MEEN 40090: Energy Systems & Climate Change
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Nuclear Energy (4)

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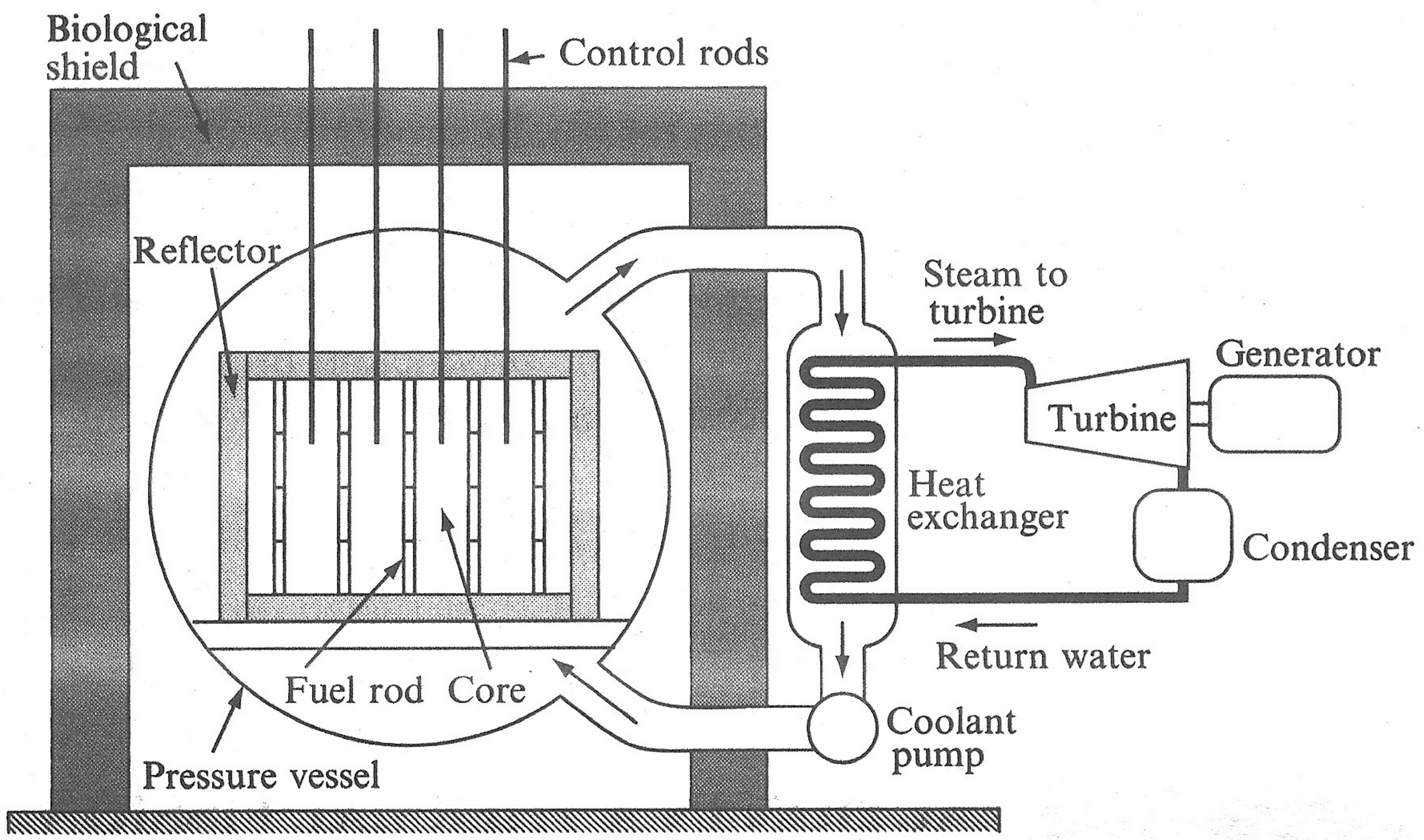
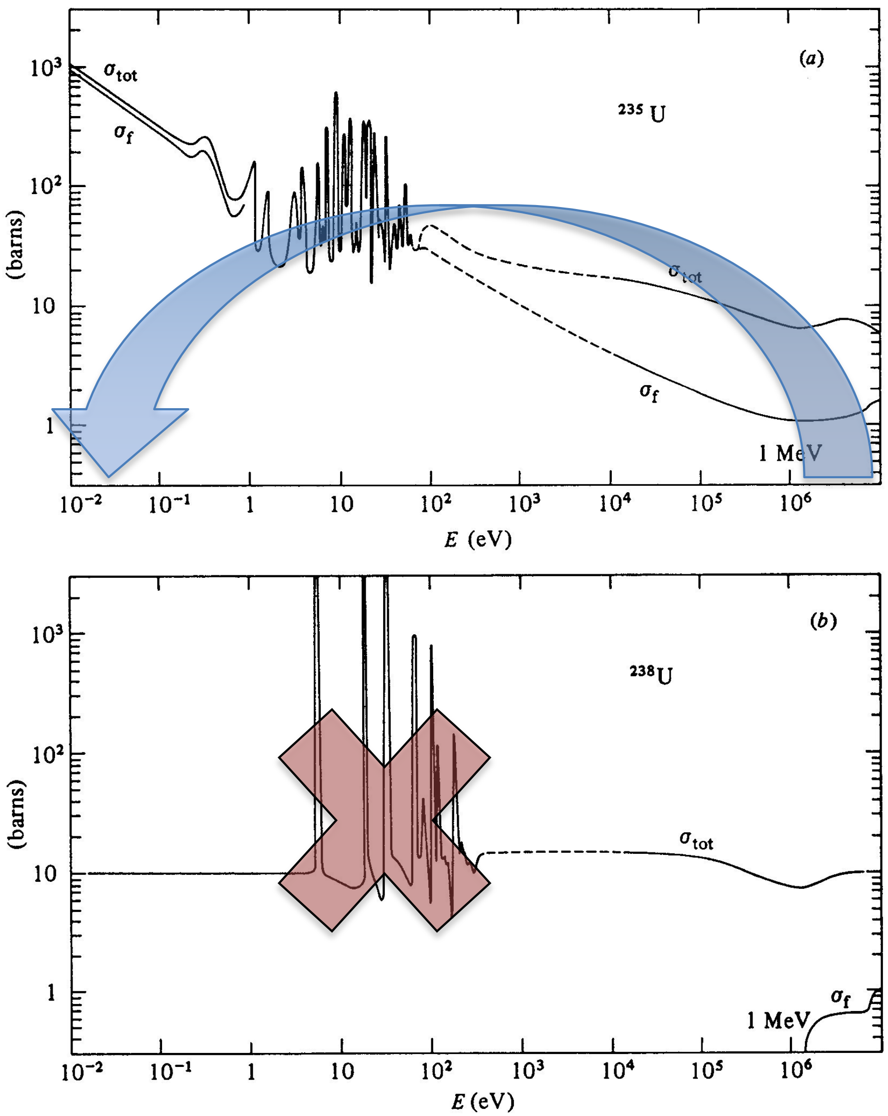
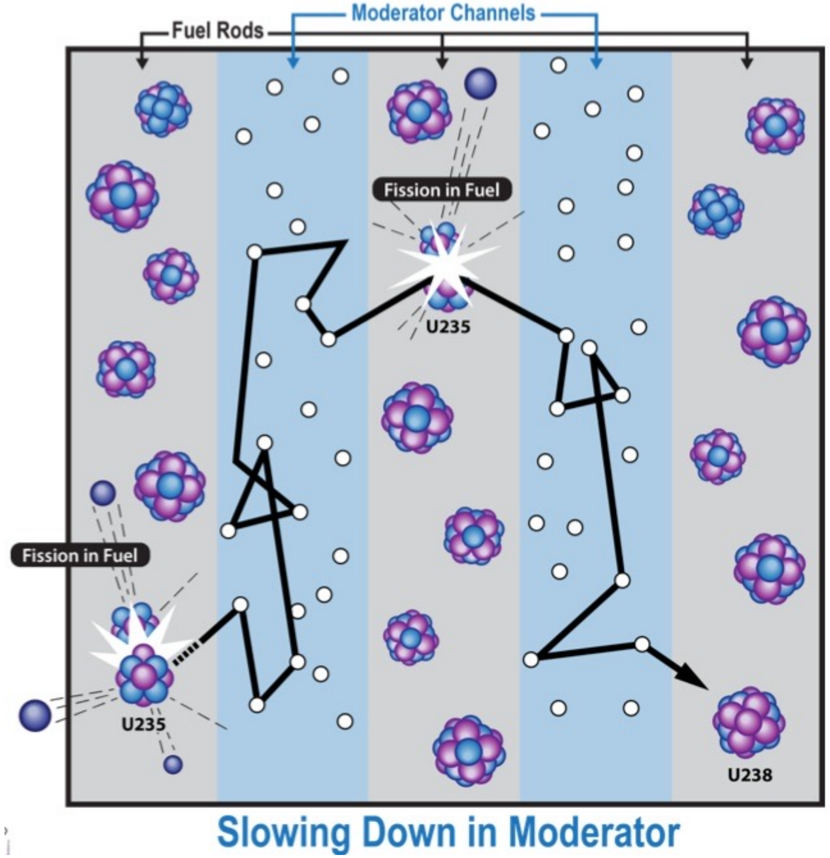
Components of a nuclear power plant

A schematic layout of a typical power plant, based on a thermal fission reactor is shown in the next viewgraph.



Simplified schematic layout of a typical reactor power plant (PWR).

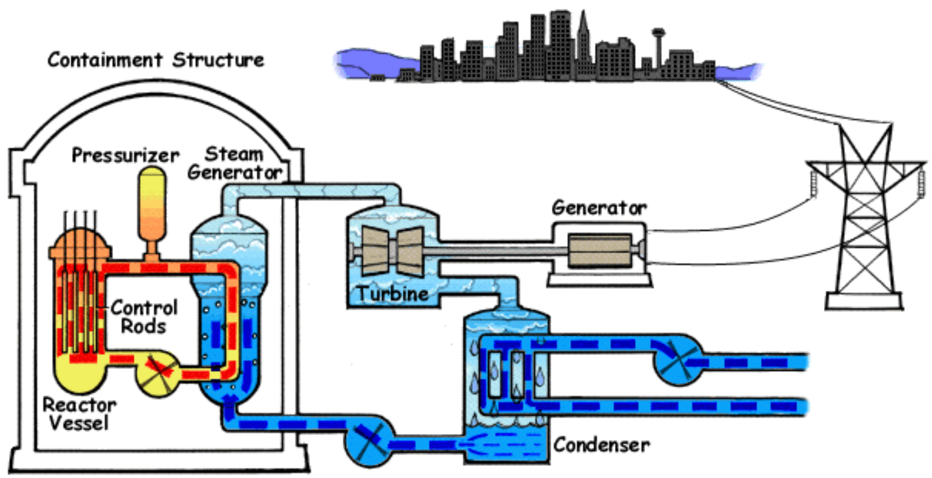




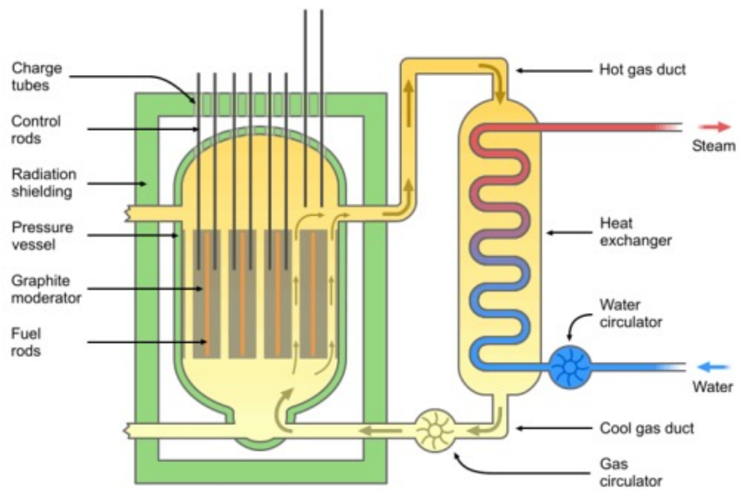
Heterogeneous configuration
of fuel and moderator

Heat generated by fission reactions in the core is removed by a circulating gas or liquid **coolant**.

