PHYS1211—part 3; nuclear

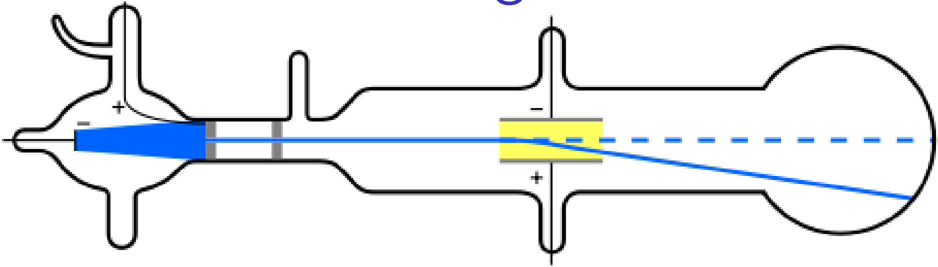
- The syllabus is based on Chapters 13, 14, and 15 of the textbook: "Energy—Its Use and the Environment", with some additional information provided in these slides.
- Prof. Michael Ashley, Room 137, Old Main Building, m.ashley@unsw.edu.au, pph 9385-5465.
- These notes are available here: `http://mcba11.phys.unsw.edu.au/~mcba/PHYS1211/` including a version with a white background to reduce the drain on your printer ink.
- NOTE: these notes will be changed as the course goes on, so don't print them all out immediately!

The atomic hypothesis

John Dalton

- Question: is matter indefinitely divisible?
- Democritus (ca. 420 BC) proposed that all matter was composed of an indivisible component: an atom.
- Aristotle: (384 BC–332 BC) matter composed of four “elements”: air, fire, water, earth.
- Dalton (1766–1844) proposed that each element (lead, aluminium, hydrogen, etc) consisted of only one kind of “atom”, unique to that element.
- Dalton conducted chemical experiments, e.g., combining hydrogen & oxygen in precise ratios to produce water, which strongly supported his atom hypothesis.

The electron charge-to-mass ratio



Thomson's experiment

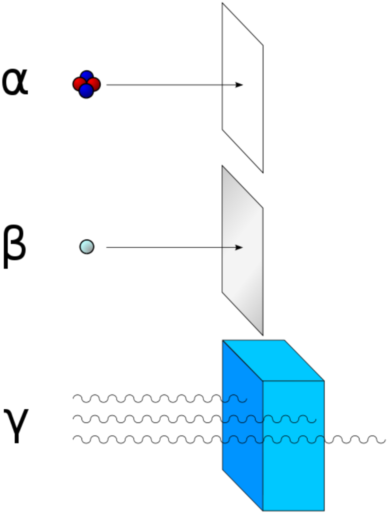
- J. J. Thomson measured the charge-to-mass ratio of the electron in 1897 using an evacuated tube.
  `http://www.youtube.com/watch?v=IdTxGJjA4Jw`
- Electrons (blue) are produced by heating a filament, and are then accelerated by a voltage to the right.
- Electric & magnetic fields deflect the electron beam.
- From the strength of the two fields, the q/m ratio can be found.
- We can do this experiment in the UNSW 2nd year laboratory.

Protons and neutrons

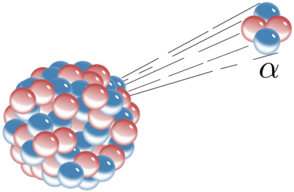
- All nuclei are composed of two particles:
  - protons—positively charged, with exactly the opposite charge of the electron,
  - neutrons—no charge
- The masses of these particles are:
  - proton—1.0072766 amu
  - neutron—1.0086654 amu
  - electron—0.0005486 amu

where an atomic mass unit (amu) is 1.66×10^{-27} kg.

Types of nuclear radiation



- α particles are the nuclei of helium atoms, and can be stopped with a sheet of paper.



- β particles are electrons (or positrons), and can be stopped with a sheet of metal.
- γ rays are highly energetic photons, and can be stopped with a sheet of lead.

Geiger & Marsden, 1909

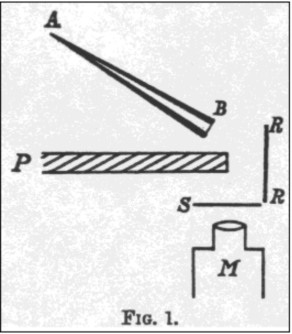


FIG. 1.

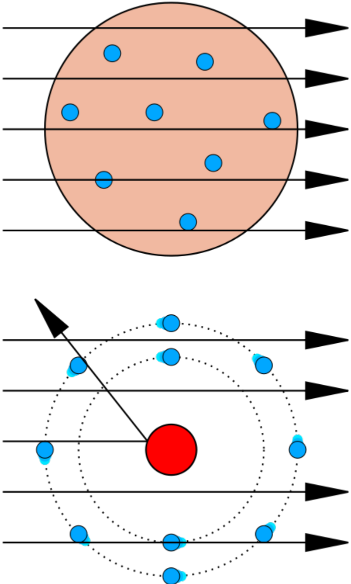
- Radium was placed in a conical glass tube sealed with a mica window.
- The resulting intense beam of α particles then hit the reflector R (they used various metals).
- A zinc sulphide screen S would glow if hit by an α particle that bounced off the reflector.
- The flashes of light were observed using the microscope M.
- The lead plate P prevented direct illumination.

Geiger and Marsden observed significant scattering of the α particles; whereas the "plum-pudding" model of the atom predicted none.

`http://www.youtube.com/watch?v=wzALbzTdnc8` Rutherford's experiment

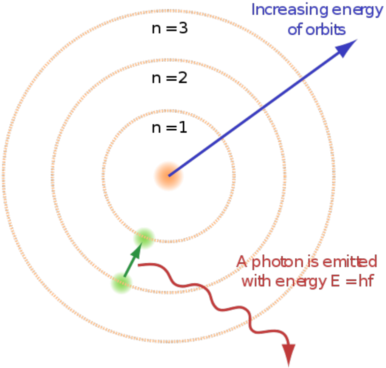
`http://www.youtube.com/watch?v=5pZj0u_XMbc` Animation of above

Implications for atomic models



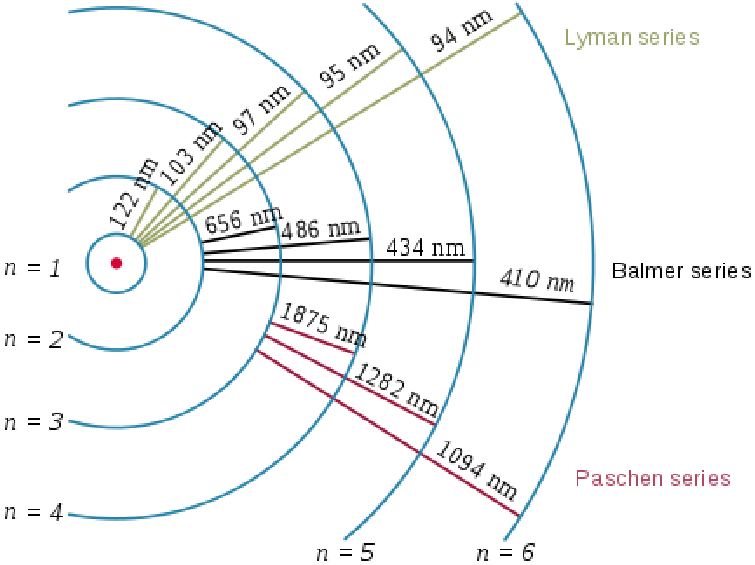
- Thomson's "plum-pudding" model supposed that atoms consist of electrons embedded in a "pudding" of uniform positive charge. Incident α particles would travel straight through.
- The results of the Geiger & Marsden experiment suggested that the positive charges were concentrated in a tiny region at the centre of the atom, so that a small fraction of incoming α particles would be deflected through large angles.
- The fraction of α particles scattered by various angles gives a measurement of the size of the nucleous.

Energy levels in a hydrogen atom



- A single proton is at the centre.
- http://www.youtube.com/watch?v=-YYBCNQnYNM
- A single electron is “orbiting” the proton; its energy is “quantized”, i.e., it is restricted to certain values.
- When an electron falls into a lower energy orbit, a photon is emitted, with an energy equal to the energy difference of the two levels.
- The photon has a well-defined energy, and hence colour.
- This explains the characteristic colours emitted by atoms when they are heated.

The energy levels of hydrogen



Atomic emission spectra

Hydrogen spectrum showing the Balmer series $n \to 2$

The emission lines from neon

Hydrogen emission from M51

NASA/ESA

Hydrogen glowing red due to the $n = 3 \rightarrow 2$ *line at 656nm*

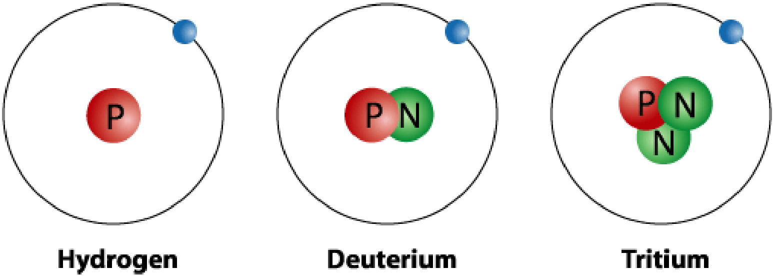
The planetary nebula NGC6302

Isotopes

- To maintain electrical neutrality, an atom has equal numbers of electrons and protons.
- This leaves freedom to choose the number of neutrons, leading to *isotopes*, e.g., ^{12}C, ^{13}C, ^{14}C.
- The chemical properties of an atom are almost entirely determined by the number of electrons, not by the number of neutrons (exceptions: reaction rates, molecular vibration spectra).
- Neutrons and protons are collectively called *nucleons*.
- Neutrons help to stabilise the nucleus by keeping the protons apart, and by the attractive *residual strong force* which exists between any two nucleons.
- The atomic weight of an element normally applies to its natural abundance, e.g., in nature, chlorine is 76% ^{35}Cl and 24% ^{37}Cl, so its atomic weight is

$$0.76 \times 35 + 0.24 \times 37 = 35.5 \text{ amu.}$$

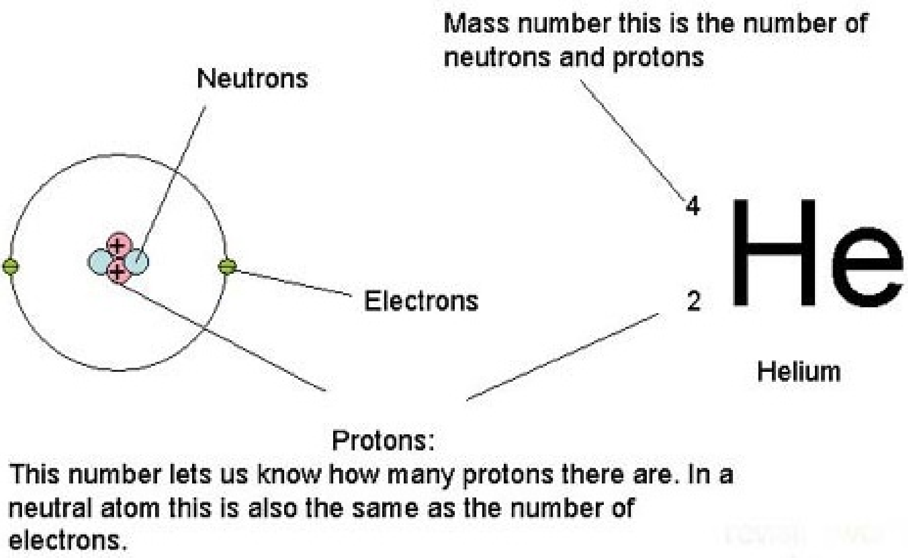
Isotopes of hydrogen



The three lightest isotopes of hydrogen

- Naturally occuring hydrogen comes in three isotopes: ^{1}H (H: protium), ^{2}H (D: deuterium) and ^{3}H (T: tritium).
- 99.985% of naturally occuring hydrogen is H; 0.015% is D, and only one atom in $\sim 10^{18}$ is T (half-life 12.3 yrs).
- Heavier isotopes, from ^{4}H to ^{7}H, have been synthesised, but they are highly unstable. Hydrogen and deuterium are both stable.

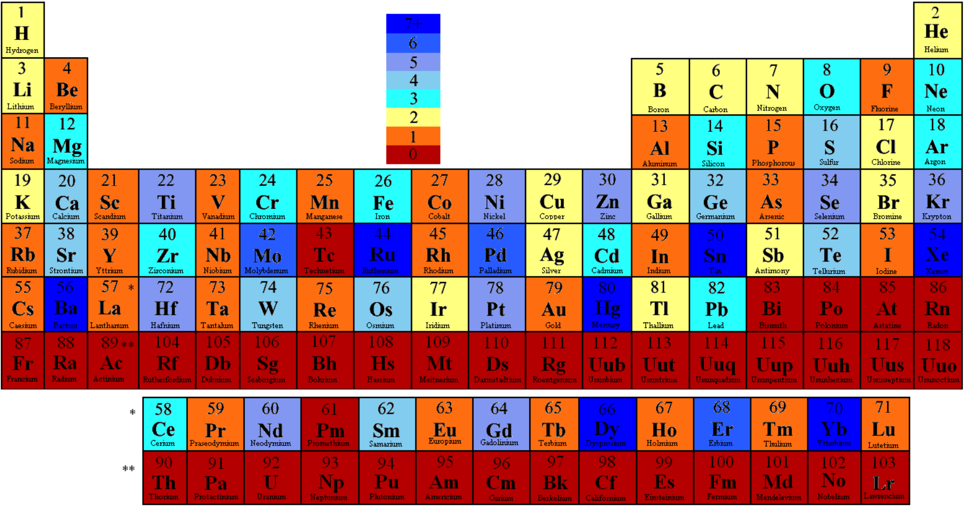
Atomic number, mass number



Mass number this is the number of neutrons and protons

Protons:
This number lets us know how many protons there are. In a neutral atom this is also the same as the number of electrons.

Periodic table—no. stable isotopes



7+
6
5
4
3
2
1
0

1 **H** Hydrogen																	2 **He** Helium
3 **Li** Lithium	4 **Be** Beryllium											5 **B** Boron	6 **C** Carbon	7 **N** Nitrogen	8 **O** Oxygen	9 **F** Fluorine	10 **Ne** Neon
11 **Na** Sodium	12 **Mg** Magnesium											13 **Al** Aluminum	14 **Si** Silicon	15 **P** Phosphorous	16 **S** Sulfur	17 **Cl** Chlorine	18 **Ar** Argon
19 **K** Potassium	20 **Ca** Calcium	21 **Sc** Scandium	22 **Ti** Titanium	23 **V** Vanadium	24 **Cr** Chromium	25 **Mn** Manganese	26 **Fe** Iron	27 **Co** Cobalt	28 **Ni** Nickel	29 **Cu** Copper	30 **Zn** Zinc	31 **Ga** Gallium	32 **Ge** Germanium	33 **As** Arsenic	34 **Se** Selenium	35 **Br** Bromine	36 **Kr** Krypton
37 **Rb** Rubidium	38 **Sr** Strontium	39 **Y** Yttrium	40 **Zr** Zirconium	41 **Nb** Niobium	42 **Mo** Molybdenum	43 **Tc** Technetium	44 **Ru** Ruthenium	45 **Rh** Rhodium	46 **Pd** Palladium	47 **Ag** Silver	48 **Cd** Cadmium	49 **In** Indium	50 **Sn** Tin	51 **Sb** Antimony	52 **Te** Tellurium	53 **I** Iodine	54 **Xe** Xenon
55 **Cs** Caesium	56 **Ba** Barium	57 * **La** Lanthanum	72 **Hf** Hafnium	73 **Ta** Tantalum	74 **W** Tungsten	75 **Re** Rhenium	76 **Os** Osmium	77 **Ir** Iridium	78 **Pt** Platinum	79 **Au** Gold	80 **Hg** Mercury	81 **Tl** Thallium	82 **Pb** Lead	83 **Bi** Bismuth	84 **Po** Polonium	85 **At** Astatine	86 **Rn** Radon
87 **Fr** Francium	88 **Ra** Radium	89 ** **Ac** Actinium	104 **Rf** Rutherfordium	105 **Db** Dubnium	106 **Sg** Seaborgium	107 **Bh** Bohrium	108 **Hs** Hassium	109 **Mt** Meitnerium	110 **Ds** Darmstadtium	111 **Rg** Roentgenium	112 **Uub** Ununbium	113 **Uut** Ununtrium	114 **Uuq** Ununquadium	115 **Uup** Ununpentium	116 **Uuh** Ununhexium	117 **Uus** Ununseptium	118 **Uuo** Ununoctium

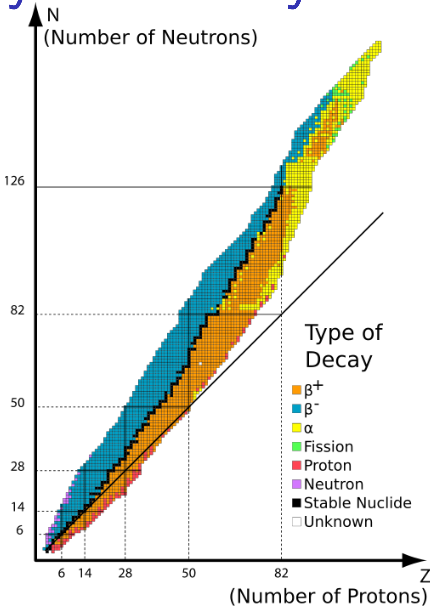
*	58 **Ce** Cerium	59 **Pr** Praseodymium	60 **Nd** Neodymium	61 **Pm** Promethium	62 **Sm** Samarium	63 **Eu** Europium	64 **Gd** Gadolinium	65 **Tb** Terbium	66 **Dy** Dysprosium	67 **Ho** Holmium	68 **Er** Erbium	69 **Tm** Thulium	70 **Yb** Ytterbium	71 **Lu** Lutetium
**	90 **Th** Thorium	91 **Pa** Protactinium	92 **U** Uranium	93 **Np** Neptunium	94 **Pu** Plutonium	95 **Am** Americium	96 **Cm** Curium	97 **Bk** Berkelium	98 **Cf** Californium	99 **Es** Einsteinium	100 **Fm** Fermium	101 **Md** Mendelevium	102 **No** Nobelium	103 **Lr** Lawrencium

Note that even atomic numbers tend to have more stable isotopes

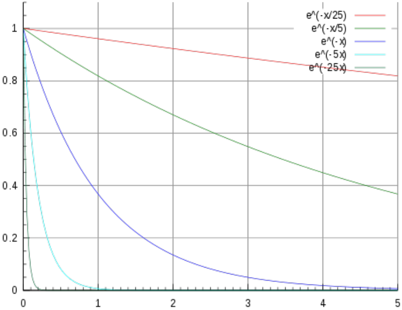
Stability of isotopes

- For light elements, the number of protons approximately equals the number of neutrons.
- As the nucleus gets heavier, proportionally more neutrons are needed to offset the electrostatic repulsion of the protons.
- All nuclei with more than 84 protons are unstable.
- Nuclei with *even numbers* of protons and/or neutrons are preferentially stable. This is due to the pairing of spins: it is energetically preferred to pair a spin-up nucleon with a spin-down one.
- $\sim$ 264 stable nuclei are known (c.f. $>$ 2000 unstable ones).
- Of these, $\sim$ 157 have even numbers of protons and neutrons.
- 53 are even-odd (protons-neutrons), 50 are odd-even, and only 4 are odd-odd (and are all light nuclei: ^{2}H, ^{6}Li, ^{10}B, ^{14}N).

