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EG5066 Energy Technologies: Current Issues and Future Directions

Nuclear Energy

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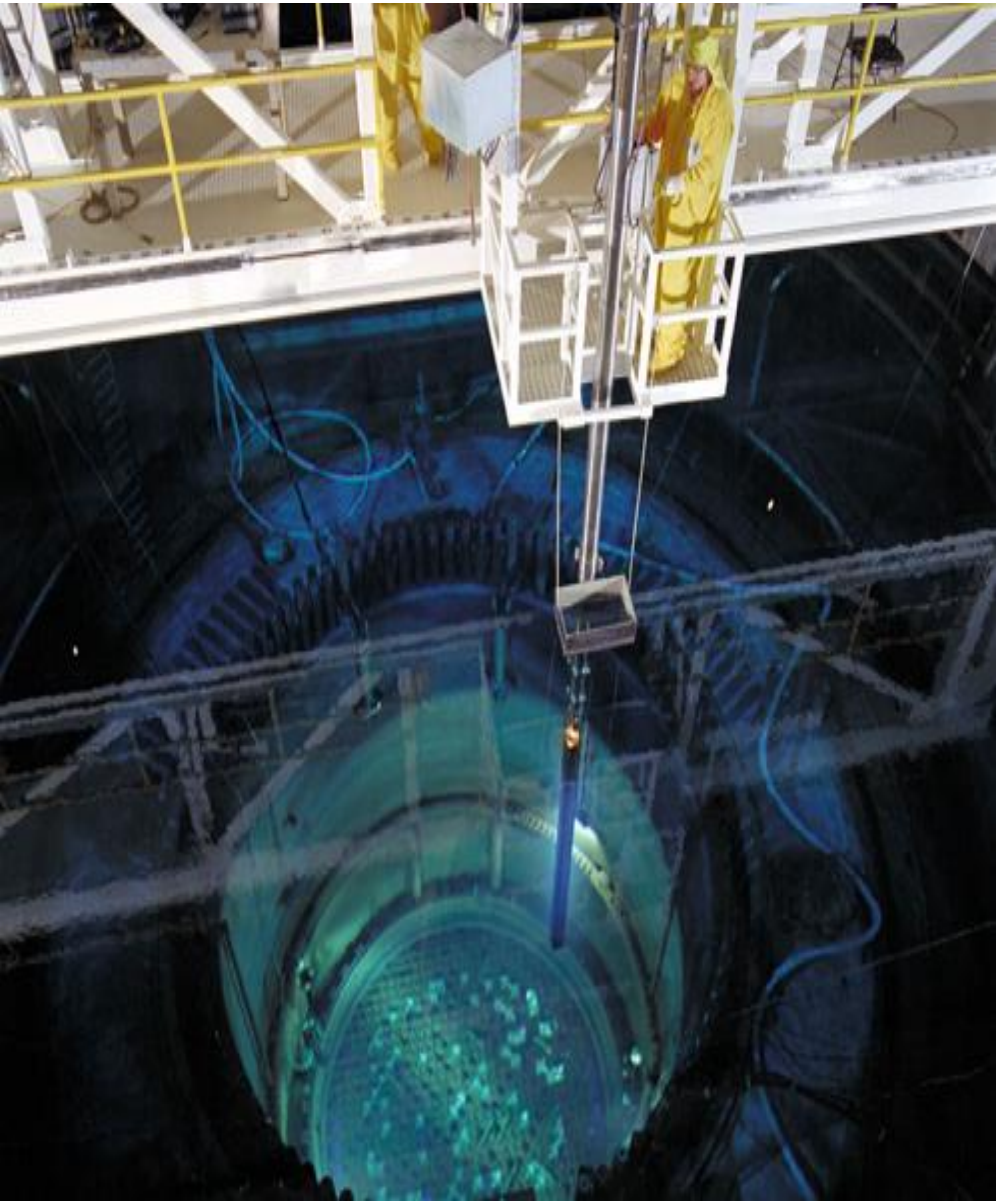
October 2013

Outline



- Energy Consumption
- Economics of Nuclear Energy
- Basics of a Power Plant
- Heat From Fission
- Current Commercial Nuclear Reactor Designs
- Nuclear Fuel Cycle
- Future Reactor Designs








Energy:
Production & Demand





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Overview of the Energy Industries

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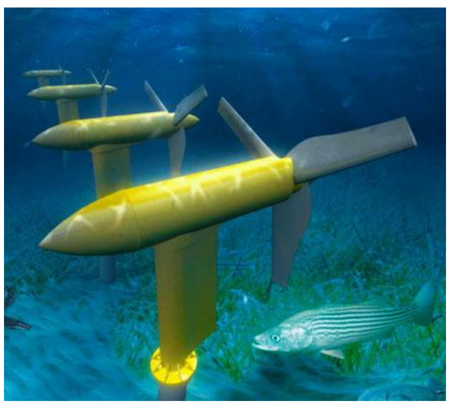
We use energy to provide:

- Electricity
- Heat
- Transport

Overview of the Energy Industries

From:

- Fossil fuels:
  - Oil;
  - Gas;
  - Coal;
- Nuclear;
- Hydroelectricity;
- Wind;
- Solar;
- Maritime (wave, tide etc);
- Geothermal;
- Etc.



Overview of the Energy Industries

- Rising energy demand;
- Need to stabilise atmospheric CO_2 at 550ppm;
- Aging fleet of coal & nuclear plant;
- Concerns about storage of nuclear waste;
- Declining oil & gas reserves 30- 50 years;
- Only 70 years of uranium left;
- Reduce reliance on hydrocarbons.

Policy drivers:

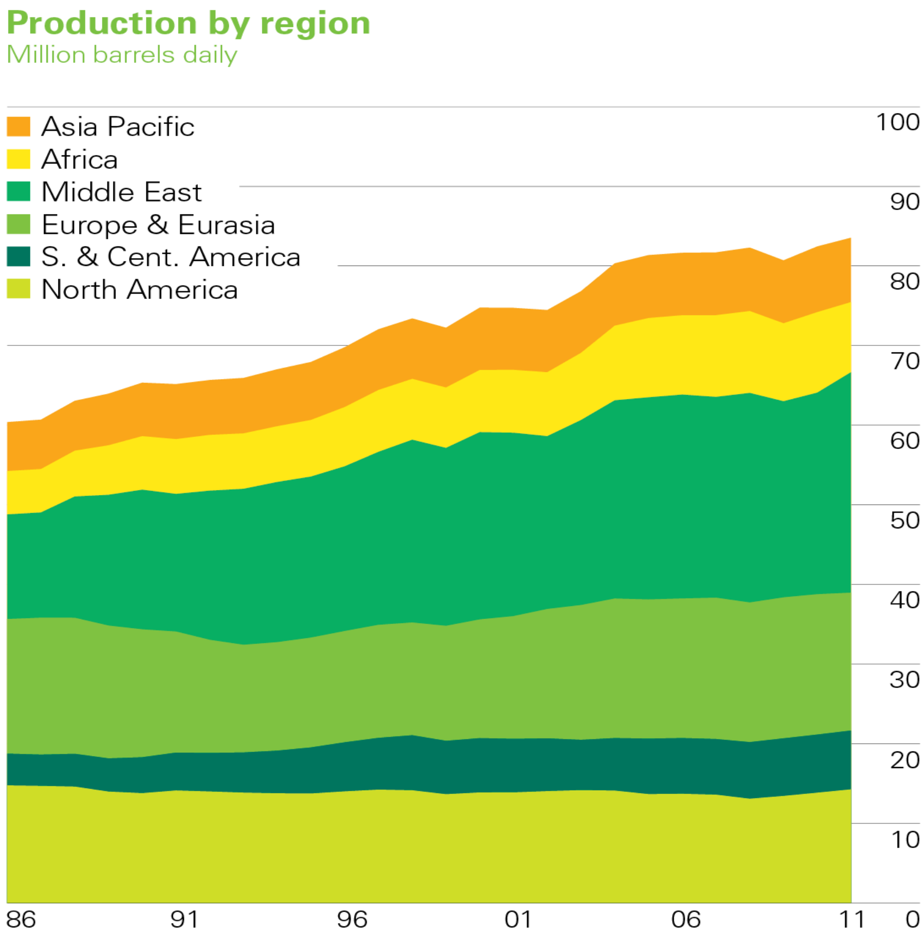
- Low Carbon Society;
- Security of Supply;
- Fuel Poverty;

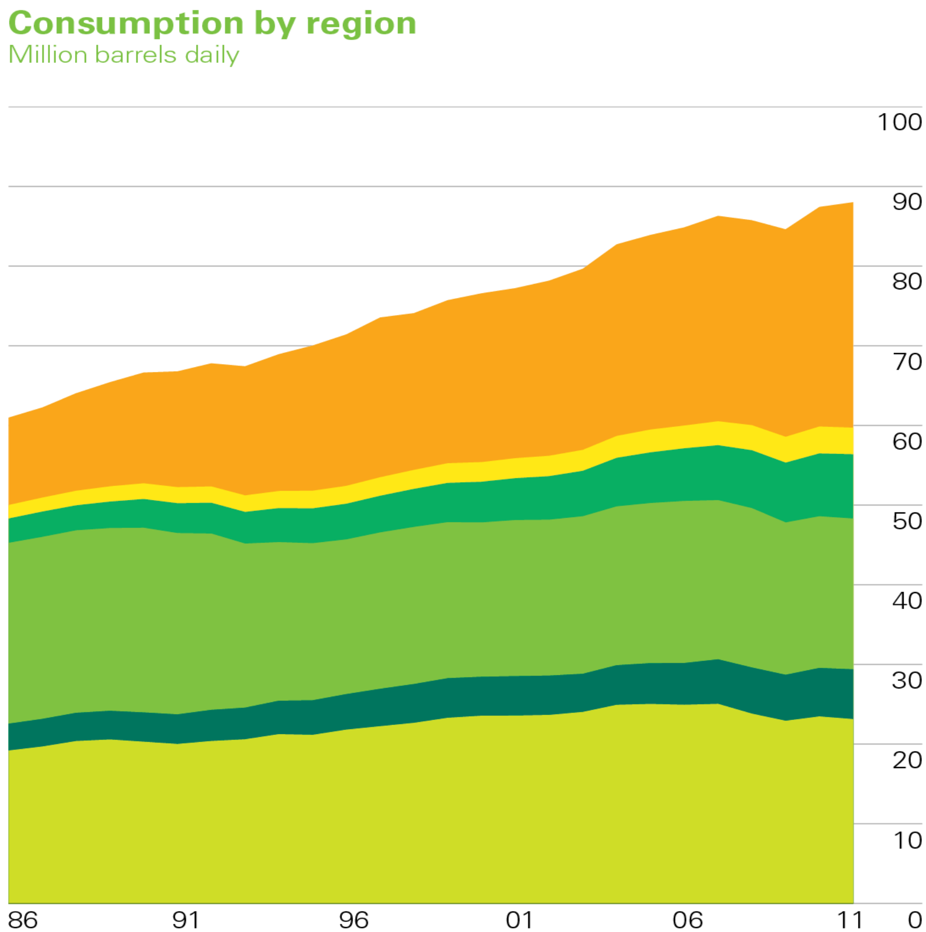





Growth Trends (1985-2010):

Oil Production/Consumption





World oil production increased by 1.1 million b/d in 2011, with OPEC accounting for nearly all of the increase despite a 1.2 million b/d reduction in Libyan production. The US had the largest growth in non-OPEC supply for a third consecutive year. World oil consumption increased by roughly 600,000 b/d. All of the net growth came from emerging economies in Asia, South & Central America, and the Middle East, offsetting declines in Europe and North America.

