Nuclear Energy

Frontiers of Physics Lecture 2 (F4)

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Summary of Lecture I

- Nuclear power around the world
- Costs, comparisons, advantages
- Public perception
- Radiation and radioactive material
- Nuclear waste
- Atomic bombs and nuclear power plants

Next: the Fukushima Daiichi accident ...

Fukushima Daiichi - 11 March 2011, Ōkuma, Japan

- INES **Level 7** accident
- Accident type: meltdown, hydrogen explosion
- Deaths: none
- Causes: complex equipment failures following an earthquake and tsunami

- Earthquake Tōhoku of magnitude 9.0 occurs Friday at 2:46 PM
- Reactors 1, 2 and 3 automatically SCRAM and diesel generators turn on (unit 4 was in cold storage and 5 and 6 were off at the time)
- The situation seems under control
- At 3:27 a first wave hits but does not overtop the seawall
- Eight minutes later, a second,15m high tsunami wave hits

Fukushima Daiichi

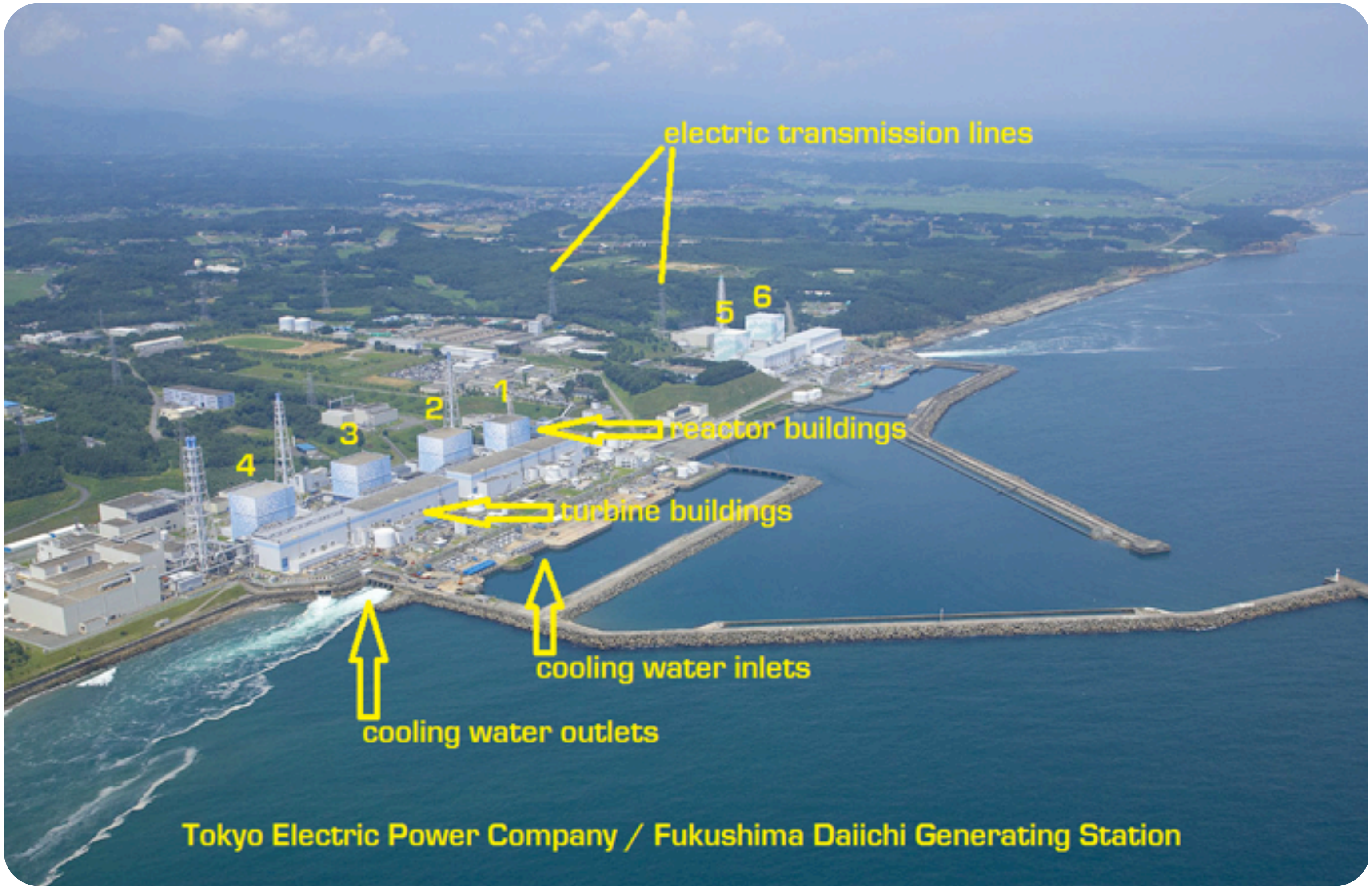


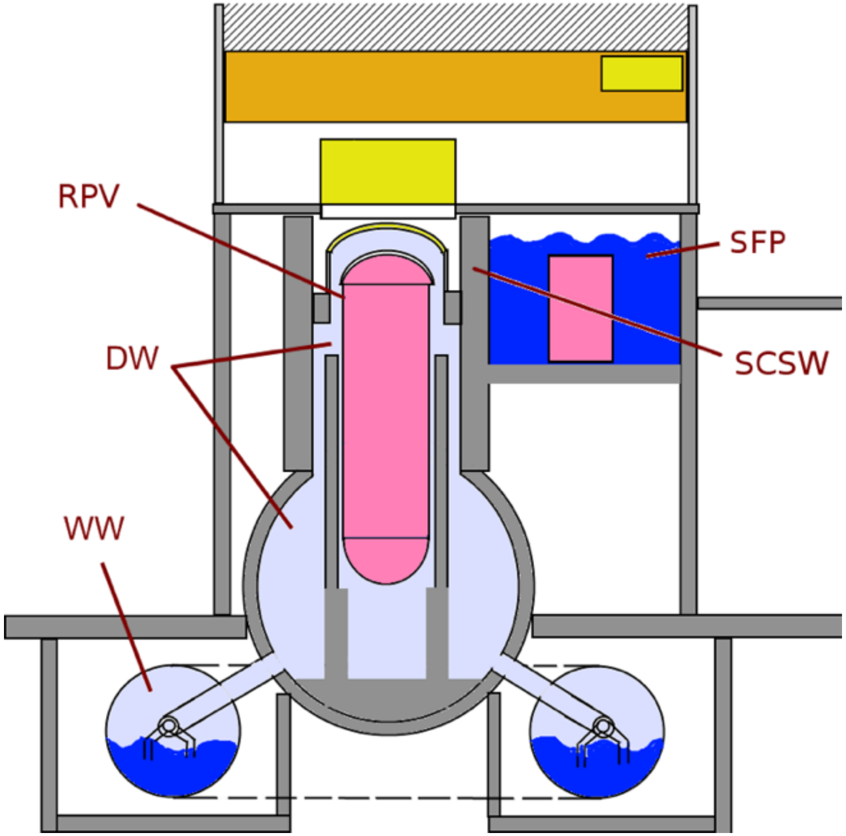
Image courtesy of TEPCO public information website

FD accident: Sequence of events (cont'd)

- Generators, electrical switchgear and external coolant pumps are flooded, power lines are cut
- Un unprecedented station blackout (SBO) results
- Reactors overheat due to the natural decay of fission products
- Due to the destruction done by the tsunami, it is impossible to cool down the reactors
- During the next hours and days, reactors 1, 2 and 3 experience full meltdown; hydrogen is produced by the oxidation of the zircaloy cladding
- Hydrogen explosions destroy the upper parts of the buildings housing reactors 1, 3, and 4
- Explosions at reactors 1 and 3 damage the secondary containment of reactor 2 and multiple fires break out
- The spent fuel rods in the storage pools overheat as water levels in the pools drop, releasing radioactivity in the atmosphere; tons of water have to be dropped in the pool of reactor 4 by helicopter or water cannon