Stability and decay of isotopes

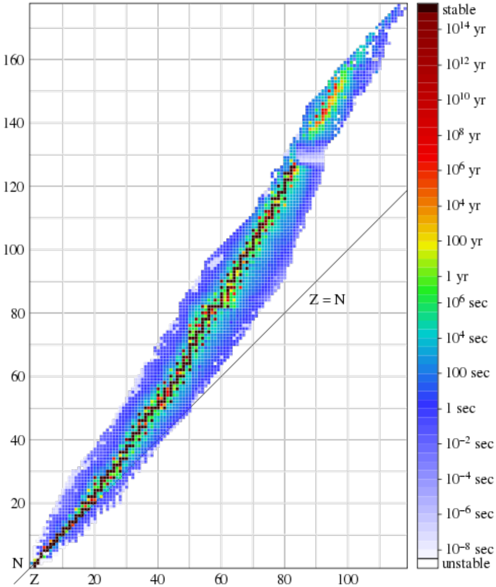


Radioactive half-life

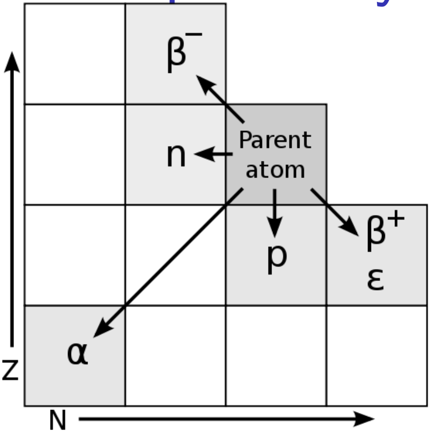


- An unstable isotope has a certain probability, in any given time interval, of "decaying" (through emission of α, β, γ, *p*, or *n*).
- This probability is normally expressed as a "half-life" $\tau_{1/2}$, which is the time is takes for one-half of the atoms to decay.
- This process is an example of *exponential decay*.

Isotopes and half-life

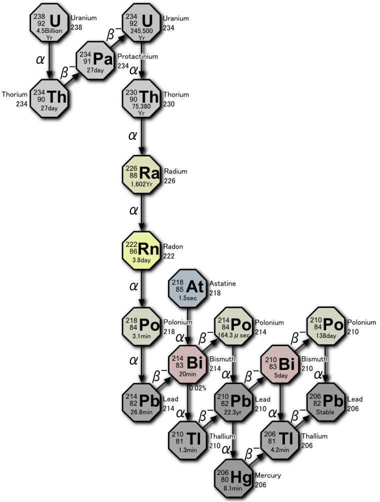


Isotopic decay in the (N, Z) plane



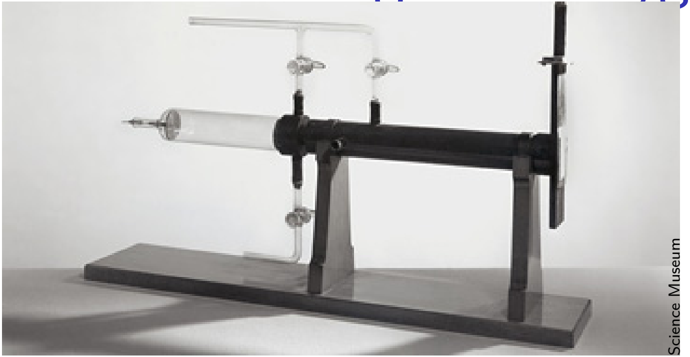
- N is the number of neutrons.
- Z is the "atomic number": the number of protrons.
- A is the "atomic weight": $A = N + Z$.

Radon decay chain



- Radon is a radioactive gas with a half-life of 3.8 days.
- It is produced from the decay of uranium-238 in the earth's crust.
- Radon is chemically inert, so remains as a gas, which accumulates in tiny air pockets in the soil.
- Radon can make its way inside houses, and be enhaled by people.
- Once radon is enhaled, its decay products remain in the lungs, and emit α particles, causing cell damage.
- `http://www.youtube.com/watch?v=-S8vr27plZs`

Rutherford: nitrogen → oxygen



Science Museum

- Rutherford, in 1917, was the first person to deliberately transmute one element into another. He did this by bombarding nitrogen gas with α particles from decaying polonium-210, and observing the resultant hydrogen gas.
- The reaction was ${}^{4}_{2}\mathrm{He} + {}^{14}_{7}\mathrm{N} \to {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H}$.
- Note that atomic number and mass number are conserved.

The first artifical radioisotope

Irene and Frederic Joliot-Curie (1934)

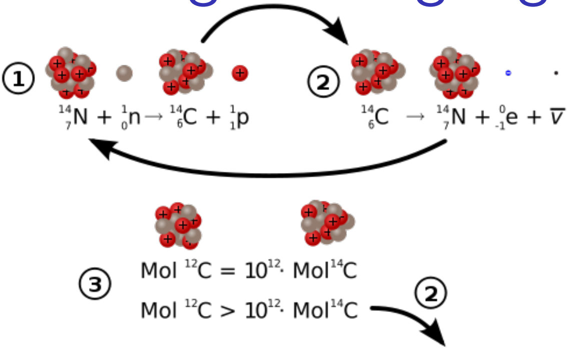
- In 1934 the Joliot-Curies created (1) nitrogen from boron, (2) phosphorus from aluminium, and (3) silicon from magnesium.
- E.g., $^{27}_{13}\mathrm{Al} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{30}_{15}\mathrm{P} + \mathrm{n}$.
- After irradiating aluminium with α particles, positrons were emitted (from decay of $^{30}_{15}\mathrm{P}$; $\tau_{1/2} = 3.5\,\mathrm{mins}$) after α bombardment ceased.
- Irene (daughter of Marie Curie) enhaled polonium when a sealed capsule broke in her lab in 1946. She died of leukemia 12 years later.

Assassination with polonium

Alexander Litvinenko

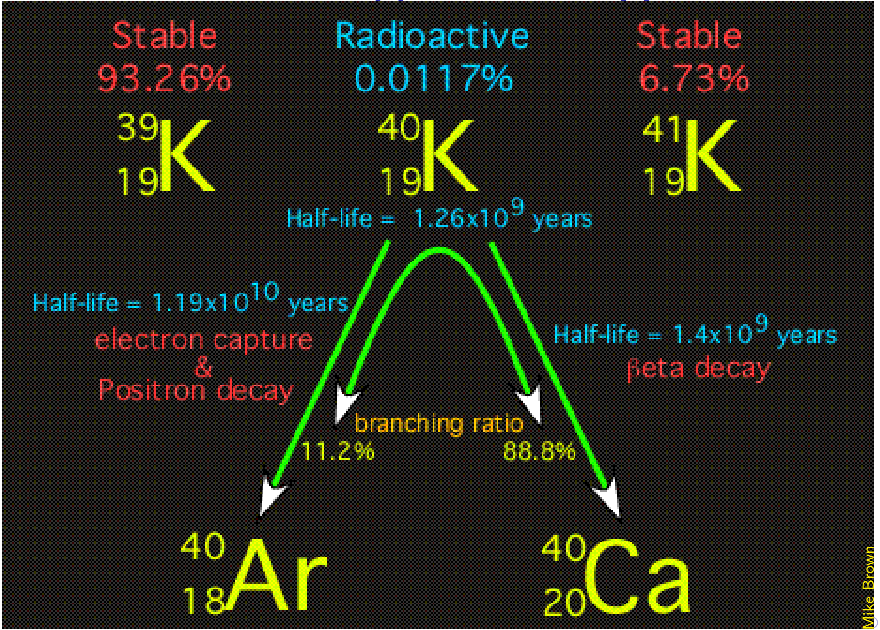
- Alexander Litvinenko was an officer in the Soviet KGB who wrote two books that implicated Vladimir Putin in underhand activities.
- In November 2006, Litvinenko became seriously ill and died within 3 weeks. An autopsy showed over 1000 rem of exposure to radiation from polonium-210.

Carbon dating of living organisms



- Naturally occuring carbon is predominantly ^{12}C.
- Cosmic rays produce neutrons and hence ^{14}C in the upper atmosphere.http://www.youtube.com/watch?v=31-P9pcPStg
- The ^{14}C is absorbed by living organisms through photosynthesis/eating.
- After death, the ^{14}C decays with a half-life of 5730 yrs.

Potassium—argon dating of rocks



Mike Brown

${}^{40}_{19}\mathrm{K} \rightarrow {}^{40}_{18}\mathrm{Ar}$ dating, continued

- Potassium, K, naturally occurs in rocks.
- 0.0117% of natural potassium is the radioactive isotope ${}^{40}_{19}\mathrm{K}$, with a half life of 1.26×10^9 years.
- 11.2% of the time, ${}^{40}_{19}\mathrm{K}$ decays to ${}^{40}_{18}\mathrm{Ar}$, which is stable, chemically inert, and present in only tiny quantities naturally.
- NOTE: the decay to ${}^{40}_{20}\mathrm{Ca}$ can not be used for dating purposes, since ${}^{40}_{20}\mathrm{Ca}$ is naturally present in relatively large quantities.
- If the rock is molten, the ${}^{40}_{18}\mathrm{Ar}$ can diffuse out.
- Once the rock solidifies, the ${}^{40}_{18}\mathrm{Ar}$ is trapped in the rock.
- So, by measuring the ${}^{40}_{19}\mathrm{K}$ to ${}^{40}_{18}\mathrm{Ar}$ ratio, the time since last melting can be determined.
- The half-life of ${}^{40}_{19}\mathrm{K}$ is comparable with the age of our solar system ($\sim 4.5 \times 10^9$ years), so this method of dating rocks works well.

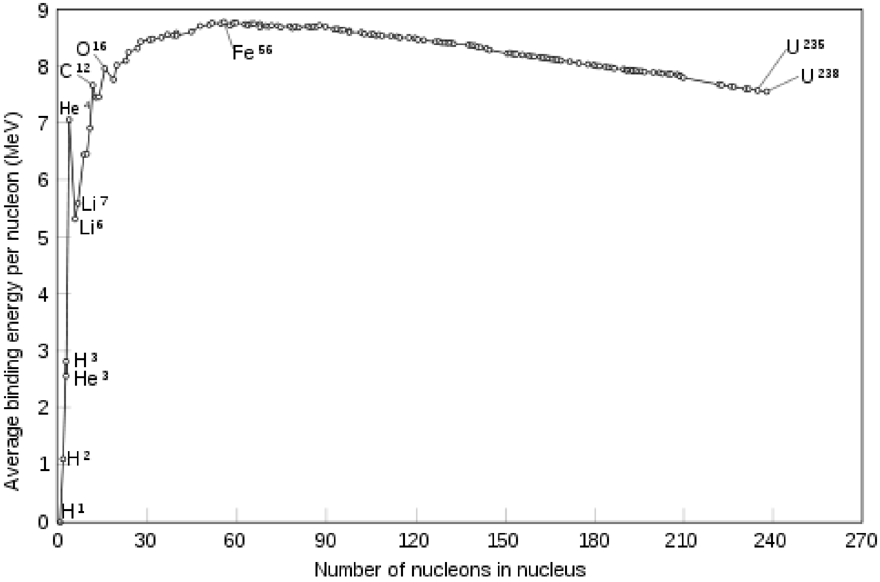
Nuclear masses

- Atomic nuclei weigh *less* than the sum of their parts.
- E.g., a helium nucleus weighs 4.0016 amu, whereas the parts (2 protons and 2 neutrons) weigh $2 \times 1.0073 + 2 \times 1.0087 = 4.0320\,\text{amu}$, which is $0.0304\,\text{amu}$ more!
- In order to pull apart a helium nucleus into its components, you need to add energy equivalent to the mass difference m, using the equation

$$E = mc^2$$

- Alternatively, creating a helium nucleus from components would generate this amount of energy.
- Now, m for helium is only $0.0304\,\text{amu}$, or $5.05 \times 10^{-29}\,\text{kg}$. However, c^2 is a big number...
- Forming one gram of helium from protons and neutrons would yield as much energy as burning 23 tonnes of coal.

Nuclear binding energy



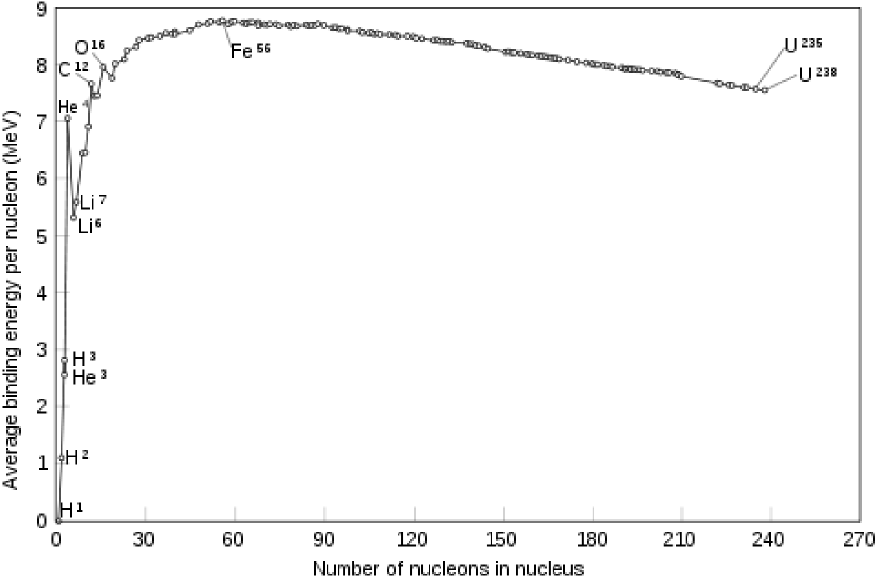
Cockcroft & Walton, fusion

- In 1932 Cockcroft & Walton bombarded a lithium target with protons, and produced helium.
- The reaction was $^1_1\mathrm{H} + {}^7_3\mathrm{Li} \rightarrow {}^4_2\mathrm{He} + {}^4_2\mathrm{He}$.
- The reaction released 30 times as much energy as was put in.
- However, this is not a practical source of energy, since the reaction rate is extremely low.

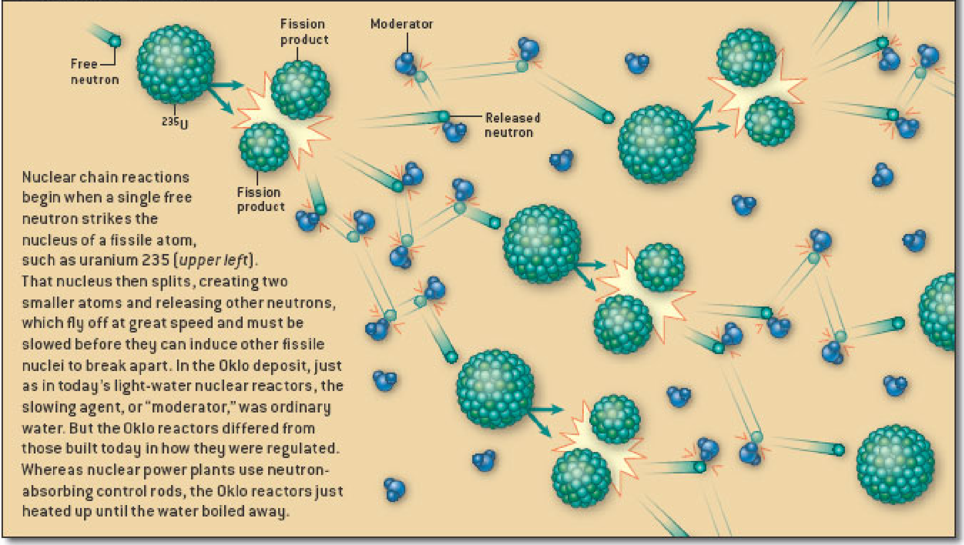
Uranium-235 and -238

- Naturally occuring uranium is almost entirely ^{238}U, with a half-life of $\tau_{1/2} = 4.5$ billion years.
- $\sim 0.72\%$ of natural uranium is ^{235}U, with $\tau_{1/2} = 700$ million years. ^{235}U has fewer neutrons than ^{238}U, and so the repulsive force from the protons is sufficient to make its nucleus unstable.
- ^{235}U can be encouraged to split into two parts by the impact of *thermal neutrons*, i.e., relatively slow neutrons.
- This process, *nuclear fission* releases a great deal of energy.
- It also liberates additional neutrons, which can go on to trigger further reactions. The net result is a sustained nuclear fission.
- ^{235}U is the only fissile nucleus found in significant quantities in nature.

