Nuclear Energy

- what is it?

-how does it work?

-why should we have it (or not..)?

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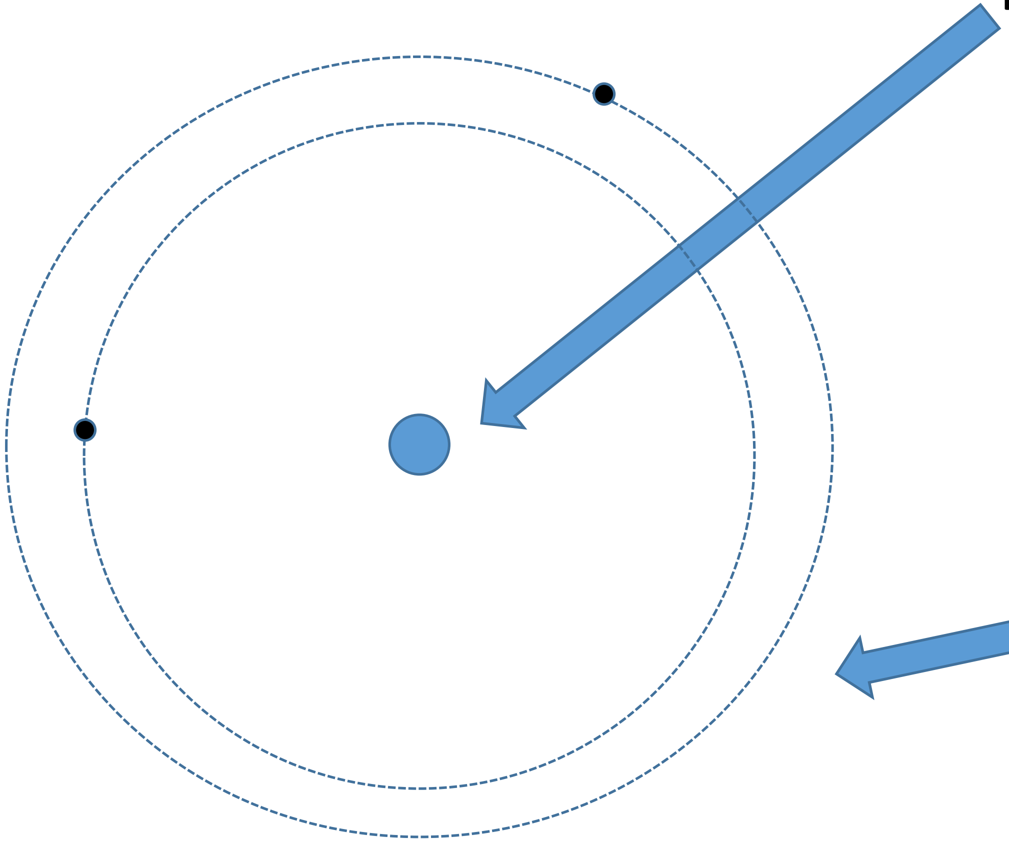
Basic Stuff

- All (normal) matter is composed of atoms



Nucleus

Protons (positive electric charge) +
Neutrons (no electric charge)