FD accident: Safety flaws

- The emergency diesel generators and DC batteries - components crucial in powering the reactors' cooling systems in the event of a power loss - were located in the basements of the reactor turbine buildings
- The plant was designed to withstand a 5.7m tsunami, although a study from 2008 indicated that higher waves could be produced by an earthquake in this region
- At reactor 1, the relief valve should have been opened to vent steam and hydrogen. Because this would have also released radioactive material, it was postponed for so long that the reactor ultimately exploded



BWR Mark I scheme: RPV - reactor pressure vessel, SFP - spent fuel pool, DW - dry well, SCSW - secondary concrete shield wall, WW - steam suppression pool

FD accident: Impact

- An area of 20km radius around the plant had to be evacuated
- 89,000 people have been displaced, with no possibility of return before less than 20 years
- Significant releases of radioactive pollutants in coastal waters
- Releases of ^{131}I and ^{137}Cs are around 10% of the ones from Chernobyl
- No deaths or serious injuries due to direct radiation exposure
- Estimated that on the order of 1,000 people will die from cancer as a result of radiation exposure (more than 20,000 died in the earthquake)
- Rectors still not in a stable condition, radioactive material still leaking today
- High levels of radiation prevent an accurate assessment of the situation
- TEPCO is close to insolvency, and will need government money to survive
- Increased anti-nuclear sentiment has been evident in many countries among which Italy, Spain, Switzerland
- Germany decided to phase out nuclear plants

Reactor Technology

Types of reactors, safety considerations, other applications

PWR

- Pressurised Water Reactors (PWR) are the most common type built
- PWRs were originally designed for nuclear submarines
- Water at 15 MPa and 290˚C enters the reactor vessel, is heated as it passes through the core region and exits at 325˚C
- The water is pressurised to minimise the risk of boiling
- A steam generator is then used to transfer this heat
- The steam drives a turbine that turns an electricity generator

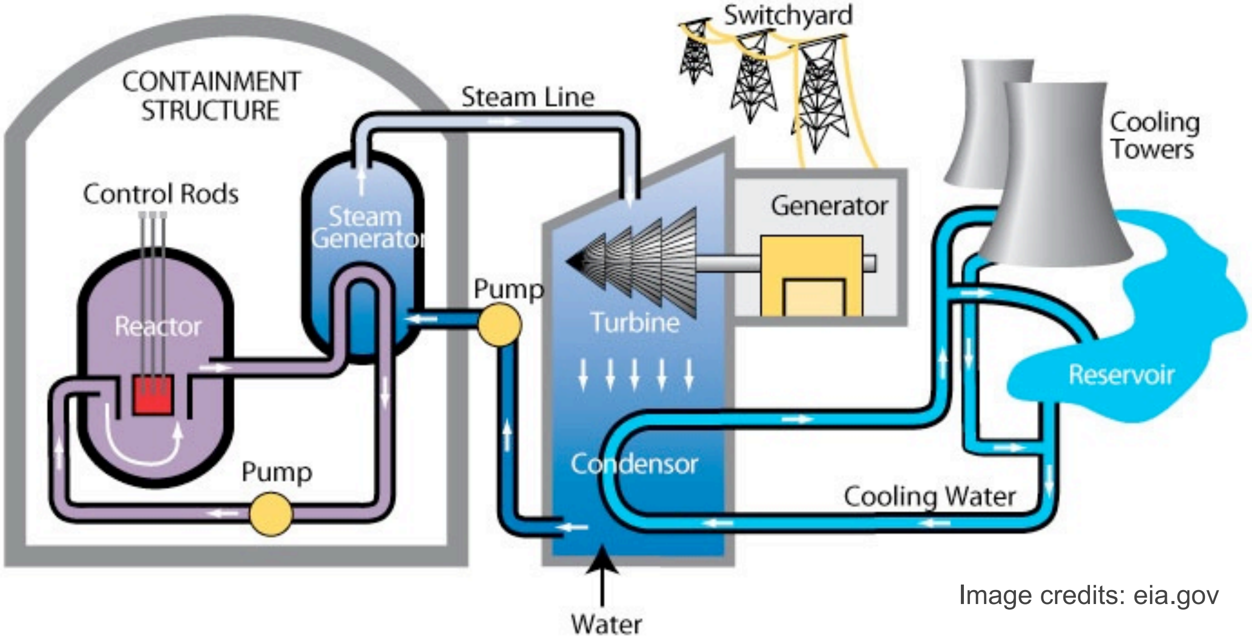
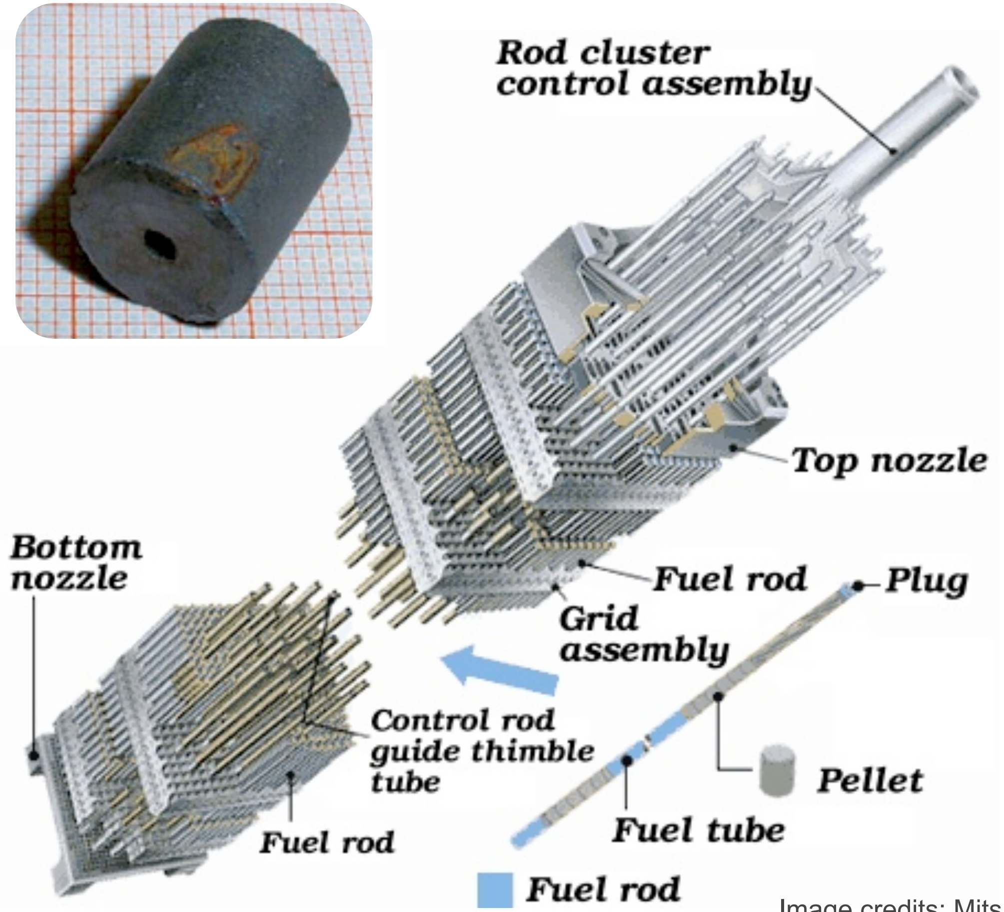


Image credits: eia.gov

PWR (cont'd)

- The H_2O *coolant* in a PWR acts also as *moderator* and *reflector*
- Slightly enriched uranium, with ^{235}U concentrations of 2–5% is used as fuel
- The fuel is loaded into typically 4m long zircalloy-clad tubes mounted in square clusters
- A typical PWR generates around 3GWt with an ≈33% efficiency
- One of the reasons for the widespread deployment of PWRs is their large *negative void coefficient*