Nuclear binding energy



FISSION UP CLOSE



Nuclear chain reactions begin when a single free neutron strikes the nucleus of a fissile atom, such as uranium 235 (*upper left*). That nucleus then splits, creating two smaller atoms and releasing other neutrons, which fly off at great speed and must be slowed before they can induce other fissile nuclei to break apart. In the Oklo deposit, just as in today's light-water nuclear reactors, the slowing agent, or "moderator," was ordinary water. But the Oklo reactors differed from those built today in how they were regulated. Whereas nuclear power plants use neutron-absorbing control rods, the Oklo reactors just heated up until the water boiled away.


AFRICA
Gabon

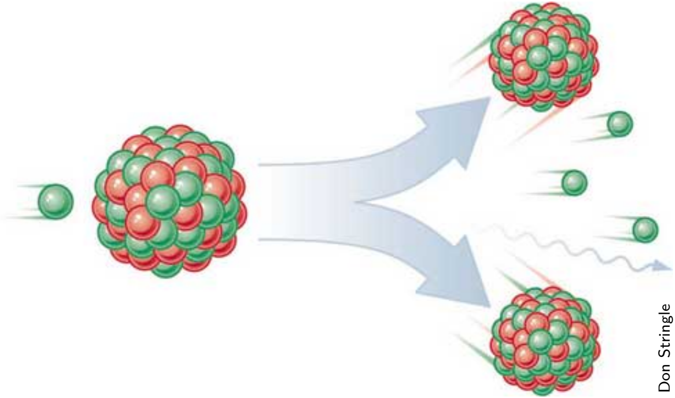

GABON
Oklo
Okelobondo
Bangombe

The open pit mine at Oklo

The Oklo reactor

- ^{235}U has $\tau_{1/2} = 700$ million years, so, earlier in the Earth's ~ 4.5 billion year history, the fraction of ^{235}U was much higher.
- This leads to the possibility of a *natural nuclear reactor*, first predicted in 1956.
- In 1972, evidence of such a reactor was found at Oklo in Gabon.
- The Oklo reactor was believed to have operated for a few thousand years, 1.7 billion years ago. Its power output averaged about 100kW.
- At the time, the ^{235}U fraction was $\sim 3.1\%$.
- The ^{235}U fraction has been measured at 0.44% at Oklo, less than the usual 0.72%, indicating fission has taken place.
- Oklo places important constraints on the variability of fundamental constants.

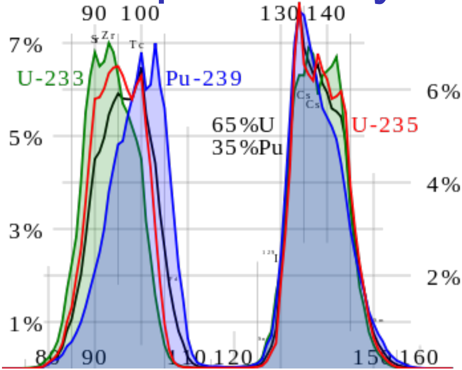
Uranium-235 fission



Don Stringle

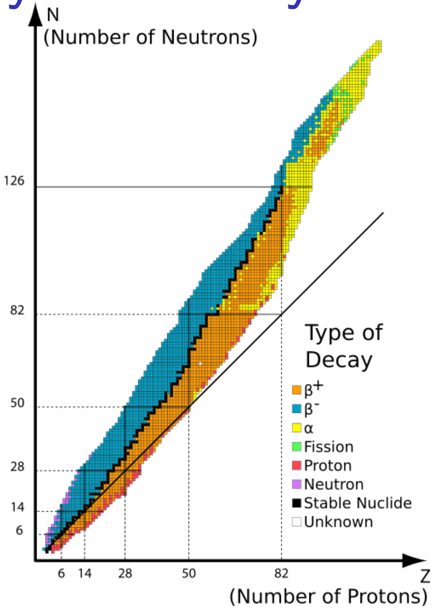
- One slow neutron initiates the reaction; 2–3 fast neutrons result.
- E.g., ${}^{235}_{92}\mathrm{U} + \mathrm{n} \rightarrow {}^{142}_{56}\mathrm{Ba} + {}^{91}_{36}\mathrm{Kr} + 3\mathrm{n}$
- The fast neutrons need to be slowed down by a *moderator* in order to increase the chance of further reactions.

Fission product yields

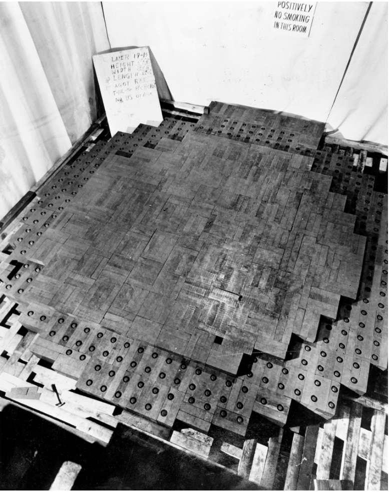


- Fission of ^{235}U (or ^{233}U, or ^{239}Pu) results in 2 (sometimes 3) nuclei.
- These nuclei are neutron rich (think about the $Z - N$ relation for stable nuclei), and hence radioactive.
- The fission products peak at around $A = 95$ and $A = 138$ for ^{235}U. (Note that $95 + 138 < 235$, explained by the release of neutrons).

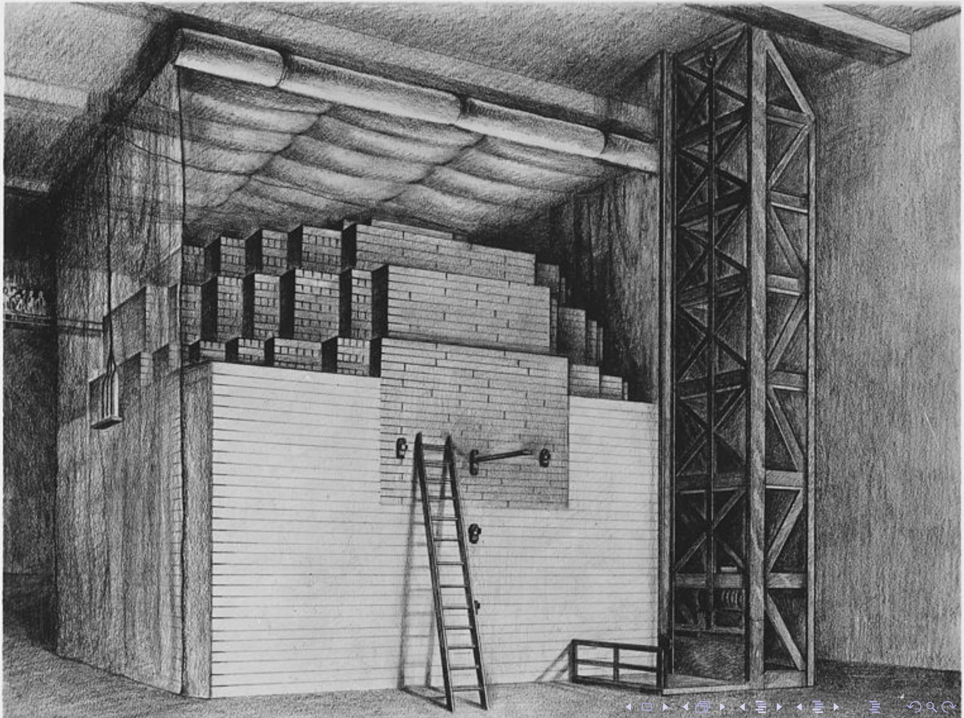
Stability and decay of isotopes



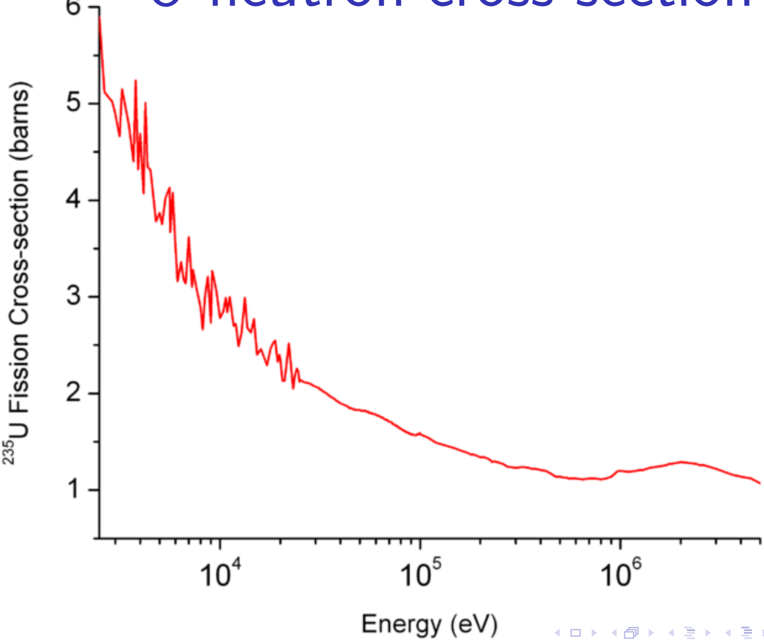
The Chicago Pile 1



- On 2 December, 1942, the world's first artificial nuclear reactor became operational; designed by Enrico Fermi and Leo Szilard.
- It consisted of uranium, with graphite blocks as a moderator, and cadmium-coated control rods.
- The reactor was built with no cooling and no radioactive shielding.
- The photo at left was taken one month before criticality.
- The reactor ran for 28 min, with exponentially increasing neutron flux.
- http://www.youtube.com/watch?v=0tKf7B2XncM



^{235}U neutron cross-section



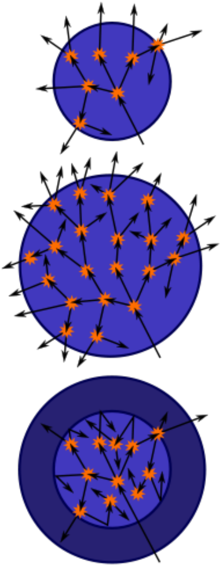
Neutron moderators

- The fast neutrons that are emitted naturally during ^{235}U fission are travelling too fast to efficiently trigger additional fission.
- Therefore a *moderator* is used to slow the neutrons down from $\sim$MeV energies to thermal velocities (i.e., energies of $< 1\,$eV).
- The moderator works by forcing the neutrons to undergo multiple collisions with slow-moving nuclei. Eventually, the neutrons slow down until they have the same energy as the nuclei in the moderator.
- Moderators used in practice include: carbon (graphite), beryllium, lithium-7, deuterium (“heavy water”), and protium (“light water”).
- The atomic bomb didn’t use a moderator, since it would slow the reaction down too much and result in a “fizzle” rather than a “bang”.

Neutron reflectors

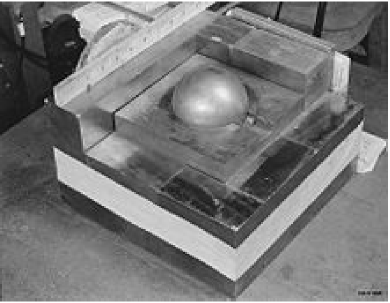
- A neutron reflector is a material that is able to reflect neutrons back along the direction they were coming from.
- Typical reflectors include graphite, beryllium, lead, steel, tungsten carbide.
- The purpose of the reflector is to reduce the size of the critical mass needed for fission.
- A neutron reflector can serve a dual purpose as a *tamper* to contain the initial explosion so that more of the fissile material participates in the reaction.

Critical mass



- The top sphere of fissile material is too small for a self-sustaining chain-reaction, since too many neutrons escape from the surface.
- The middle sphere is larger, and hence above critical mass.
- The critical mass for a sphere of ^{235}U is 52 kg, with a diameter of 17 cm.
- For ^{241}Pu the critical mass is 12 kg, with a diameter of 10.5 cm.
- By encasing the top sphere in a neutron reflector (as at left), it can become critical. Alternatively, if the sphere is compressed to a smaller size, it can become critical.

The demon core, part I

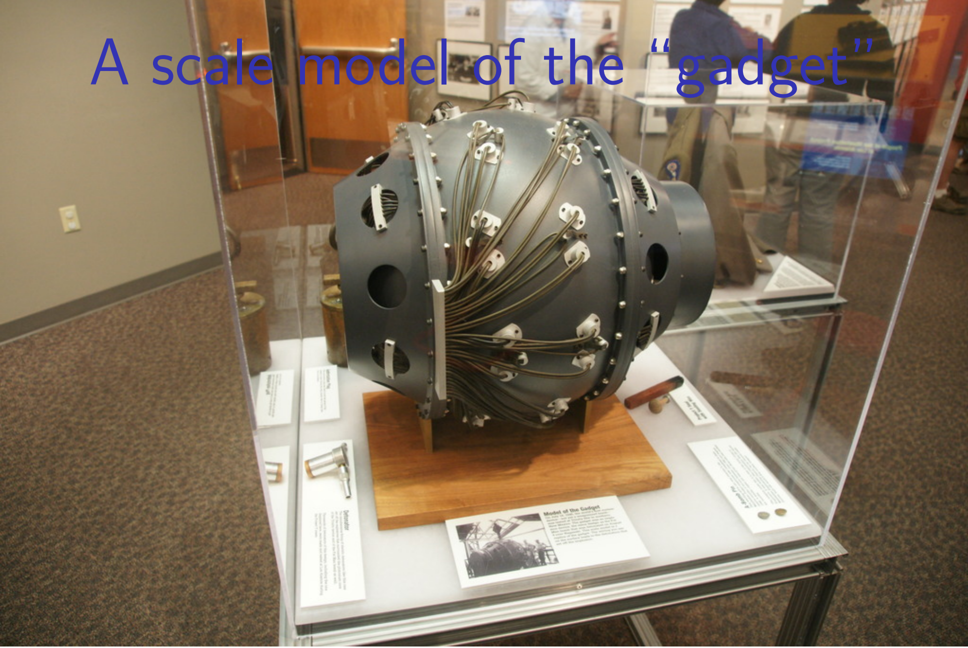


- The so-called "demon core" was a 6.2kg sub-critical mass of plutonium.
- On August 21, 1945 Harry Daghlian was working alone on neutron reflection experiments on the core. The core was within a stack of neutron-reflecting tungsten carbide bricks; the addition of each brick moved the core closer to criticality. Daghlian accidentally dropped a brick onto the core, causing it to go critical. He received a fatal dose of radiation and died 25 days later.

The demon core, part II

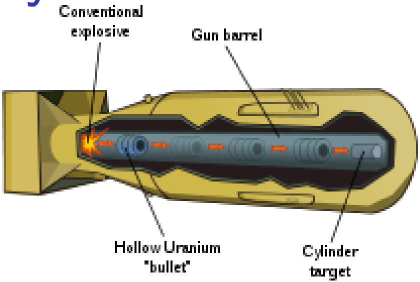
- On May 21, 1946, Louis Slotin and 7 scientists were attempting to verify the exact point of criticality using neutron reflecting spheres made of beryllium.
- The blade of a screwdriver was the only thing keeping the spheres apart.
- The blade slipped a few mm.
- In the second it took Slotin to knock the hemispheres apart, he received a lethal dose of neutron radiation.
- He died 9 days later.
- A dramatisation of this incident.

A scale model of the “gadget”



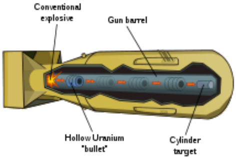
Little Boy and Fat Man

Little Boy: the Hiroshima bomb



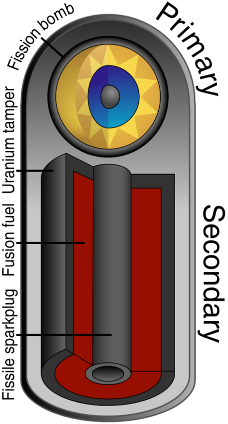
- 3m long, 4.4 t; http://www.youtube.com/watch?v=AtSt5XZ7fq4
- The design was so simple that it was essentially guaranteed to work, and so was not tested.
- It contained 64 kg of ^{235}U; less that 1 kg underwent fission.
- Only 0.6 gram was converted into energy (via $E = mc^2$), the equivalent of 13–18 kilotonnes of TNT (c.f. the biggest conventional bomb today, 44 tonnes of TNT). $\sim$150,000 people died within a year or so.