Source: BP Statistical Review of World Energy (2012)

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Growth Trends (1985-2010):

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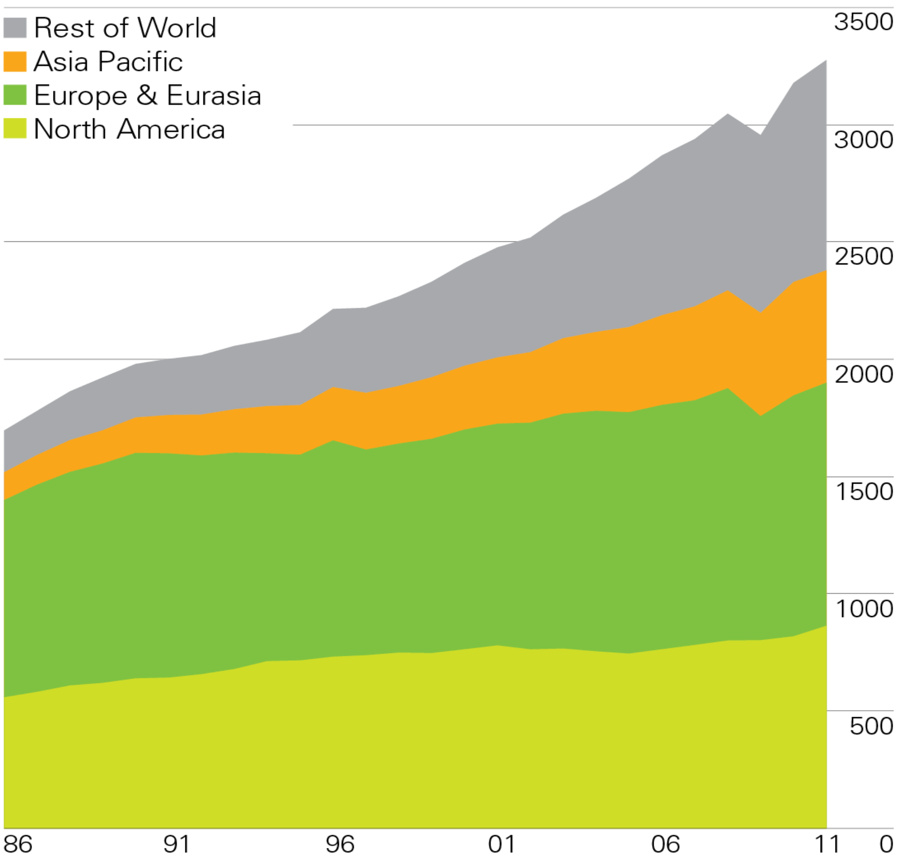
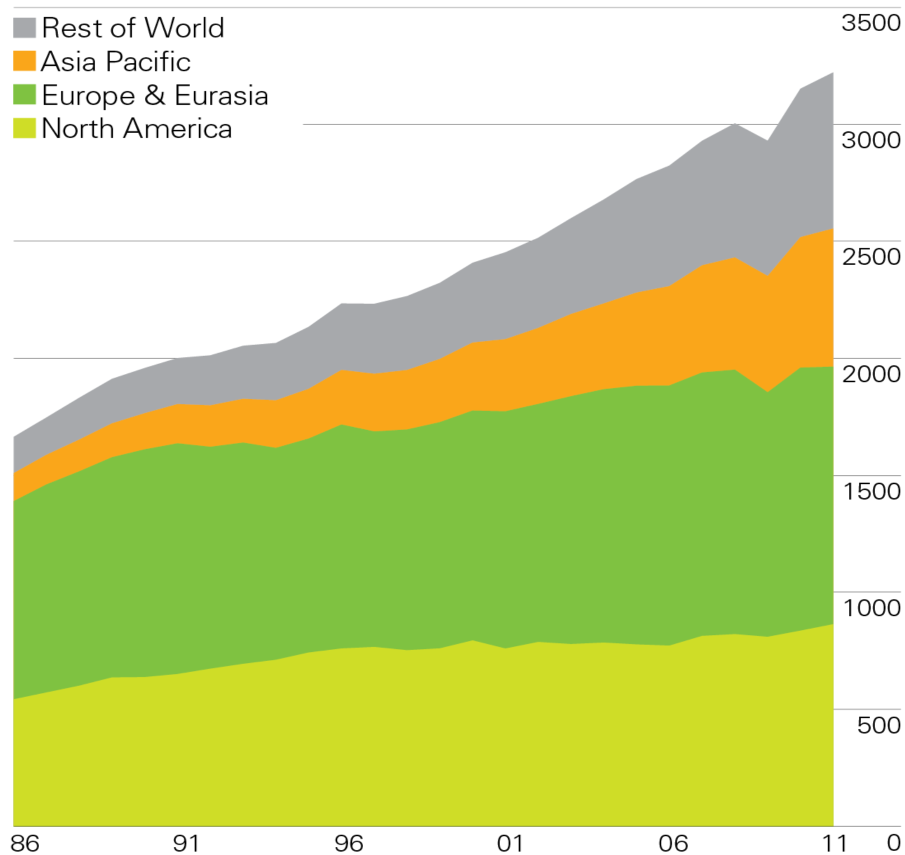
Natural Gas Production/Consumption

Production by region
Billion cubic metres



Consumption by region
Billion cubic metres



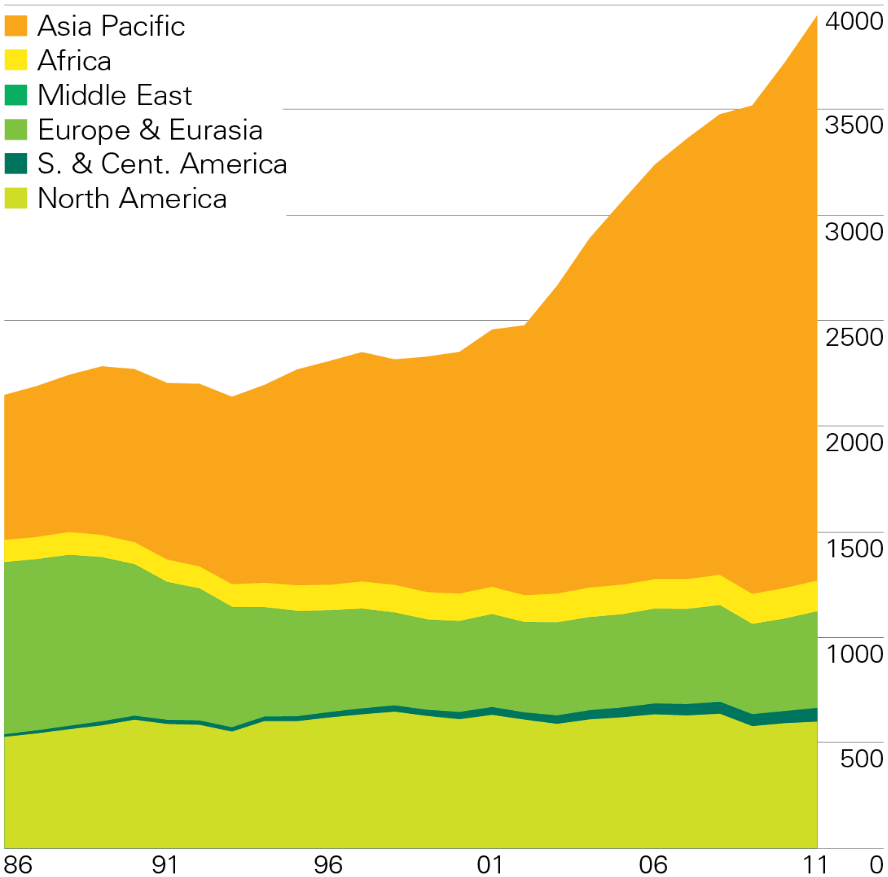
World natural gas production increased by 3.1% in 2011. While the US saw the largest national increase, the Middle East recorded the largest regional increment to production. Production growth in Russia and Turkmenistan was partly offset by a large decline in European production. Natural gas consumption increased by 2.2%, with below-average growth in all regions but North America. The European Union experienced the sharpest decline in natural gas consumption (–9.9%) on record.

Source: BP Statistical Review of World Energy (2012)

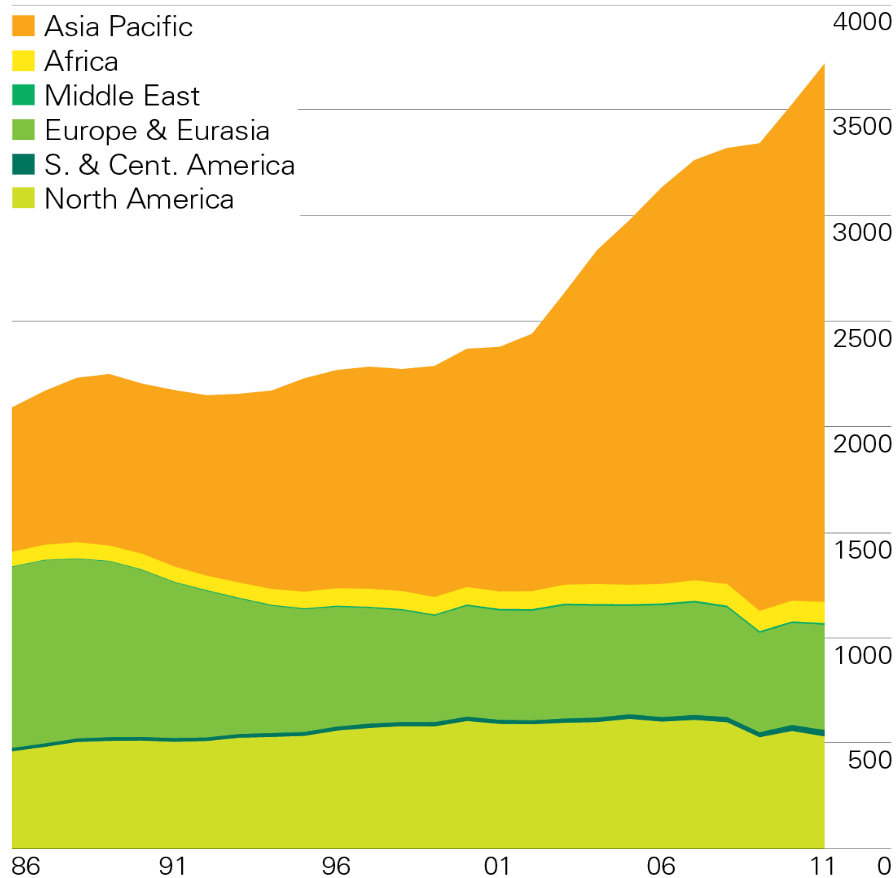
Growth Trends (1985-2010):

Coal Production/Consumption

Production by region
Million tonnes oil equivalent



Consumption by region
Million tonnes oil equivalent



Coal was again the fastest-growing fossil fuel. Global production grew by 6.1%. The Asia Pacific region accounted for 85% of global production growth, led by an 8.8% increase in China, the world's largest supplier. Global coal consumption increased by 5.4%, with the Asia Pacific region accounting for all of the net growth. Elsewhere, large declines in North American consumption were offset by growth in all other regions.