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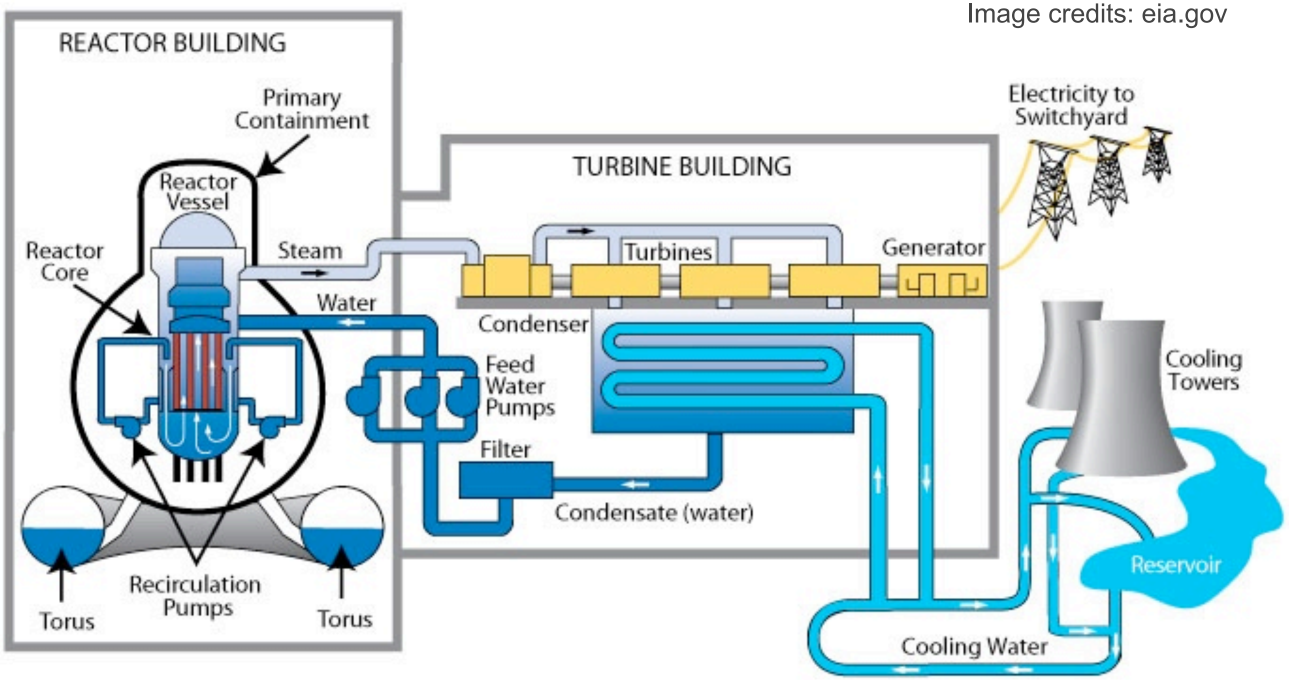
BWR

- Boiling Water Reactors (BWR) have negative void coefficients as well
- The boiling water H_2O acts as coolant, moderator and reflector
- Operates with less water than a PWR in a *direct-cycle*, i.e. the steam produced in the core vessel directly turns the turbines
- Pressure is about half of that in a PWR
- Reactivity is adjusted via feedwater flow
- Efficiency and fuel similar with PWR
- Steam is radioactive



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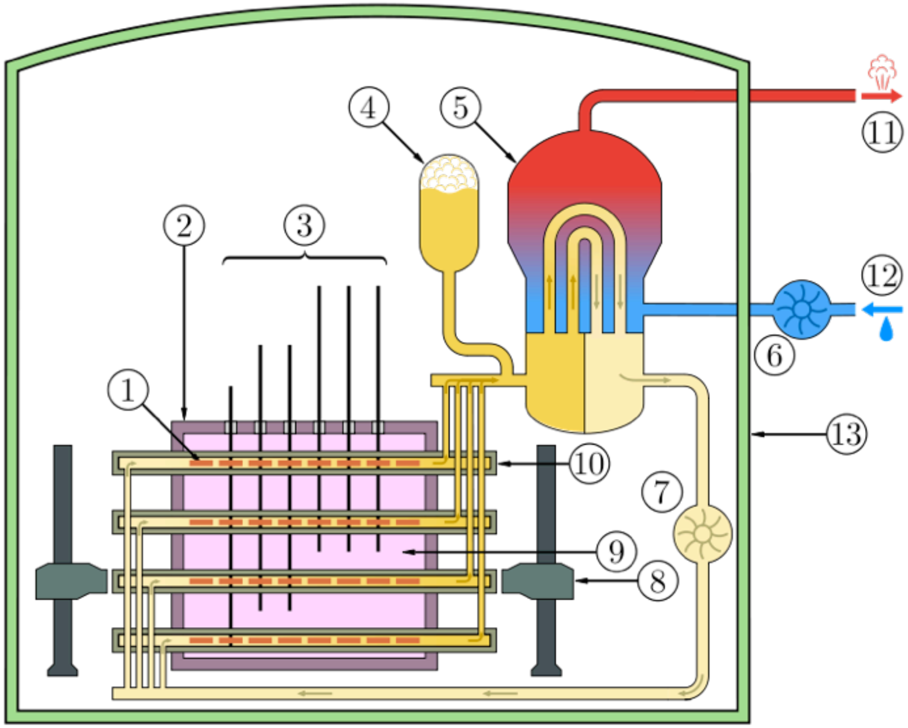
HWR

- (Pressurised) Heavy Water Reactors use D_2O as coolant and moderator
- The advantage is that they work with natural (unenriched) uranium, because of the lower neutron absorption in D_2O
- The coolant tubes are pressurised, but not the whole reactor
- Small positive void coefficient
- Plant efficiency is around 28%
- Can be refuelled online
- CANDU is the industry standard