Gun-type atomic bombs



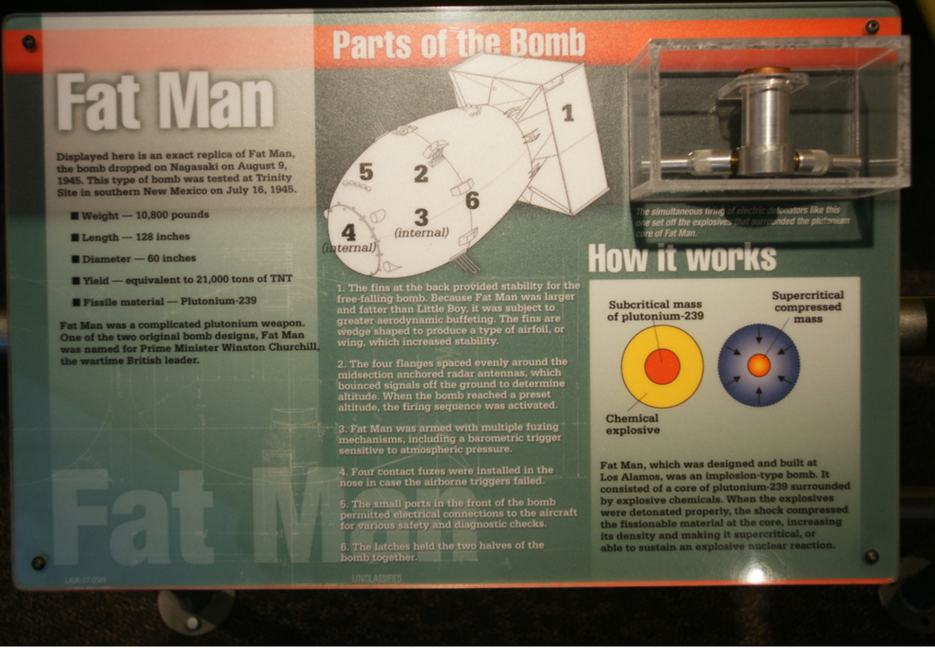
- The gun-type design uses a conventional explosive to bring together two sub-critical masses of ^{235}U.
- This requires 64 kg of ^{235}U, which is very hard to separate from natural uranium.
- If a gun-type bomb would work with ^{239}Pu, this has the advantages that (1) only 10 kg or so of ^{239}Pu is needed, and (2) ^{239}Pu can be easily made in a fission reactor.
- However, plutonium from a reactor contains ^{240}Pu in addition to ^{239}Pu, and the ^{240}Pu is less stable and emits more neutrons, which causes predetonation.

The hydrogen bomb



H-bomb design

- Los Alamos abandoned the gun-type plutonium bomb in July 1944, when they realised that it was impossible.
- They accelerated work on the implosion-type bomb, which was then used in the Trinity Test and the Fat Man bomb on Nagasaki.
- Fission bombs, such as the uranium and plutonium bombs, were limited in explosive power due to the size of the critical mass.
- Edward Teller was an enthusiastic proponent of the hydrogen bomb, or h-bomb, or fusion bomb, which had no such limits.
- The h-bomb was first tested in 1952.



Fat Man

Displayed here is an exact replica of Fat Man, the bomb dropped on Nagasaki on August 9, 1945. This type of bomb was tested at Trinity Site in southern New Mexico on July 16, 1945.

- Weight — 10,800 pounds
- Length — 128 inches
- Diameter — 60 inches
- Yield — equivalent to 21,000 tons of TNT
- Fissile material — Plutonium-239

Fat Man was a complicated plutonium weapon. One of the two original bomb designs, Fat Man was named for Prime Minister Winston Churchill, the wartime British leader.

Parts of the Bomb

1. The fins at the back provided stability for the free-falling bomb. Because Fat Man was larger and fatter than Little Boy, it was subject to greater aerodynamic buffeting. The fins are wedge shaped to produce a type of airfoil, or wing, which increased stability.

2. The four flanges spaced evenly around the midsection anchored radar antennas, which bounced signals off the ground to determine altitude. When the bomb reached a preset altitude, the firing sequence was activated.

3. Fat Man was armed with multiple fuzing mechanisms, including a barometric trigger sensitive to atmospheric pressure.

4. Four contact fuzes were installed in the nose in case the airborne triggers failed.

5. The small ports in the front of the bomb permitted electrical connections to the aircraft for various safety and diagnostic checks.

6. The latches held the two halves of the bomb together.

The simultaneous firing of electric detonators like this one set off the explosives that surrounded the plutonium core of Fat Man.

How it works

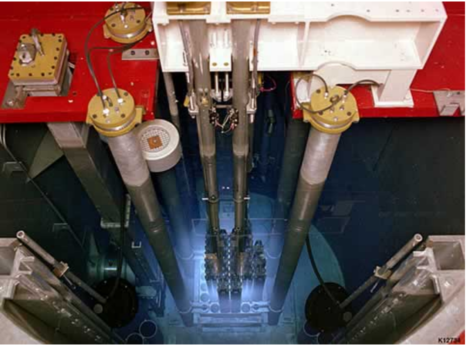
Fat Man, which was designed and built at Los Alamos, was an implosion-type bomb. It consisted of a core of plutonium-239 surrounded by explosive chemicals. When the explosives were detonated properly, the shock compressed the fissionable material at the core, increasing its density and making it supercritical, or able to sustain an explosive nuclear reaction.

LAUR-07-0569

UNCLASSIFIED

Nuclear fission reactors are basically simple in concept

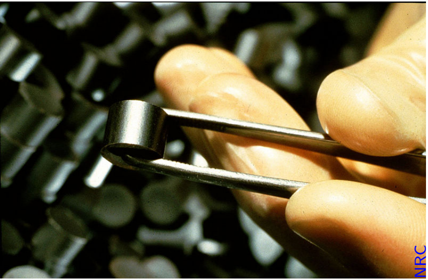
- The ^{235}U fuel is manufactured into pellets.
- When clustered together in sufficient numbers, in a water bath, the ^{235}U undergoes fission, producing lots of heat.
- The heat is converted into electricity via conventional steam turbines.



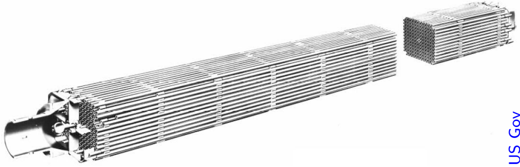
In practice, there are a few problems...

- Massive power excursions must be prevented.
- The fuel rod casings must be kept below a few hundred °C (this requires cooling water to be present).
- The pellets must be kept below $\sim$ 3300K (cooling water can do this).
- The spent fuel rods need to be stored in water for up to a year or more until air-cooling becomes sufficient.
- The spent fuel is highly radiative for decades to hundreds of years.
- The spent fuel may be used for nuclear weapon proliferation.

Fuel pellets and fuel rods


NRC

UO_2 fuel pellets

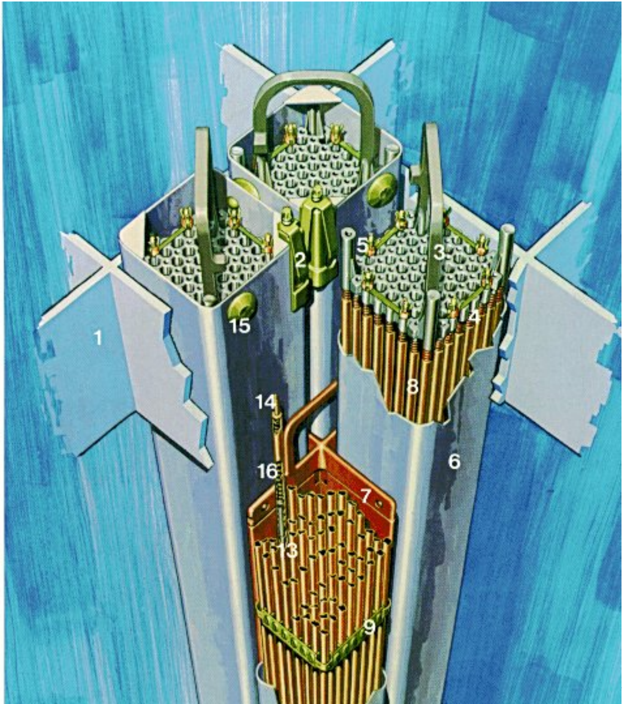

US Gov

A bundle of fuel rods

- Rather than using metallic uranium, the ^{235}U is normally in the form of uranium dioxide (UO_2); this has a higher melting point and has the advantage that it won't burn easily, since it is already oxidized.
- The UO_2 is compacted into cylindrical pellets and sintered at high temperatures to produce highly dense and stable ceramic fuel pellets.
- The pellets are then stacked inside tubes (fuel rods), and the tubes filled with pressurized helium to increase the thermal conduction.

BWR/6 FUEL ASSEMBLIES & CONTROL ROD MODULE

1.TOP FUEL GUIDE
2.CHANNEL FASTENER
3.UPPER TIE PLATE
4.EXPANSION SPRING
5.LOCKING TAB
6.CHANNEL
7.CONTROL ROD
8.FUEL ROD
9.SPACER
10.CORE PLATE



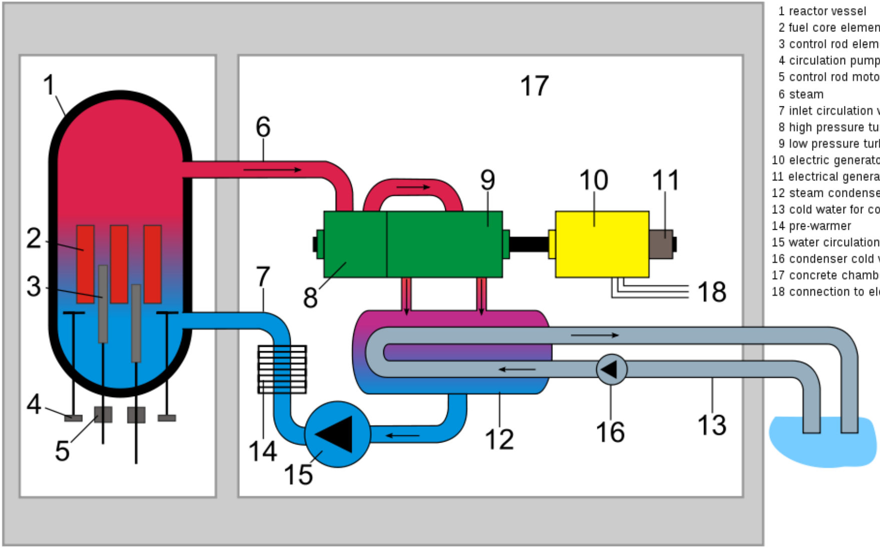
Zircalloy fuel rods

- The purpose of the fuel rods is to contain the ^{235}U nuclei.
- The key features of the fuel rods are:
  1. They contain the ^{235}U fuel and its fission products, and keep them away from the coolant water.
  2. Their casing is resistant to high-temperatures.
- The fuel-rod casings are usually made of $> 95\%$ zirconium since it has a very low cross-section for thermal neutrons ($< 10\%$ that of iron and nickel). Other metals are alloyed with the zirconium to improve corrosion resistance. Hence zircalloy.
- The main problem with zircalloy is that at high temperatures it reacts with steam to produce explosive hydrogen gas:
  $\mathrm{Zr} + 2\,\mathrm{H_2O} \;\rightarrow\; \mathrm{ZrO_2} + 2\,\mathrm{H_2}$.

Fuel pellet/rod degradation

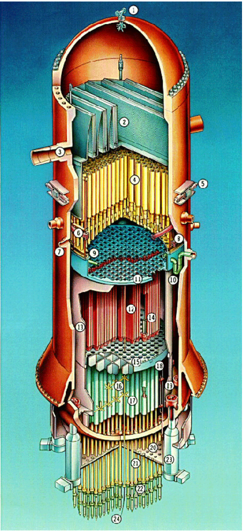
- Before use, the fuel pellets and rods are only slightly radioactive and can be safely manipulated by hand.
- During use, the ^{235}U is slowly converted into highly radioactive fission decay products. These remain in-situ within the fuel pellets, and cause fuel swelling. Oxygen gas is also produced.
- Irradiation damages the fuel rod casings, leading to embrittlement.
- To remain safe, the pellets must be kept under the melting point of UO_2 ($\sim$ 3300K).
- The zircalloy cladding temperature must be less than a few hundred °C to reduce oxidation via $Zr + 2\,H_2O \rightarrow ZrO_2 + 2\,H_2$.
- Since the heat is produced inside the fuel pellets, it is crucial that there is good thermal conductivity to the casing, and good cooling of the casing.
- The heat generation doesn't stop when the neutron flux stops, due to radioactivity from the decay products. The fuel rods need to be cooled for months/years after use.

Boiling Water Reactor



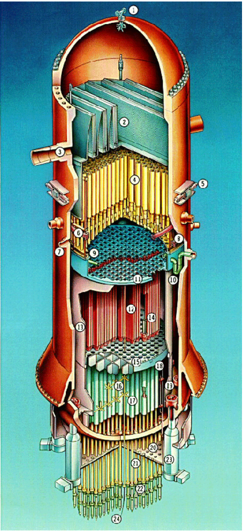
1 reactor vessel
2 fuel core element
3 control rod element
4 circulation pumps
5 control rod motors
6 steam
7 inlet circulation water
8 high pressure turbine
9 low pressure turbine
10 electric generator
11 electrical generator exciter
12 steam condenser
13 cold water for condenser
14 pre-warmer
15 water circulation pump
16 condenser cold water pump
17 concrete chamber
18 connection to electricity grid

The boiling water reactor (BWR)



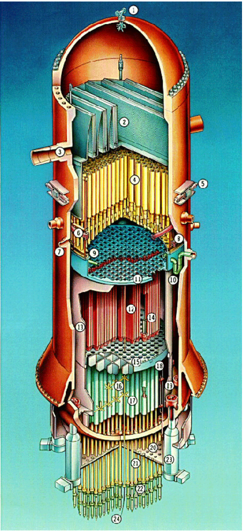
- The BWR uses water as both a coolant and a moderator.
- Heat from fission boils the water in the core (the water is pressurized to $\sim 75\,\text{atm}$, and hence boils at $\sim 285^\circ\text{C}$).
- The resultant steam is used to directly drive a turbine (and hence a generator to produce electricity).
- The steam is condensed to water and returned to the core.
- The design has natural negative feedback to assist stability: as the core temperature increases, more water boils, which creates voids of steam, which reduce neutron moderation, leading to less heat input from fission.

BWR control systems



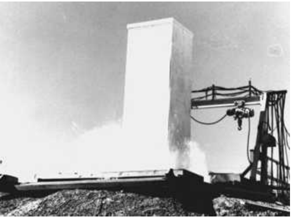
- A BWR reactor uses two mechanisms to control the reactor power output:
  1. **Control rods** which absorb neutrons when inserted into the core.
  2. **Coolant water flow**. By increasing the flow rate, the fraction of steam voids is reduced, so the slow neutron flux increases, and the reactor power goes up.

BWR containment



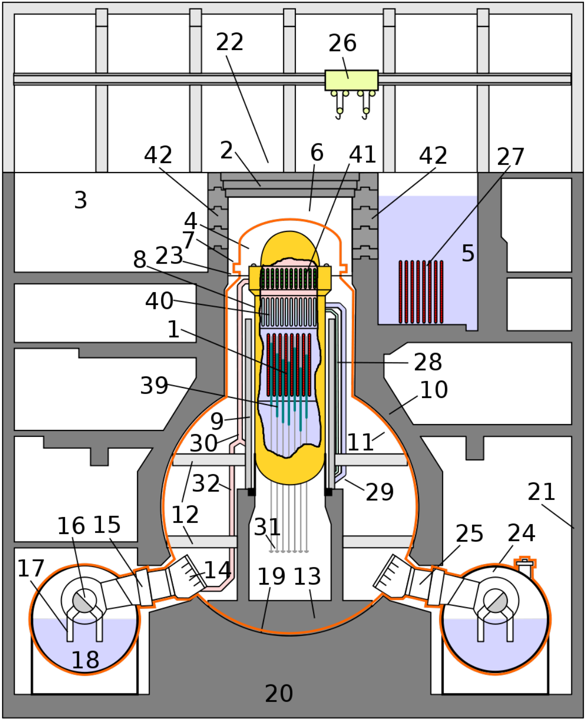
- There are many layers of containment to prevent the release of radioactive material into the environment.
- The fuel pellets contain most of the radioactivity.
- The fuel rod casings contain the pellets.
- The reactor pressure vessel and coolant piping contains any material which leaves the fuel rods.
- The drywell surrounding the pressure vessel contains any steam that is released from the pressure vessel, and recondenses it to water in the wetwell (the torus, or surpression pool).
- The building walls provide an additional limited ability to contain small releases of radioactivity.