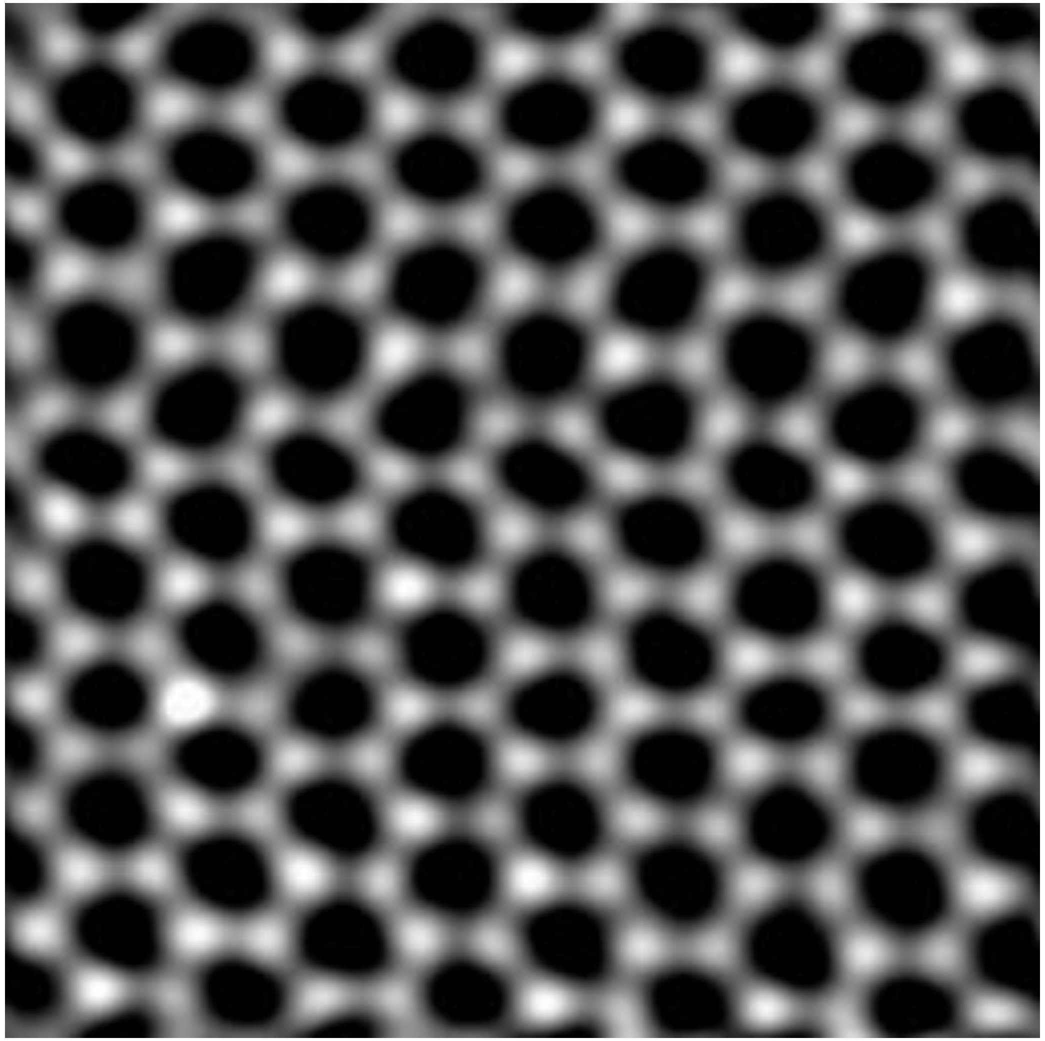
Strong nuclear force

Electrons

- Negative electric charges

Chemical reactions involve the outer electrons

A Picture of some Atoms



Graphene atomic lattice

courtesy
of Dr William Pierce

Elements

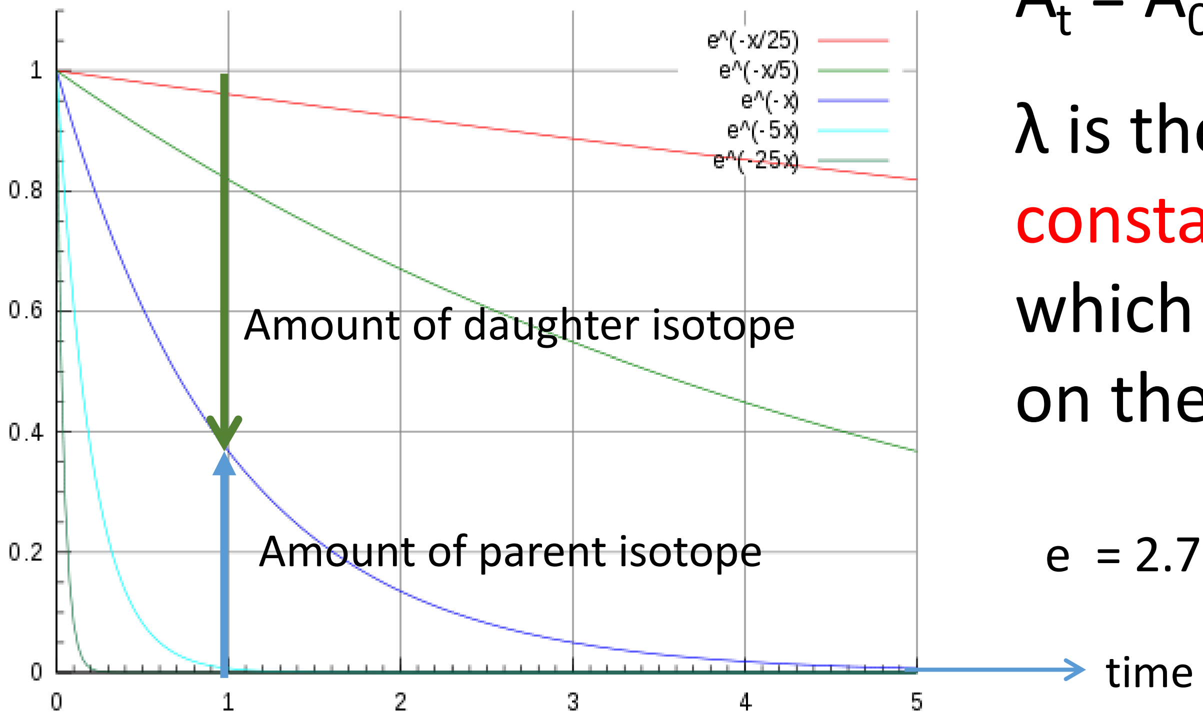
- Number of protons in the nucleus defines the chemical element