BP Statistical Review of World Energy 2012

Growth Trends (1985-2010):

	Production 2010	Historical Growth	Growth(%)
Oil	86M mbo/day	1M mbo/year	1.2
Coal	3.6B Toe	160M toe/year	4.4
Gas	3150B m^3	60B m^3/year	1.9

toe: Tonnes oil equivalent
mbo: million barrel of oil

1 toe = 11.63 MWh = 41.87 GJ = 39.7M BTU
1 toe = 7.4 barrel of oil equivalent (boe)
1 barrel of oil = 159 litres

Growth Trends (1985-2010):

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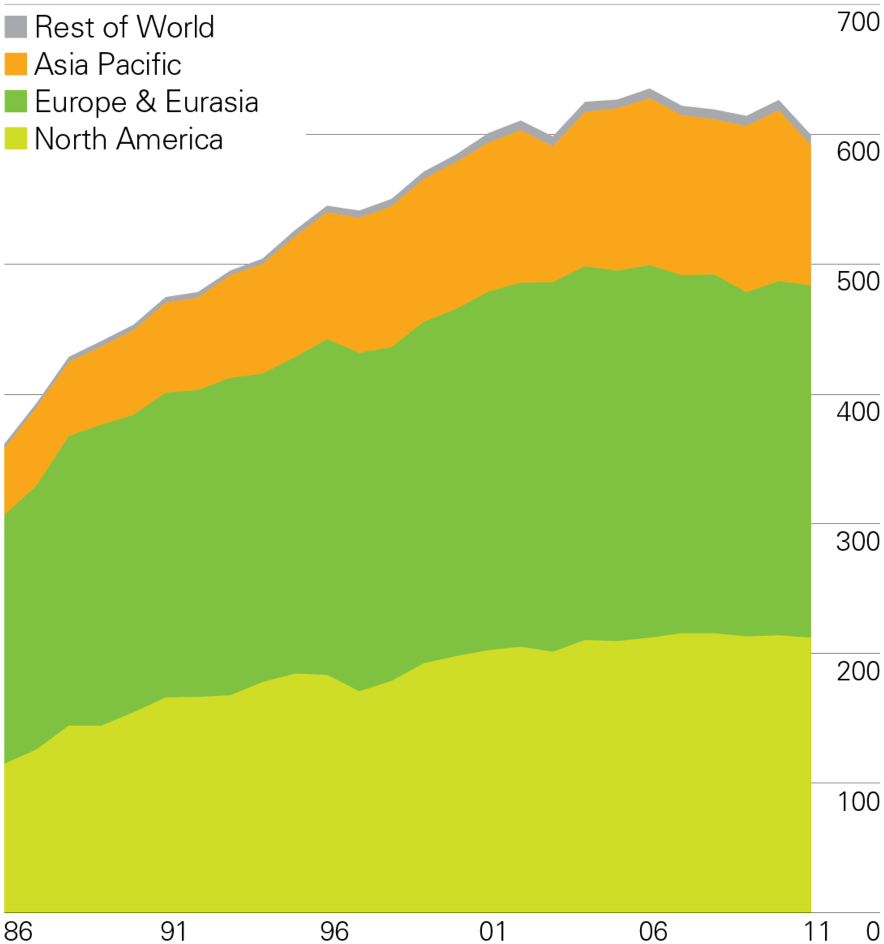
Nuclear energy consumption by region

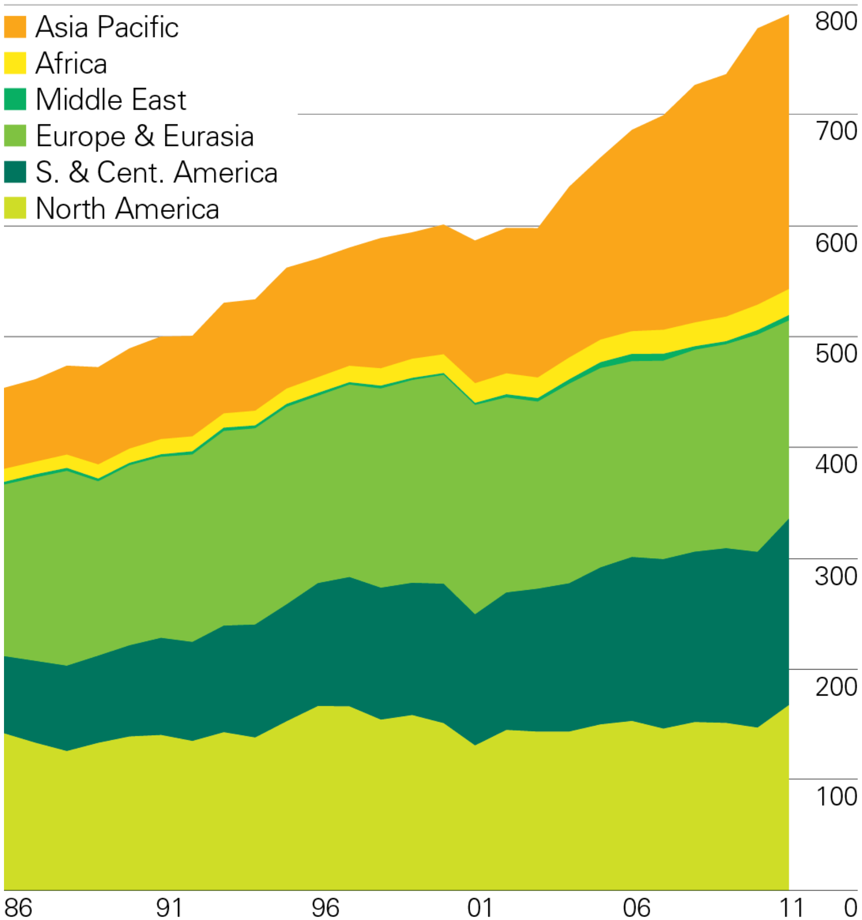
Million tonnes oil equivalent



World nuclear power generation declined by 4.3%, the largest decline on record. Japanese nuclear output fell by 44.3%, and German output fell by 23.2%.

Hydroelectricity consumption by region

Million tonnes oil equivalent



Global hydroelectric output grew by a below-average 1.6%. Strong growth in North America (+13.9%) was offset by drought-related declines in Europe & Eurasia and Asia Pacific.

Source: BP Statistical Review of World Energy (2012)

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World Energy Consumption (10^{15} BTU)

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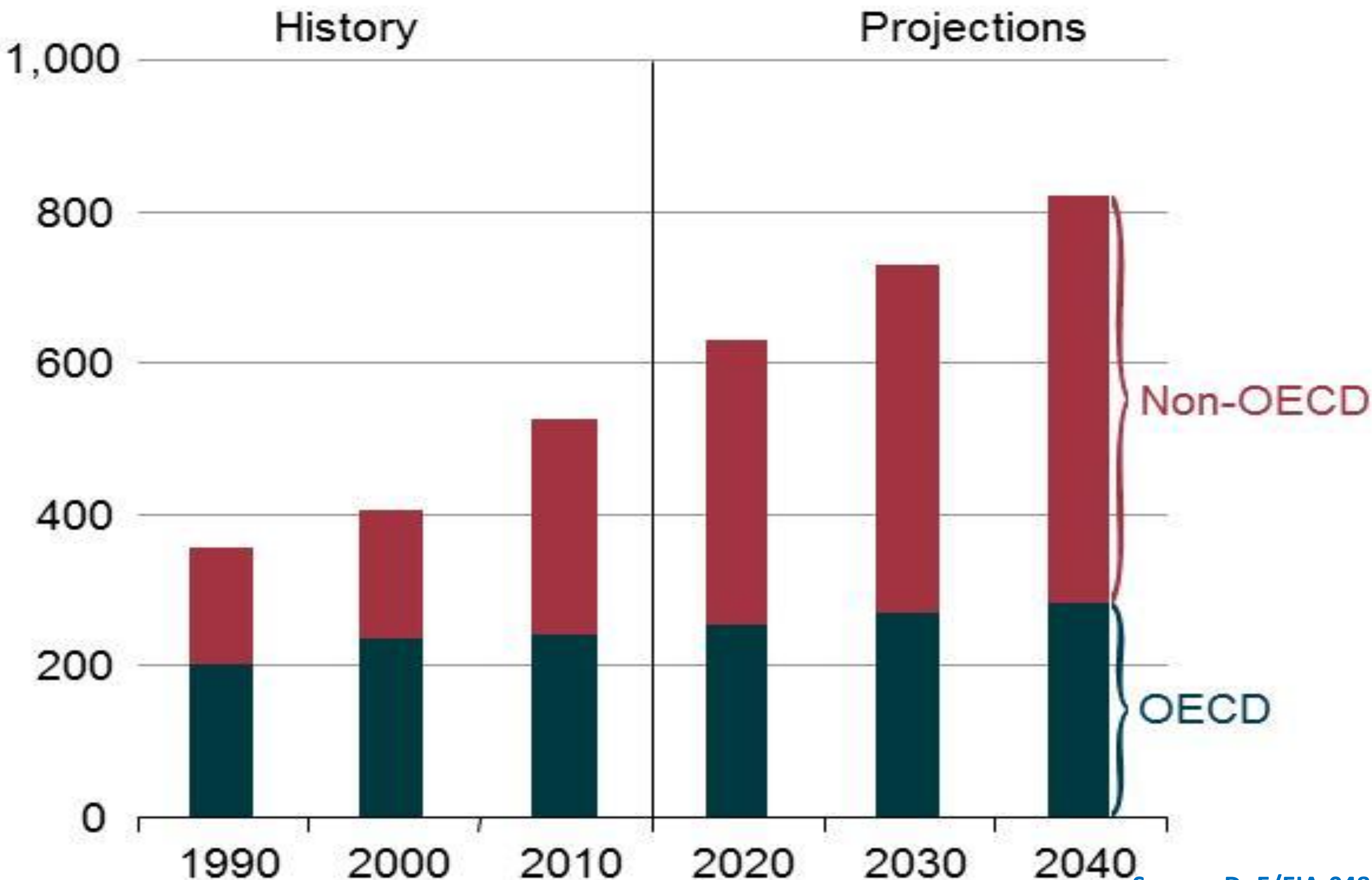
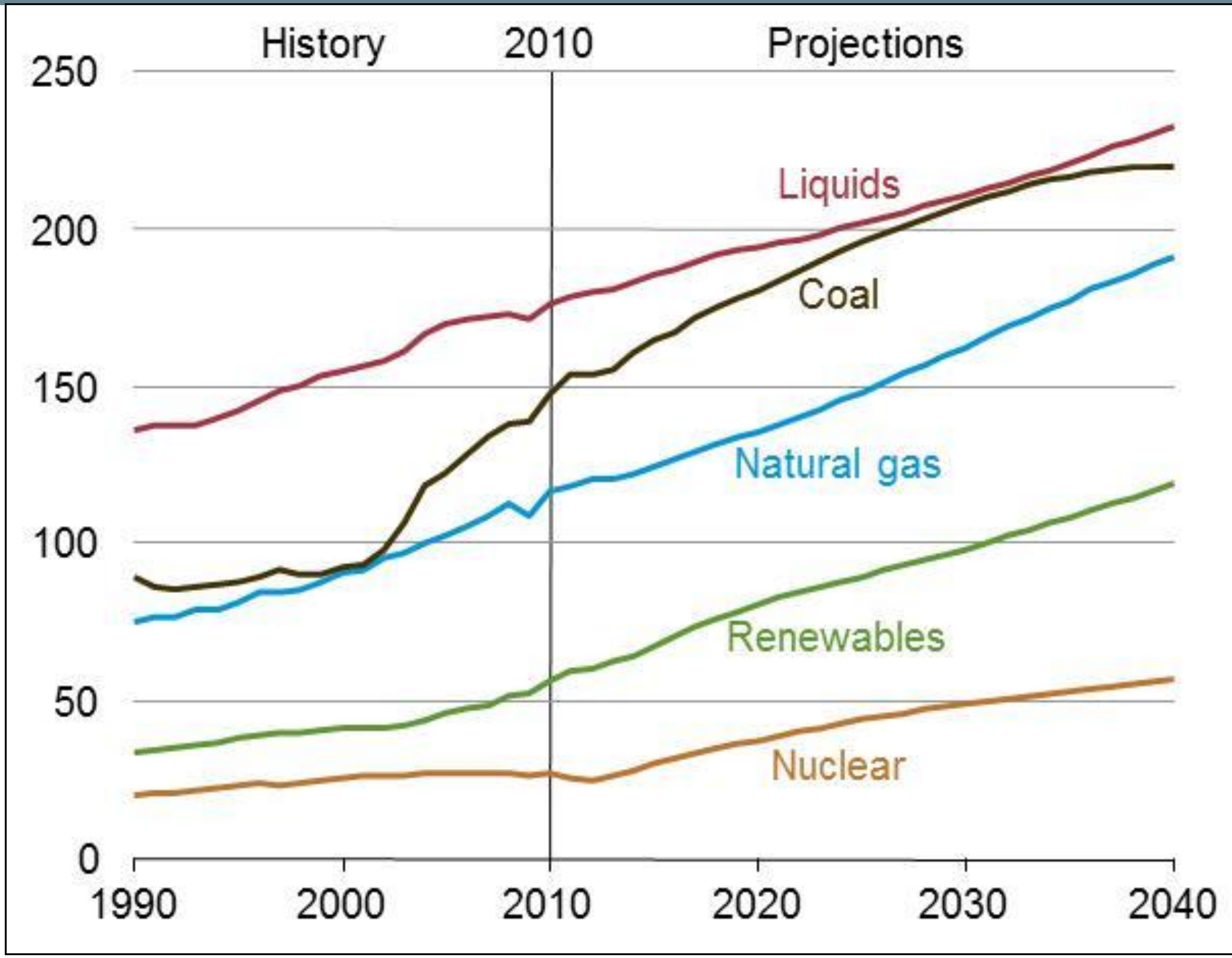