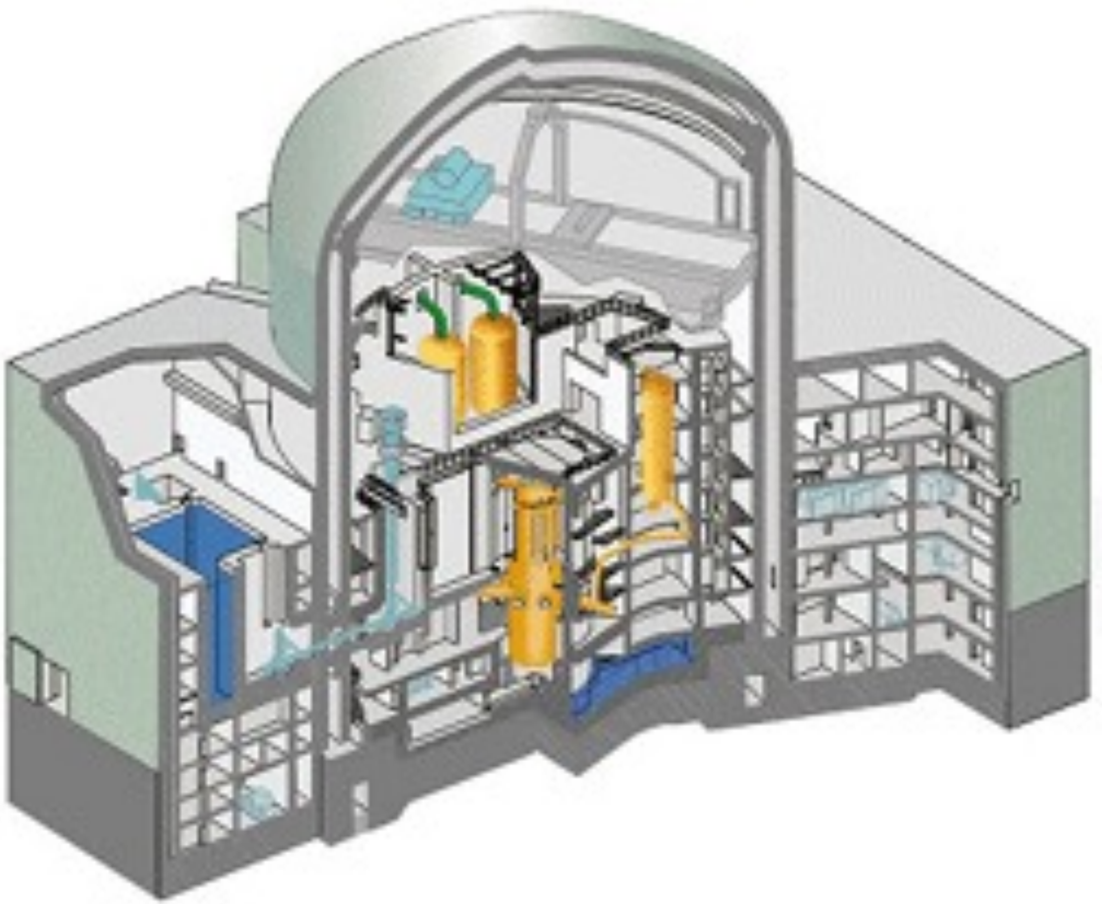
In most reactors the fuel is either natural uranium or uranium enriched in ^{235}U. In some designs, the moderator is a solid (e.g., graphite), with the coolant (liquid or gas) circulated through open channels; in others, water (both light H_2O and/or heavy D_2O) is used both as a moderator and coolant.



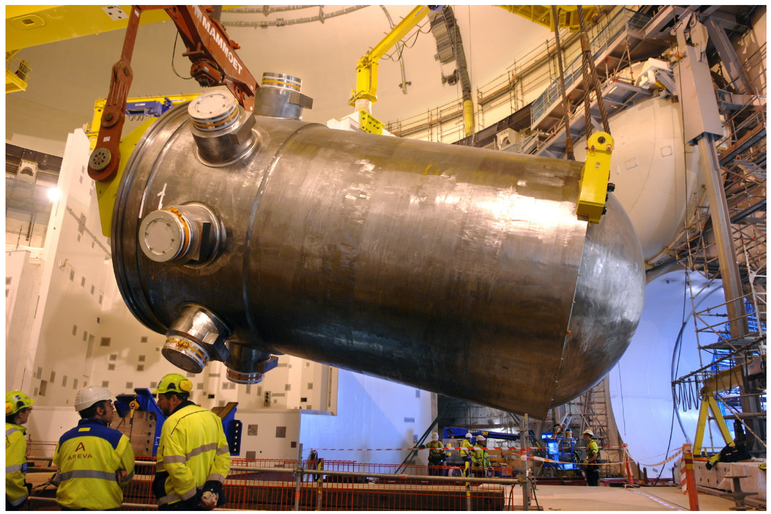
Water-cooled nuclear reactor (PWR)



Gas-cooled nuclear reactor (Magnox)



Areva’s Olkiluoto nuclear power plant
Under construction in Finland



Reactor designs: mature technologies and emerging alternatives

The majority of the NPPs operating in the world today are light-water reactors (PWRs or BWRs).

However, national programmes to develop nuclear energy in various countries resulted in a number of other alternative designs (Magnox, AGRs,CANDU) which still remain in use.

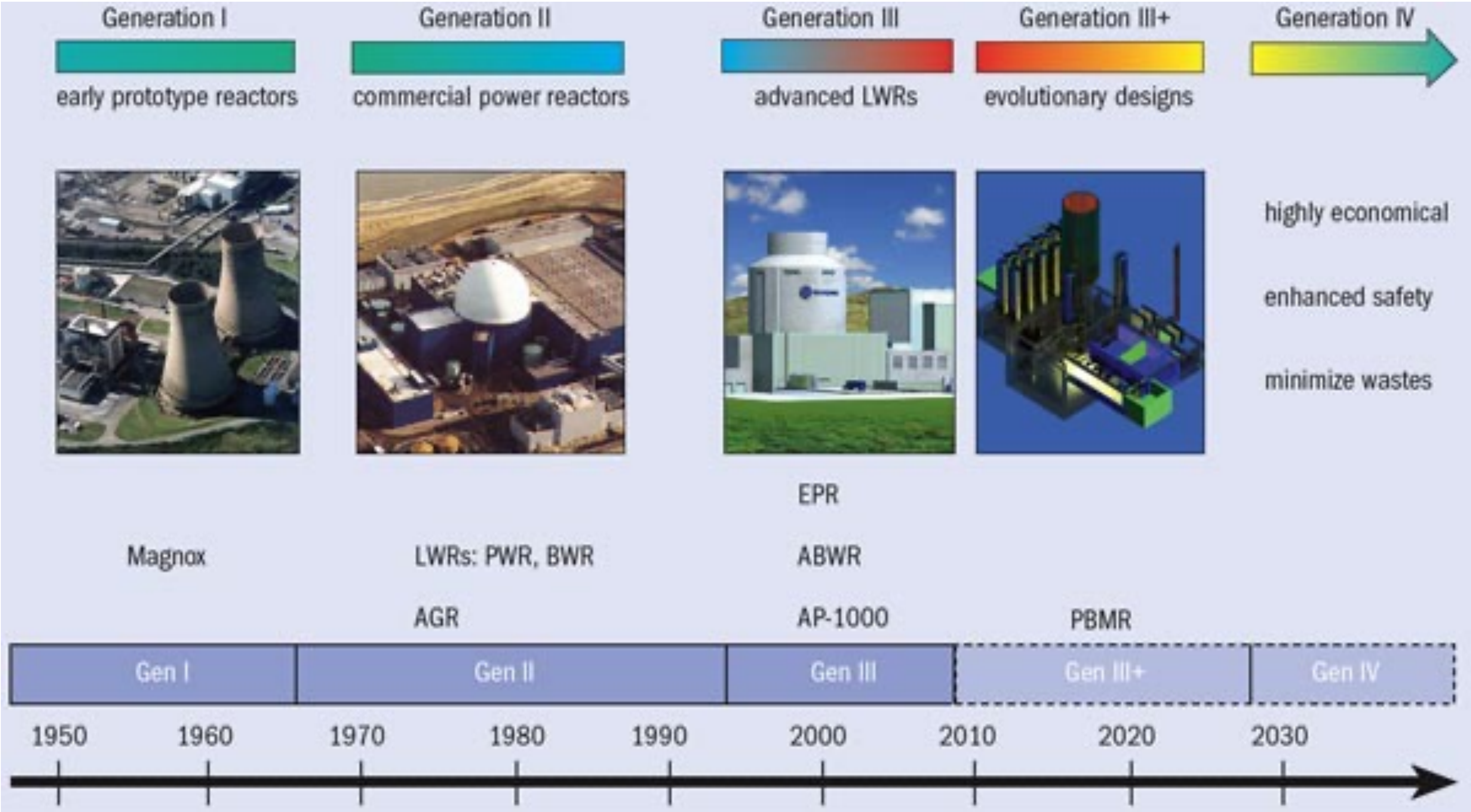
In the future, three main factors will drive the evolution of new reactor designs:

(1) the need to reduce capital costs;

(2) the desire to make use of new fuels;

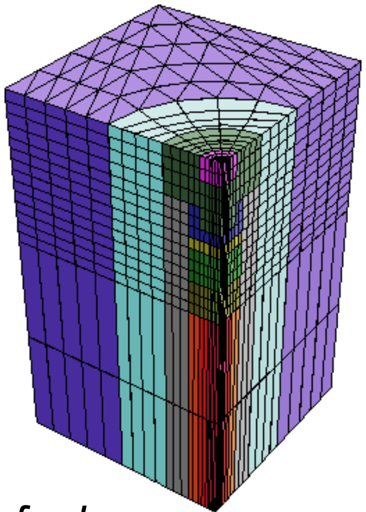
(3) increased safety.

Evolution of nuclear power – A history of design

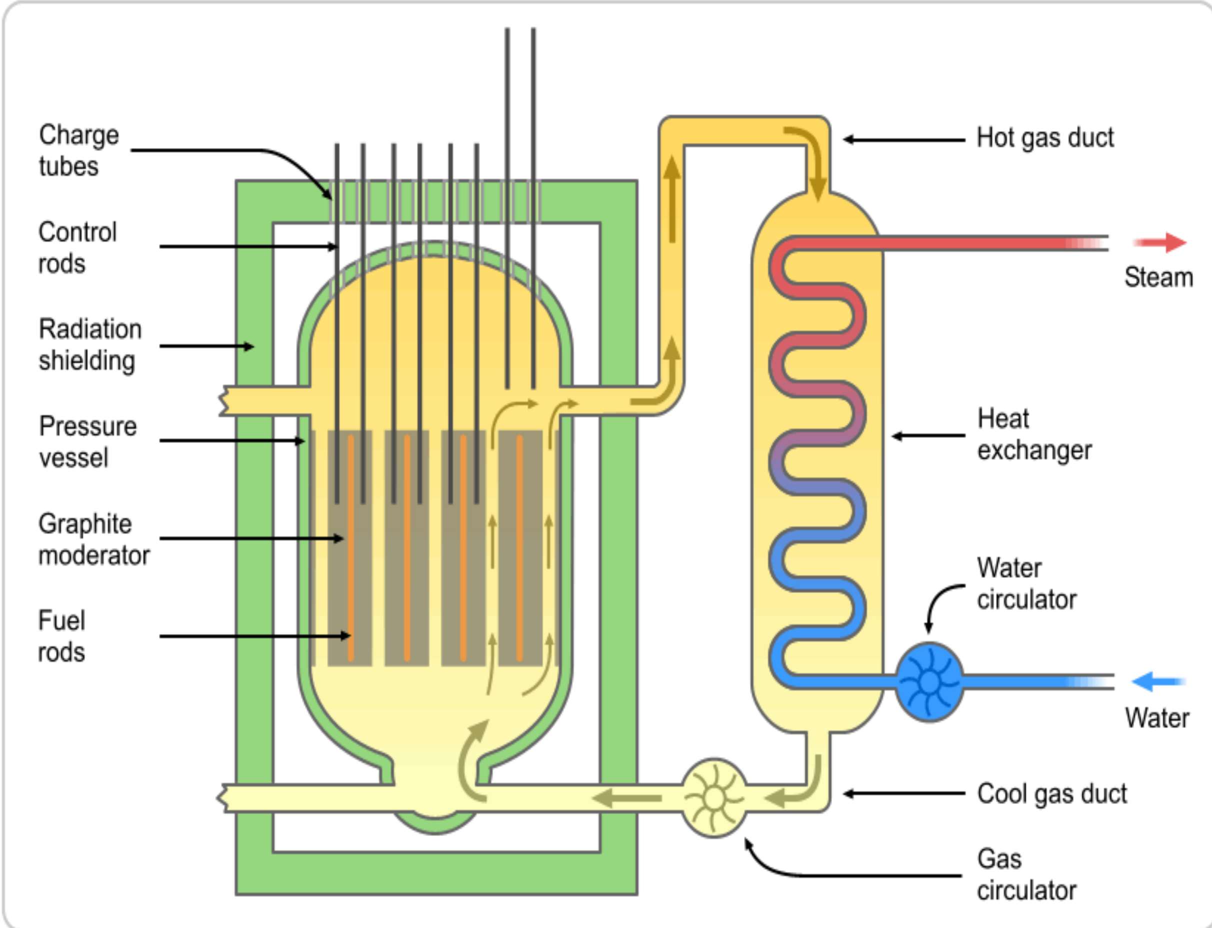


Generation I: Magnox reactor (UK design)

Wylfa, Anglesey (UK)
2 $\times$ 900 MW_t units



Magnox fuel assembly



Schematic of a typical Magnox reactor

Natural uranium
Graphite moderated

CO_2 cooled
Relatively inefficient

The Magnox reactor class

Key features:

- Natural uranium encased in tubes of Mg-alloy
- CO_2 coolant (20 bar; 365°C at outlet)
- Graphite moderator
- Boron-steel control rods
- Shut-down: extra set of boron-steel control rods
- On-load refuelling a design feature.