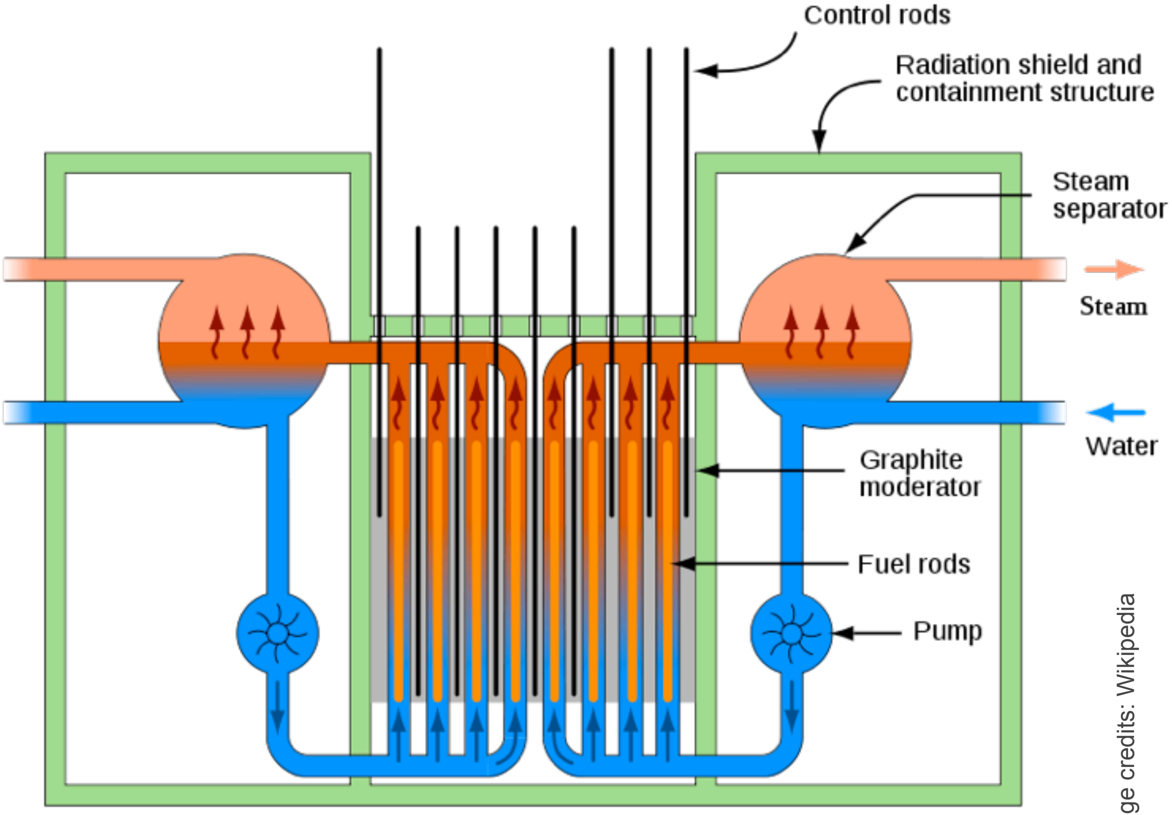


1 - Fuel bundle, 2 - Rector core vessel, 3 - Control rods, 4 - D_2O pressure reservoir, 5 - Steam generator, 6 - H_2O pump, 7 - D_2O pump, 8 - Online refuelling machine, 9 - D_2O moderator, 10 - Pressure tube, 11 - Steam going to the turbine, 12 - Cold water returning from turbine 13 - Reinforced concrete containment building

Image credits: Wikipedia

RBMK

- RBMK (standing for High Power Channel-type Reactor) is a Soviet-design, graphite-moderated, boiling water cooled reactor
- Fuel elements are enclosed in pressure tubes
- Runs on natural U, but does not require a D_2O moderator
- No containment building
- Allows online refuelling
- Efficiency at ≈32%
- Power output of 1.5GWe
- *Post-Chernobyl, all RBMK in operation were updated to increase their safety*



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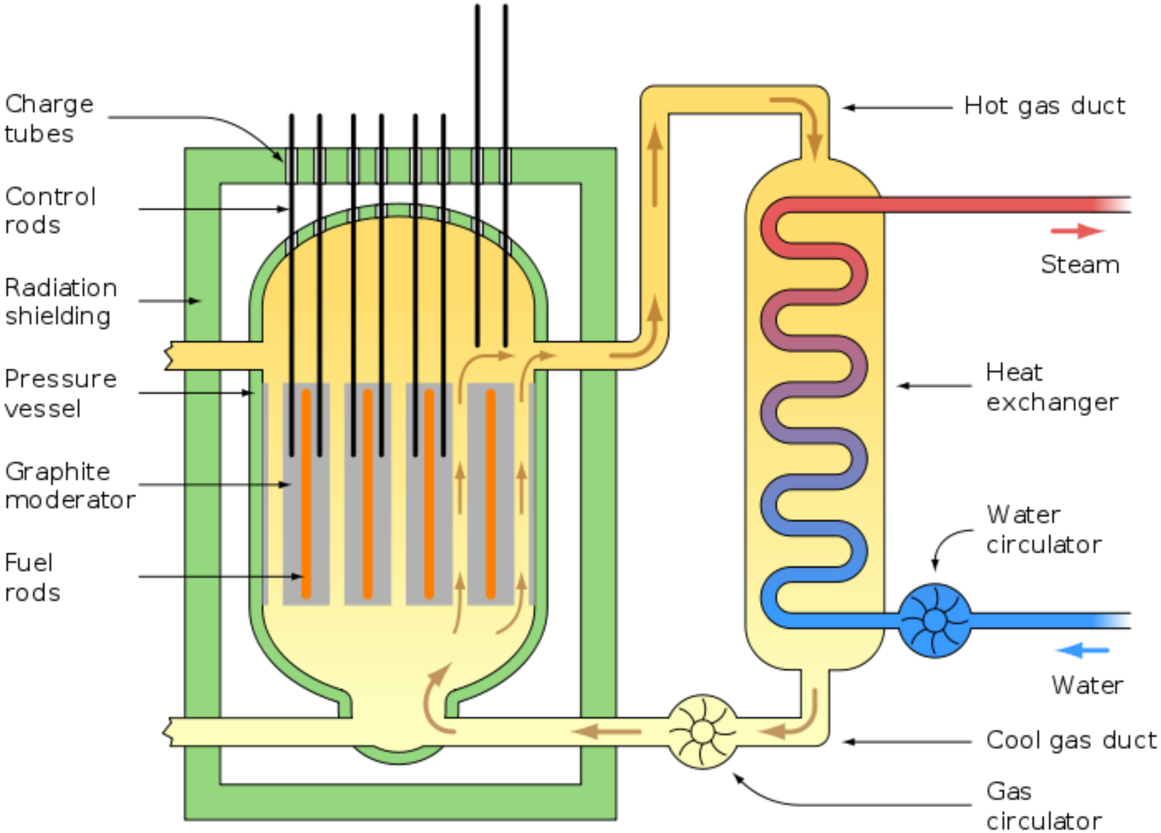
GCR

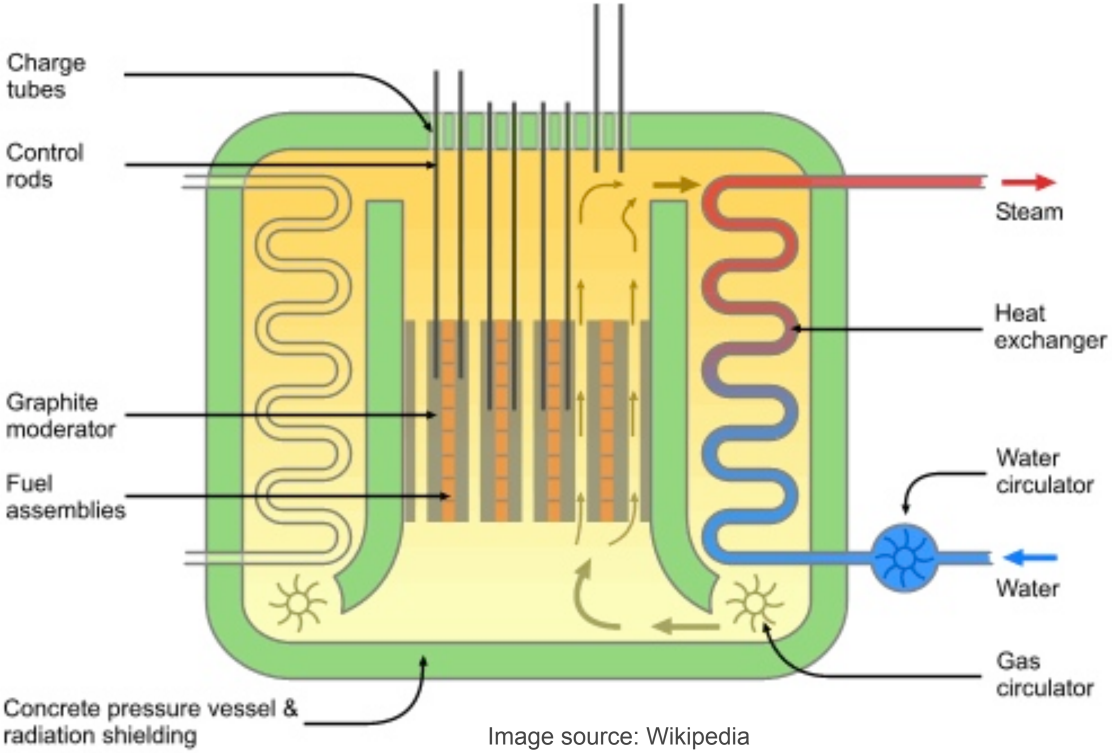
- Pressurised Gas-Cooled Reactors mostly of UK design (Magnox)
- Use graphite moderator, CO_2 coolant and boron-steel control rods
- Use natural U fuel, in magnesium alloy cladding
- Temperature of CO_2 gas is 180˚ to 360˚C
- Efficiency of ≈40%
- Lower power outputs up to 215MWe
- Operating since 1956, many now decommissioned