Source: DoE/EIA-0484

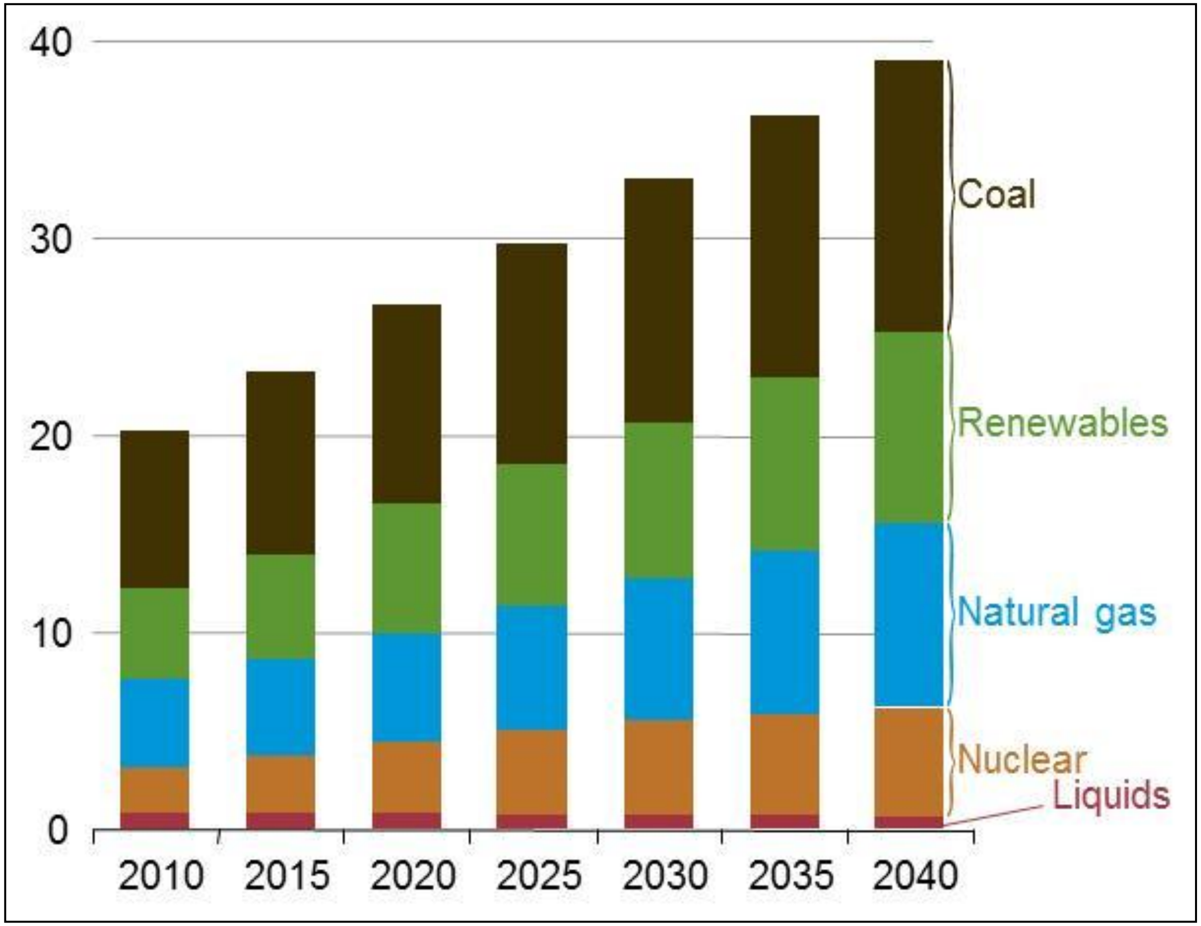
World Energy Consumption (fuel type, 10^{15} BTU)



Source: DoE/EIA-0484

- Petroleum liquids fuels: crude oil and lease condensate, natural gas plant liquids, bitumen, extra-heavy oil, and refinery gains;
- Other liquids fuels: gas-to-liquids, coal-to-liquids, kerogen and biofuels.

World Net Electricity Generation (fuel type, 10^{12} kWh)

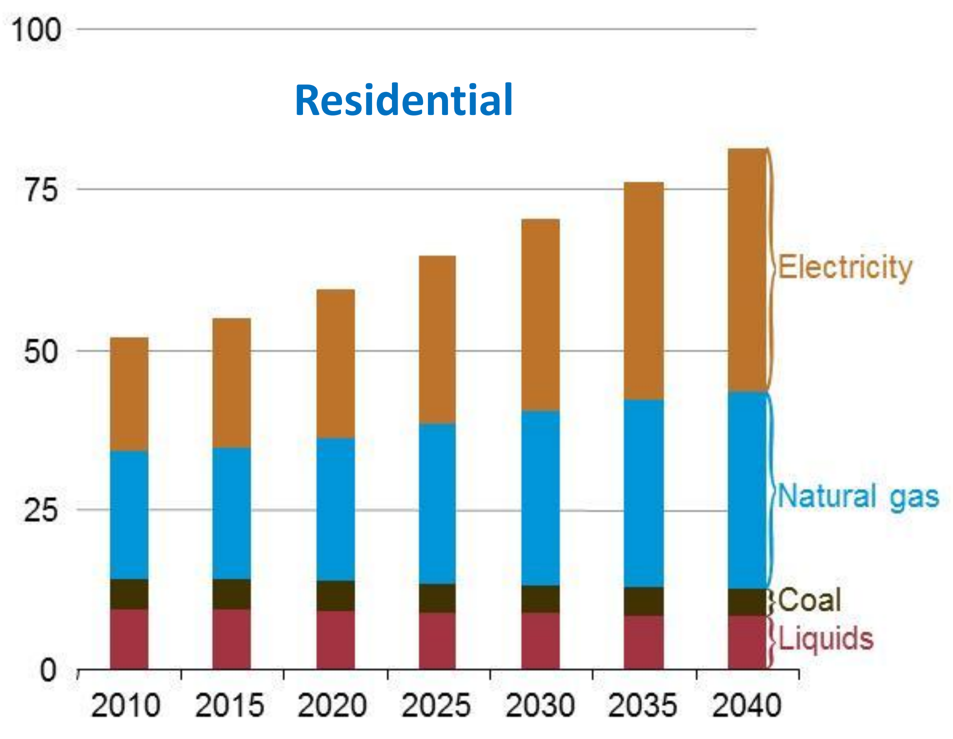


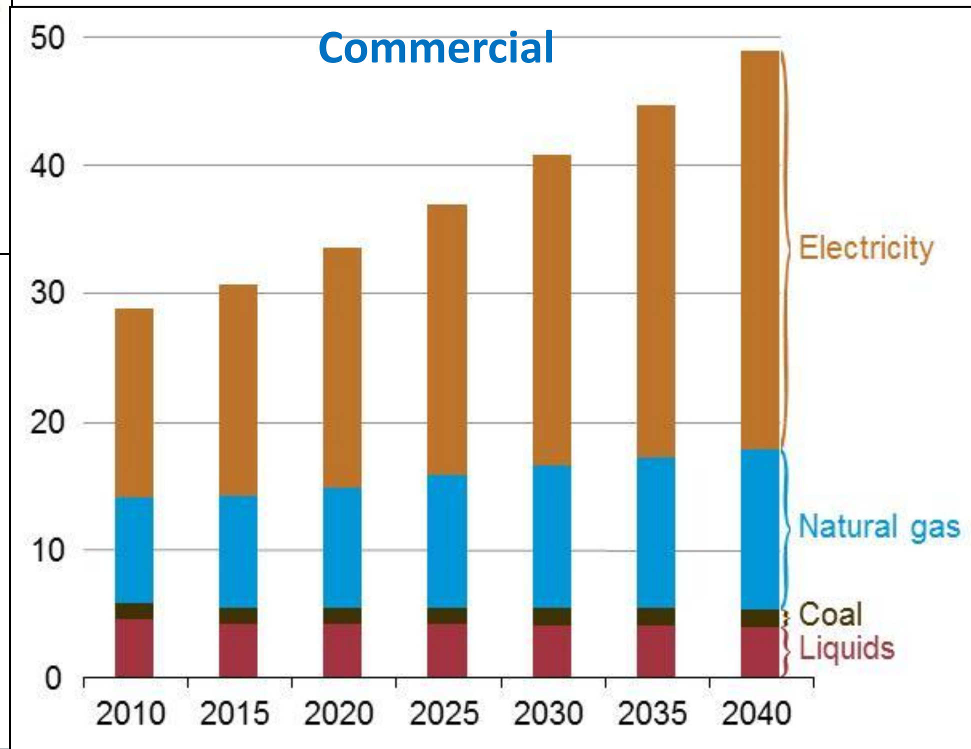
Variation (2010-40):

