Plants are retired after 60 years so the forecast is a decreasing number in the coming years…

Nuclear Power in Minnesota

Monticello Nuclear Power Plant | Monticello, MN



Prairie Island Nuclear Power Plant | Red Wing, MN

Nuclear Waste

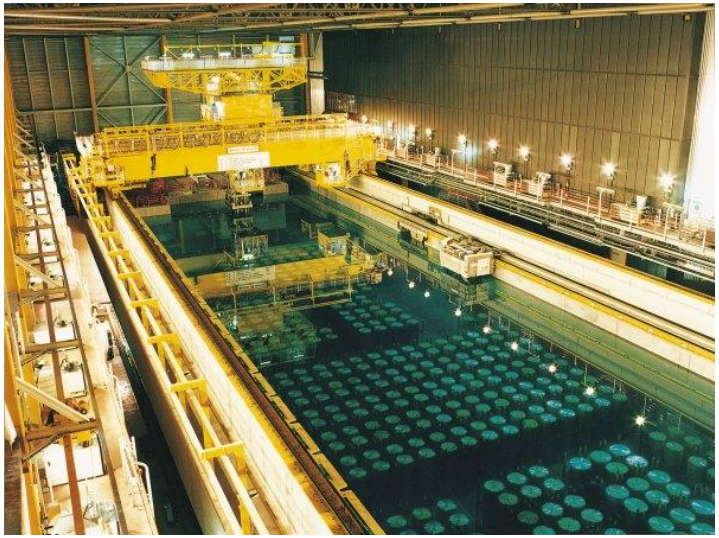
After the fuel can no longer be used to efficiently create electricity, the spent nuclear waste needs to be disposed of.

Isotope	Half Life
Strontium-90	28 years
Caesium-137	30 years
Plutonium-239	24,000 years
Caesium-135	2.3 million years
Iodine-129	15.7 million years

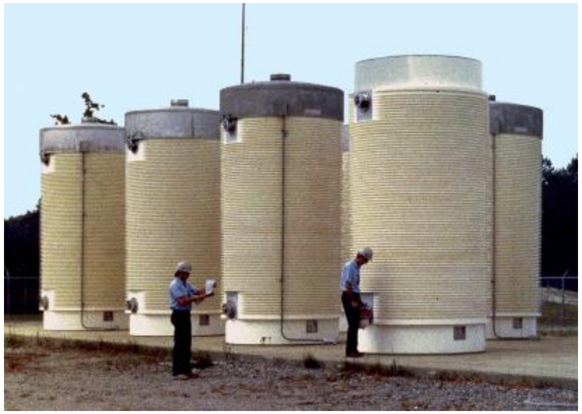
Radioactive Isotopes found in spent nuclear fuel

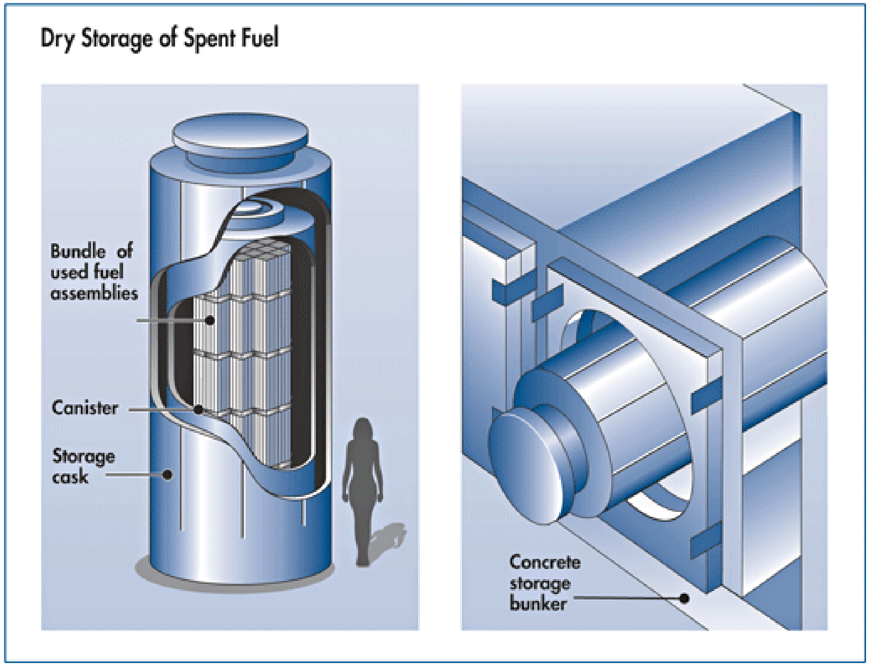
How long until it's safe?