Hydrogen	1 proton
Helium	2 protons + 2 neutrons
Boron	6 protons + 6 neutrons
Iron	26 protons + 30 neutrons
Mercury	80 protons + 120 neutrons
Uranium	92 protons + 146 neutrons

Isotopes

- Nuclei of the same element can exist in two or more forms – isotopes
  - same number of protons, more or fewer neutrons
- Radioactive isotopes are unstable – nucleus decays into another element
  - and emits a high energy particle: ionizing radiation (radioactivity) (dangerous)
  - Alpha particle (helium nucleus)
  - Beta particle (electron)
- Rate of decay is unchanging over time and unaffected by heat, pressure or chemical reactions
  - at least on Earth

Radioactive decay



$A_t = A_0\, e^{-\lambda t}$

λ is the “decay constant” which depends on the isotope

$e = 2.718.....$

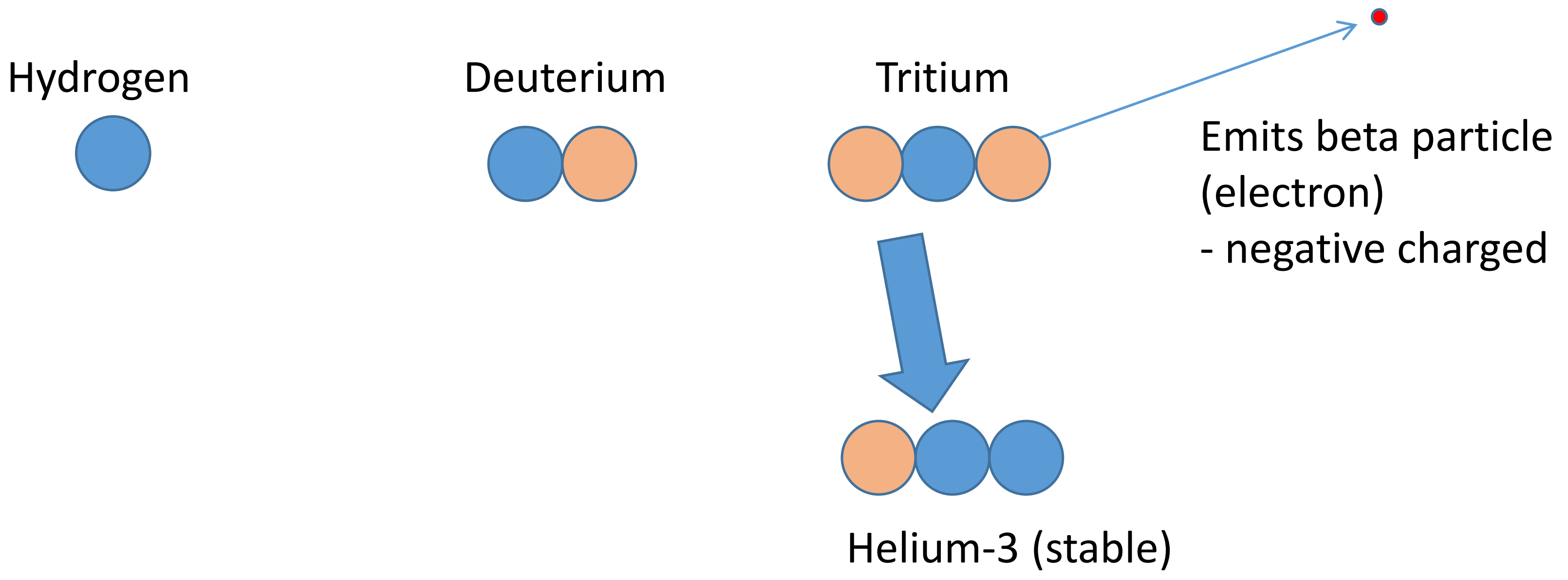
H can be from milliseconds to billions of years

It’s easier to think of the “half life” - time for half the original amount of isotope to decay