Liquids	-1.0 %
Nuclear	2.5%
Natural Gas	2.5%
Renewables	2.8%
Coal	1.8%
WORLD	**2.2%**

Source: DoE/EIA-0484

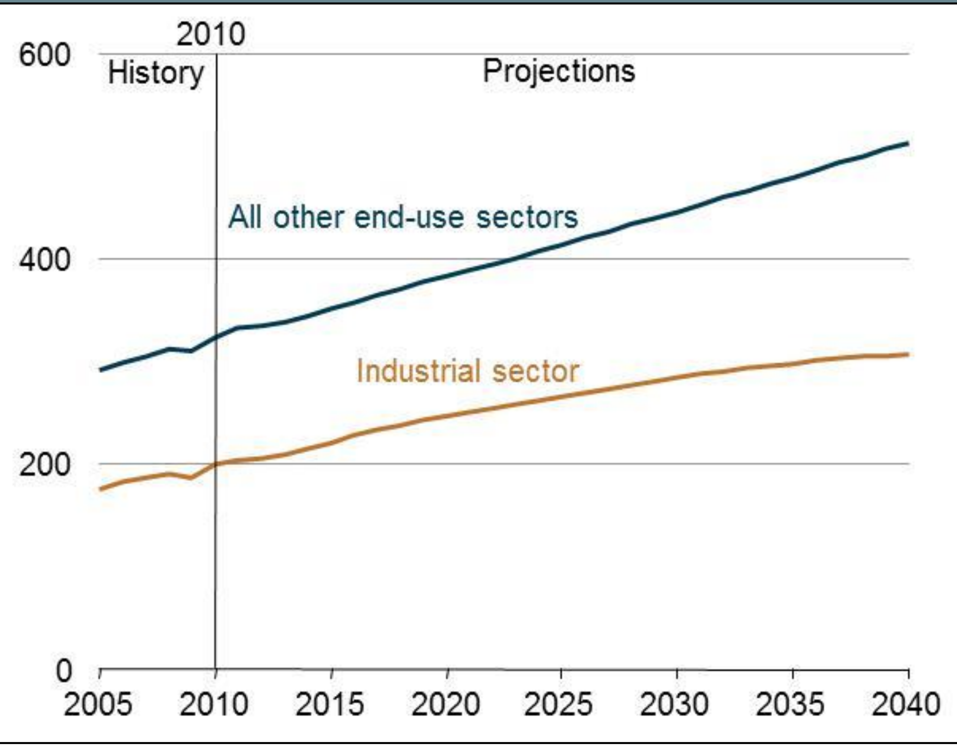
World Residential/Commercial Consumption (10^{15} BTU)

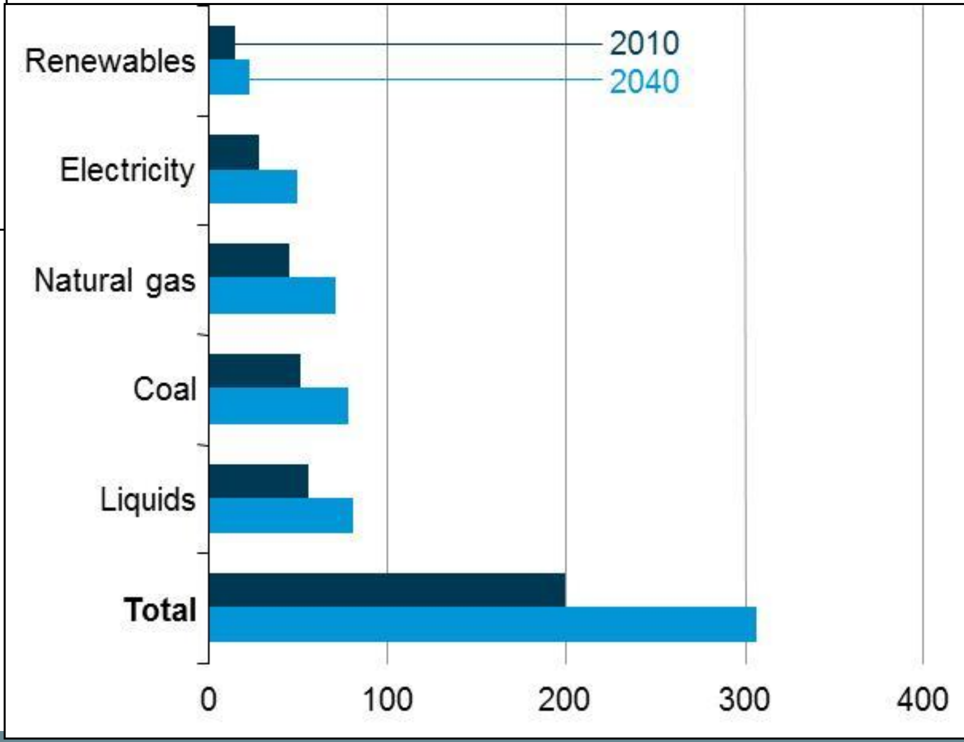




Source: DoE/EIA-0484

World Industrial Sector Consumption (10^{15} BTU)





Source: DoE/EIA-0484

Energy Consumption: Transport Sector (10^{15} BTU)

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Region	2010	2015	2020	2030	2040	Aver. Annual % change
OECD	**57.9**	**56.0**	**55.9**	**54.5**	**55.5**	**-0.1**
Americas	32.7	32.5	32.5	31.7	32.9	0.0
Europe	18	16.3	16.2	15.7	15.7	-0.5
Asia	7.1	7.2	7.1	7.0	7	-0.1
Non-OECD	**43.1**	**50.3**	**56.4**	**68.3**	**83.9**	**2.2**
Europe and Euroasia	6.7	8.0	8.5	9.5	10.6	1.5
Asia	19.9	23.5	28.0	37.0	49.2	3.1
Middle-East	6	7.4	8.1	8.6	9.5	1.5
Africa	3.8	4.0	4.1	4.5	4.8	0.8
Central and South America	6.6	7.3	7.7	8.8	9.8	1.3
TOTAL	**101.0**	**106.2**	**112.2**	**122.8**	**139.5**	**1.1**

Energy used to move people and goods by road, rail, air, water and pipeline.

Source: DoE/EIA-0484

World liquid consumption (10^{15} BTU)

- Petroleum and other liquid fuels are the main component of energy sector energy;
- Transport accounts for 63% of total growth in energy consumption over 2010-40;
- Transport Sector (2010-40): **+36x10^{15} BTU**;
- Industry Sector (2010-40): **+25x10^{15} BTU**;

Source: DoE/EIA-0484

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10 Largest Power Plants of the World (2011)

Rank	Plant	Country	Capacity (MW_{el})	Aver. Annual Elect. Gen. (TWh)	Plant Type
1	3-Gorges Dam	China	22500	98.1	Hydro
2	Itaipu Dam	Brazil/Paraguay	14000	98.2	Hydro
3	Guri Dam	Venezuela	10235	53.41	Hydro
4	Tucurui Dam	Brazil	8370	21.4	Hydro
5	Kashiwaazaki-Kariwa NPP	Japan	8212	24.63	Nuclear
6	Grand Coulee Dam	USA	6809	21	Hydro
7	Longtan Dam	China	6426	18.7	Hydro
8	Bruce NPP	Canada	6272	36.25	Nuclear
9	Uljin NPP	South Korea	6157	44.81	Nuclear
10	Yeonggwang NPP	South Korea	6139	48.16	Nuclear

Wikipedia

Largest Power Plants by Energy Source (2011)

Rank	Plant	Country	Capacity (MW_{el})	Plant Type
1	3-Gorges Dam	China	22500	Hydro
2	**Kashiwaazaki-Kariwa NPP**	**Japan**	**8212**	**Nuclear**
3	Taichung Power Plant	Taiwan	5780	Coal
4	Shoaiba Power Plant	Saudi Arabia	5600	Fuel Oil
5	Surgut-2 Power Plant	Russia	5597	Natural Gas
6	Eesti Power Plant	Estonia	1615	Oil Shale
7	Shatura Power Plant	Russia	1500	Peat
8	Alta Wind Energy Center	USA	1020	Wind (onshore)
9	Tilbury B Power Station	UK	750	Biofuel
10	Hellisheioi Power Station	Iceland	303	Geothermal
11	Sihwa Lake Tidal Power Station	South Korea	254	Tidal
12	Agua Calient Solar Project	USA	251	Solar
13	Agucadora Wave Farm	Portugal	2	Marine (wave)