Nuclear Waste - Disposal



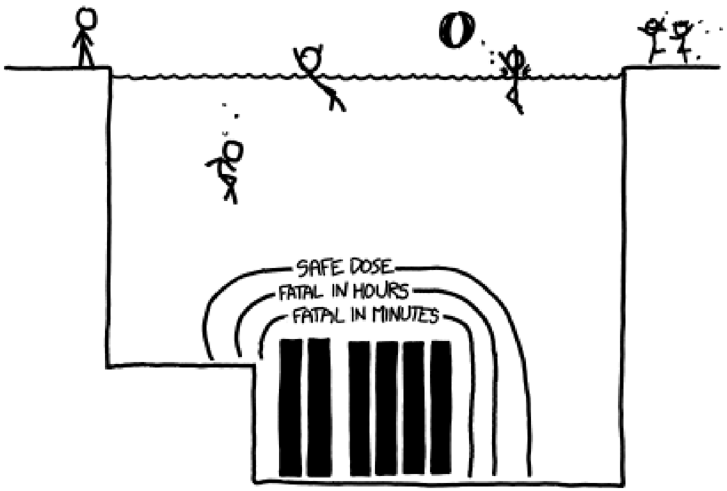
Most of the waste is stored onsite





Nuclear Waste - Disposal

what if?



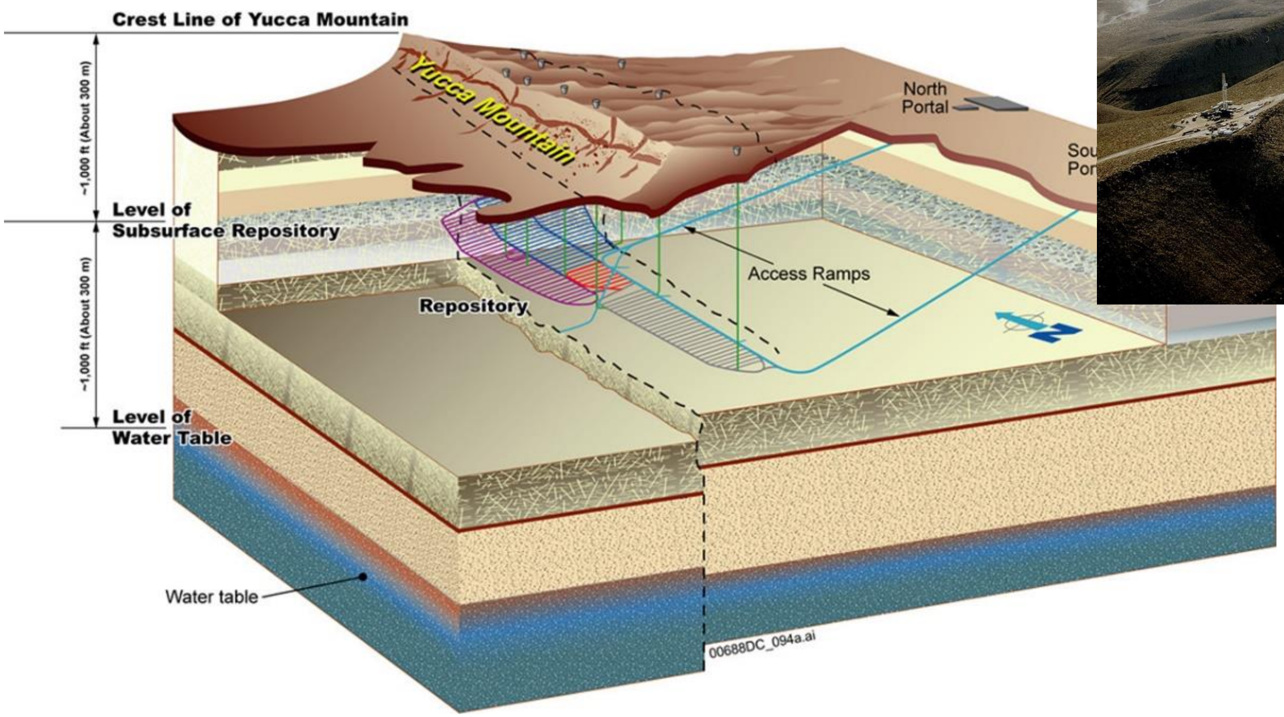
Spent Fuel Pool

What if I took a swim in a typical spent nuclear fuel pool? Would I need to dive to actually experience a fatal amount of radiation? How long could I stay safely at the surface?