$H = \log_e 2 / \lambda$

$H = 0.693 / \lambda$

Example: Deuterium and Tritium

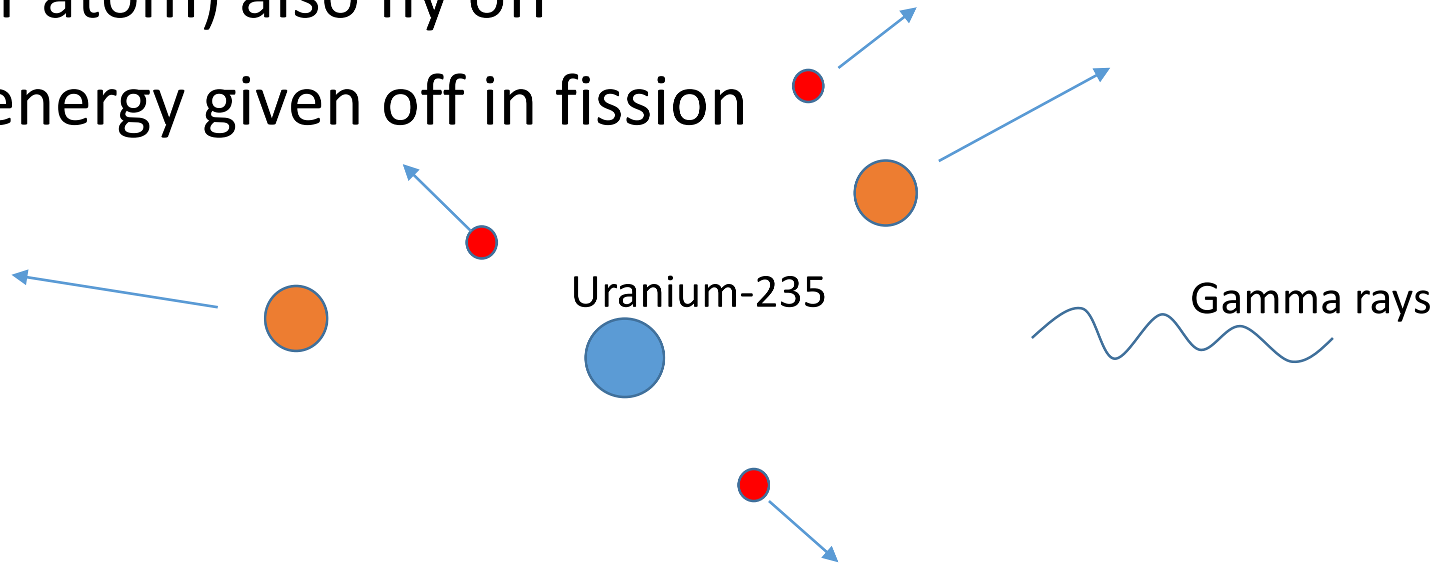


Fission

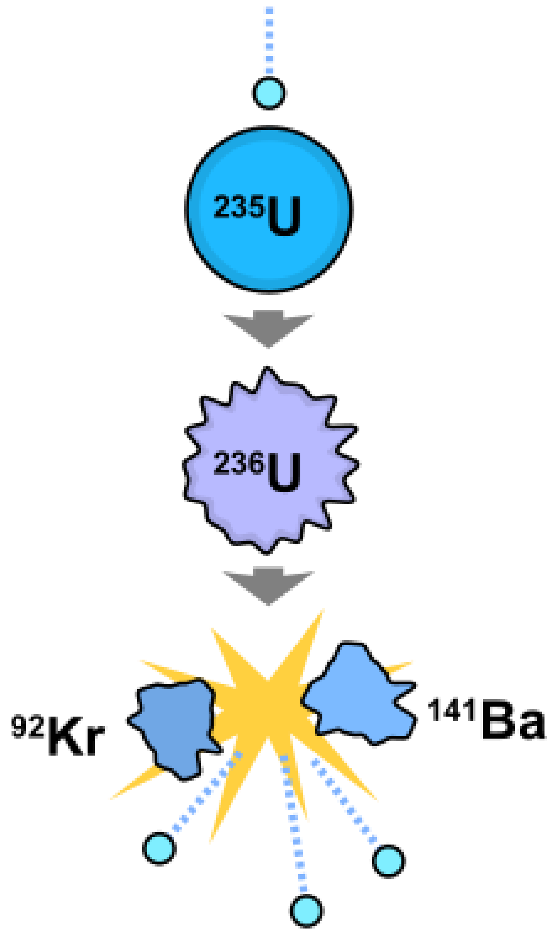
- Uranium decays into lead (eventually) by normal radioactivity
- But - occasionally a Uranium nucleus can split into 2 more or less equally sized fragments
- This is nuclear fission (also with Thorium, Plutonium-239..)
- Fission products are elements like Iodine-131, Strontium-90.. - all very radioactive
- Spare neutrons (2 or 3 per atom) also fly off
- ENORMOUS amounts of energy given off in fission