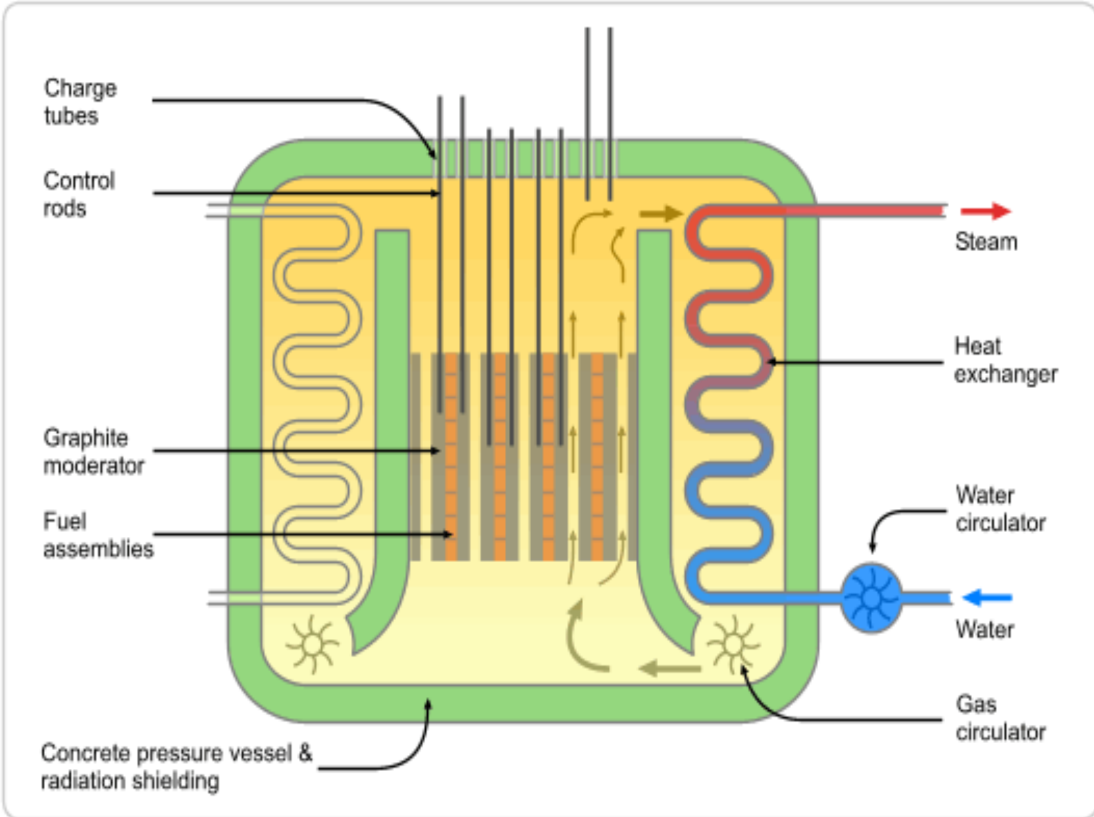
Example:

- Wylfa Power Station, Anglesey (Wales)
- Power output (2 units) of about 900 MW_t each
- Thermal efficiency approximately 28%
- Total of 26 built in 11 power stations in the UK.

Generation II: advanced gas-cooled reactor (AGR)

Hinkley Point B

- Enriched uranium
- Carbon dioxide coolant
- Larger reactor core
- Good thermal efficiency
- Less efficient burn-up



Note that the heat exchanger is contained within the stee/reinforced concrete combined pressure vessel and radiation shield

The Advanced Gas-cooled Reactor (AGR) class

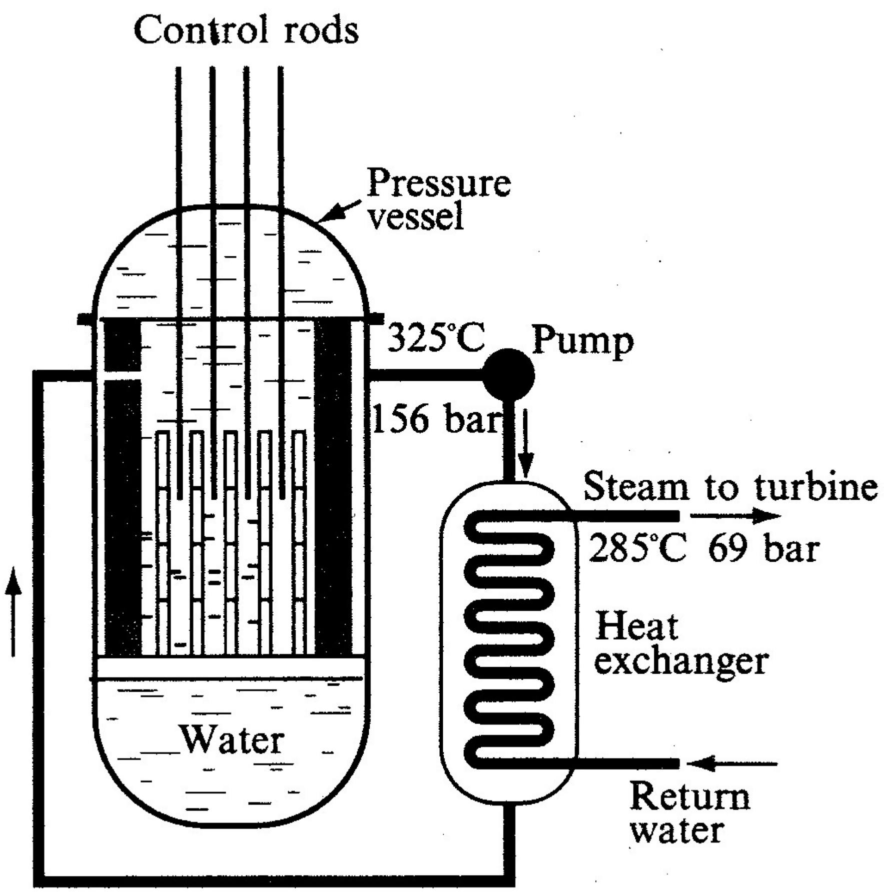
Key features:

- Enriched (2.5%) UO_2 fuel
- Stainless steel or Zr-alloy-clad fuel rods
- CO_2 coolant (40 bar; 650°C max. at outlet)
- Graphite moderator
- Boron-steel control rods
- Shut-down: boron spheres
- Relatively expensive to build
- On-load refuelling a design feature *(but not done)*.

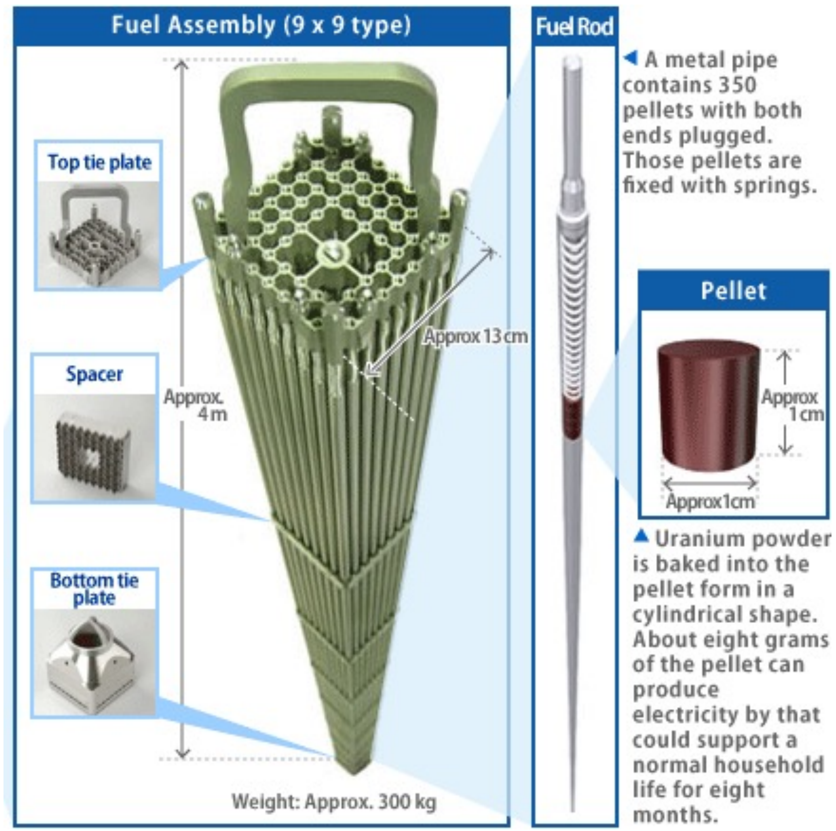
Example:

- Heysham Power Station, UK (1989)
- Power output (2 reactor units) of 625 MW(e) each
- Thermal efficiency about 42%

Generation II: Pressurised water reactor (PWR)

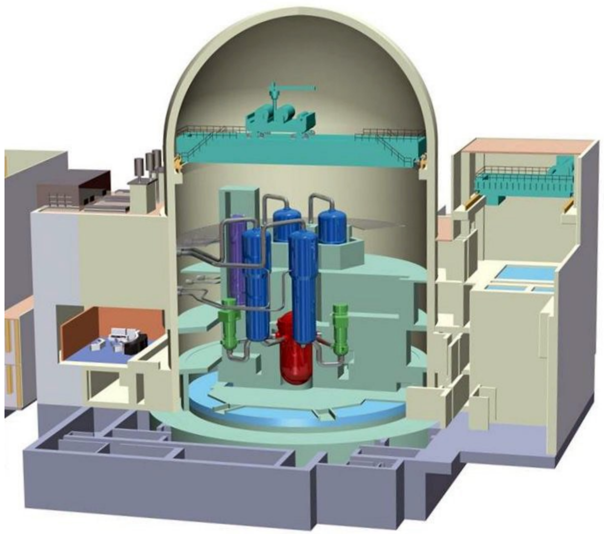


Schematic diagram of the core and pressure vessel, and simplified steam cycle for a PWR