Original image: Wikipedia

AGCR

- Advanced Gas-Cooled Reactors are an improved version of the Magnox design
- Use the same graphite moderator, CO_2 coolant and boron-steel control rods
- Use low enriched UO_2 fuel (2.5-3.5%), in stainless steel cladding
- Have reinforced concrete pressure vessels
- Temperature of CO_2 gas is 280˚ to 630˚C
- Efficiencies of ≈42%
- Higher power outputs up to 500MWe



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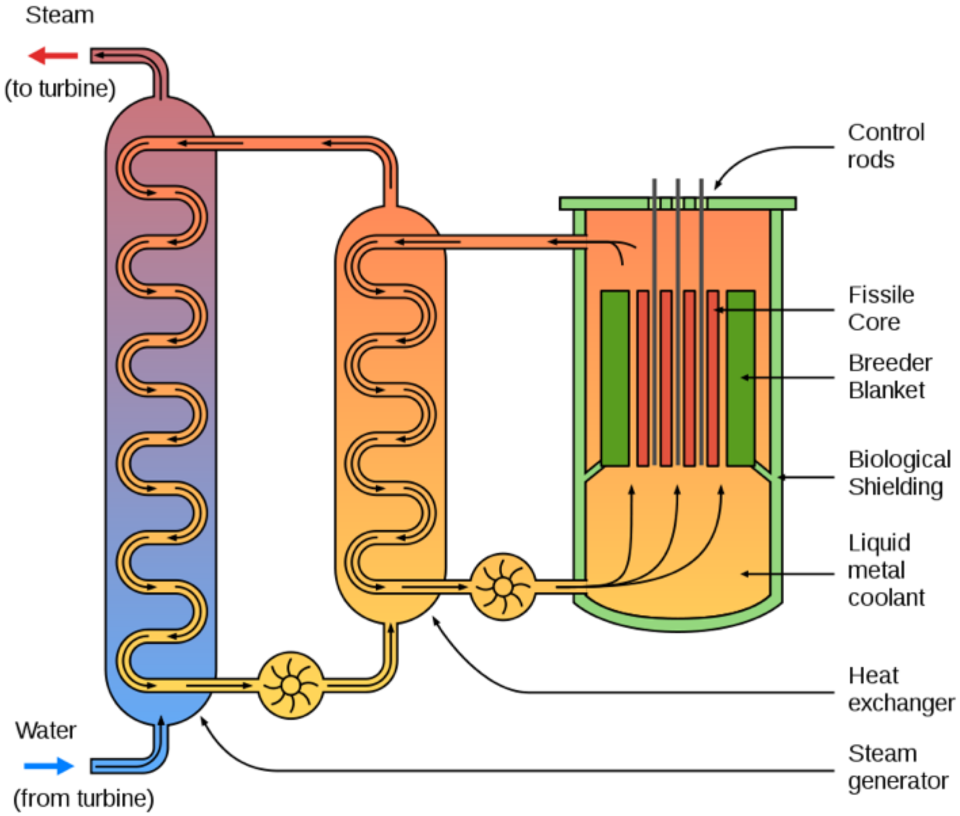
LMFBR

- Liquid Metal Fast Breeder Reactors produce more fuel than they consume
- Use liquid metal coolant (Na or Pb), which does not need to be pressurised
- Unmoderated (fast **n**)
- Pb is transparent to neutrons, does not become radioactive, and adds the advantage of excellent radiation shielding. But is toxic and not easy to dispose of
- Most LMFBR use Na, however, sodium explodes in contact with water
- Breeders pose a certain proliferation danger



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Other types

- **ABWR** (Advanced Boiling Water Reactor) and BWR
  - has *load follow* capabilities: using a combination of coolant flow and control rods, power can be ramped down to 60% of power when demand is low
- **MSR** (Molten Salt Reactors)
  - fuel is dissolved in fluoride salts, or use fluoride salts for coolant (e.g. UF_4)
  - no high pressure (they operate at near atmospheric pressures) or flammable components in the core
  - many safety features, 0.1% of the radioactive waste of a standard reactor
  - high efficiency, small core size, suitable for vehicles
- **PBR** (Pebble Bed Reactor)
  - gas cooled, standardised fuel molded into ceramic balls
  - efficient, low-maintenance, very safe reactor with inexpensive fuel
- **AHR** (Aqueous Homogeneous Reactor)
  - use soluble nuclear salts dissolved in water and mixed with a coolant and a neutron moderator
  - self controlling, safest reactors, but very few were built

Third generation reactors

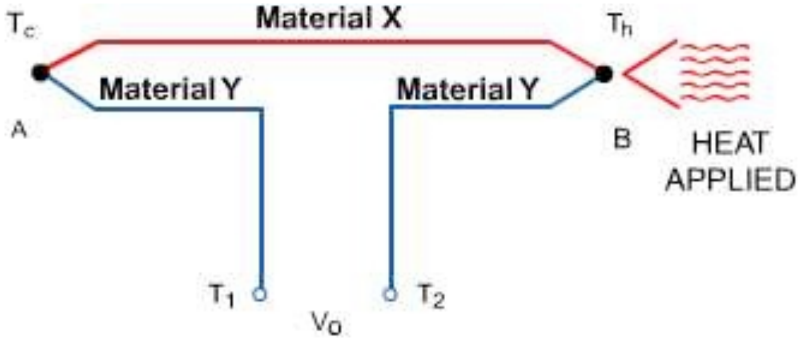
- Are advanced designs of the Generation II designs (BWR, PWR, AGR, CANDU etc. built until the late 1990s)
- Feature standardised designs that expedite licensing, reduce capital cost and construction time
- A simpler and more rugged design that makes them easier to operate and less vulnerable to operational incidents
- Passive safety systems that rely on gravity, natural convection or resistance to high temperatures and require no active controls or operator intervention to avoid an accident in case of malfunctions
- Higher availability and longer operating life (typically 60 years)
- Higher fuel burn-up to reduce fuel use and the amount of waste
- Reduced possibility of core meltdowns
- Equipped with core-catchers below the reactor vessel
- Designed such that following a shutdown the reactors requires no active intervention for 3 days (‘72h grace period’)
- Built to resist an aircraft impact without serious damage that would allow radiological release

Other applications of nuclear energy

- Nuclear power can be used to
  - generate heat and/or electricity for general use (buried reactor powering remote villages)
  - produce hydrogen for fuel cells
  - desalinate seawater for human consumption
- Propulsion for nuclear ships and submarines
  - 1 pound of highly enriched U replaces 1,000,000 gallons of gasoline
- Peaceful nuclear explosions
  - have been used to extinguish gas field fires, for large-scale excavations, create cavities for underground gas, oil or waste storage
  - PNEs will be banned under the Comprehensive Nuclear Test-Ban Treaty when it enters into force
- Production of radioisotopes or nuclear fuel
- In space: electric power for satellites and space probes
- Accelerator-driven reactors; research reactors

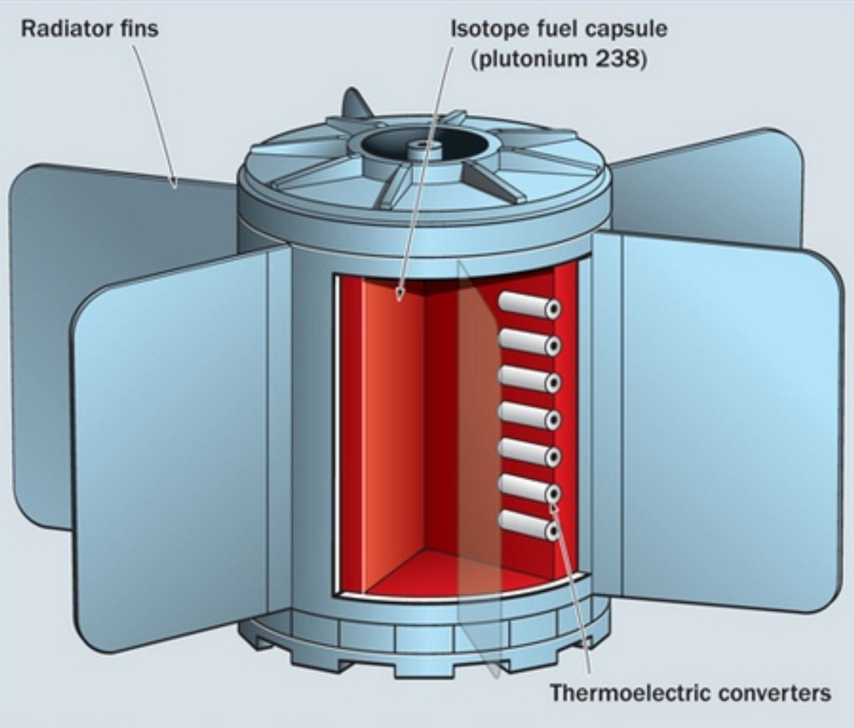
RTG

- Heat is produced through passive radioactive decay
- Heat is converted to electricity via thermoelectric (Seebeck) effect