Chemical reaction - 1-3 units of energy

Nuclear fission – 200 MILLION units of energy



Another picture



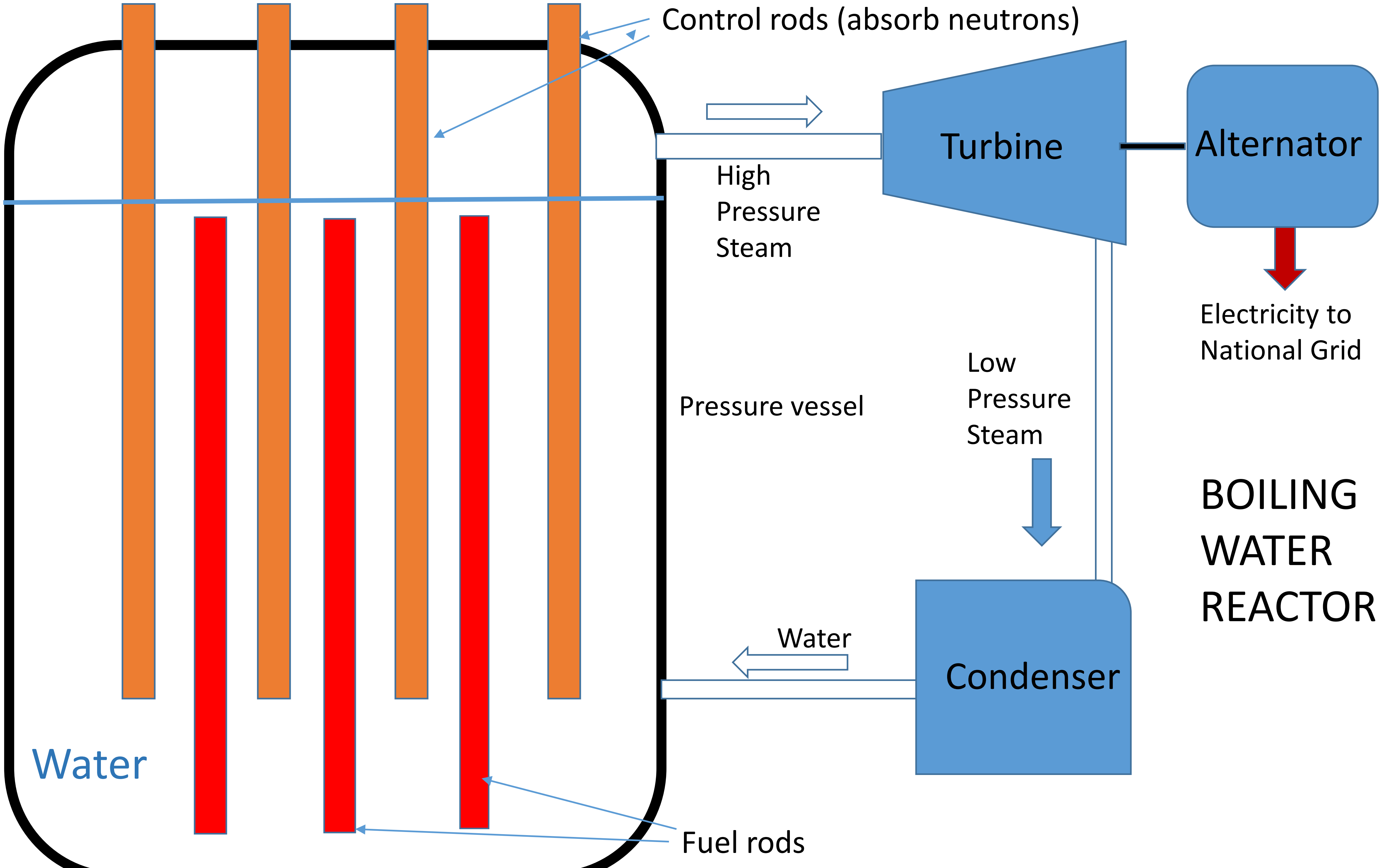
Chain reaction

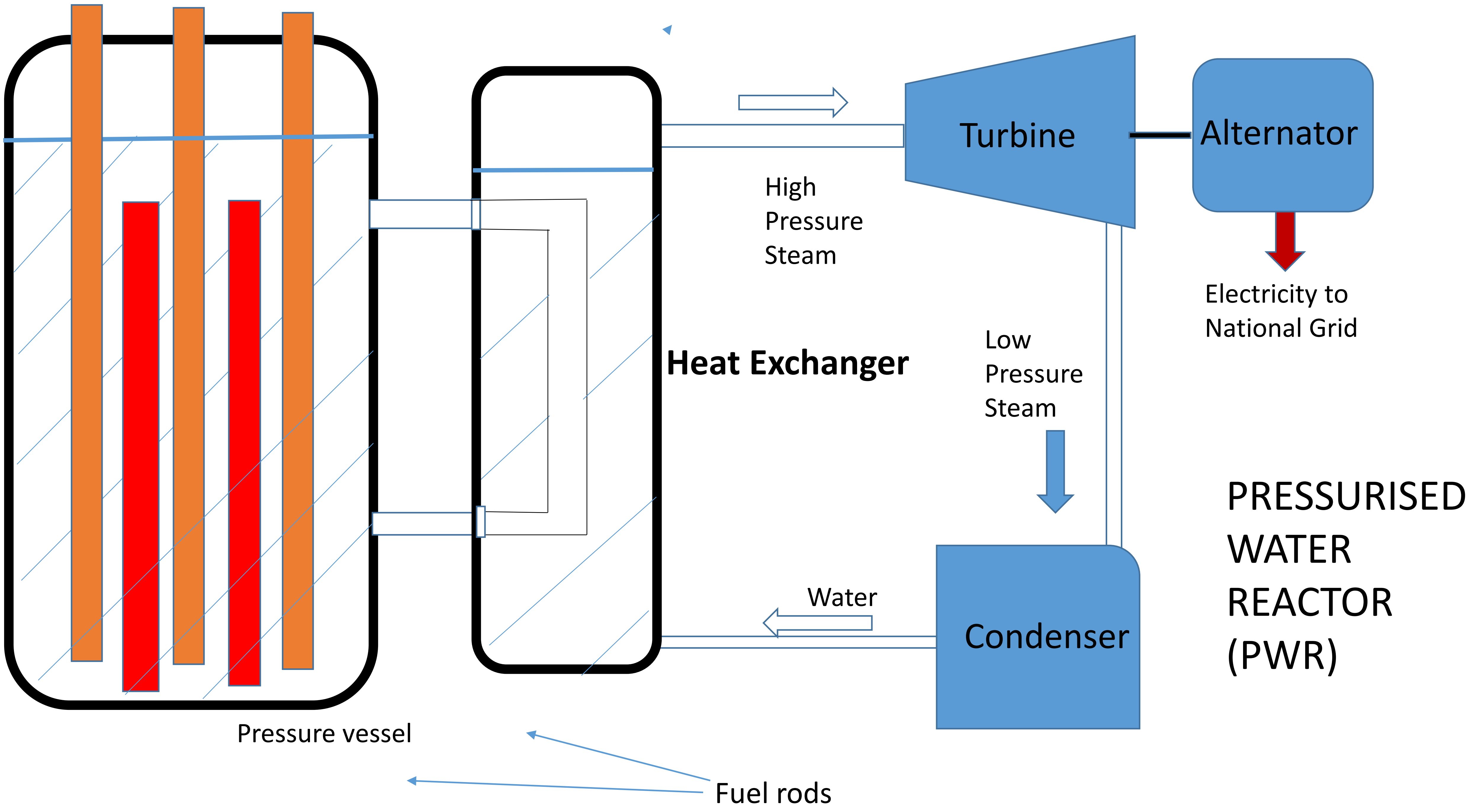
- Neutrons from one fission event can trigger another Uranium nucleus to undergo fission, and so on in a cascade (realised in 1938)
- Self-sustaining process – basis for nuclear energy
- Only U-235 isotope is useful, U-238 won't work in a normal reactor
- 0.7% of natural Uranium is U-235 – not enough for a self-sustaining chain reaction unless the reactor is very big (UK Magnox type)
- Needs to be ENRICHED for most reactors (and bombs!) – *IRAN*
  - Increase concentration of U-235 up to around 4% for a reactor

Nuclear fission reactors have occurred naturally in Uranium ore deposits!