The BORAX-1 experiment



BORAX-1

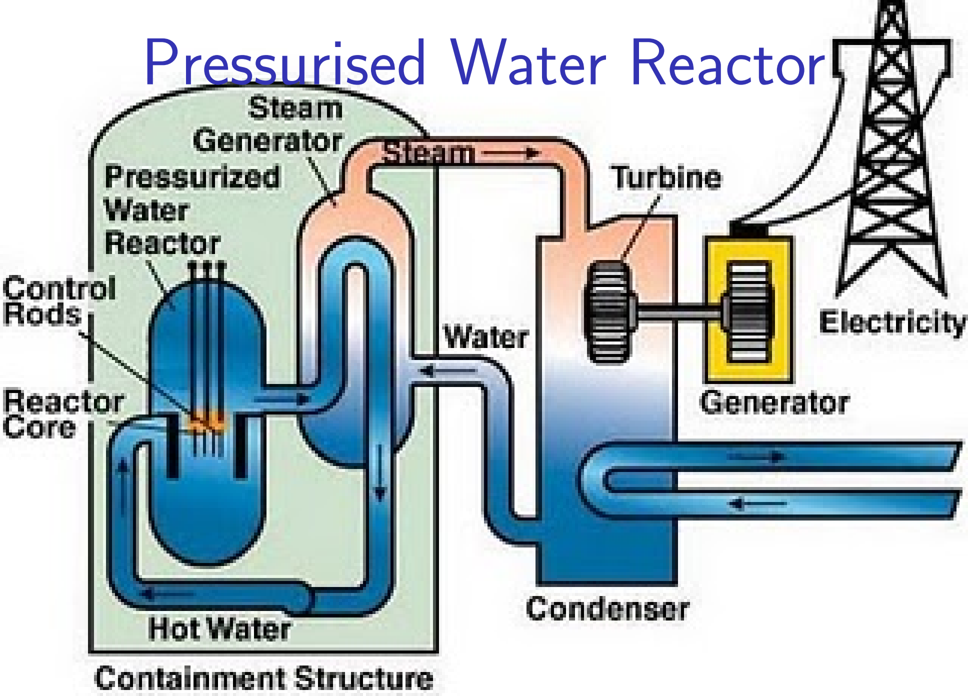
- To test the design of Boiling Water Reactors, a series of experiments were conducted at the National Reactor Testing Station in Idaho, USA.
- The first of these, BORAX-1, was designed to test whether steam formation in the water would be sufficient to self-regulate the nuclear reaction, as had been proposed by Samuel Untermyer II, in 1952.
- BORAX-1 was built in 1953, and subjected to 70 deliberate "runaway" excursions to test its stability; interesting sections: 0–4:00, 7:28–10.00, 14:40–.

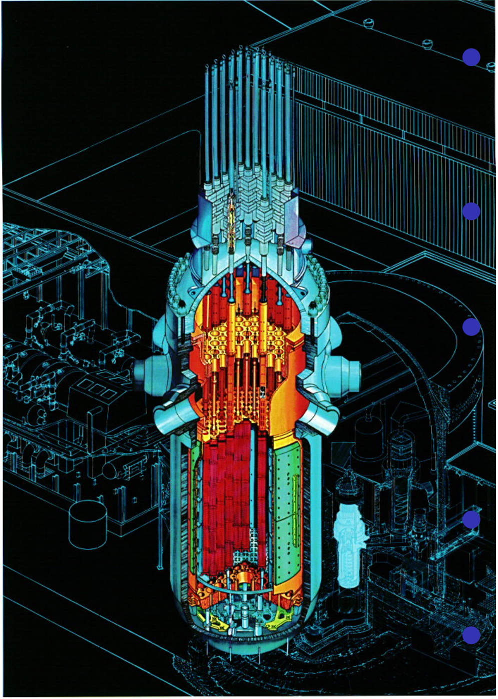


Schematic of a BWR, similar to Fukushima. And here is a good video fly-through.

1	The reactor core.
8	Reactor pressure vessel.
31	Control rods.
4	Drywell.
24	Supression chamber (torus, wetwell).
20	Concrete casing.
21	Building walls.
27	Spent fuel rods.
5	Water pool containing spent fuel rods.

Pressurised Water Reactor

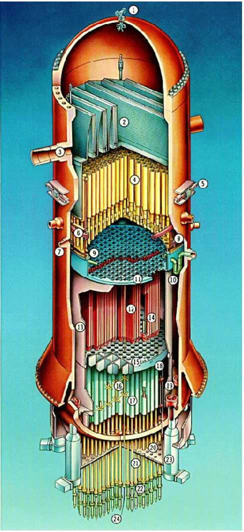




Westinghouse NUCLEAR REACTOR

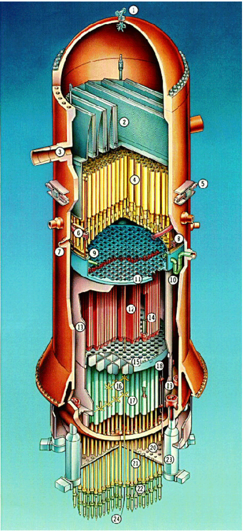
- The PWR is similar to the BWR, except that the water is pressurized to $\sim 155\,\text{atm}$ and so can reach 370°C without boiling.
- A secondary cooling loop produces steam to drive turbines, thereby isolating the radioactive water.
- The PWR is stable since as the water temperature increases, its density drops, its ability to slow neutrons drops, and so the power output drops.
- PWRs can be more compact than BWRs, and so are often used in submarines and ships.
- Control rods are dropped in from the top, which is a convenient fail-safe feature.

BWR advantages

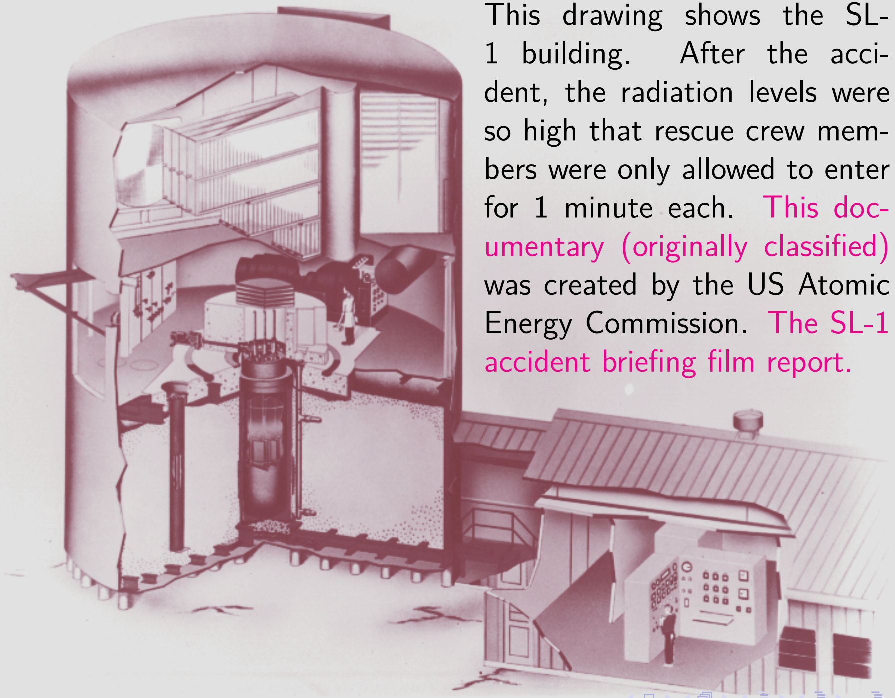


- Lower pressure that a PWR (Pressurised Water Reactor).
- Less irradiation-induced brittleness in the pressure vessel than a PWR.
- Fewer pipes, fewer welds, less chance of a rupture.
- The design can be modified to avoid reliance on pumps.

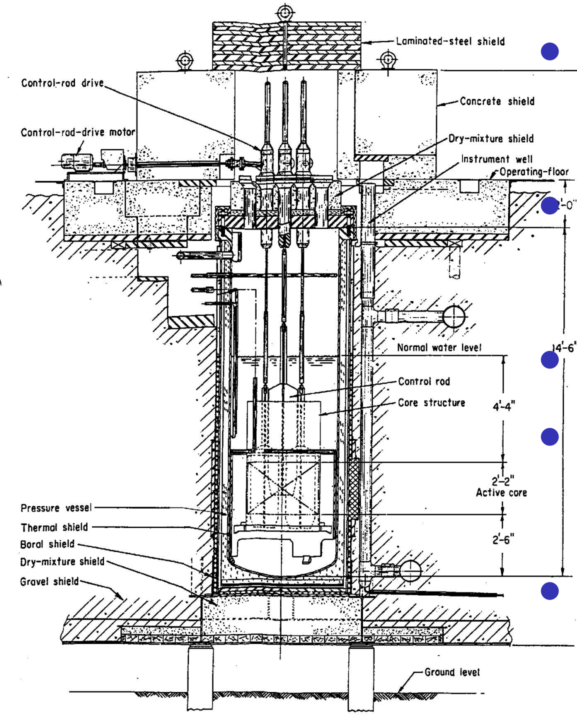
BWR disadvantages



- A BWR is much larger than a PWR (Pressurised Water Reactor).
- The water in the turbine contains radioactive nuclides (although this isn't too bad, since most of the radioactivity comes from ^{16}N, with a half-life of seconds).
- The core *must* be actively cooled after shut-down for days, and kept under water for months/years, so avoid melting of the fuel rods.
- The control rods are inserted from below, which is non-ideal from a fail-safety point-of-view (you would like a failure to lead to the rods dropping into the core under gravity).



This drawing shows the SL-1 building. After the accident, the radiation levels were so high that rescue crew members were only allowed to enter for 1 minute each. This documentary (originally classified) was created by the US Atomic Energy Commission. The SL-1 accident briefing film report.



- SL-1 (Stationary Low-power reactor no. 1), was an experimental reactor for Arctic radar stations.
- "Stationary" distinguishes it from the "mobile" and "portable" units that the US Army was considering.
- SL-1 went critical for the first time on August 11, 1958.
- Over the next two years it was regularly turned on/off for maintenance and training a number of army crews.
- On December 23, 1960, SL-1 was shut down to install neutron monitors.

The SL-1 accident

- On January 3, 1960, it was the job of the 3 men of the 4pm shift to reconnect the control rods in preparation for starting the reactor.
- It was a cold, bleak day, with outside temperatures of -27°C.
- The control rods required lifting by about 8cm.
- In attempting to free a stuck rod, it was moved by about 0.67m—the reactor went critical at 0.58m. The additional 0.09m movement caused the core to go *prompt critical* at 9:01pm.
- Normally, criticality is reached through neutrons resulting from decay of fission products, with a time-constant of seconds. However, if the core is "prompt critical", there are sufficient neutrons even without those from decay, so the time-constant shrinks to ~ 0.00001 sec.
- 0.04 sec after moving the control rod, the power reached 20 GW, some 6,700 times the design output of 3 MW.
- The coolant water vapourised. The 12 tonne reactor vessel leapt 3 m, hitting the roof. All three men were killed, one surviving for 2 hours, another pinned to the roof by a metal shield-plug through his body.

After the accident, a two-year investigation was conducted. This photo shows tests being conducted to determine the ease with which the control rods could be removed from a simulated core.

The Chernobyl disaster—1

- The Chernobyl reactor was an old design built in the Soviet Union using graphite as a moderator, producing 3.2GW of thermal power.
- The core required 12 tonnes of water per second for cooling, using 5MW water pumps.
- Backup diesel generators were used to provide power to run the pumps in the event of electrical failure.
- However, the diesels took 60–75 seconds to reach operating speed, leaving a gap in cooling.
- There was a proposal to use the residual momentum from the steam turbines to power the cooling pumps to cover the gap.
- On the day of the accident a test was underway to verify whether this technique would work.

The Chernobyl disaster—2

- 00:05am on April 26, 1986, the reactor power was reduced too rapidly to 700MW (from 3.5GW) to prepare for the test.
- The reactor power continued to drop below 700MW due to *reactor poisioning* which is the buildup of the fission decay product xenon-135. Xenon-135 has an extremely large cross-section for thermal neutrons, and so will greatly reduce the reactor power if present in large amounts. Xenon-135 is normally destroyed by fast neutrons, but it can build up if the reactor is run at low power. Once xenon-135 builds up, it can take 1–2 days for it to decay sufficiently to allow the reactor to work normally.
- The control rods were inadvertently inserted too far, leading to an almost total reactor shutdown (30MW).
- The operators then withdrew the control rods, to restart the reactor. Due to the earlier build-up of xenon-135, they had to withdraw the rods much further than usual.

The Chernobyl disaster—3

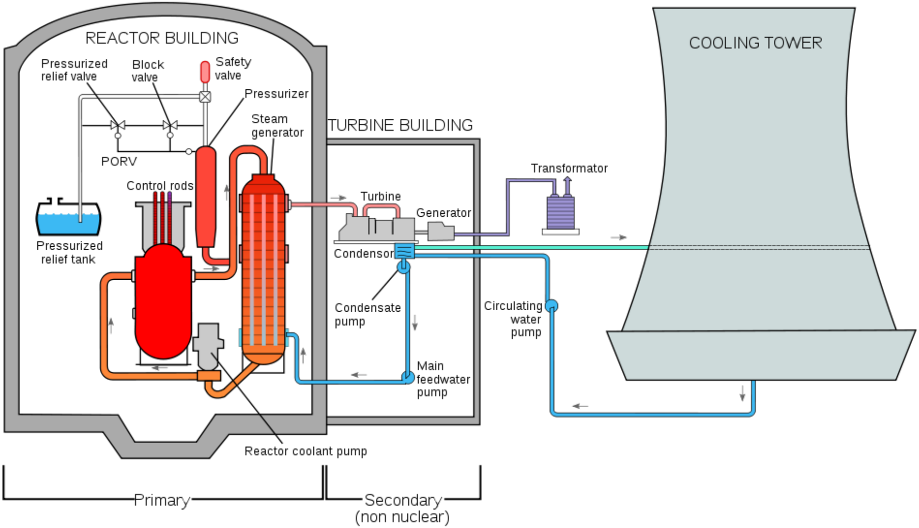
- 00:45am—the reactor core is now at 200MW, but is hard to control at this low power. At this time the operators should have aborted the planned test, but they continued.
- 01:23:04am—the test of the reactor started. The steam for the turbines was turned off.
- 01:23:30am—the coolant flow rate decreased, as the main circulating pumps started to loose power; this led to an increase in reactor power.
- 01:23:40am—the reactor was SCRAMed (control rods fully inserted) to stop the power rise.
- 01:23:43am—the control rods have a design flaw, whereby where their tip is graphite and so leads to a momentary increase in reactor power when they are first inserted. This results in the reactor power rising from 200 to 450MW in 3 seconds.

The Chernobyl disaster—4

- 01:23:44am—rapid boiling of the water leads to a power spike to around 30 GW, ten times the normal maximum power, and causes a steam explosion. A second explosion a few seconds later is equivalent to 10 tonnes of TNT. The graphite core catches fire, as does parts of the building.
- An interesting video on Chernobyl; Seconds from Disaster—Meltdown at Chernobyl—25:00 onwards.
- BBC documentary Surviving Disaster.
- Inside reactor #4 in 2016.
- The Chernobyl sarcophagus, completed in November 2016.

Three Mile Island

Three Mile Island



The Three Mile Island accident—1

- Three Mile Island consists of two PWR reactors, built in 1968–1970 in Pennslyvania, USA.
- A week before the accident on March 28, 1979, the water valves for the three auxillary pumps for the secondary water loop were closed for routine maintenance. The reactor should have been shut down for this operation, but wasn't.
- Overnight on March 27–28, 1979, a maintenance team was cleaning one of eight filters in the secondary water loop.
- At 4am on March 28, 1979, the pumps feeding the filters stopped, for reasons unknown.
- A bypass valve failed, so the secondary water loop stopped. Since the auxillary pumps were useless due to the valves being off, this led to the entire secondary water loop turning off.
- "Meltdown at Three Mile Island" a relevant documentary.
- Another documentary.

The Three Mile Island accident—2

- Without the secondary loop running, the primary loop was unable to cool, so pressure built up in the reactor. Within 3 seconds a valve (the PORV) opened to relieve the pressure through release of steam.
- This triggered an emergency shutdown (SCRAM): the control rods were inserted, and the reactor shut down within 8 seconds. The reactor continue to generate heat due to the radioactive decay of fission products.
- After relieving the pressure, the PORV was supposed to close, but due to a mechanical problem, the valve remained open. This led to continuing loss of primary coolant.
- 4:02am—Emergency core cooling pumps turned on automatically, but operators turned them off due to not realising that the PORV was still open (the indicator light on the panel said the value was closed, but this didn't allow for the mechanical problem with the valve).

The Three Mile Island accident—3

- 4:08am—operators realise that the secondary loop backup valves are closed, and open them. The secondary loop is now working.
- 5:20am—the primary loop pumps become ineffective since they were trying to pump steam, not water.
- 6:10am—the top of the core is exposed, and the zircalloy fuel rods start to react with oxygen to produce hydrogen.
- 6:20am—finally, the PORV's backup valve is closed. By now, 250,000 gallons of radioactive cooling water has been discharged.
- 6:45am—site emergency declared.
- 7:12am—general emergency declared (i.e., danger of radioactive release to the environment).
- 8:00am—half of the core has melted.
- 1:00pm—the accumulated hydrogen explodes, with a force equivalent to a couple of 1000-pound bombs (but the reactor survived).
- 7:50pm—finally, primary coolant flow is restored.

The Fukishima accident—background

- The Fukishima-Daiichi nuclear power plant consists of 6 nuclear reactors, typically 780 MWe (megawatts electrical, as opposed to megawatts thermal).
- BWR design with Mark 1 containment, designed by General Electric.
- Constructed in 1967–1973, and on-line from 1971–1979.
- Designed for ∼0.5 g acceleration, for earthquake protection.
- Designed for a 5.7 m tsunami.
- Located on the coast, for cooling.
- Originally, there was a 35 m high cliff at the location. This was reduced to 10 m to reduce pumping costs.
- Some engineers were concerned about the pumps being susceptible to flooding due to their location in the basement.