- Used to power space probes, remote lighthouses in the arctic etc.
- Power output decreased over time

RADIOISOTOPE THERMO ELECTRIC GENERATOR

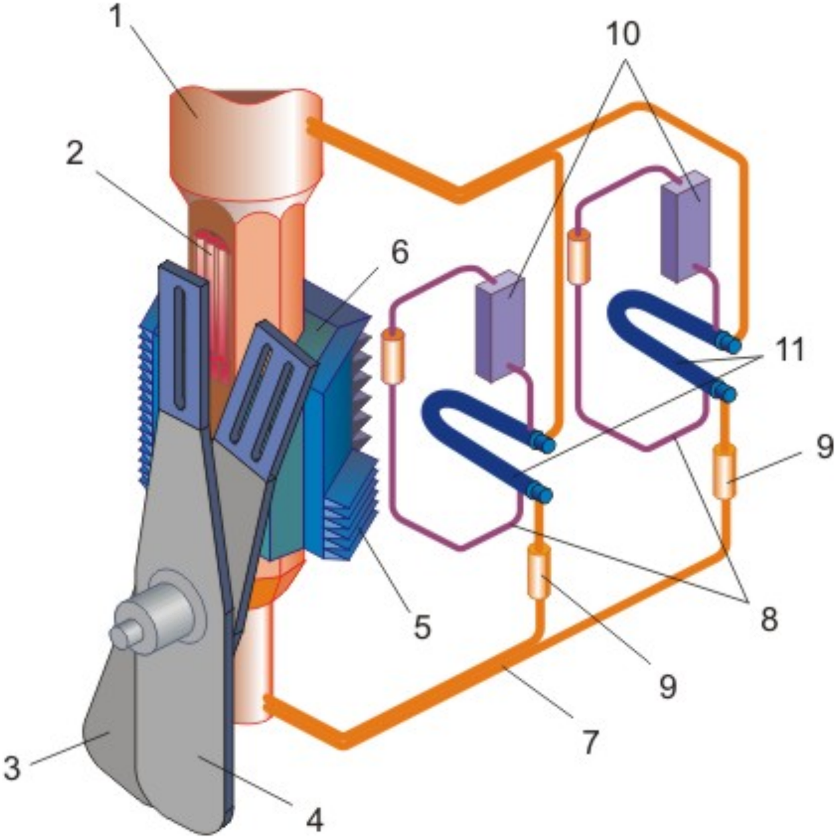


Note: Nimbus weather satellite and Pioneer/Viking probes

SOURCE: US Department of Energy

Research reactors

- IBR-2 is a pulsed fast reactor at FLNP/JINR research centre in Dubna, Russia
- Reactivity is modulated mechanically using two nickel-steel rotating reflectors
- Uses PuO_2 fuel pellets
- Coolant is liquid sodium
- Uses multiple moderators, of which one is water
- Average power is 2MW
- Pulse frequency 10Hz
- Pulse half-width ~200s



1 - Reactor vessel, 2 - Core, 3 - Main movable reflector, 4 - Additional movable reflector, 5 - Moderator, 6 - Stationary reflector, 7,8 - Cooling loops, 9 - Na pump, 10 - Na/Air heat exchanger, 11 - intermediate heat exchanger

Future Technologies

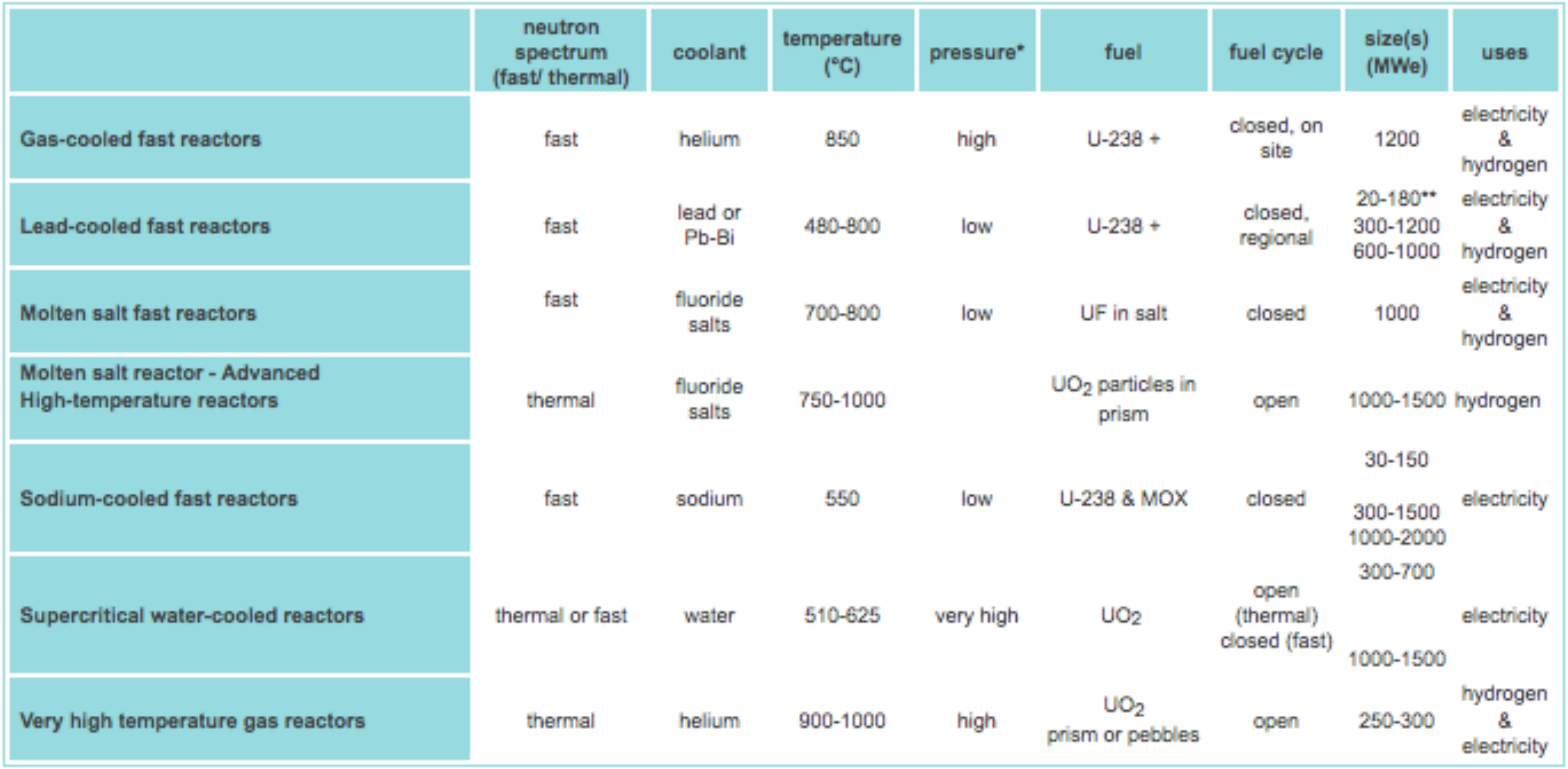
New technologies and applications, fusion reactors