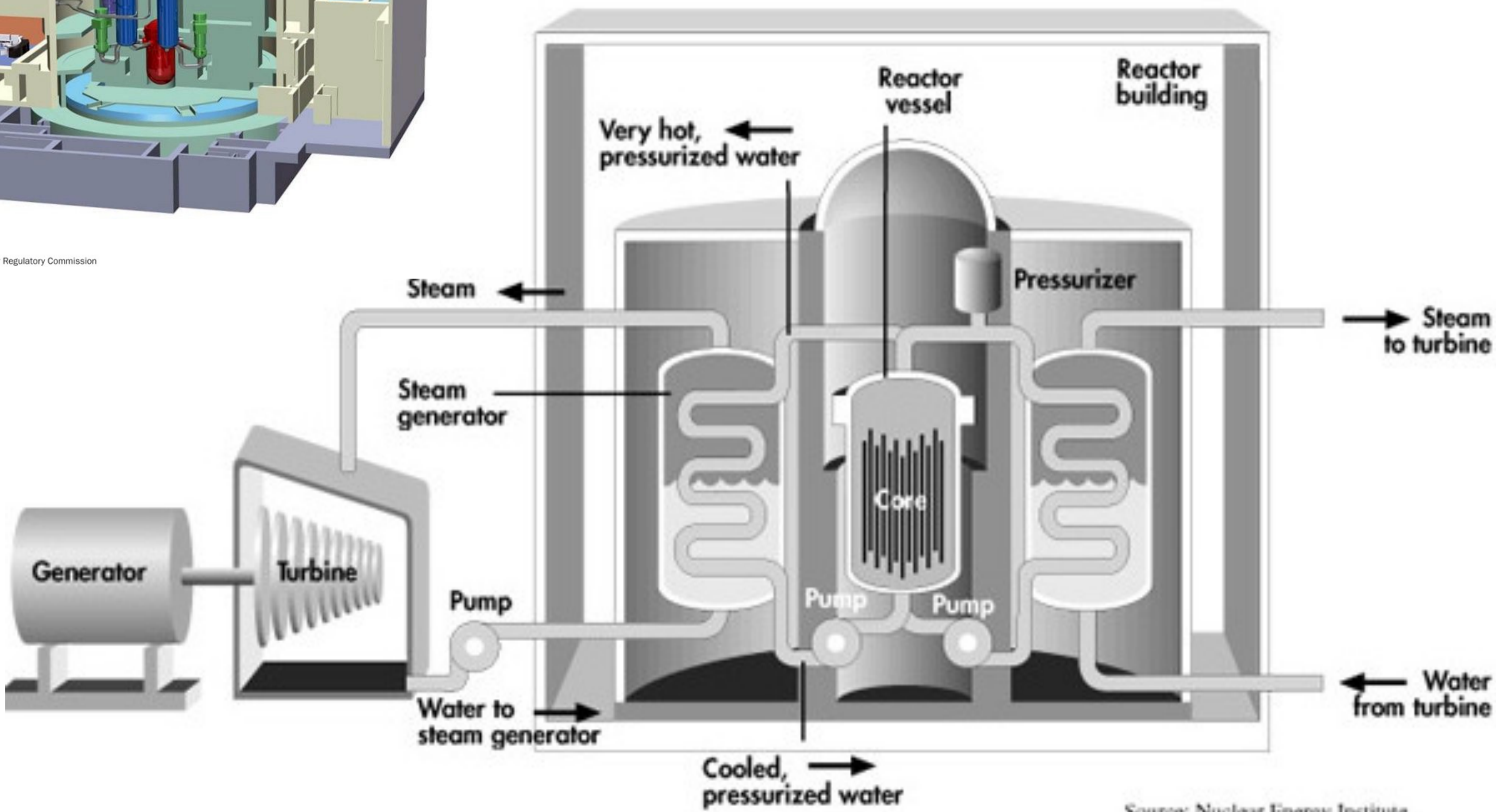


Typical fuel assembly configuration in a PWR

Typical Pressurized Water Reactor



Source: U.S. Nuclear Regulatory Commission



Source: Nuclear Energy Institute

Layout of a typical PWR

The pressurised-water reactor (PWR)

Key features:

Sizewell B PWR (UK)

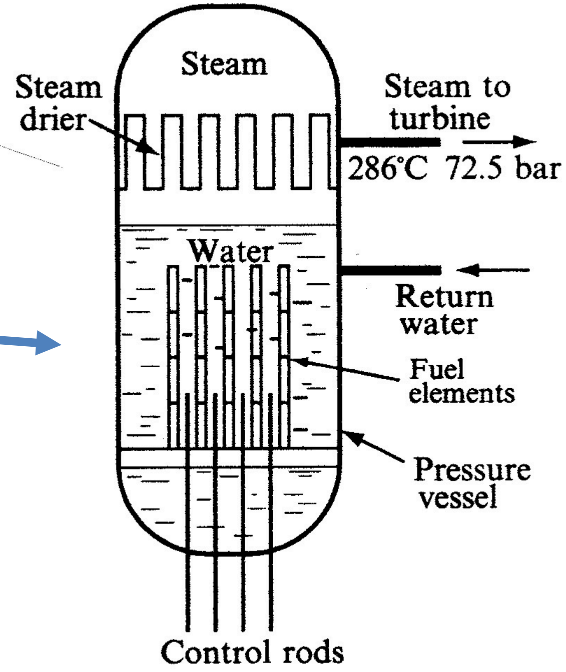
- Enriched (2.5%) UO_2 fuel
- Stainless steel or Zr-alloy-clad fuel rods
- H_2O coolant/moderator (155 bar; 326°C at outlet)
- Ag/In/Cd control rods
- Shut-down: injection of boric acid into moderator
- Very compact core/commercially attractive
- On-load refuelling not possible

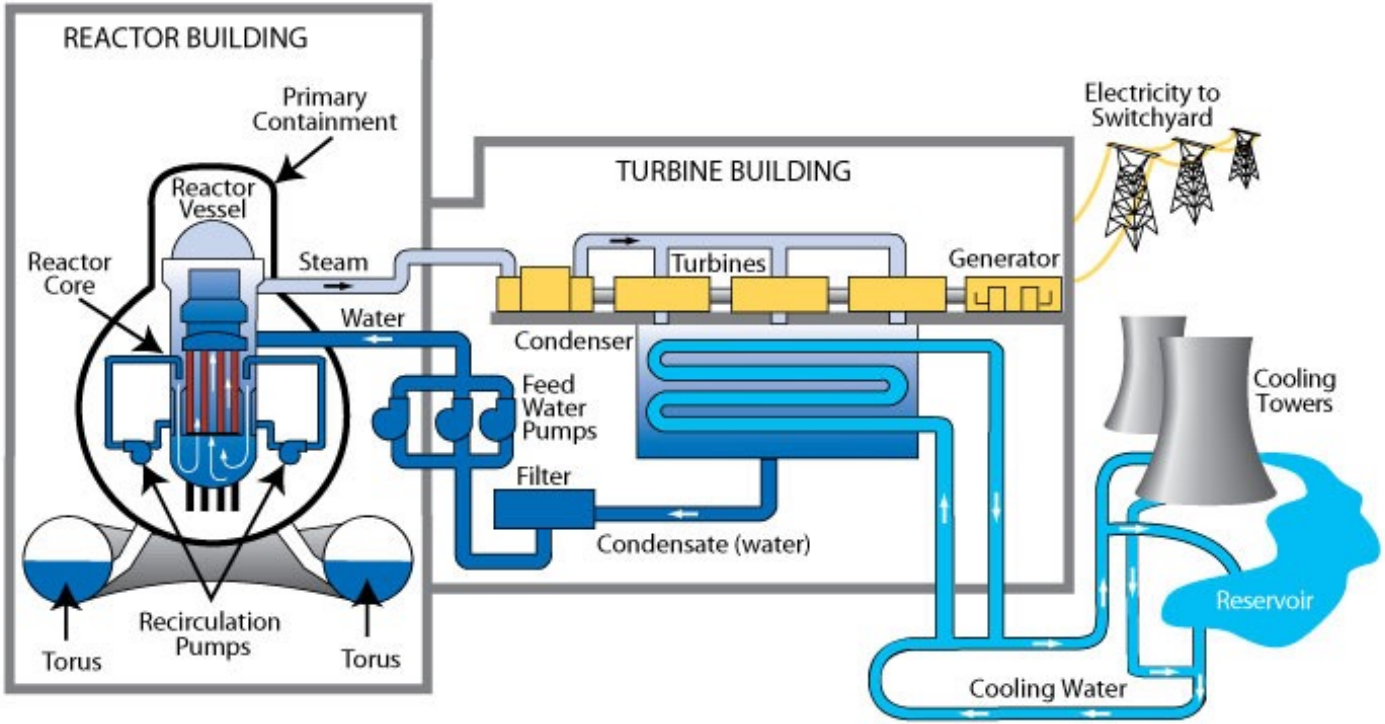
Example:

- Sizewell Power Station, UK (4.5% enrichment)
- Power output approximately 1000 MW(e)
- Thermal efficiency about 32%

Generation II: Boiling water reactor (BWR)

Schematic diagram of the core and pressure vessel, and simplified steam cycle for a BWR





Layout of a typical BWR

The boiling-water reactor (BWR)

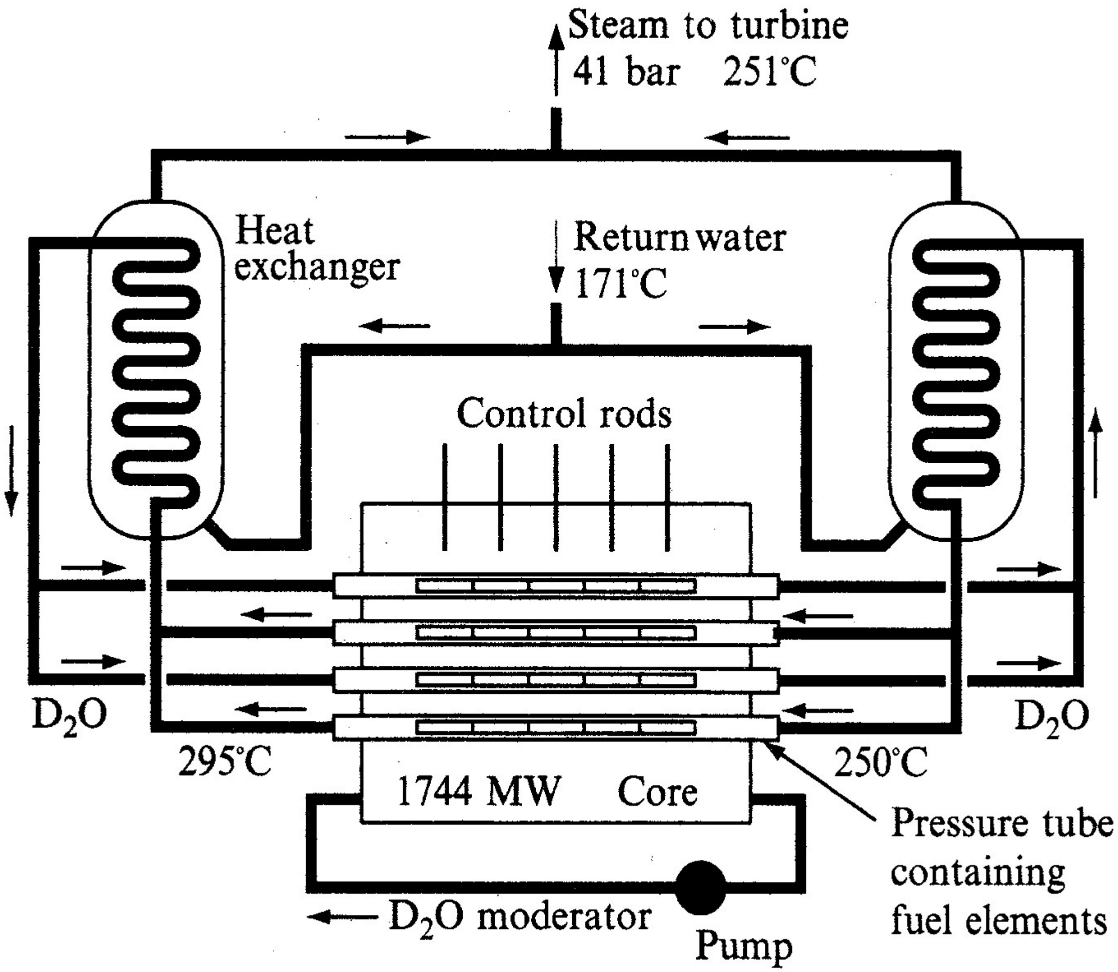
Key features:

- Enriched (1.7–2.5%) UO_2 fuel in Zr-alloy-clad fuel rods
- H_2O coolant/moderator (70 bar; 288°C at outlet)
- Boron carbide control rods
- Shut-down: injection of boric acid into moderator
- Need for heat exchangers eliminated (reduces cost and improves efficiency). Any fuel leakage can contaminate turbine via steam
- On-load refuelling not possible

Example:

- Pilgrim 1 Reactor, Plymouth, USA
- Power output 664 MW(e)
- Thermal efficiency about 33%

Generation II: Pressurised heavy water reactor



Layout of a CANDU reactor showing heat exchangers and simplified steam cycle

The pressurised heavy water reactor

Key features:

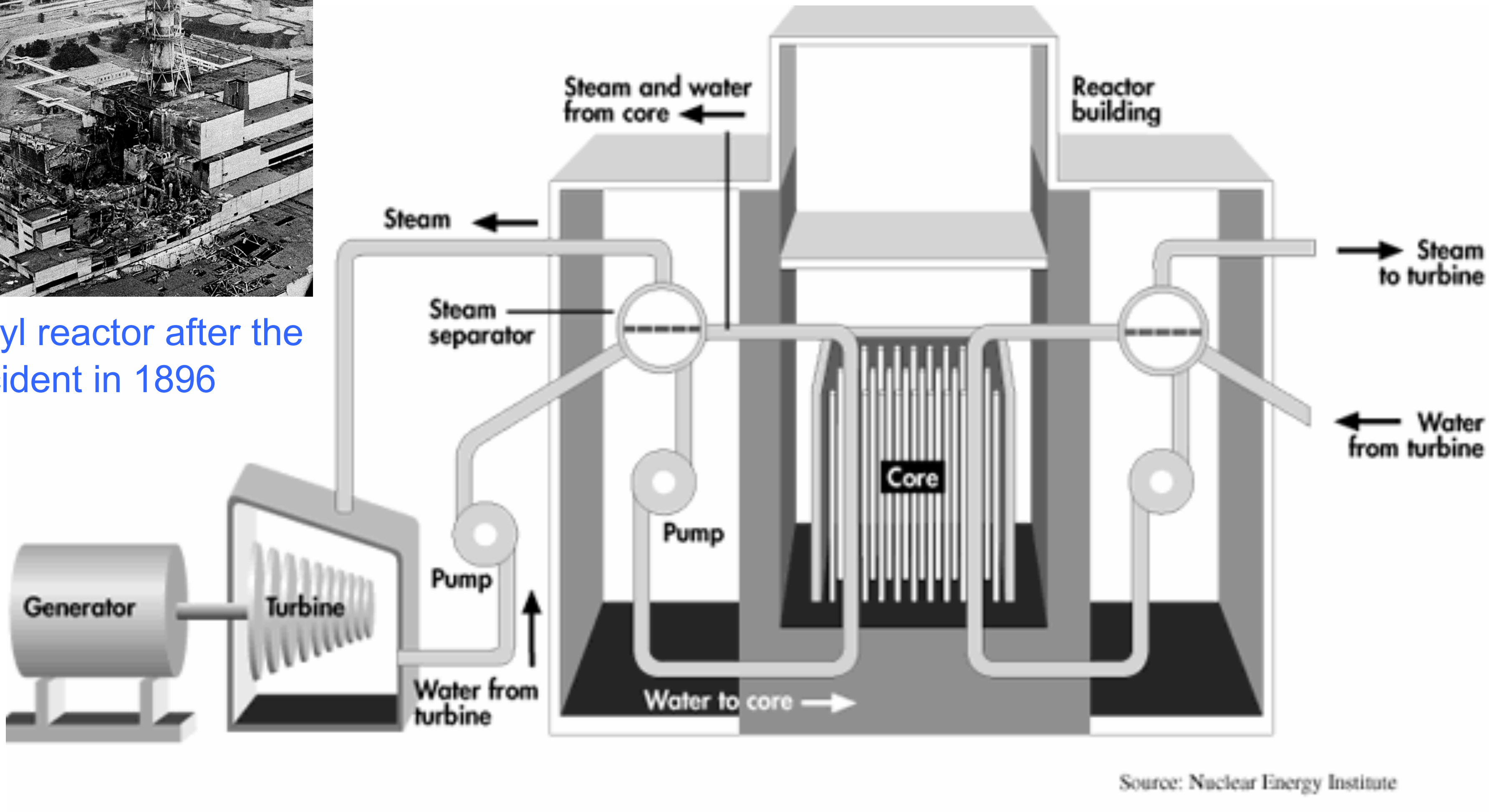
- Natural UO_2 fuel pellets in Zr-alloy-clad fuel rods
- D_2O (or H_2O) coolant (90 bar; 300°C at outlet)
- D_2O moderator
- Cd control rods
- Shut-down: Cd rods, plus dump tank or poison
- On-load refuelling is a design feature
- Economic, despite high cost of separating D_2O

Example:

- Bruce Power Station, Lake Huron (8 reactors)
- Power output ~740 MW(e) each
- Thermal efficiency a little under 30%

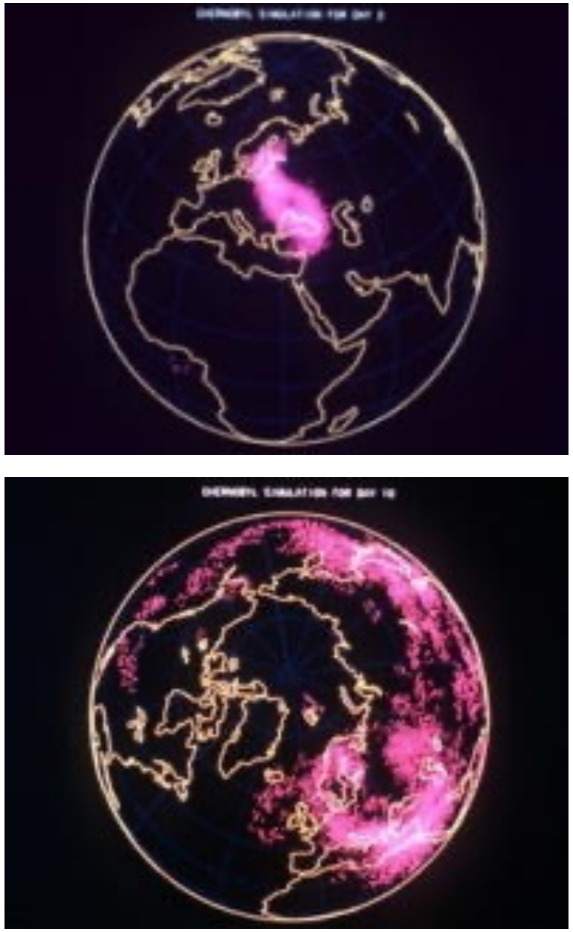
Generation II: Soviet-designed RBMK

Chernobyl reactor after the accident in 1896

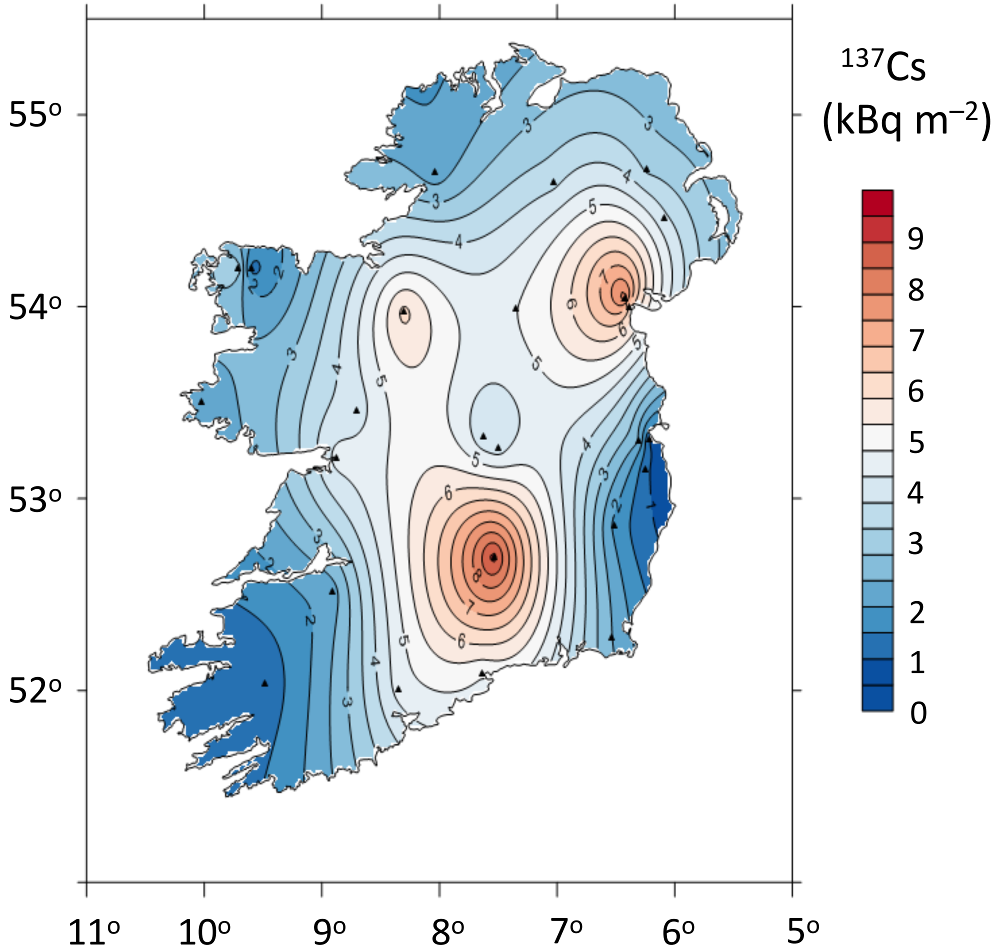


Layout of a RBMK reactor, combining graphite moderation and light water (H_2O) cooling

The cumulative release from Chernobyl is estimated to have been $\sim 2 \times 10^{18}$ Bq (54 MCi).

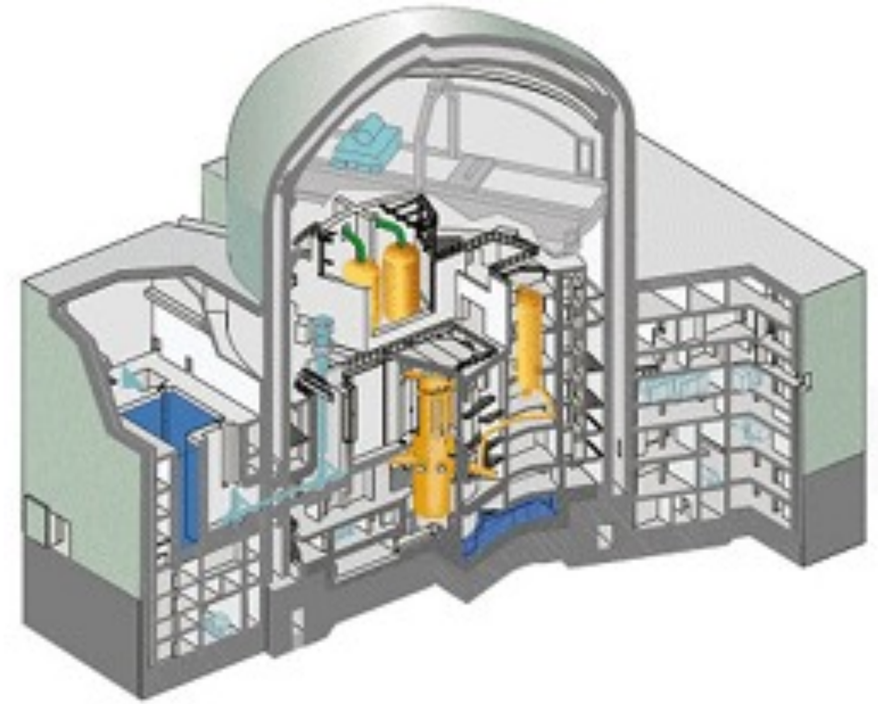


Areas covered by the main body of the radioactive cloud from Chernobyl on days 2 and 10 after the accident (source: US DOE)



Geographical distribution of Chernobyl-sourced ^{137}Cs (kBq m^{-2}) deposition throughout Ireland (Ryan, 1991)

Generation III: European Pressurised (Water) Reactor (EPR) – Areva (France)



Layout of Areva's EPR reactor and containment vessels

Key features:

Performance level greatly improved

Advanced technological features that makes it extremely safe

Maintenance simplified

Generates less waste & effluents

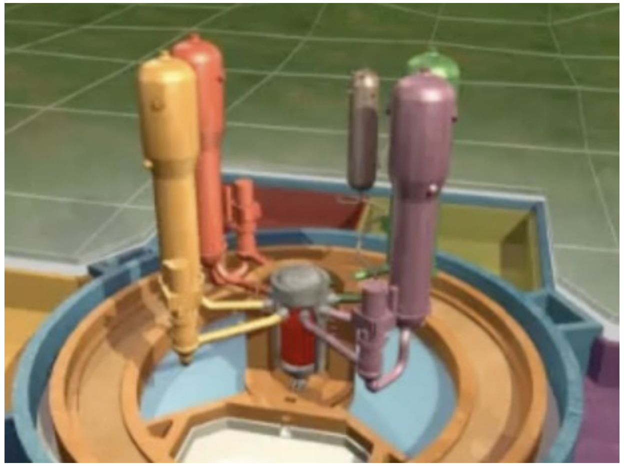
The Ariva EPR – An advanced power reactor