SKYTRUTH
619 ft
Image © 2011 DigitalGlobe
© 2011 Geocentre Consulting
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Fukushima Daiichi

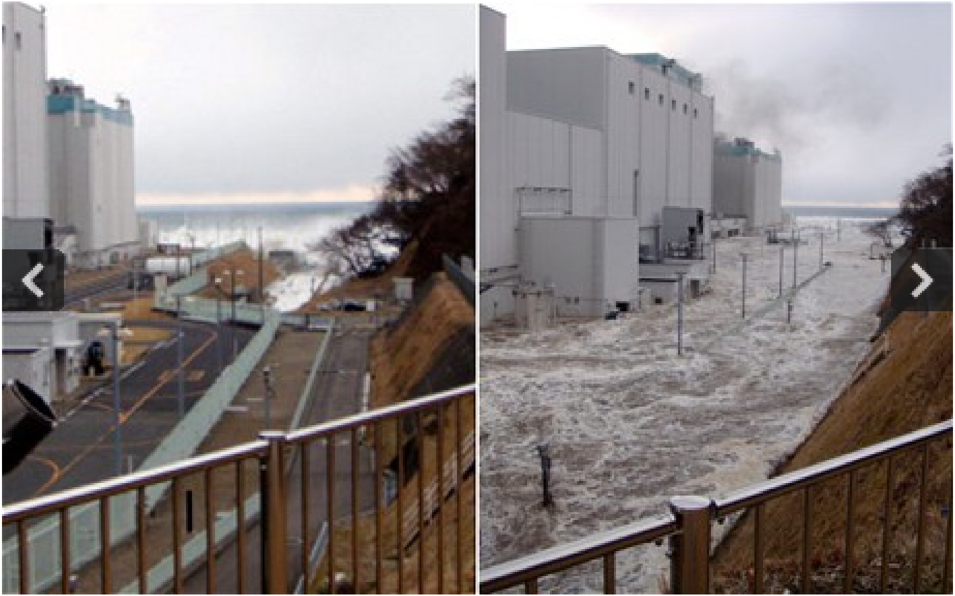
In this image released by Tokyo Electric Power Co., smoke billows from the No. 3 unit among four housings cover four reactors at the Fukushima Dai-ichi nuclear complex in Okumamachi, Fukushima Prefecture, northeastern Japan, on Tuesday, March 15, 2011. Japan ordered emergency workers to withdraw from its stricken nuclear complex Wednesday amid a surge in radiation, temporarily suspending efforts to cool the overheating reactors. Hours later, officials said they were preparing to send the team back in. (AP Photo/Tokyo Electric Power Co)

REUTERS/Tokyo Electric Power

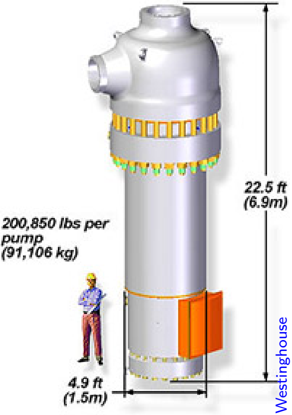
One of the Fukushima reactors, post accident.

The Fukishima accident—1

- Three of the six reactors were operating at the time of the accident.
- A magnitude 9.0 earthquake occurred at 2:46pm on March 11, 2011.
- The resultant peak ground acceleration was $\sim$0.56 g, slightly above the design limit of $\sim$ 0.5 g, but no damage occurred as a result.
- The reactors were SCRAMed automatically as a result of the earthquake.
- External power was also partially cut by the earthquake (and completely cut by the later tsunami). The on-site diesel generators started up to power the cooling pumps.
- 50 minutes later, a 13-15 m tsunami hit, overflowing the 5.7 m sea-wall.
- The water flooded the diesel engines, and washed away their fuel tanks.
- Backup generators higher up the hill were OK, but switchgear needed to put them on-line was in the flooded area, and so could not be used.



The Fukishima accident—2



Cooling pump

- The cooling pumps are partially running on batteries, designed to supply power for 8 hours. Some batteries were damaged by tsunami.
- Attempts were made to bring in new batteries and portable generators. This was difficult due to the damage to roads, but was achieved after about 6 hours. However, the portable generators could not be used due to flooding where the connections needed to be made, and difficulties finding cables.
- The plant operators struggled to run various cooling systems for the reactor cores and spent fuel rods.
- After about 3 hours, the water level in reactor 1 has dropped to the top of the fuel rods.

The Fukishima accident—3

- After about 4.5 hours, the reactor 1 core is fully exposed and begins to melt (although this wasn't known at the time).
- After about 16 hours, the reactor 1 core is entirely molten and falls to the bottom of the reactor vessel.
- An excellent summary of the early stages of the accident
- Understanding the accident
- The molten zirconium fuel-rod casing react with water to produce hydrogen gas.
- Pressure builds in the reactor vessel to such a level that gas has to be released into the building.
- The hydrogen explodes, blowing off the top of the building, damaging many systems, and releasing radioactive steam and gasses.

Fukishima—current status

- An excellent report on the status as of September 2013 is here.
- A video as of March 2016.
- The Fukishima Daiichi plant consists of 6 reactors. Units 5 & 6 were in cold shutdown. Unit 4 had no fuel in its RPV (reactor pressure vessel). Units 1, 2, and 3 have molten cores that have breached the RPV. All cores and spent fuel rods are now been cooled to less than 44°C.
- Large quantities of contaminated coolant water has to be stored on site. Some of the storage tanks are leaking.
- There are about 900 tanks, with no automatic water level sensing.
- The sea water radioactivity is mostly below the detection limit, apart from a region close to the plant.
- Some of the groundwater is highly contaminated.
- Attempts are being made to construct sealing walls in the ground, possibly composed of ice, to reduce the spread of contaminated ground water.

Nuclear power plant accidents, the effects

Date	Event	Deaths	^{131}I released [1,000 Ci]	Cost [US$m]
Jan 3, 1961	SL-1	3	0.08	22
Apr 26, 1986	Chernobyl	56+4,000	7,000	6,700
Mar 28, 1979	Three Mile Island	0	0.017	2,400
Mar 11, 2011	Fukushima	3	2,400	98,000

An interesting graphical representation of the size of various radiation doses.

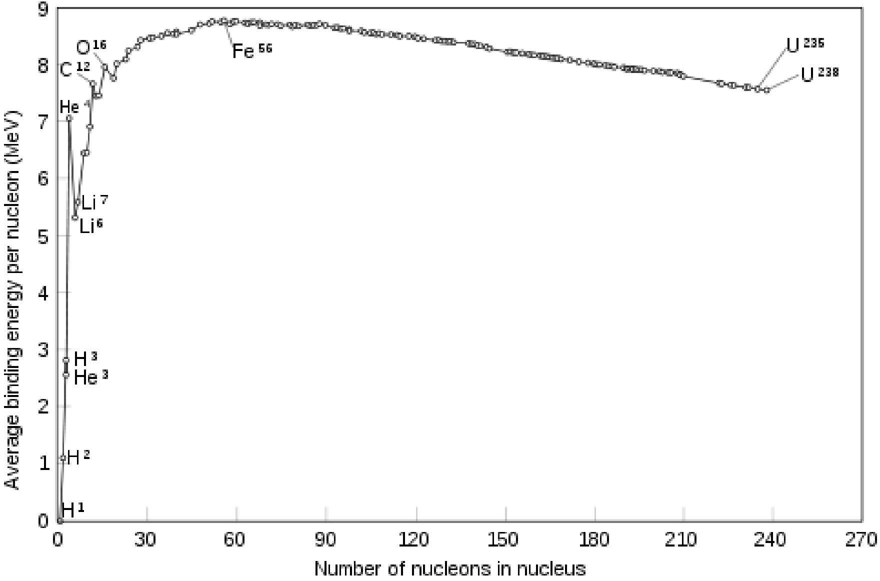
C.f., coal mining kills about 30 people each year in the US alone, and over 6,000 in China in one year (2004).

Deaths per TWh

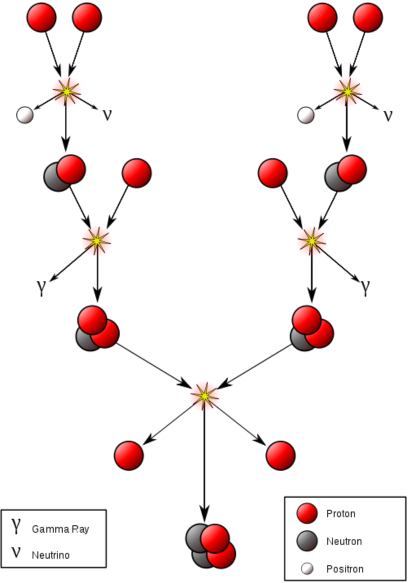
Source	Death rate [deaths per TWh]	Fraction of world energy
Coal	244	10%
Oil	52	40%
Natural gas	20	15%
Solar (rooftop)	0.1	<1%
Wind	0.15	<2.8%
Hydro	0.10	2.2%
Nuclear	0.04	3%

The above information comes from http://nextbigfuture.com; I do not know how reliable it is.

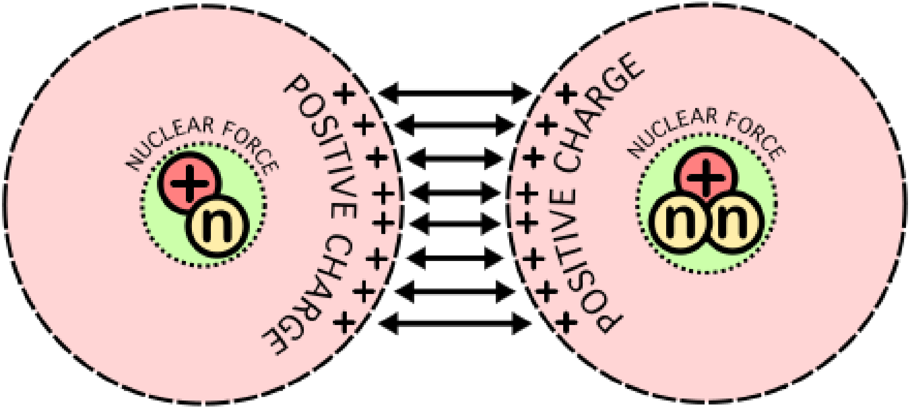
Nuclear binding energy



Fusion in the core of the sun



- The sun is converting 4 million tonnes of mass into energy via $E = mc^2$ every second through fusion of hydrogen into helium.
- The dominant reaction in the sun is the *proton-proton chain* at left.
- The fusion reaction occurs in the sun's core, where the temperature is $\sim 15\,\text{million K}$, and the density about 150 times that of water.
- While the power output of the sun is immense, the power production per unit volume in the core is relatively modest at $280\,\text{W}/\text{m}^3$, about the same as a compost heap!



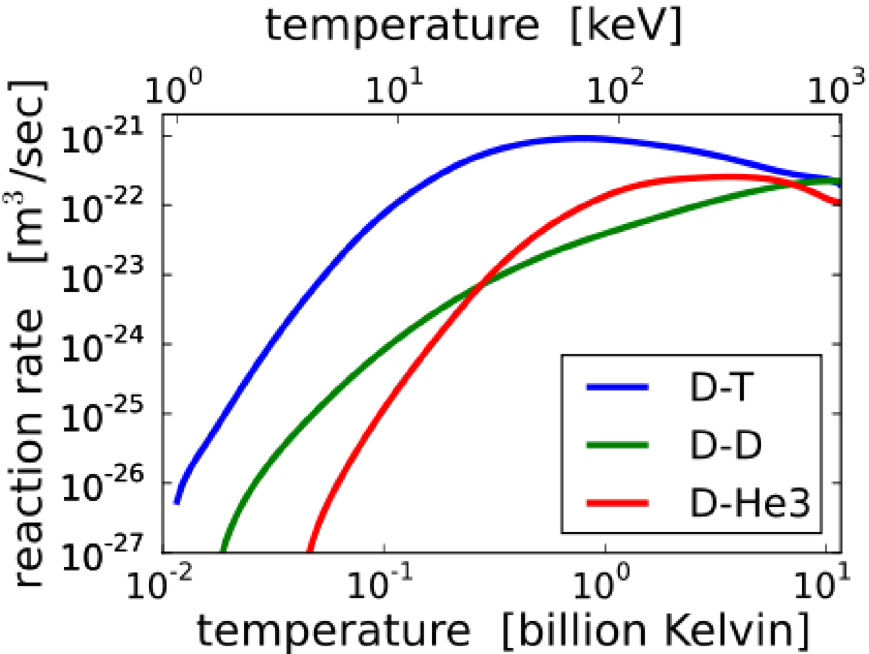
Fusion requires large energies to overcome electrostatic repulsion

- In the core of the sun, it takes about a billion years for a proton to react with another proton to form deuterium.
- It then only takes 4 seconds for the deuterium to react with another proton to form ^{3}He.
- And then 400 years for two ^{3}He nuclei to react to form ^{4}He.

Nuclear fusion—1

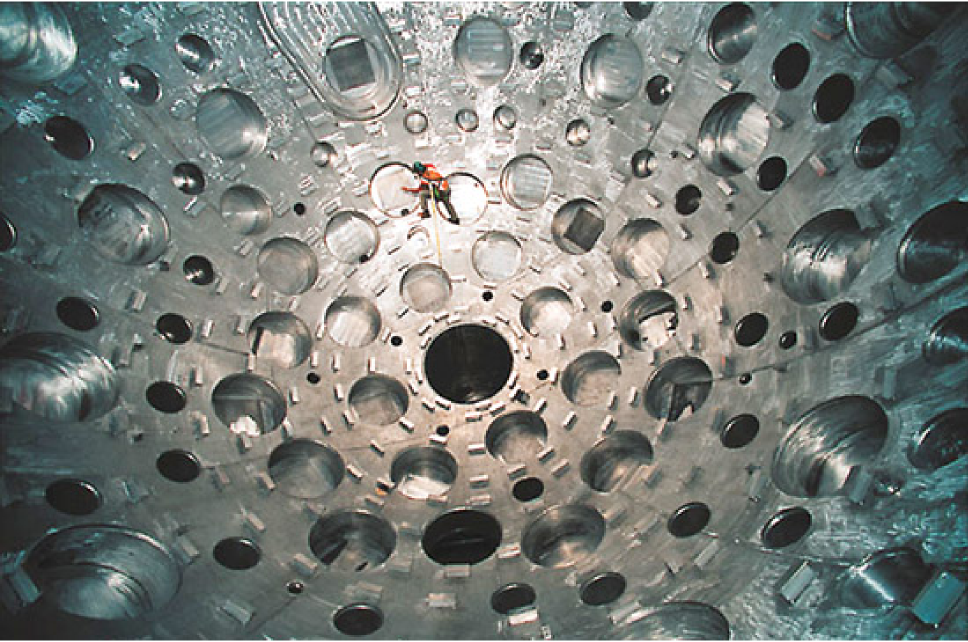
- Nuclear fusion is where two atomic nuclei combine to form a heavier nucleus. If the resultant nucleus is less massive than ^{56}Fe, then the process releases energy. This is how stars get their energy for most of their lives.
- The fusion reactions of most interest for producing energy on earth are:
  - $\mathrm{D} + \mathrm{D} \rightarrow \mathrm{p} + \mathrm{T} + 3.3\mathrm{MeV}$
  - $\mathrm{D} + \mathrm{D} \rightarrow \mathrm{n} +^{3} \mathrm{He} + 4.0\mathrm{MeV}$
  - $\mathrm{D} + \mathrm{T} \rightarrow \mathrm{n} +^{4} \mathrm{He} + 17.6\mathrm{MeV}$
  - $\mathrm{D} +^{3} \mathrm{He} \rightarrow \mathrm{p} +^{4} \mathrm{He} + 18.3\mathrm{MeV}$

  where D is deuterium and T is tritium. Both are isotopes of hydrogen. They can also be shown as ^{2}H and ^{3}H.
- The D–T reaction is the one of most interest at the moment, since it requires the lowest ignition temperature.


temperature [keV]
10^0
10^1
10^2
10^3
reaction rate [m^3/sec]
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
D-T
D-D
D-He3
10^{-2}
10^{-1}
10^0
10^1
temperature [billion Kelvin]

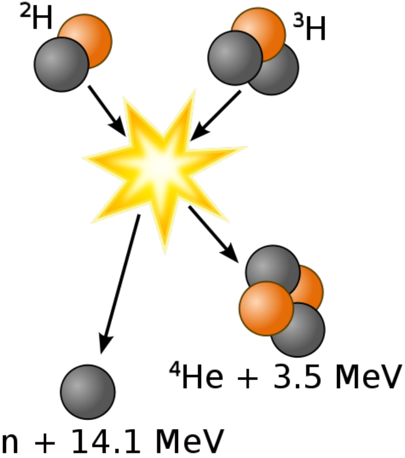
Nuclear fusion—2

- Tritium is rare on earth (perhaps only 20 kg in total in the earth's crust) due to its half-life of only 12 years.
- Fortunately, tritium can be produced in a reactor from $\mathrm{n} +^{6} \mathrm{Li} \rightarrow^{4} \mathrm{He} + \mathrm{T} + 4.8\mathrm{MeV}$.
- Deuterium is relatively abundant, and easily separated from hydrogen.
- About one in every 6,500 hydrogen atoms on earth is deuterium.
- The energy that could be released from complete fusion of all the deuterium in 1 cubic kilometre of water is double that from all of the earth's oil reserves.
- So. . . , fusion is in principle a very desirable energy source: almost unlimited fuel is available, no carbon dioxide emissions, no bomb implications, and no radioactive waste products (apart from induced radioactivity in the reactor parts).
- However, the technological challenges of building a working fusion reactor are immense.