Generation IV reactors

- Gas cooled fast reactor
  - helium-cooled (850˚C), thick steel pressure vessel, breeding core, fast **n** spectrum
- Lead cooled fast reactor
  - flexible fast neutron reactor, natural convection cooling, can be built as ‘battery’ unit
- Molten salt reactor (two variants)
- Sodium-cooled fast reactor
- Supercritical water-cooled reactor
  - very high-pressure water coolant, functioning above the thermodynamic critical point of water (374ºC, 22 MPa)
  - coolant directly drives the turbine
  - thermal efficiency ~50% is about one third higher than today's LWRs
- Very high temperature reactor
  - graphite-moderated, helium-cooled reactors, up to 1000ºC outlet temperatures
  - can be used for thermochemical hydrogen production via an intermediate heat exchanger, with electricity cogeneration, or for direct high-efficiency driving of a turbine
  - completely passive safety, low operation and maintenance costs, modular construction

Planned and future types of nuclear reactors

- Generation VI models proposed for deployment between 2020 and 2030:

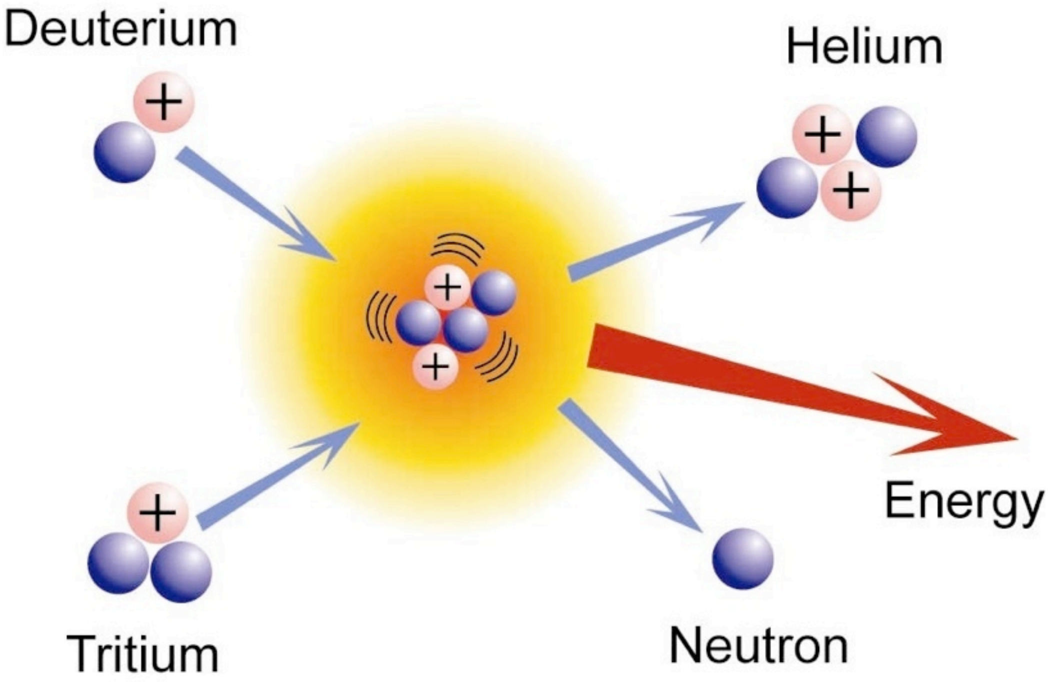


	neutron spectrum (fast/ thermal)	coolant	temperature (°C)	pressure*	fuel	fuel cycle	size(s) (MWe)	uses
Gas-cooled fast reactors	fast	helium	850	high	U-238 +	closed, on site	1200	electricity & hydrogen
Lead-cooled fast reactors	fast	lead or Pb-Bi	480-800	low	U-238 +	closed, regional	20-180** 300-1200 600-1000	electricity & hydrogen
Molten salt fast reactors	fast	fluoride salts	700-800	low	UF in salt	closed	1000	electricity & hydrogen
Molten salt reactor - Advanced High-temperature reactors	thermal	fluoride salts	750-1000		UO_2 particles in prism	open	1000-1500	hydrogen
Sodium-cooled fast reactors	fast	sodium	550	low	U-238 & MOX	closed	30-150 300-1500 1000-2000	electricity
Supercritical water-cooled reactors	thermal or fast	water	510-625	very high	UO_2	open (thermal) closed (fast)	300-700 1000-1500	electricity
Very high temperature gas reactors	thermal	helium	900-1000	high	UO_2 prism or pebbles	open	250-300	hydrogen & electricity

- **Generation V**: liquid or gas core reactors, gas core EM, fission-fragment reactors

Fusion

- Nuclear fusion is the process by which two or more atomic nuclei fuse together to form a single heavier nucleus
- Accompanied by release or absorption of large quantities of energy
- The fusion of nuclei with mass lower than iron (Fe) releases energy
- Fusion is the process that powers active stars or the hydrogen bomb



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Fusion reactors

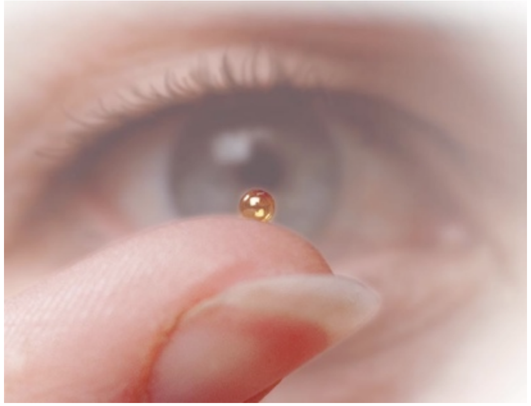
- Imply none of the complexities associated with handling radioactive materials
- No CO_2 or other atmospheric pollutants, waste products are short-lived
- Does not pose a radiation threat, as the plasma will immediately vanish if the reaction process goes awry
- Based on the reaction

$$^{2}_{1}\mathrm{D} + ^{3}_{1}\mathrm{T} \rightarrow ^{4}_{2}\mathrm{He} + ^{1}_{0}\mathrm{n} + 17.6\ \mathrm{MeV}$$

- Deuterium is relatively abundant and tritium can be mass-produced in nuclear reactors by enclosing the plasma in a breeder blanket of lithium
- Since the 1950s, several fusion reactors have been built, but as yet none has produced more thermal energy than electrical energy consumed
- Many technical challenges

Inertial confinement fusion

- Where the nuclear fusion reactions are initiated by heating and compressing a fuel target containing a mixture of deuterium and tritium
- Fuel micro-balloons filled with either D and T gas or DT ice
  - Energy is delivered to the outer layer of the target using high-energy lasers (1)
  - The heated surface explodes and compresses the inside fuel (2)
  - During the final part of the capsule implosion, the fuel core reaches 20 times the density of Pb and ignites at 100,000,000˚C (3)
  - Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy (4)