Wikipedia

Energy Mix in UK

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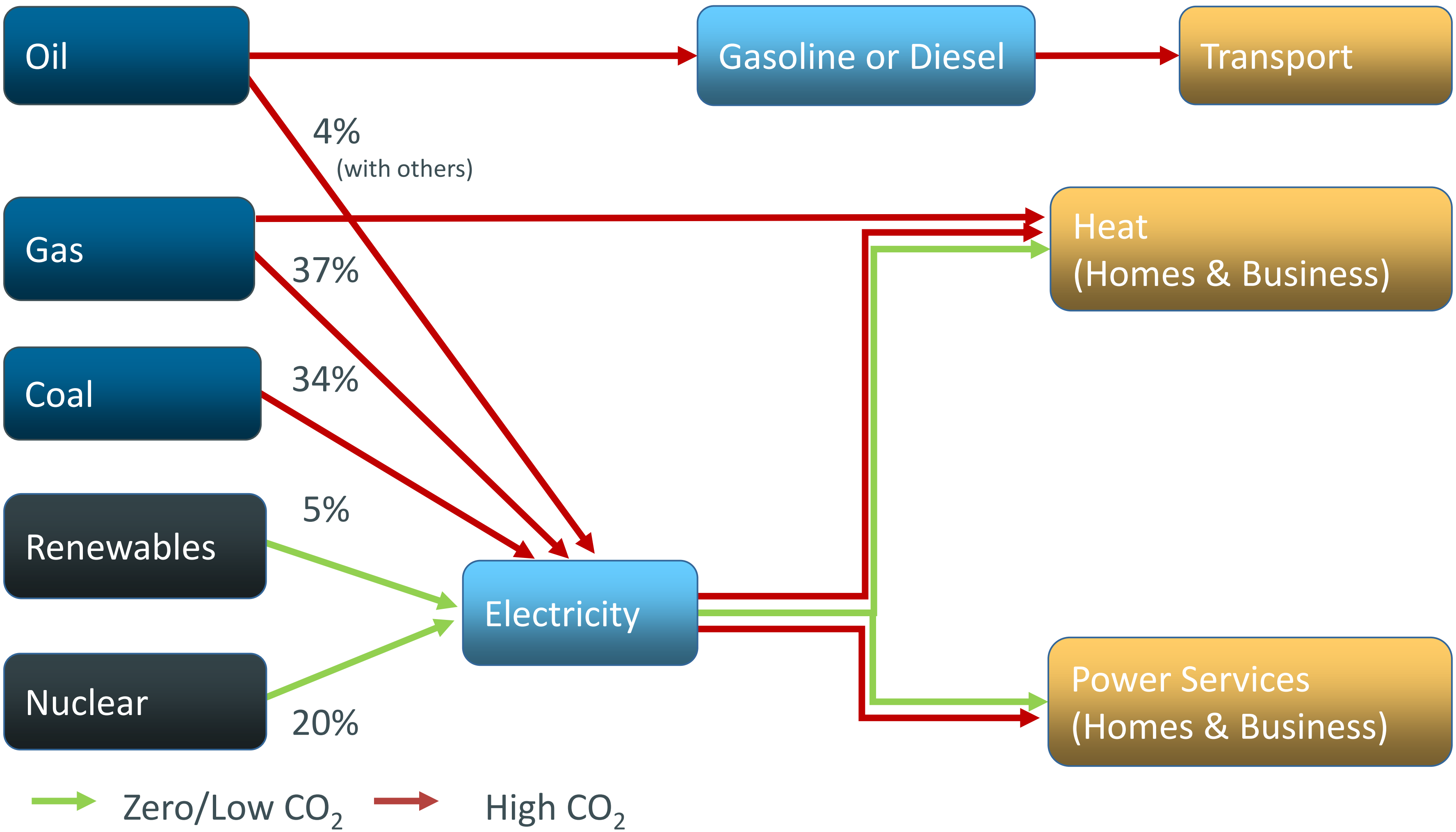
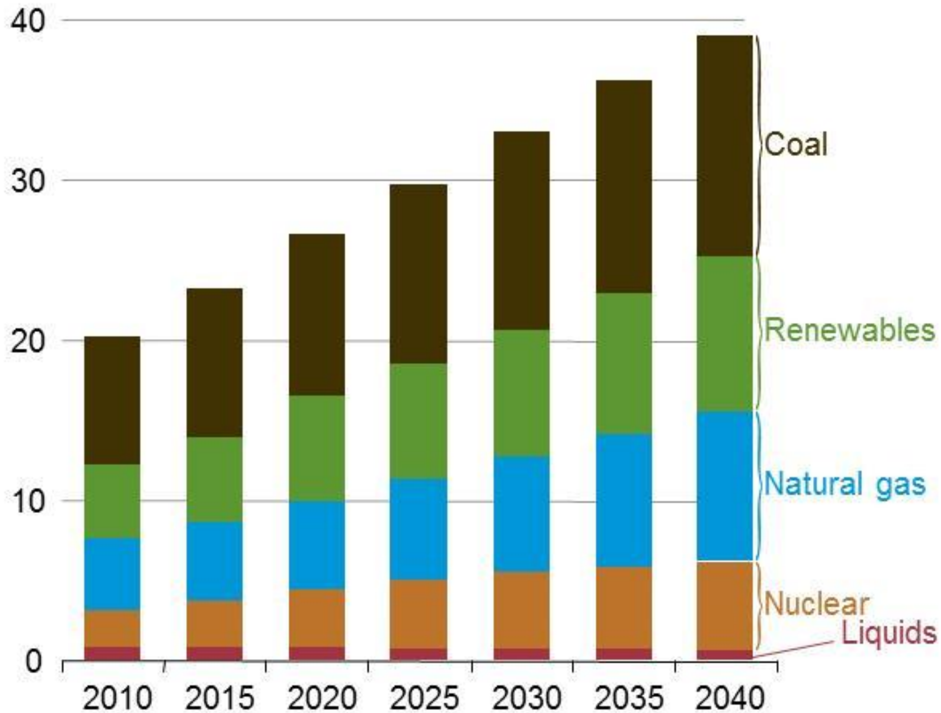
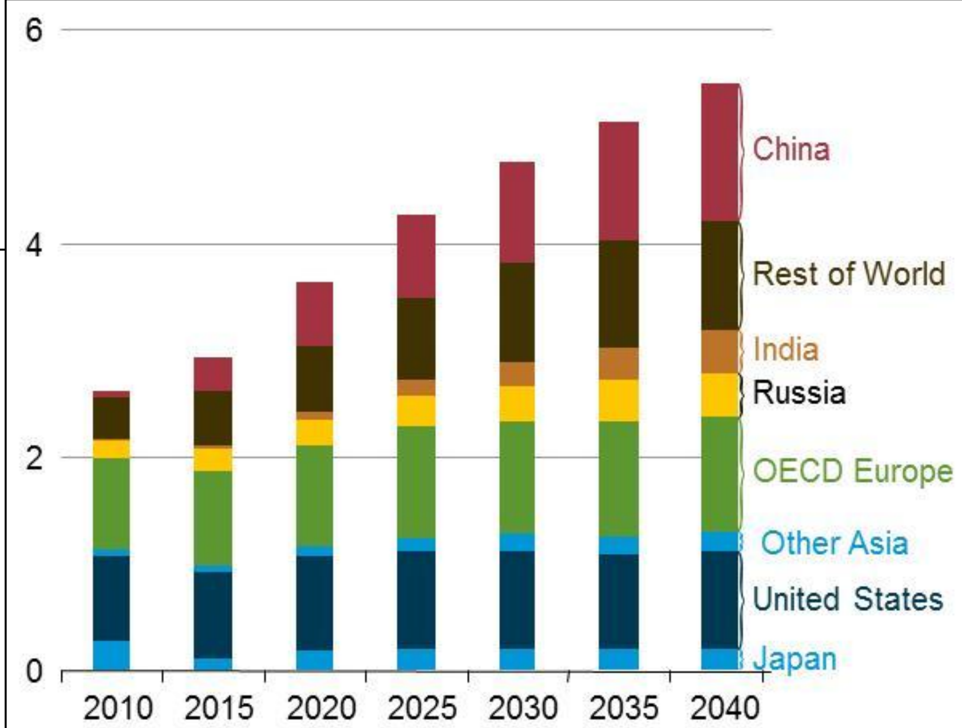


Nuclear Energy Consumption in Perspective



World electricity generation
(10^{12} kWh)

World net electricity generation from nuclear
(10^{12} kWh)



Source: DoE/EIA-0484

World Energy-related CO_2 Emissions (in billion metric tons)

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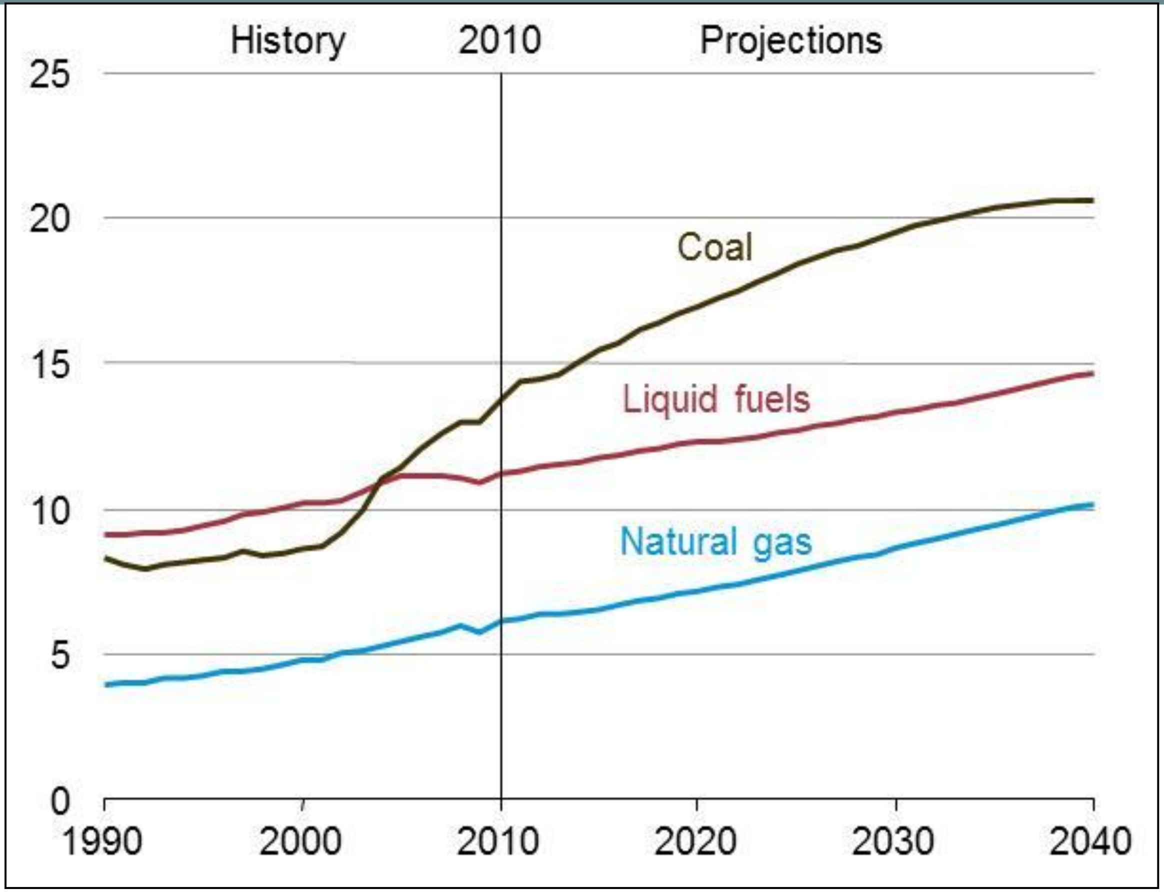
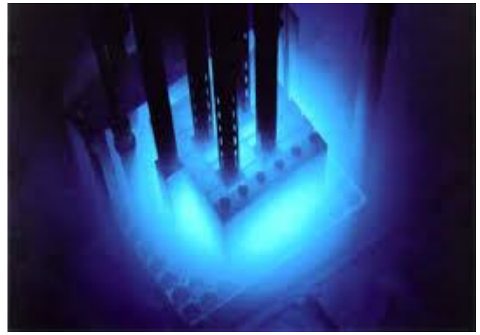


Source: DoE/EIA-0484

1 cubic ton =40 cubic feet = 1.133 cubic meters

- Increase of coal power stations → Increase coal consumption → more GHC (Greenhouse gases);
- Growth in consumption of liquid fuels and natural/shale gas over the next 30 years;
- Solar, wind, biomass (renewables) will benefit from intensive R&D and will continue to grow, but;
- Solar and wind: unlikely to produce more than 25% of world demand of electricity by 2050.