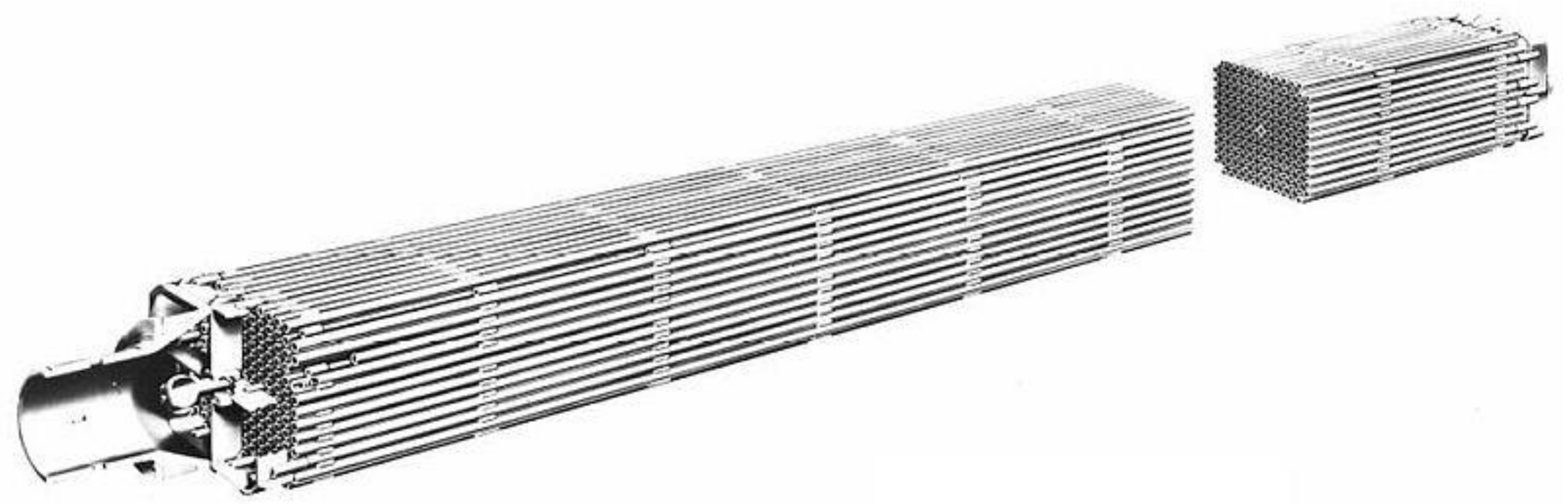
Moderators

- A MODERATOR slows down the neutrons resulting from fission
- Slow neutrons are more likely to be captured by another U-235 nucleus than the fast neutrons from the fissions
  - so less enrichment needed, and power output is higher
- Moderator is usually either:
  - Water - which also removes the heat generated
  - Graphite – heat is removed by gas coolant (e.g. CO_2) – UK Magnox and Advanced Gas-Cooled reactors


Control rods (absorb neutrons)
Turbine
Alternator
High
Pressure
Steam
Electricity to
National Grid
Low
Pressure
Steam
Pressure vessel
BOILING
WATER
REACTOR
Water
Condenser
Water
Fuel rods


Turbine
Alternator
High
Pressure
Steam
Electricity to
National Grid
Heat Exchanger
Low
Pressure
Steam
PRESSURISED
WATER
REACTOR
(PWR)
Water
Condenser
Pressure vessel
Fuel rods

Fuel Rod Assembly (US)



Plutonium

- U-238 nuclei can capture neutrons from fission of U-235
- U-238 changes into Plutonium (Pu)
- Plutonium is fissile so can be used as reactor fuel
  - and nuclear weapons
- “Breeder reactors” could make Plutonium fuel
- Nasty stuff – highly radioactive and toxic

Nuclear Safety

- Principle: Multiple barriers between radiation source and environment
  - Pressure vessel
  - Containment building
  - Isolated location
- Primary shutdown system
  - Drops control rods when abnormal instrument readings (neutron flux, temperature, pressure) detected
- Secondary shutdown system
  - Independent of primary system, different sensors and technologies
- Emergency Core Cooling System

UK Office of Nuclear Regulation

- Approves and licences design and construction
- Approves Safety Cases
- Oversees ongoing operations

Pros and Cons of Nuclear Fission Energy

Advantages

- No CO_2 greenhouse gas emission
- Running cost is low – 12 tons of enriched Uranium per reactor per year
  - 1 p/KWH (??)
- Reasonable supplies of uranium ore (300 years+?)

Kazakhstan, Canada and Australia

Disadvantages

- Costly to build relative to gas or coal fired stations
  - Because of the need for containment and safety systems
- Costly to decommission
- Waste (fission products in fuel rods) needs to be safety stored for a long time – also costly
  - Sellafield cooling ponds

Is Nuclear (fission) Energy safe?

- What happened at Fukushima
- Could it happen here?

Fukushima No 1 Accident

- Earthquake occurred – reactors shut down automatically as planned
  - Fission reaction stopped instantly
- BUT – fuel rods are still producing heat from radioactivity (5 MW)
  - so some emergency cooling system pumps need to carry on working
- Tsunami destroyed all electrical systems including batteries, diesel generators and switchgear/controls
  - tsunami overtopped protective wall (bund), cooling pumps could not work
- Fuel rods melted and damaged containment, allowing radioactive substances to escape to environment
- No one died!
- Other Japanese reactors were OK

Could it happen here?