—Jonathan Bastien-Filiatrault

Nuclear Waste - Disposal

Yucca Mountain



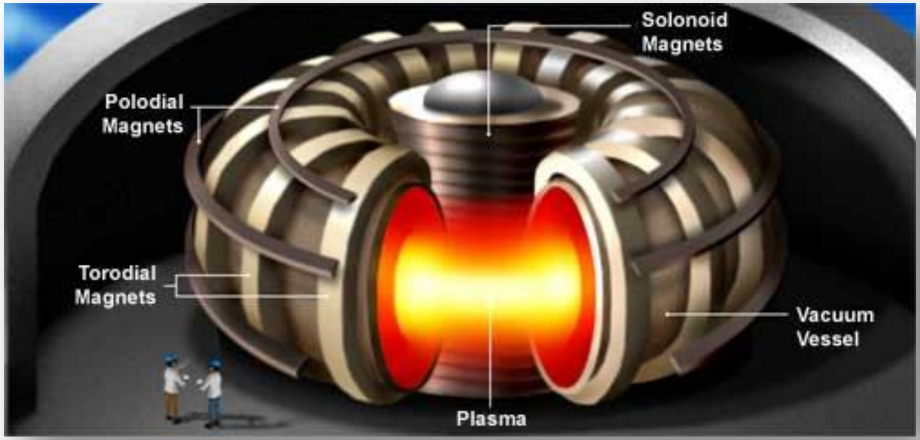
Nuclear Waste - Disposal

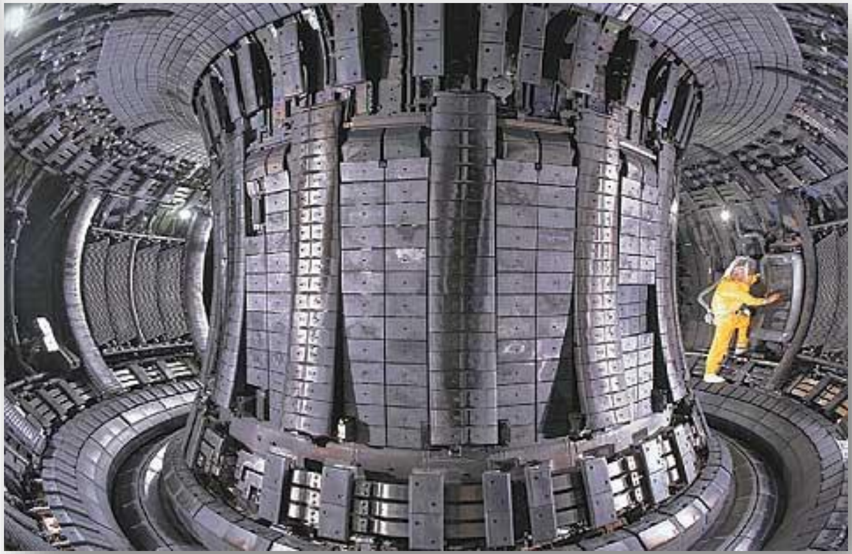
Any better options out there???

Ideas	Examples
Long-term above ground storage	•Investigated in France, Netherlands, Switzerland, UK, and USA. •Not currently planned to be implemented anywhere.
Disposal in outer space (proposed for wastes that are highly concentrated)	•Investigated by USA. •Investigations now abandoned due to cost and potential risks of launch failure.
Rock-melting (proposed for wastes that are heat-generating)	•Investigated by Russia, UK, and USA. •Not implemented anywhere. •Laboratory studies performed in the UK.
Disposal at subduction zones	•Investigated by USA. •Not implemented anywhere. •Not permitted by international agreements.
Sea disposal	•Implemented by Belgium, France, Germany, Italy, Japan, Netherlands, Russia, South Korea, Switzerland, UK, and USA. •Not permitted by international agreements.
Sub seabed disposal	•Investigated by Sweden and UK (and organisations such as the OECD Nuclear Energy Agency). •Not implemented anywhere. •Not permitted by international agreements.
Disposal in ice sheets (proposed for wastes that are heat-generating)	•Investigated by USA. •Rejected by countries that have signed the Antarctic Treaty or committed to providing solutions within national boundaries.
Deep well injection (for liquid wastes)	•Implemented in Russia for many years for LLW and ILW. •Investigations abandoned in the USA in favour of deep geological disposal of wastes in solid form.

Fusion as a Power Source

Fusion reactions have been successfully controlled using strong magnetic fields but the energy used to run the magnets exceeds the energy released in the reaction…





Conditions for Fusion

It's significantly more difficult to create fusion reactions here on earth

- High Pressure
- High Temperature