Nuclear Energy: Fundamental Physics

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Why Nuclear ??

- To address **CLIMATE CHANGE** we must:
  - ✓ improve efficiency and;
  - ✓ reduce use of fossil fuel-based energy source.
- GHG emissions should be mitigated by the development of new cost-effective technologies:
  - ✓ Carbon Capture Storage and Transportation (CCST);
  - ✓ Nuclear → Management of nuclear waste storage;
  - ✓ Low-carbon energy sources (wind, solar, maritime etc);
  - ✓ Integrated Gasification Combined Cycle (IGCC):
    - Converting carbon-based fuels into syngas (gas-synthesis - mainly H_2, CO);
    - Combined steam (e.g., Rankine) and gas (e.g., Brayton) cycles using advanced turbines with high thermal efficiency;
- Energy security: some countries do not have fossil-fuel resources to sustain their economies.

How Nuclear Works? Chain Reactions!

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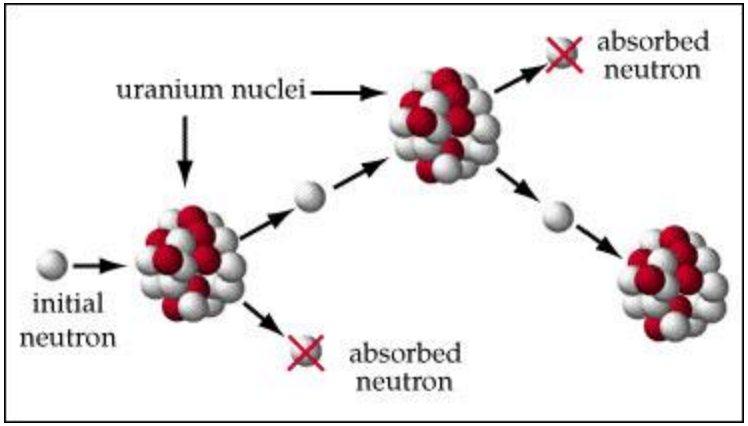
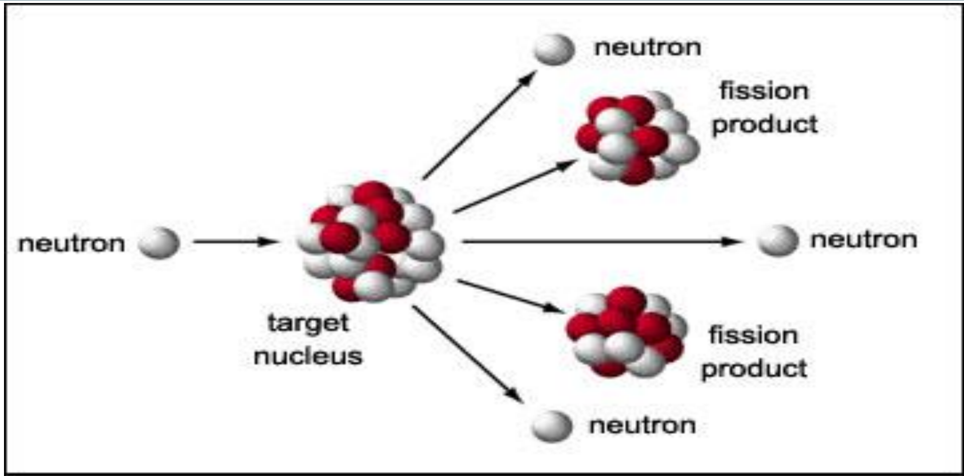
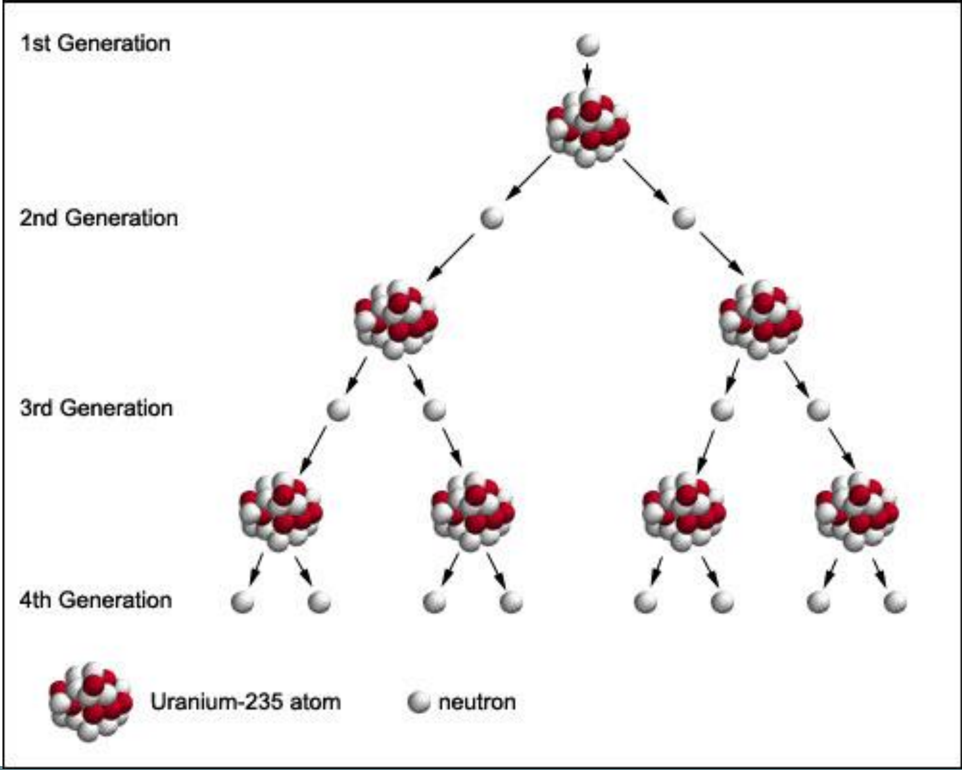
- When a relatively large fissile atomic nucleus (e.g., U^{235}) absorbs a neutron ($\bar{n}$);
- It splits into 2 or more lighter nuclei releasing fission products:
  - Kinetic energy;
  - Gamma radiation and ;
  - Free neutrons ($\nu\bar{n}$) that
- Will continue the reaction, i.e., a chain reaction (also called criticality event or excursion).

$$1\bar{n} + U^{235} \rightarrow U^{236} \rightarrow \begin{cases} Ba^{141} \\ Kr^{92} \end{cases} + Energy + \nu\,\bar{n}$$







How Power Plants Work? Heat Sources!

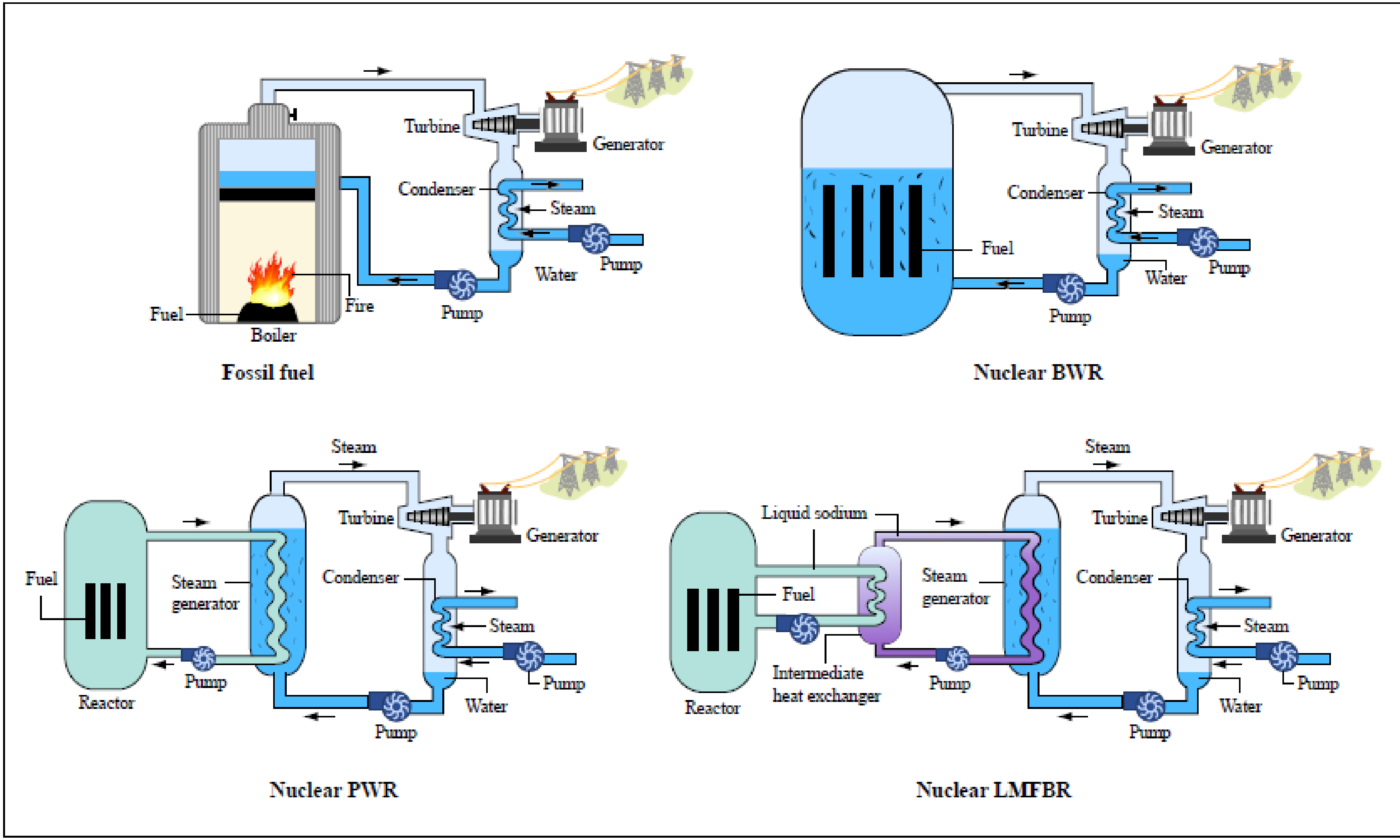


Image by MIT OpenCourseWare.

How Power Plants Work? Heat Sources!