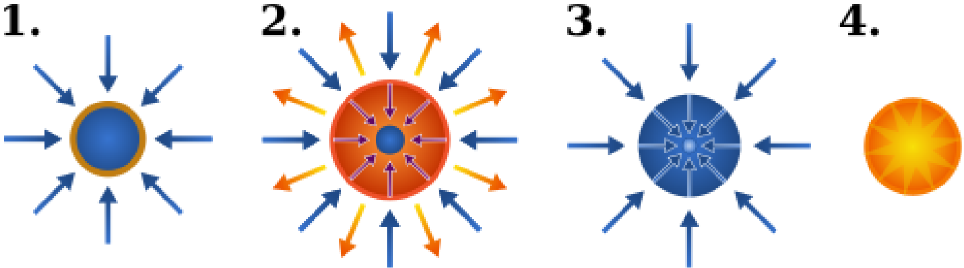


The National Ignition Facility laser target chamber

The D–T reaction

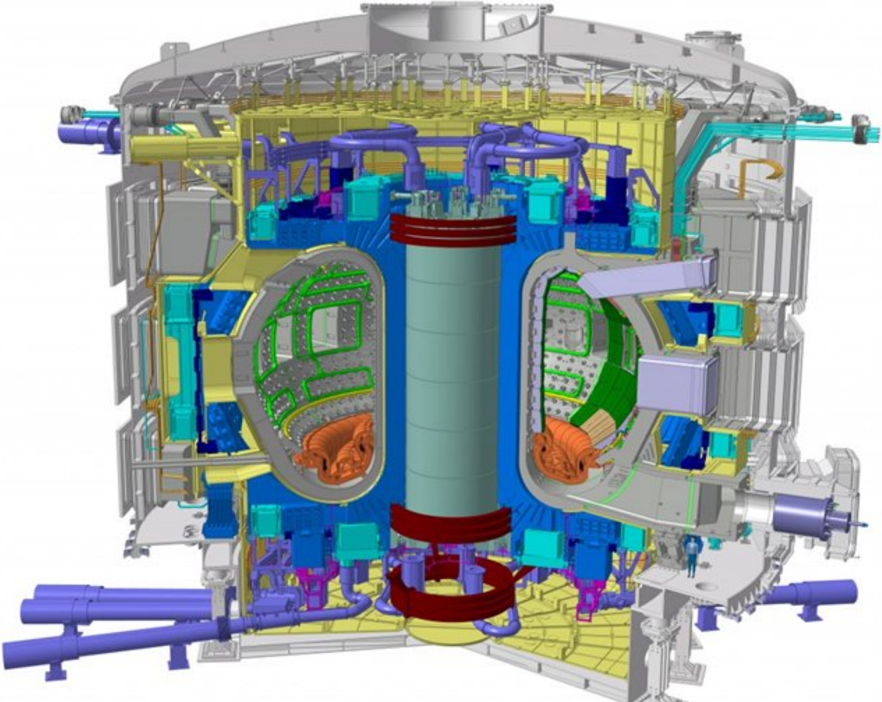


- $\mathrm{D} + \mathrm{T} \rightarrow \mathrm{n} +^{4} \mathrm{He} + 17.6\mathrm{MeV}$
- At the temperatures needed for fusion (∼100 million K), matter is a *plasma* (i.e., electrons and nuclei are separated).
- To achieve a reasonable reaction rate, the plasma has to be sufficiently dense for a sufficiently long time.
- This can be achieved with magnetic confinement (Tokamak), or inertial confinment using lasers.
- Tokamaks are running at JET in the UK and ITER in France.
- Laser systems are running at NIF in the US

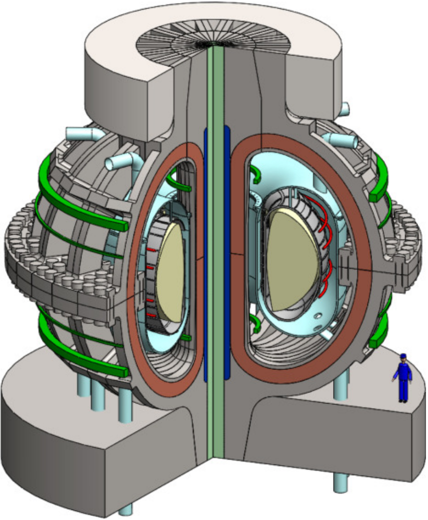


Schematic of the stages of inertial confinement fusion using lasers. The blue arrows represent radiation; orange is blowoff; purple is inwardly transported thermal energy (source: wikipedia).

- Laser beams or laser-produced X-rays rapidly heat the surface of the fusion target, forming a surrounding plasma envelope.
- Fuel is compressed by the rocket-like blowoff of the hot surface material.
- During the final part of the capsule implosion, the fuel core reaches 20 times the density of lead and ignites at 100,000,000K.
- Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.

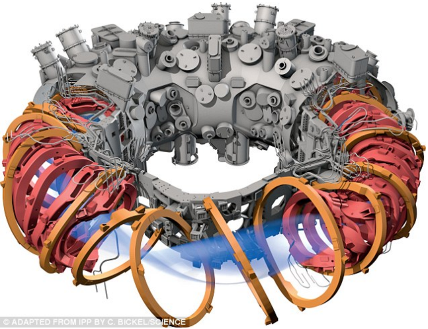


The MIT ARC design, 2015

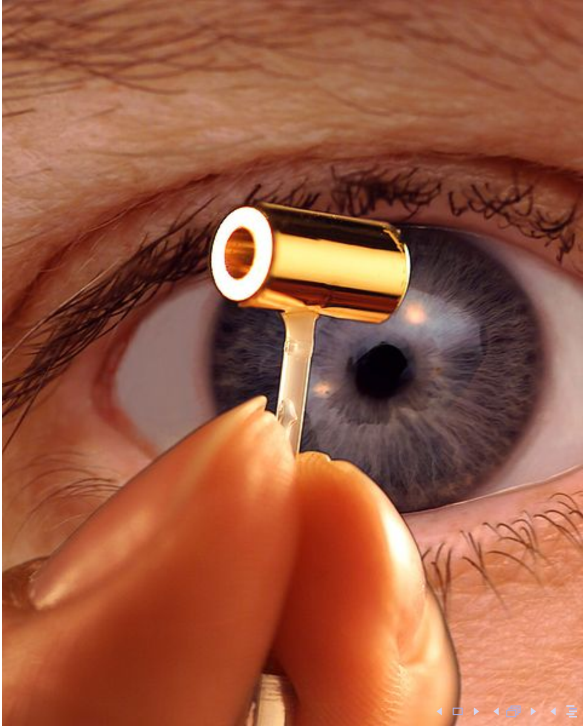


- ARC (Affordable Robust Compact) reactor design from MIT.
- Uses REBCO (rare earth barium copper oxide) magnets, that can support greater magnetic fields than ITER.
- The fusion output goes as the magnetic field to the fourth power, and the cost goes as the linear size cubed.
- ARC has the potential to be a viable fusion reactor.

Stellarators



- The stellarator is an alternative to the tokomak design for fusion.
- The design is very complex, and only became possible to calculate with the development of fast computers.
- Germany's Wendelstein-7X stellarator became operational in December 2015.
- Details of the design of Wendelstein-7X.



- A good description of nuclear binding energies and the relevance to fission and fusion.
- An excellent video showing how the NIF works
- NIF target chamber [BROKEN LINK]
- NIF crystal growth
- Brian Cox on investment in fusion research.
- 28 Sep 2013— breakthrough at the NIF had the amount of energy released through fusion exceeding the energy absorbed by the fuel. However, only a fraction of the input power that drives the lasers is eventually absorbed by the fuel, so we are still a long way (a factor of 130) from breakeven.
- An alternative approach by General Fusion, using pistons

Nuclear fusion—0

- fission and fusion
- discovery of neutrinos from the pp process in the Sun
- an interesting video on ITER, with nice music
- the e-cat cold fusion scam
- Lockheed Martin pursuing fusion and a video describing what they propose.
- Nuclear powered bomber documentary interesting from 17:38

Radiation dose units

- The amount of energy absorbed per unit mass of an object, when exposed to radiation, is given in units of *grays*. It is measured in joules (a unit of energy) per kilogram.
- The *sievert* is also a unit of radiation dose, and is also measured in joules per kilogram. An interesting video on radiation sickness.
- The difference is that a sievert attempts to measure the biological effect of the dose. An exposure to a given dose in sieverts has the same biological effect, regardless of whether the radiation is alpha, beta, protons, neutrons, or gamma-rays, and regardless of where the radiation is absorbed in the body.
- So the actual dose in grays is corrected for both the type of radiation, and the part of the body, before being expressed in sieverts.
- Note that the US uses an older unit, the *rem*. There are 100 rems in a sievert.

Symptoms of radiation exposure

- 0–0.25 Sv (0–250 mSv): None
- 0.25–1 Sv (250–1000 mSv): Some people feel nausea and loss of appetite; bone marrow, lymph nodes, spleen damaged.
- 1–3 Sv (1000–3000 mSv): Mild to severe nausea, loss of appetite, infection; more severe bone marrow, lymph node, spleen damage; recovery probable, not assured.
- 3–6 Sv (3000–6000 mSv): Severe nausea, loss of appetite; hemorrhaging, infection, diarrhea, peeling of skin, sterility; death if untreated.
- 6–10 Sv (6000–10000 mSv): Above symptoms plus central nervous system impairment; death expected.
- Above 10 Sv (10000 mSv): Incapacitation and death.
- An interesting graphical representation of the size of various radiation doses. A Canadian video on radiation.

Galactic cosmic radiation (GCR)

- Galactic cosmic rays are very high energy charged nuclei (mostly protons, but can be all the way up to iron in mass).
- They are produced by astrophysical phenomena (e.g., supernovae, black holes) in our Galaxy.
- The very highest energy GCRs contain as much kinetic energy as a thrown ball.
- If a one microgram speck of dust had the same velocity as one of these GCRs it would have as much energy as 40 of the most powerful hydrogen bombs ever detonated.
- We are shielded from GCRs to a large extent by the earth's atmosphere.
- GCRs interact with atoms high in the atmosphere, and cause a cascade of interactions that eventually absorb their energy.
- Pilots and airline crew face a greater risk from GCRs.

Solar Particle Events (SPE)

- Solar particle events are the release of large numbers of electrons and nuclei during a solar flare on the sun.
- The SPE travels outwards along lines of magnetic flux, and can hit the earth.
- Mostly, the particles are deflected by the earth's magnetic field
- Astronauts are particularly vulnerable to SPEs.

Trapped radiation

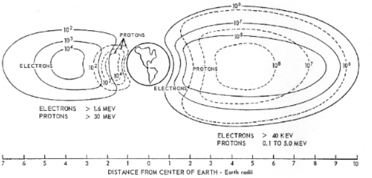


Figure 1. Trapped radiation belts as a function of energy and distance from the earth.

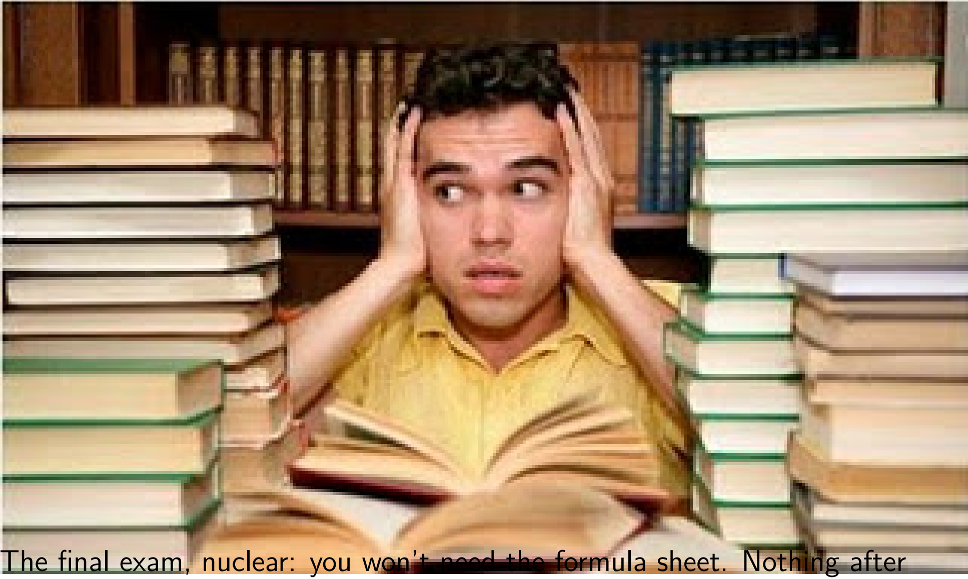
- The earth's magnetic field acts as a trap for charged particles, which can bounce back and forth between the north and south poles.
- This causes aurorae, and strong radiation in space.
- Due to the tilt of the earth's magnetic field with respect to its spin axis, the trapped particles are particular strong off the coast of Brazil, and a couple of hundred km up, in the "South Atlantic Anomaly" (SAA).
- When spacecraft pass through the SAA, they received a large dose of radiation.
- As do space shuttle crewmembers.

Consequence for space travel

- NASA video on radiation effects on astronauts.
- NASA video on the Orion spacecraft design.
- NASA video on radiation measurements from the Curiosity rover on Mars.

Sample exam questions

- Describe what the various symbols and numbers mean in the following: ${}^{235}_{92}\mathrm{U} + \mathrm{n} \rightarrow {}^{142}_{56}\mathrm{Ba} + {}^{91}_{36}\mathrm{Kr} + 3\mathrm{n}$. What is this describing?
- Give a concise description of the key events leading to the Chernobyl disaster.
- Describe how a hydrogen gas explosion can occur following the failure of cooling in a nuclear reactor.
- With reference to the plot of nuclear binding energies, describe the relevance of this plot to fission and fusion reactors.
- Describe how the 700 million year half-life of ${}^{235}\mathrm{U}$ is relevant to the discoveries made at the Oklo pit mine in the 1970s.
- What is the purpose of a moderator in a nuclear fission reactor?
- How is radon gas relevant to uranium decay and human health?



The final exam, nuclear: you won't need the formula sheet. Nothing after this slide is examinable. The lecture slides cover all the examinable material. Supplement them with the textbook and/or internet resources. Wikipedia is very good. The exam will require written responses showing an understanding of the lectures.

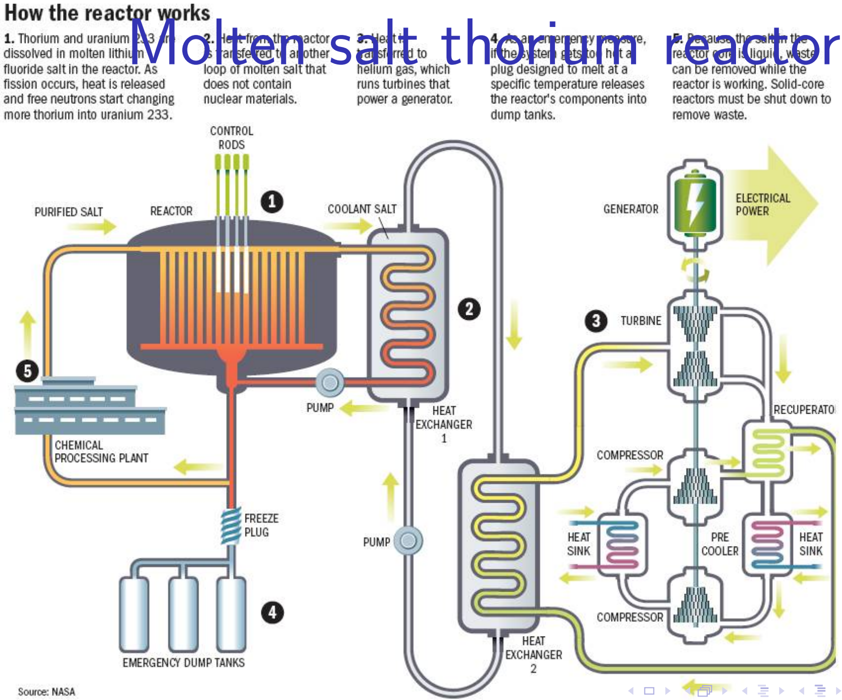
Thorium fission reactors

- NOTE: thorium fission reactors are NOT examinable, Gen IV and alternative reactors are NOT examinable.

How thorium reactors work

- Natural thorium is mostly ^{232}Th, which is a *fertile* nucleus, i.e., it can be converted into a *fissile* nucleus (one that is able to undergo sustained nuclear fission in a reactor) by irradiation by neutrons.
- In a thorium reactor ^{232}Th is in the presence of other fissile nuclei to get the reaction started.
- As time goes on, the ^{232}Th is transmuted to fissile ^{233}U by the neutron bombardment within the reactor.
- The ^{233}U can be chemically separated from the remaining ^{232}Th and used as a fuel to keep the reaction going. More details of thorium reactors here, and here.

Molten salt thorium reactor



How the reactor works

1. Thorium and uranium 233 are dissolved in molten lithium fluoride salt in the reactor. As fission occurs, heat is released and free neutrons start changing more thorium into uranium 233.

2. Heat from the reactor is transferred to another loop of molten salt that does not contain nuclear materials.

3. Heat is transferred to helium gas, which runs turbines that power a generator.

4. As an emergency measure, if the system gets too hot a plug designed to melt at a specific temperature releases the reactor's components into dump tanks.

5. Because the salt in the reactor core is liquid, waste can be removed while the reactor is working. Solid-core reactors must be shut down to remove waste.

Source: NASA

Possible advantages of thorium

- ^{232}Th is the most abundant isotope of thorium, and is 3–4 times as abundant as uranium.
- Thorium dioxide has a higher melting point that uranium dioxide, as well as better thermal conductivity, lower coefficient of thermal expansion, and greater chemical stability (i.e., it does not oxidize further).
- The waste products of a thorium reactor are relatively benign. While they are initially highly radioactive, this means that they decay quickly, and achieve lower radioacivity that natural uranium ore after a few hundred years (I'm unsure of the accuracy of this statement).
- The waste is hard to use for any weapons production, since it contains a mixture of ^{232}U and ^{233}U, which can't be easily separated.
- Thorium reactors operate at lower pressure than uranium reactors, and are immune from core meltdown.