Salient features of the AREVA EPR at Olkiluoto (Finland):

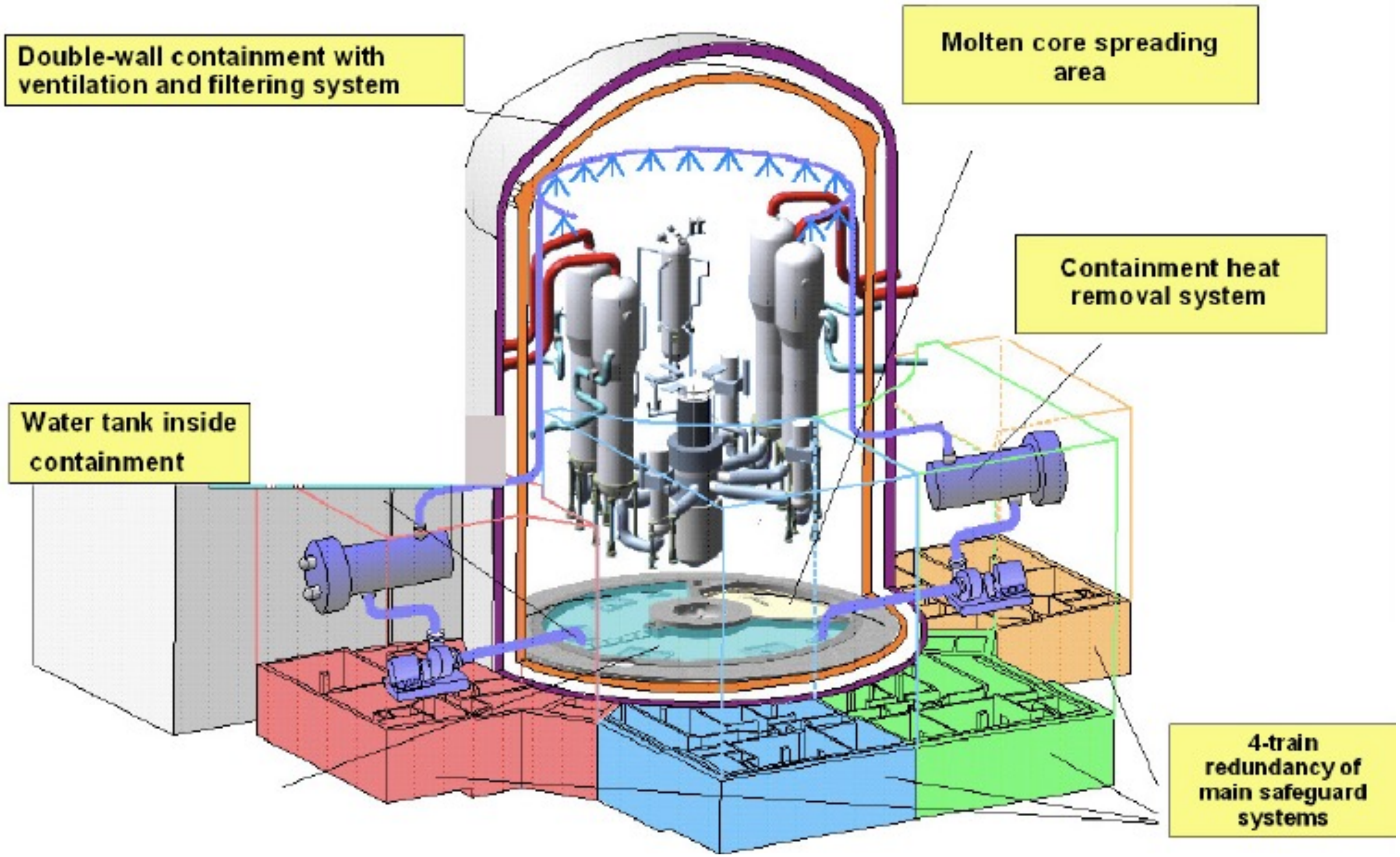
- Uranium oxide (5% enrichment) or mixed uranium and plutonium oxide (MOX) fuel
- Net electrical power output 1600 MW_e
- Net efficiency is approximately 37%
- Coolant inlet temperature is 296ºC
- Coolant outlet temperature is 328ºC

The Ariva EPR – An advanced power reactor

- Evolutionary reactor based on proven technology incorporating innovative features from research programmes carried out by France and Germany
- Can work with enriched uranium or MOX fuel. This means that the Pu inventory can be controlled or even reduced
- Designed to have a working life of ~60 years
- Better use of fuel (15% less uranium required to generate the same amount of electricity, thereby reducing volume of waste)



The Ariva EPR – Safety features



Increased safety features introduced for the Ariva EPR

The Ariva EPR – Safety features

- In the unlikely event of core damage occurring, preventive measures have been taken to protect the public and the environment
- The EPR containment is extremely robust. It rests on a 6-m thick concrete base mat and is enclosed by a double shell: the inner containment is made of leak-tight, pre-stressed concrete, and the outer one of reinforced concrete, each 1.3 m thick.
- This containment structure is capable to withstanding external hazards such as an aircraft crash

EPR containment vessels

The Ariva EPR – Safety features

- Even in the case of core melting and escaping the steel reactor vessel, the fuel would be contained in a dedicated spreading compartment. This compartment would then be cooled (adjacent water tank) to remove the residual heat
- Supplemented by a heat removal spray system to lower T and help maintain mechanical integrity and leak resistance of containment

Molten core spreading area and cooling water tank

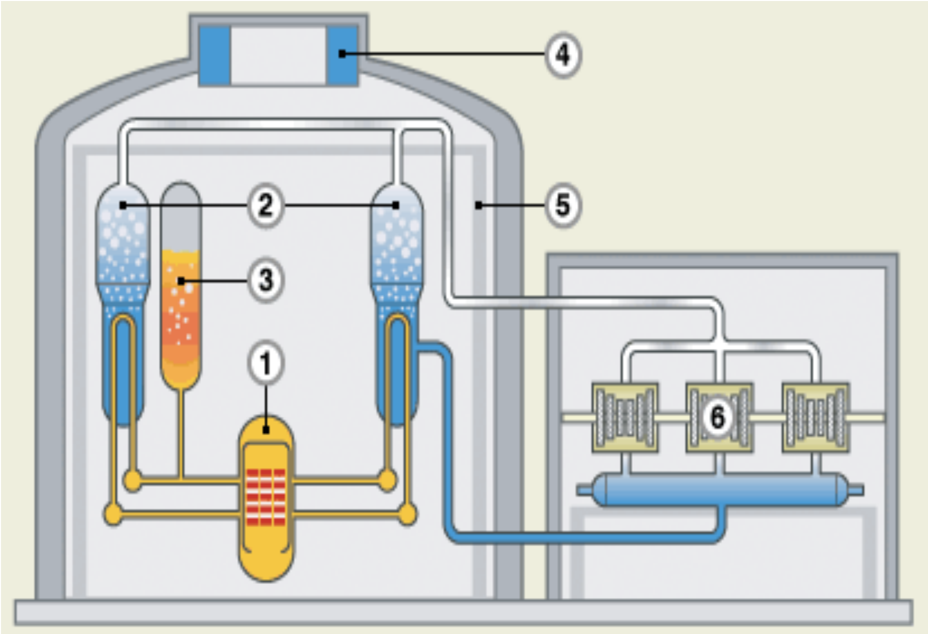
Heat removal spray system

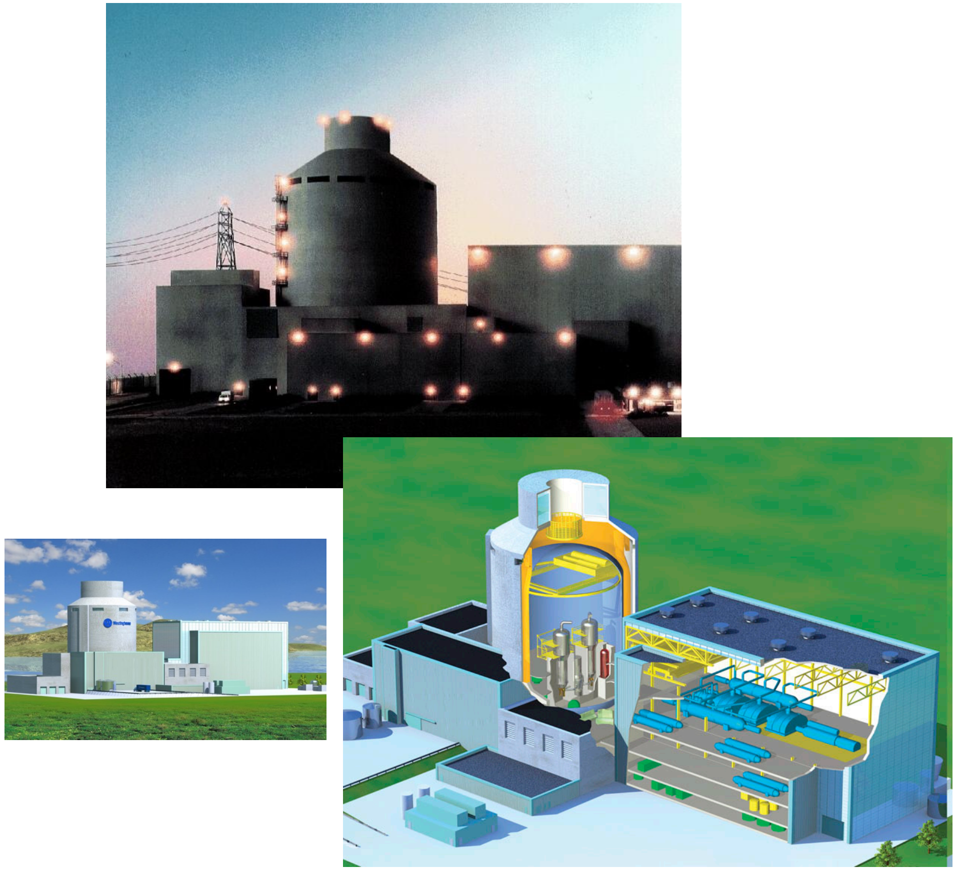
The Ariva EPR – Safety features

- Four separate major safety systems, each capable of performing the entire safety function independently
- Two of the safeguard buildings protected by the double concrete outer shell
- The other two protected by being at a separate location
- Two separate buildings containing auxiliary diesel generators

Four safeguard buildings physically separated from each other, two within the containment shell