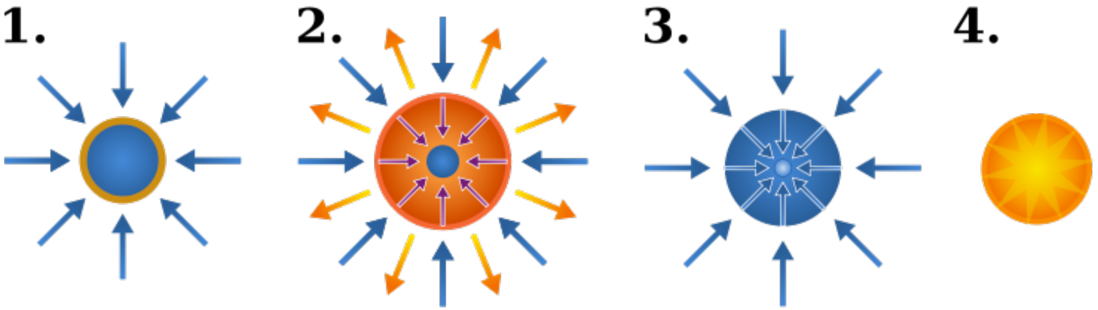
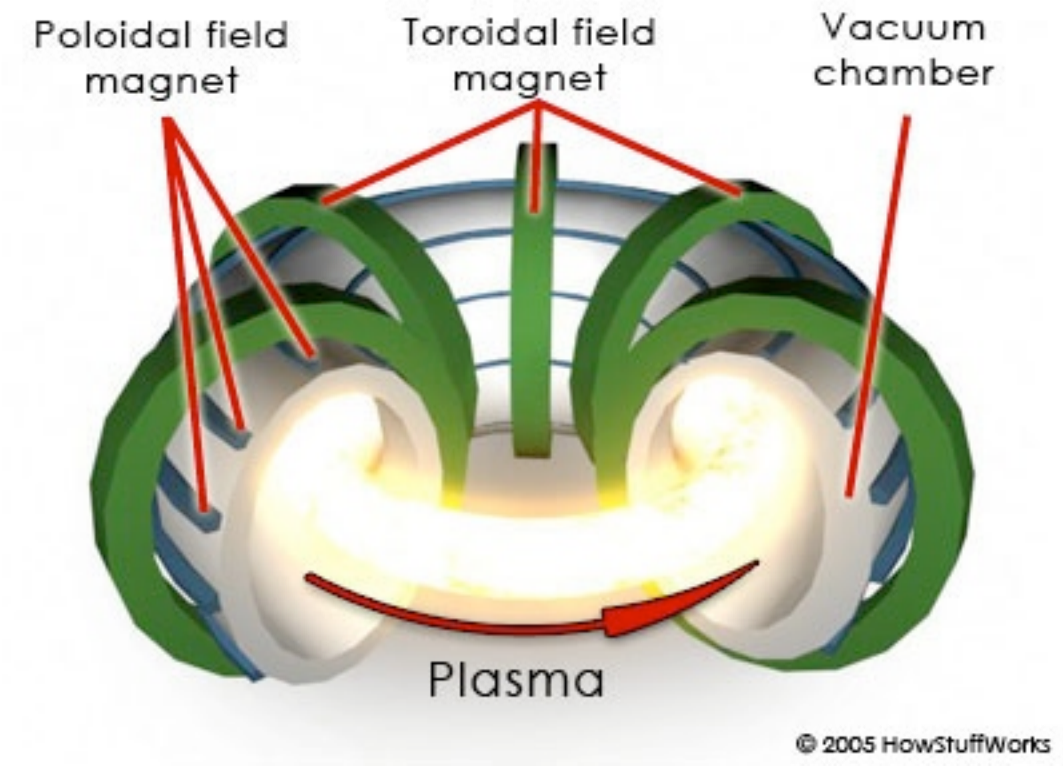


Image source: Wikipedia

Tokamak

- Research pioneered by Russians in the late 1950s; First successful test in 1968
- Uses a magnetic field to confine a D+T plasma to a toroidal shape and keep it away from the containment wall
- Stable plasma equilibrium is achieved via a combination of toroidal and poloidal fields
- Plasma high temperatures are achieved via ohmic heating, neutral beam injection or via RF or microwave heating
- Solid vacuum vessel acts also as shielding
- Energy is extracted from the escaping neutrons and transferred to a primary coolant



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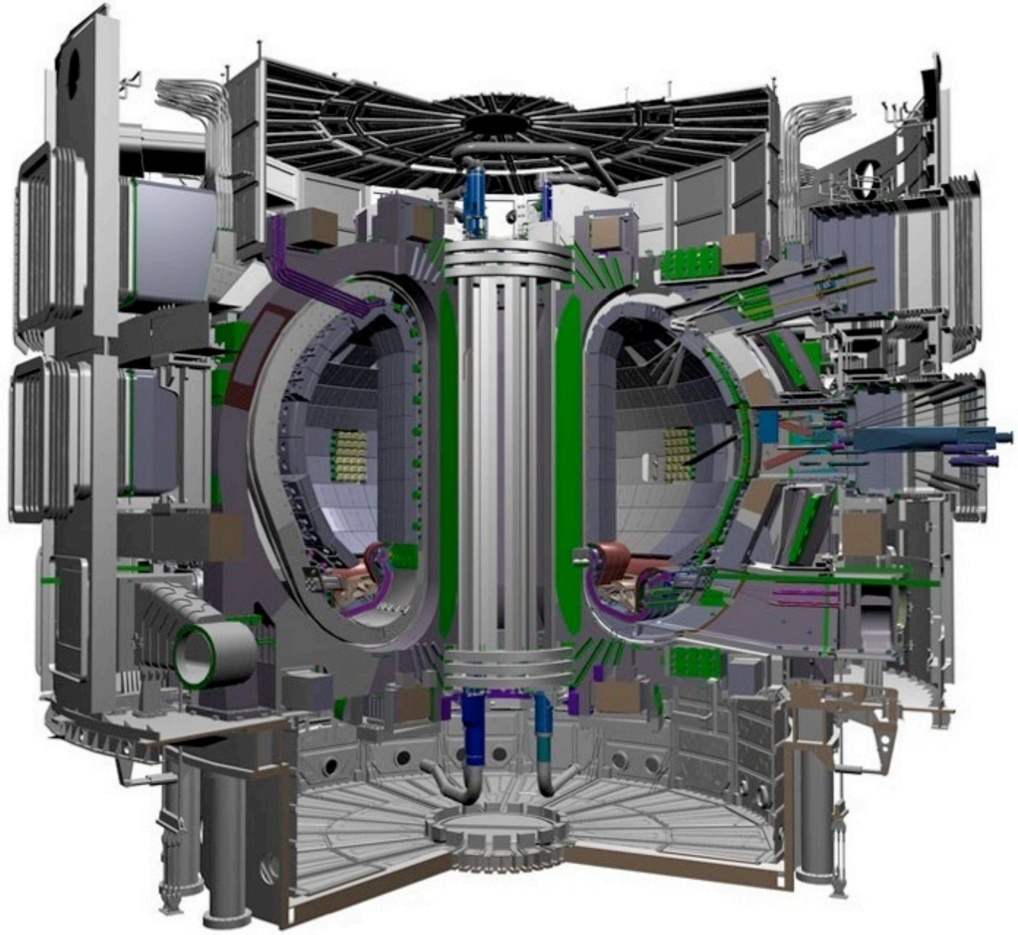
Fusion

- Advantages:
  - virtually zero pollution: no gaseous CO_2, SO_2 or NO_x by-products
  - produces hundreds of times less radioactive waste than that of a fission reactor
  - no long-lived radioactive waste
  - a large-scale runaway *chain reaction* is impossible. Direct contact with the walls of the reactor chamber would contaminate the plasma, cooling it down immediately and stopping the fusion process
  - the amount of fuel planned to be contained in a fusion reactor chamber is very small (at any given time, ITER's plasma would contain ~0.5g of D+T fuel, only enough to sustain the reaction for about one hour)
  - an accident would release very small amounts of radioactive material
- Technical challenges:
  - maintain a stable plasma configuration
  - find materials that can withstand the *intense neutron fluxe*s produced
  - extract energy for useful purposes
  - produce sizeably more energy than what is put in

ITER

- Currently leading the effort to commercialise fusion power
- ITER Organisation was established in October 2007 but project dates from 1985
- Members: China, EU, India, Japan, S. Korea, Russia, USA
- The machine is being built now in Cadarache, France
- Project timescale: 30 years
- Max. power: 500MW
- Fusion energy gain factor Q between 5 and 10
- *iter* is the Latin for ‘journey’



Original image: ITER

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- ITER project: www.iter.org
- HowStuffWorks.com
- Wikipedia
- www.tepco.co.jp
- For details on the nuclear fuel cycle see David Hamilton’s course: http://nuclear.gla.ac.uk/twiki/bin/view.pl/Main/NuclearFuelCycle

Informal feedback to
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