Possible disadvantages of thorium

- Fuel rod production is much more complex than for ^{235}U reactors.
- Chemically extracting the ^{233}U required handling highly radioactive material, which is not easy.
- There are a number of technical challenges in the design of thorium reactors which will require a large research investment to solve. There is currently no financial incentive to do this. It may require many decades of research and development, during which time alternative energy sources are likely to become more economical.

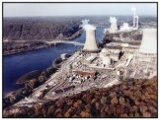
Current status of thorium reactor development

- There are currently no commercial thorium reactors in operation.
- A number of nations (Canada, China, India, Norway) have active research and development programs related to thorium reactors.
- Norway has significant reserves of thorium, and there is interest in developing small thorium reactors.
- In September 2012, the UK National Nuclear Laboratory produced a report on the potential for thorium reactors. The conclusion was that advantages for thorium are often overstated, and that it had limited relevance to the UK.
- In general, it appears that the economic case for thorium reactors is not strong enough to justify commercial development at this stage.

Generation IV: Nuclear Energy Systems Deployable no later than 2030 and offering significant advances in sustainability, safety and reliability, and economics

Generation I

Early Prototype Reactors



- Shippingport
- Dresden, Fermi I
- Magnox

Generation II

Commercial Power Reactors

- LWR-PWR, BWR
- CANDU
- VVER/RBMK

Generation III

Advanced LWRs

- ABWR
- System 80+
- AP600
- EPR

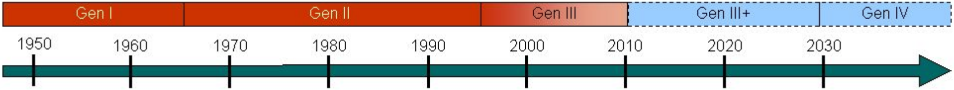
Near-Term Deployment

Generation III+ Evolutionary Designs Offering Improved Economics

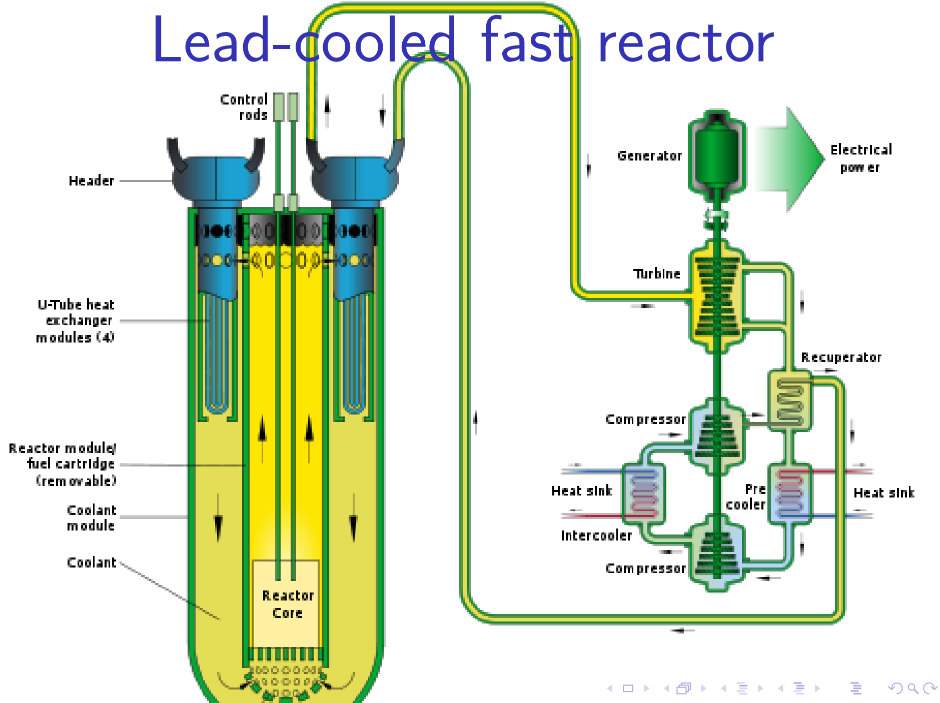
....

Generation IV

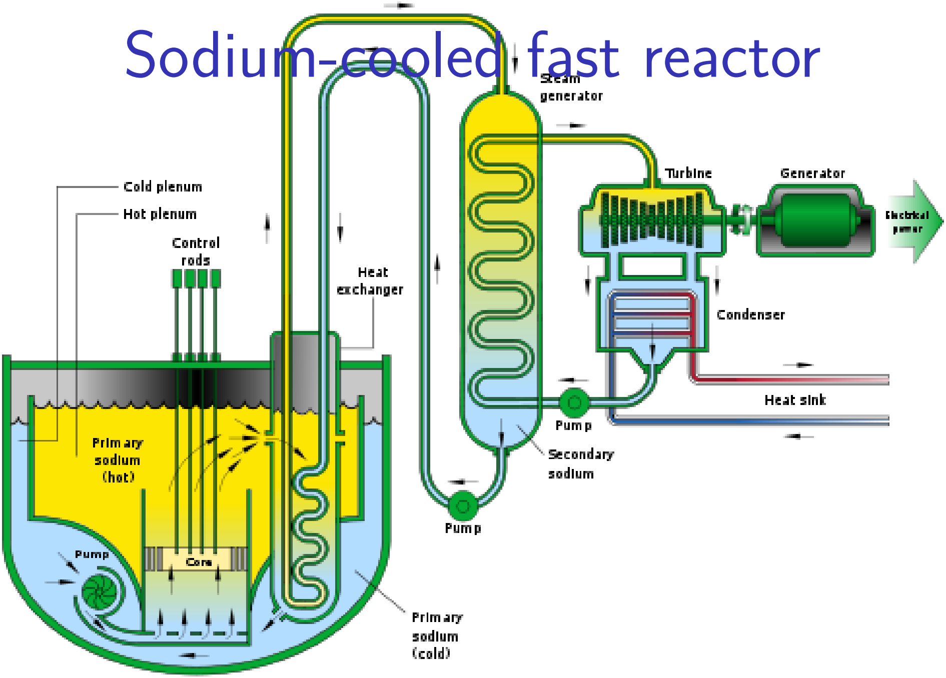
- Highly Economical
- Enhanced Safety
- Minimal Waste
- Proliferation Resistant



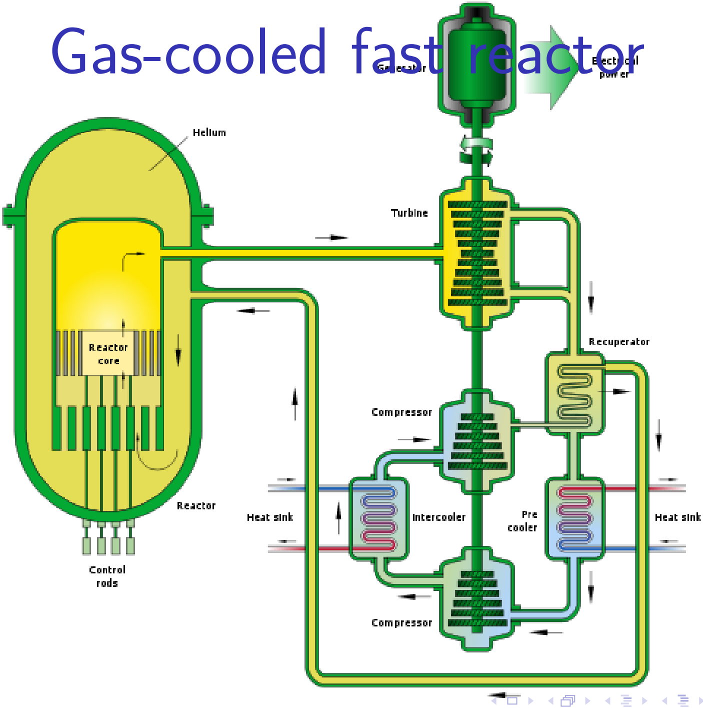
Lead-cooled fast reactor



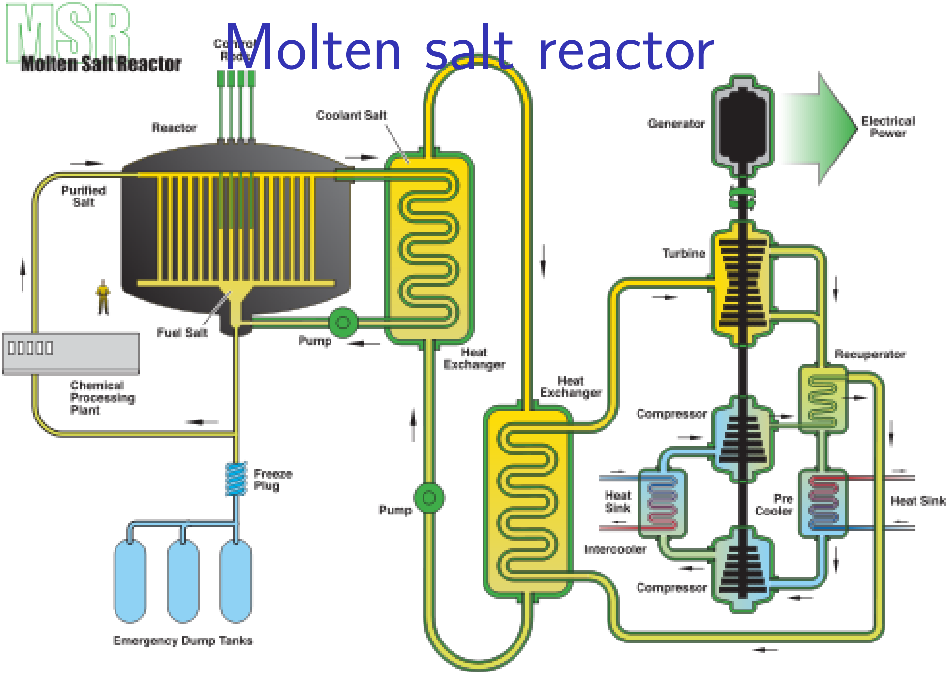
Sodium-cooled fast reactor



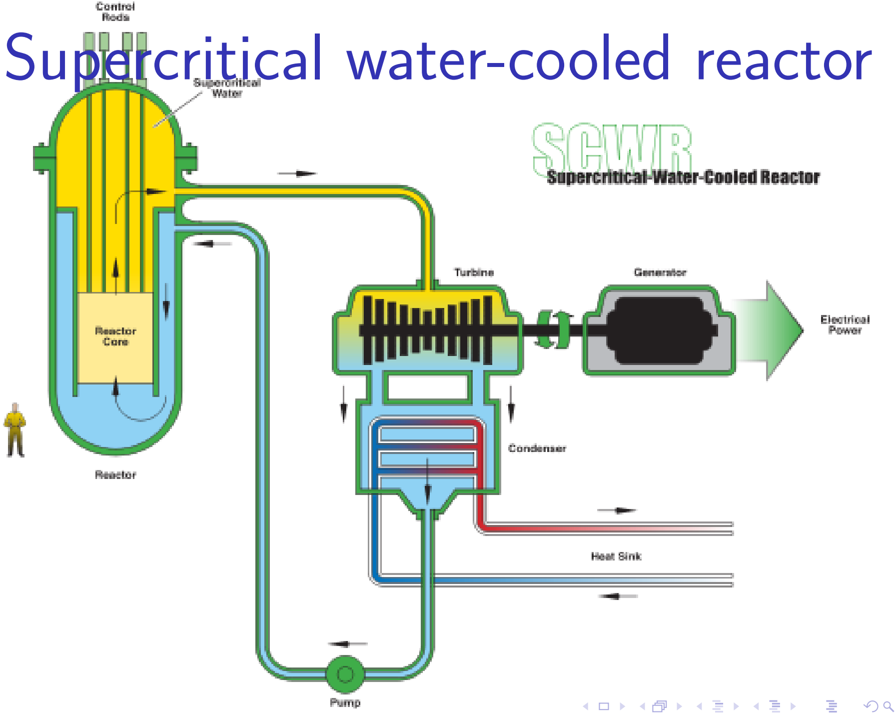
Gas-cooled fast reactor



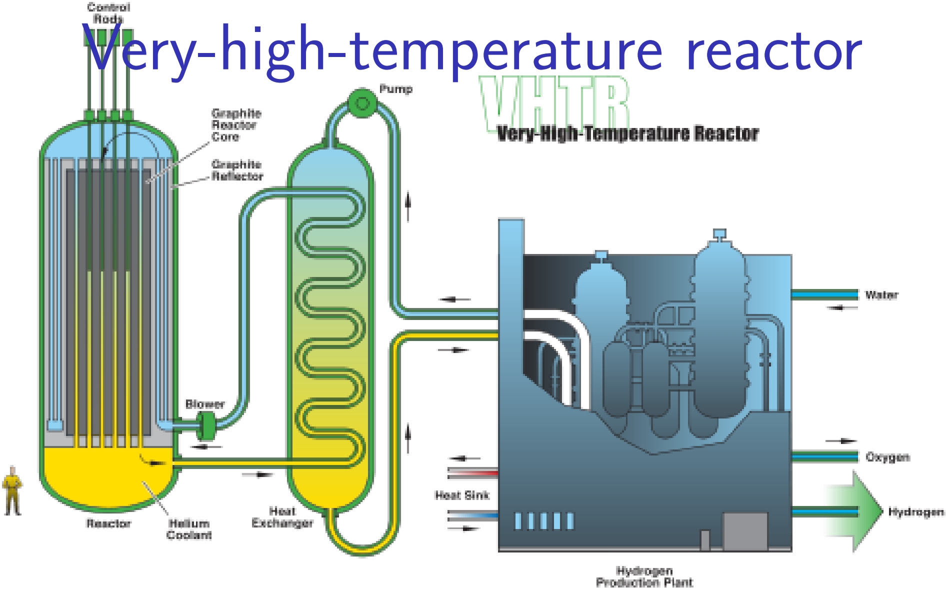
Molten salt reactor



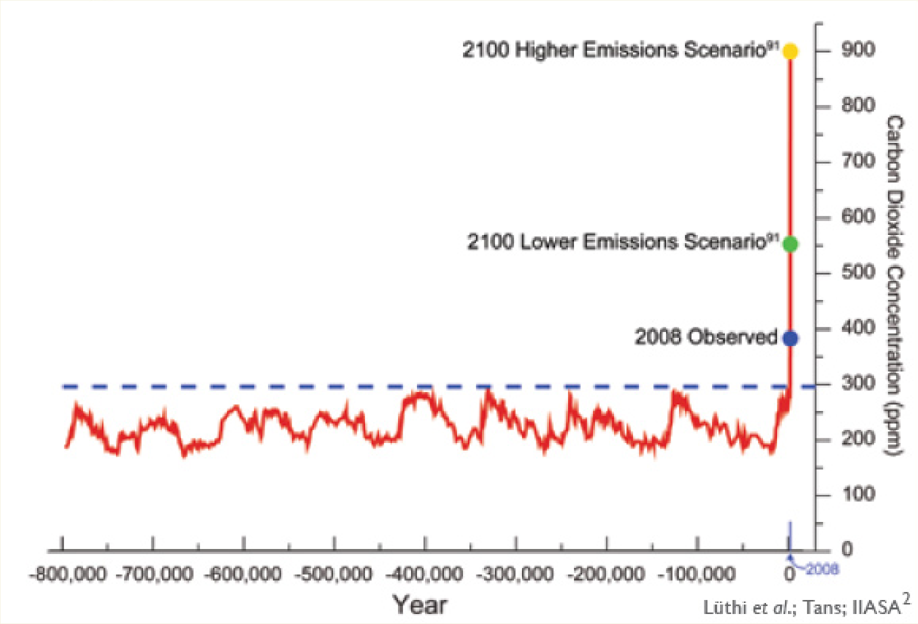
Supercritical water-cooled reactor



Very-high-temperature reactor



800,000 Year Record of Carbon Dioxide Concentration

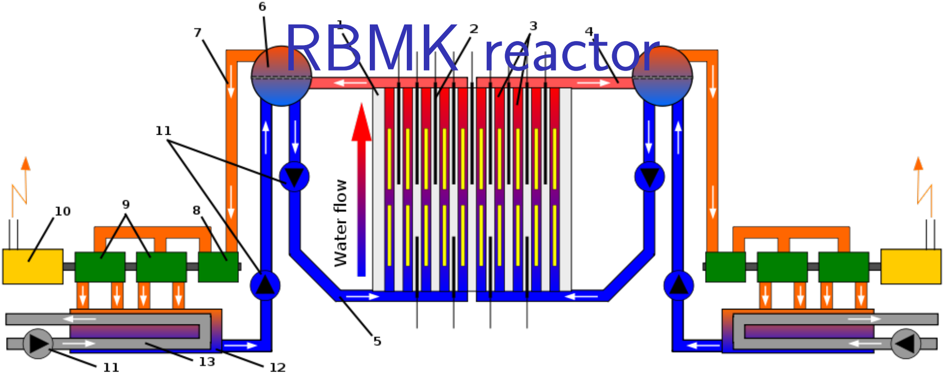


Lüthi *et al.*; Tans; IIASA[2]

Climate links

- Isaac Asimov 1989
- Skeptical science website
- Debunking contrarian arguments
- Skeptical scientists and others
- My article on The Australian
- Decline of glaciers
- NASA on sea ice
- NOAA multi-year ice
- Climate crock on sea ice
- CO2 was higher in the past, and we had glaciers
- 32000 scientists

RBMK reactor



Legend :

1. Graphite moderated reactor core
2. Control rods
3. Pressure channels with fuel rods
4. Water/steam mixture
5. Water
6. Water/steam separator
7. Steam inlet
8. High-pressure steam turbine
9. Low-pressure steam turbine
10. Generator
11. Pump
12. Steam condenser
13. Cooling water (from river, sea, etc.)