Generation III: Westinghouse AP-1000 – advanced passive reactor





1. Reactor core
2. Steam generators
3. Pressuriser
4. Passive cooling water tank
5. Steel containment tank
6. Turbines

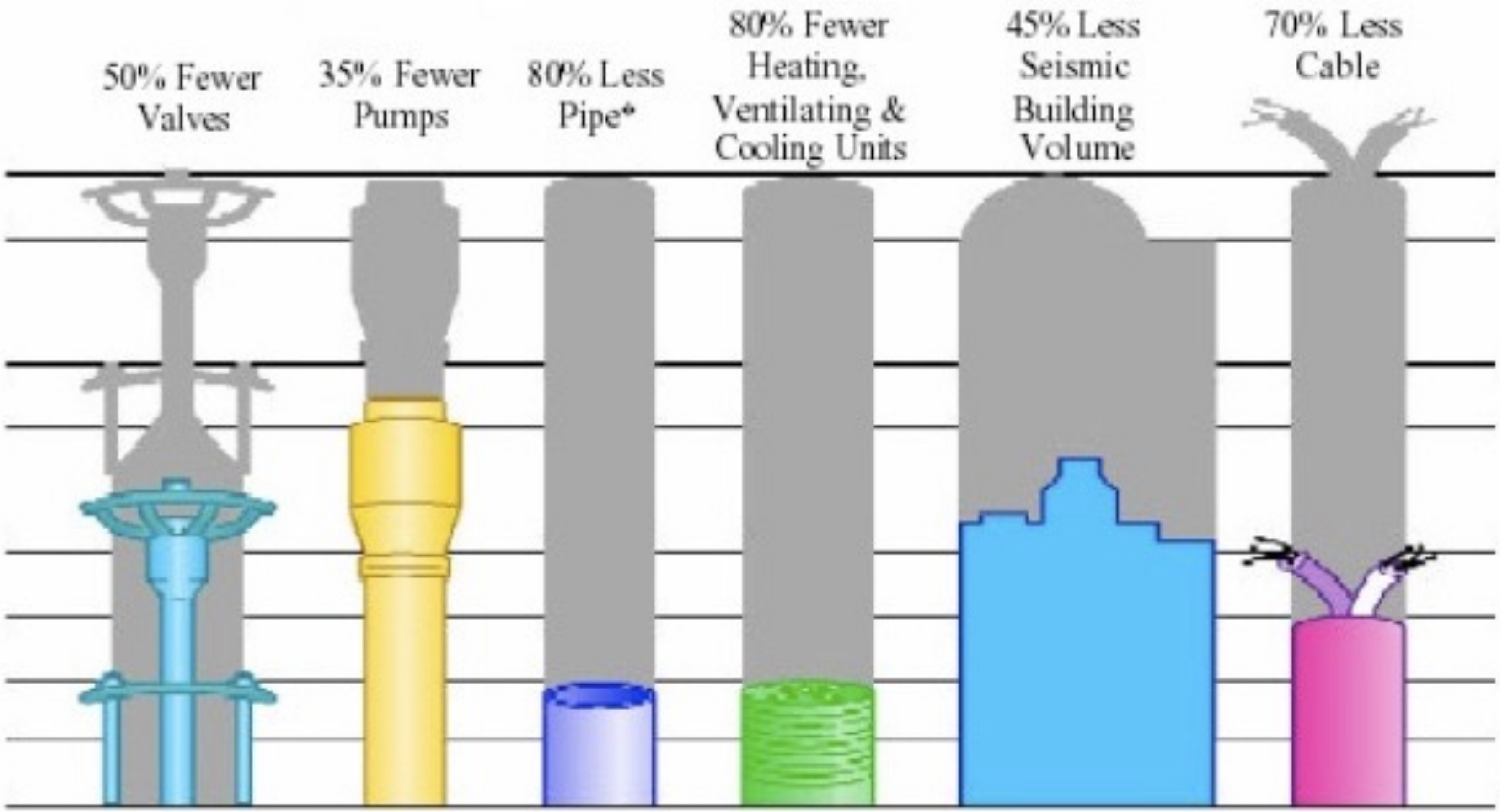
Passive safety systems

50% fewer valves

35% fewer pumps

80% less pipework & cables

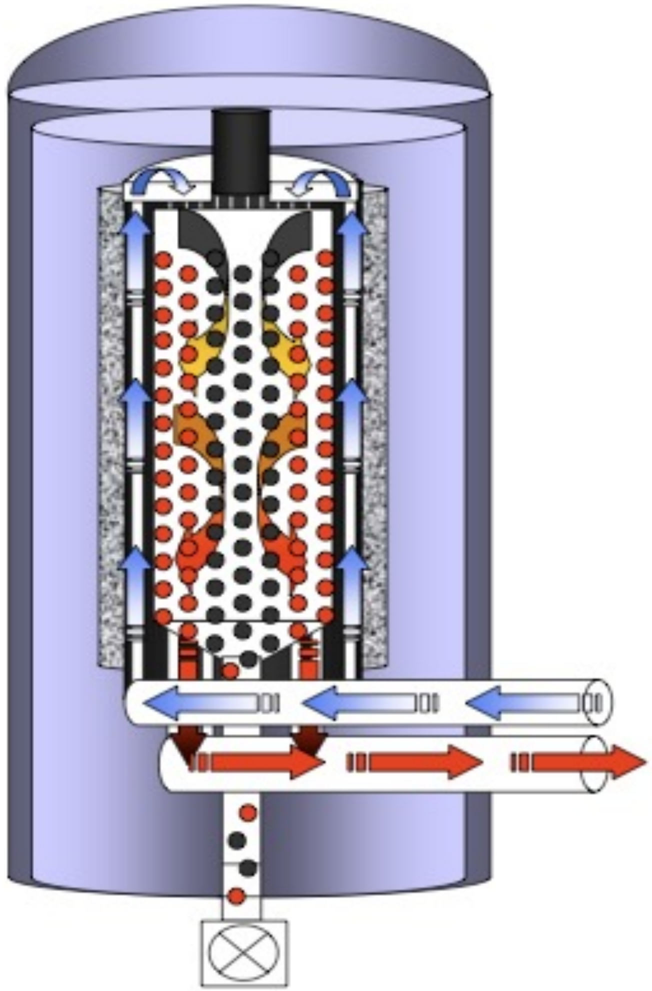
The AP-1000 (continued)

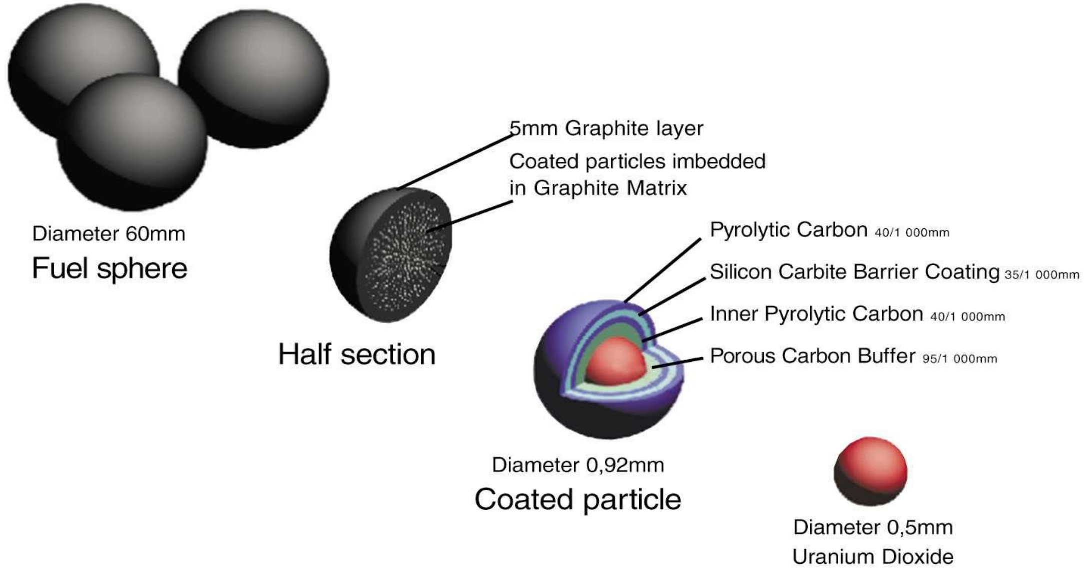


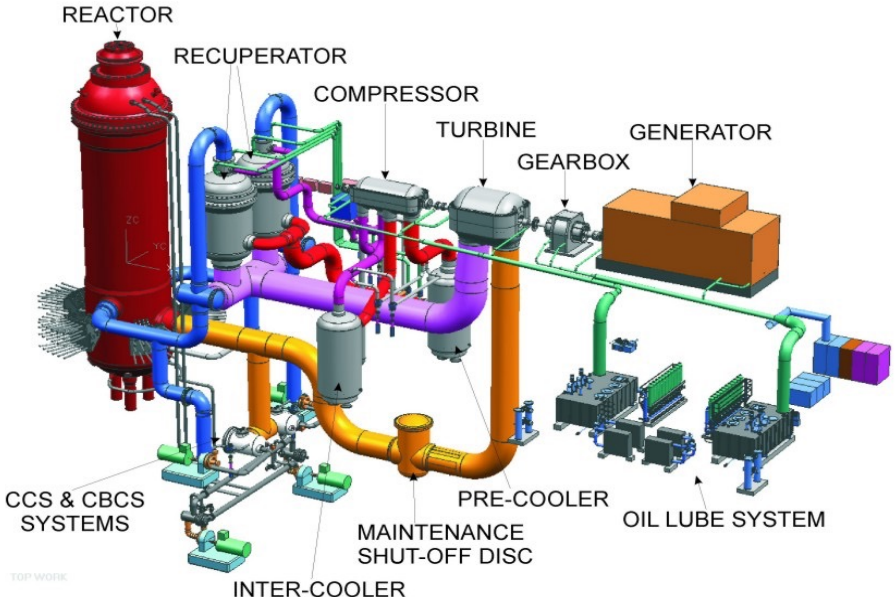
* Safety Grade Compared to a conventional, 2-loop 600 MWe plant

Generation III+: The pebble-bed modular reactor (PBMR)

Reactor Unit

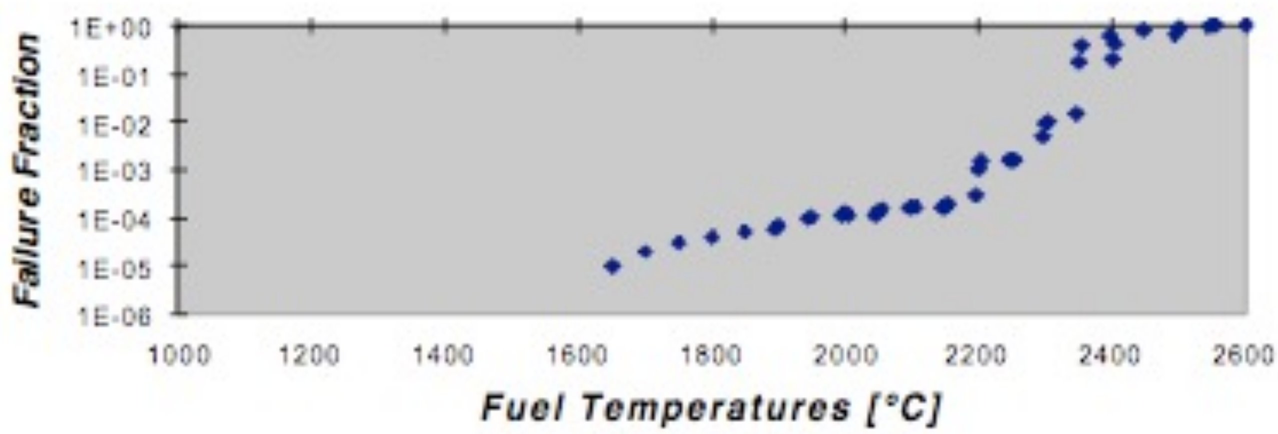






Fuel performance

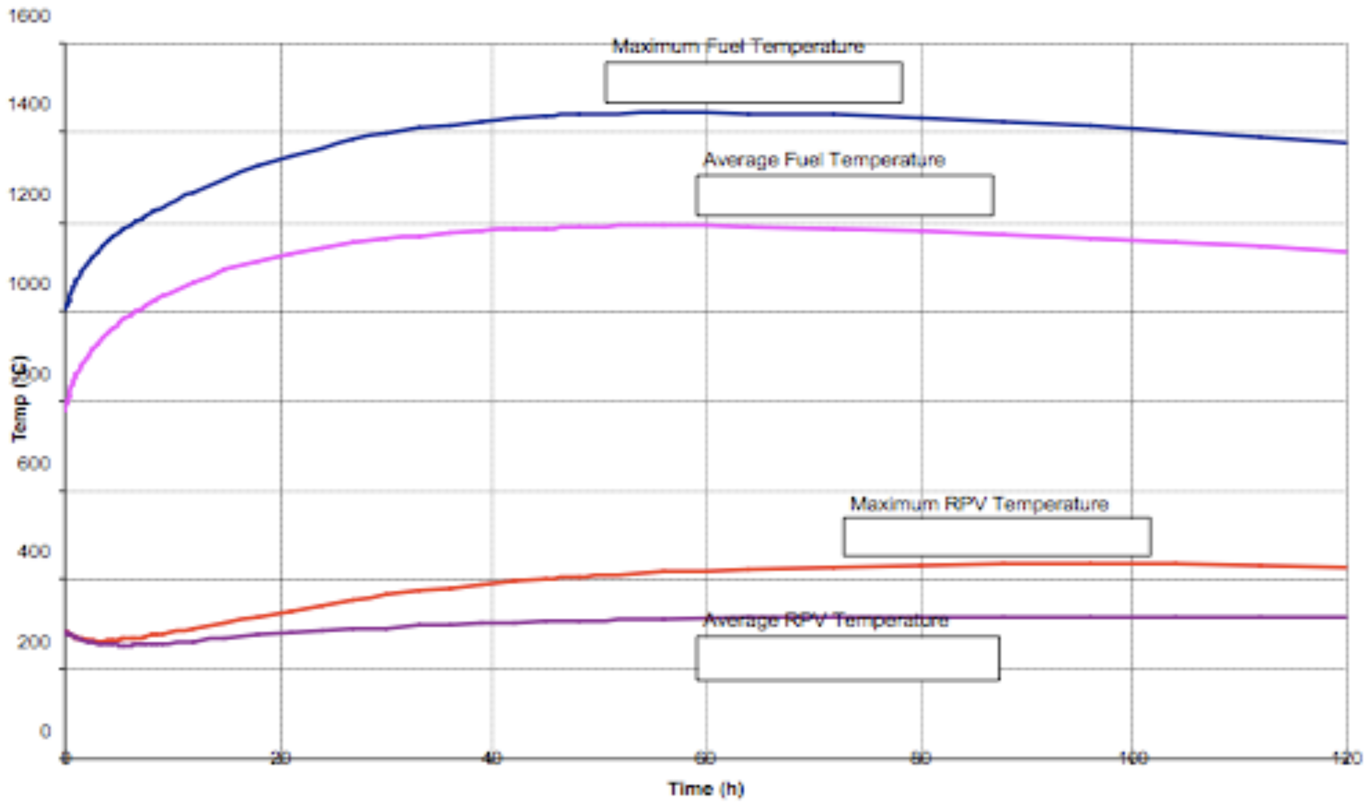
The peak temperature that can be reached in the core of the reactor (1600°C) under the most severe conditions is well below the temperature that can cause damage to the fuel.