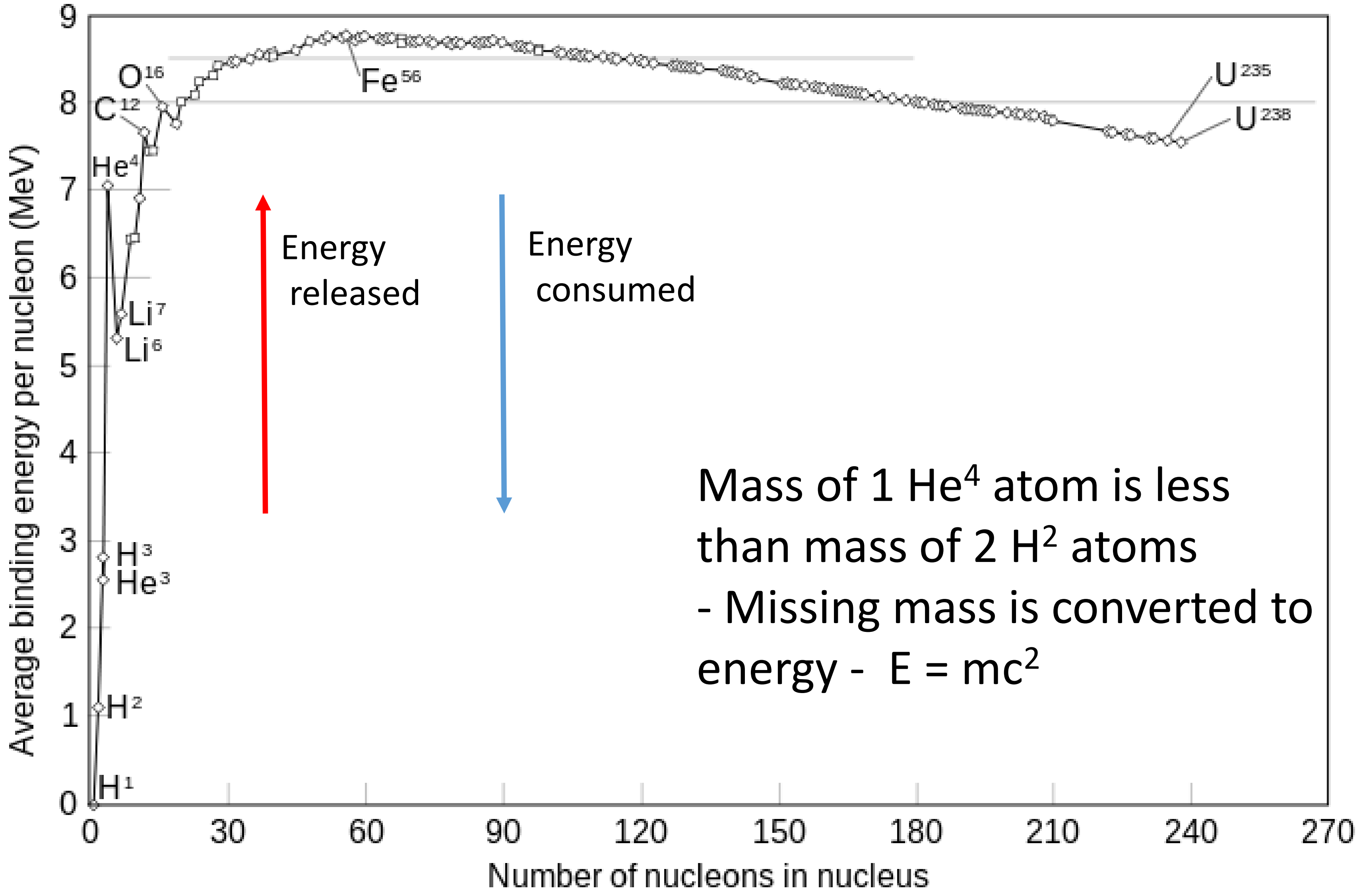
- UK reactors are of a different (better) design
  - Fukushima design was not/would never be licensed in UK (or in USA)
- UK does not have major earthquakes or tsunamis
  - But reactors are designed to withstand them anyway!
- New build reactors have “passive” cooling – no need for pumps after reactor has shut down, at least for several days
- UK reviewed its emergency provisions after Fukushima accident
  - concluded that UK reactors are very safe
  - Improved emergency materials holding on site recommended

France gets 70% of its electricity from nuclear reactors. 300 operating world-wide.

Nuclear Fusion

- Energy obtained by fusing light nuclei (deuterium) to form helium
- This is how the Sun shines
- *Terribly* difficult to do it on Earth – enormous pressure and temperature needed to overcome electrostatic repulsion of nuclei
  - JET reactor at Culham can do it, although not economically!
  - ITER under construction in France
- No fission products – helium is not radioactive! – so no <u>serious</u> waste problem
- Limitless supplies of fuel in Earth's oceans ("heavy water", deuterium oxide)

Fission versus Fusion – Binding Energy



Mass of 1 He^4 atom is less than mass of 2 H^2 atoms

- Missing mass is converted to energy - $E = mc^2$

Fusion reactor concepts

- TOKAMAK – turn hydrogen into a very hot plasma (gas with electrons stripped away from nuclei)
  - Contained by powerful magnetic field in a vacuum
  - Toroidal shaped vessel
  - Heated by induction and injecting beams of neutral atoms
  - JET uses copper wire for magnets, ITER will have superconducting magnets
- INERTIAL CONFINEMENT
  - Blast a small pellet of deuterium (?) with intense laser beams
  - Shock wave heats the material to extreme temperature and pressure
  - Demonstrated to work, but far from break-even point

Why doesn’t a fission reactor just blow up?

- Reactor must be “critical” – 1 fission reaction should result in exactly 1 neutron causing a further reaction
- “Multiplication factor”
  - Subcritical – less than 1: reaction will die away
  - Critical – exactly 1: reaction carries on at constant power
  - Supercritical – more than 1: reaction can increase rapidly and run away

Delayed neutrons are important here – these get produced from the fission fragments within milliseconds to seconds, giving control systems time to work (bombs don’t need these)

Also as reaction speeds up, the moderator expands with the extra heat and this results in fewer fissions