The figure shows the performance of the fuel under extended periods at high temperatures

Source: Eskom (2007)

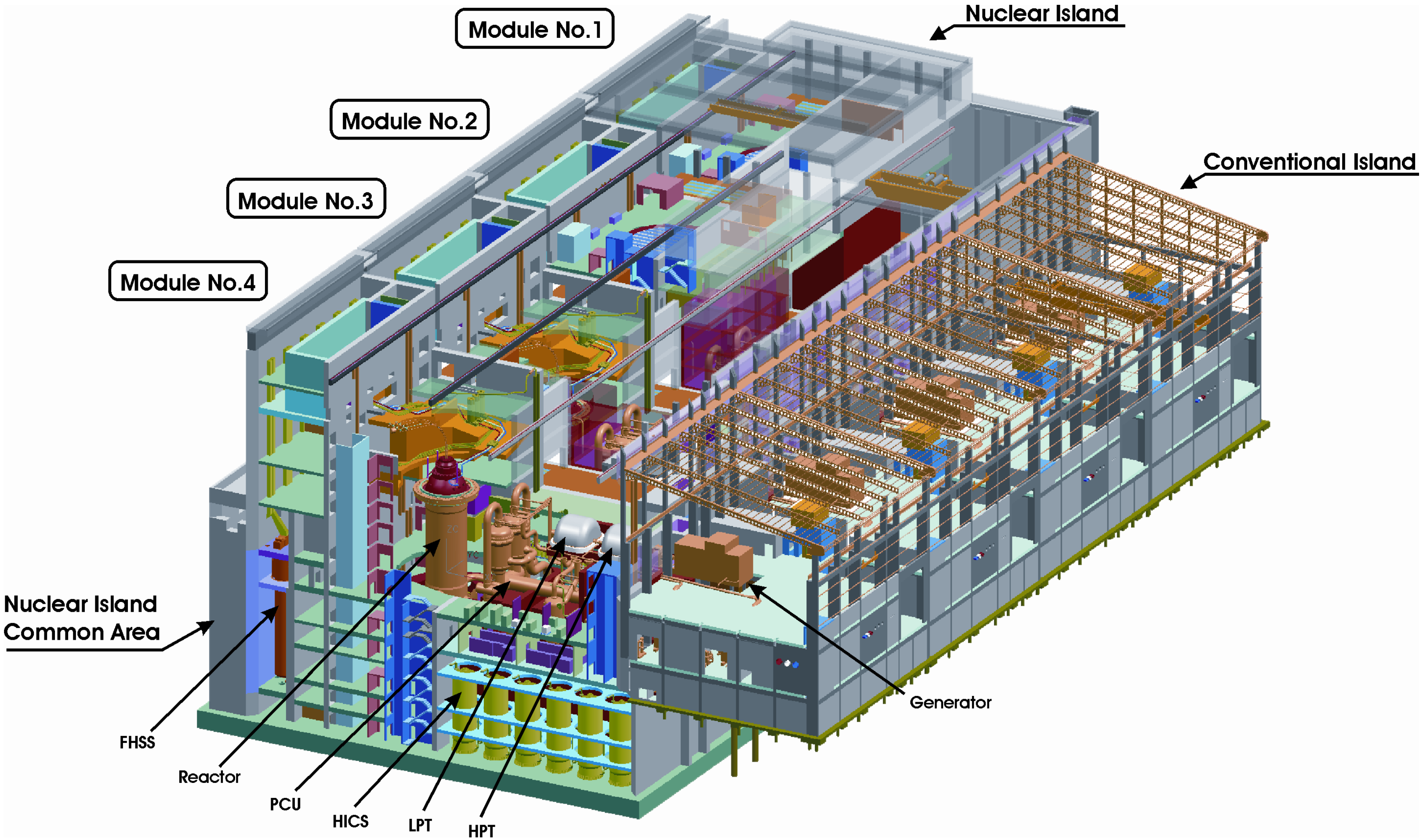
Loss of coolant event



The figure shows the temperature of the hottest part of the fuel and overall average after a total loss of coolant

Source: Eskom (2007)

Multimodule concept



Emerging designs that extend the uranium fuel supply (Generation-IV rectors)

Generation III reactor designs still make use of ^{235}U as fuel (with or without reprocessing). They incorporate additional safety features, but their basic designs remain essentially the same.

Moving beyond these existing technologies will require extensive R&D, and a great deal of international cooperation.

In 2001, 9 countries set up the Generation-IV International Forum (GIF) to foster the development of new reactors that improve on current designs in four key aspects:

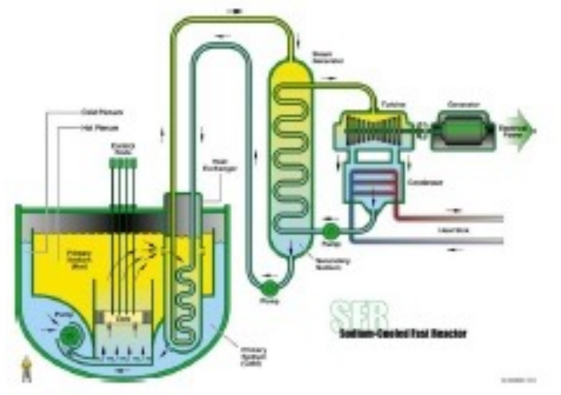
(1) sustainability

(2) economics

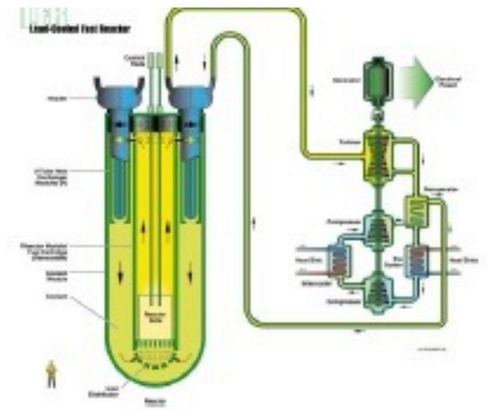
(3) safety and reliability

(4) non-proliferation

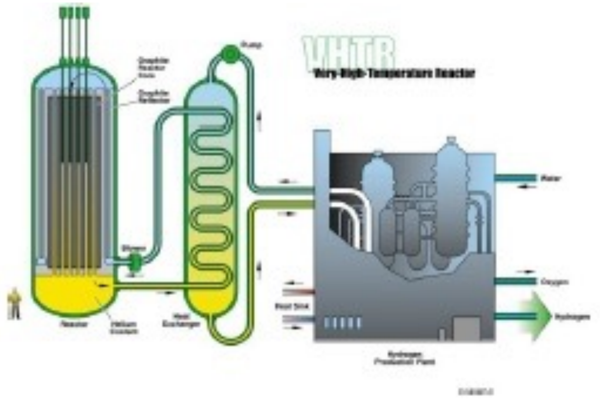
Six designs identified, with the hope that one or more will be ready for commercial deployment in the 2030s or 2040s.



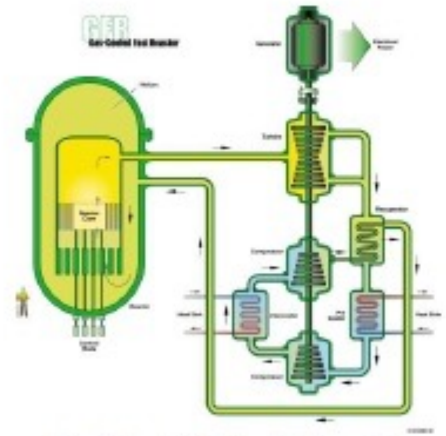
Sodium Fast Reactor



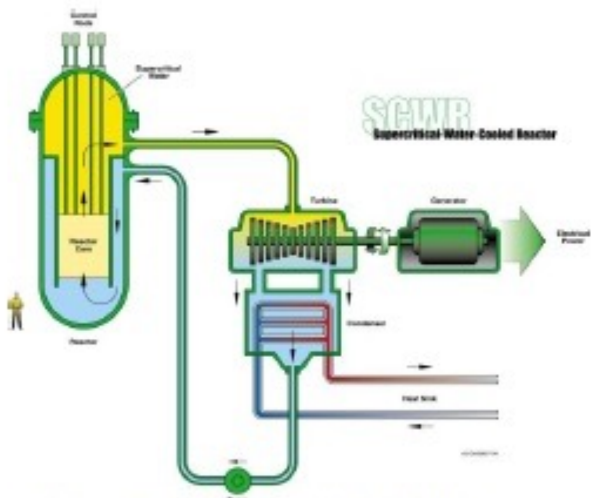
Lead Fast Reactor



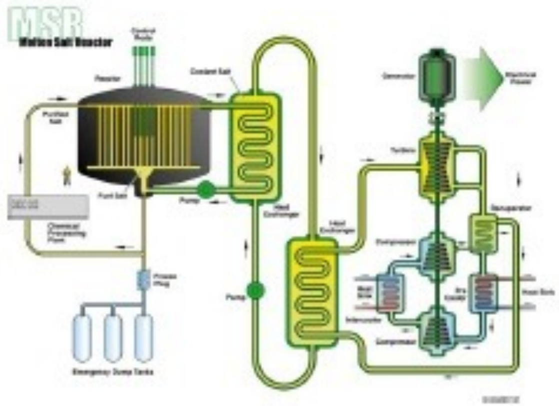
Very High Temperature Reactor



Gas Cooled Fast Reactor



Supercritical Water Cooled Reactor



Molten Salt Cooled Reactor

Generation IV reactors

Reactors for a new generation – promises and problems

Design	How it works	Advantages	Disadvantages
Supercritical water-cooled reactor	Water is heated to above its critical point (where it has both liquid and gas properties) and used to drive a turbine directly	High efficiencies; reduced plant cost due to a simpler heat- exchange system	New materials needed to withstand high temperatures and pressures; chemistry of supercritical water poorly understood
Very-high-temperature reactor	Uses helium as a coolant, allowing the reactor to reach temperatures of up to 1000°C; fuel is contained in pebbles or blocks to improve safety and refuelling	Very high efficiencies; potentially able to produce heat and hydrogen as well as electricity	New fuels and reactor components needed for such high temperatures
Sodium-cooled fast reactor	Builds on existing sodium-cooled reactors, which use "fast" rather than "thermal" neutrons	Potential to breed plutonium fuel and burn radioactive waste, thus "closing" fuel cycle	Reactivity and radioactivity of sodium coolant complicate operation and upkeep, and increase plant cost
Gas-cooled fast reactor	Fast reactor with helium coolant	Fuel breeding and waste burning; potential to provide heat and hydrogen; uses inert coolant	Helium is much poorer coolant than sodium
Lead-cooled fast reactor	Fast reactor with liquid-lead coolant	Fuel breeding and waste burning; inert coolant	Corrosion of other metals in reactor
Molten-salt reactor	Uses nuclear fuel dissolved in a circulating molten-salt coolant; could use either fast or thermal neutrons	No need to fabricate fuel; could be used to breed fissile thorium	Chemistry of molten salt not well understood; corrosion is a problem

(source: Physics World **23**, Oct. 2010)