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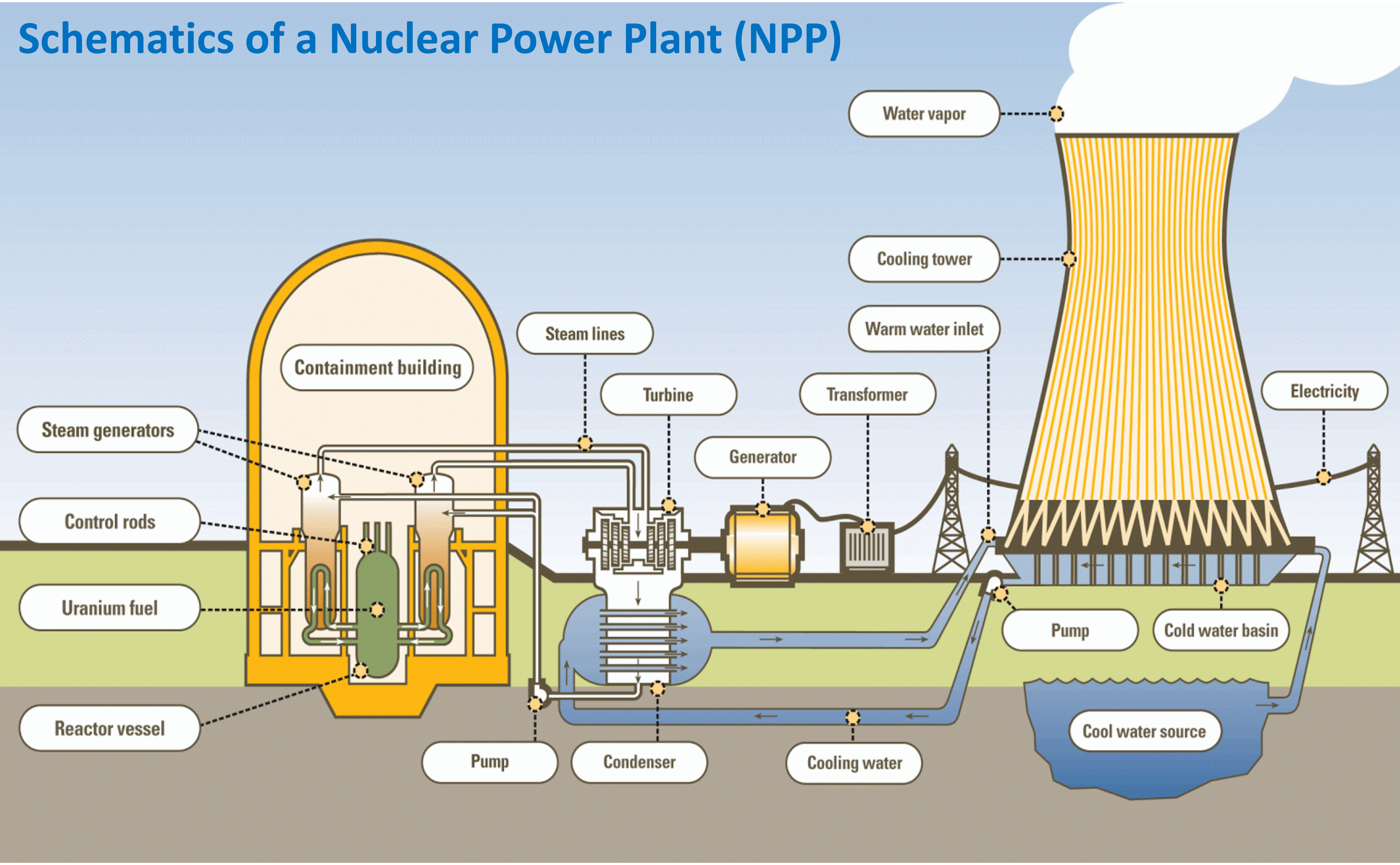
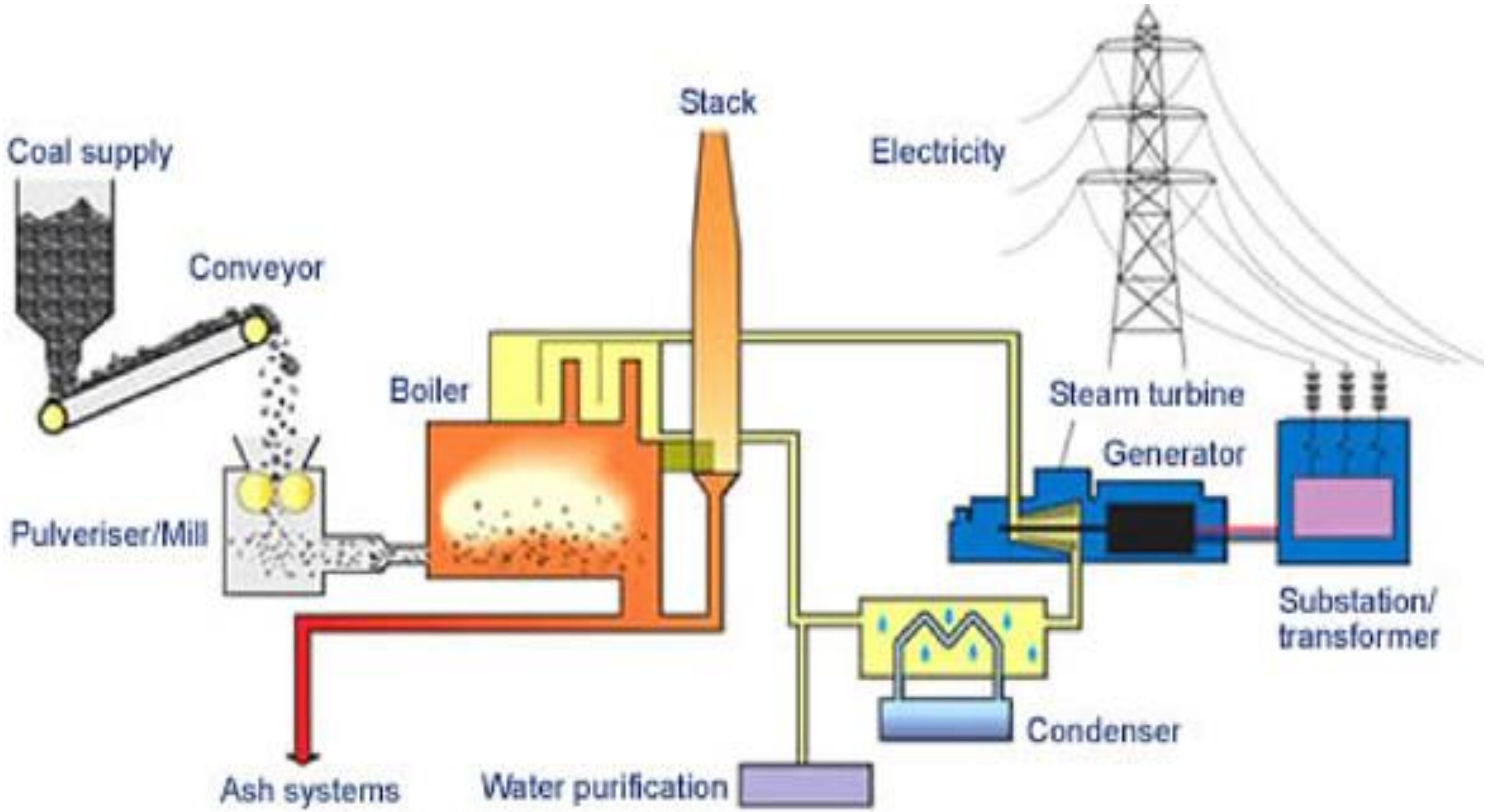
Schematics of a Nuclear Power Plant (NPP)



Schematics of a Coal-Fired Power Station



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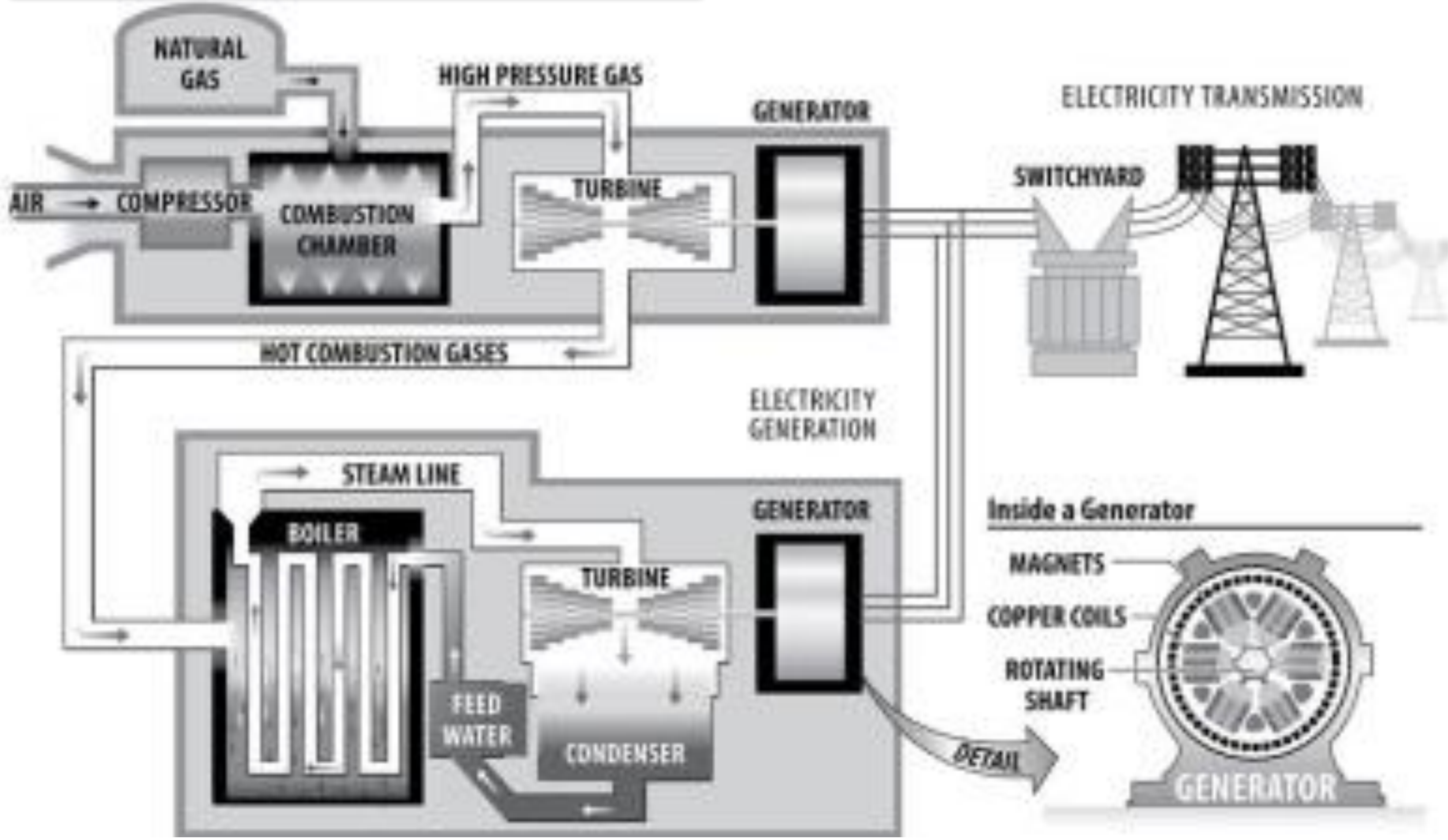
Natural Gas Power Plant



Combined Thermodynamic Gas- and Steam-Turbines Cycles

How Power Plants Work? Heat Sources!

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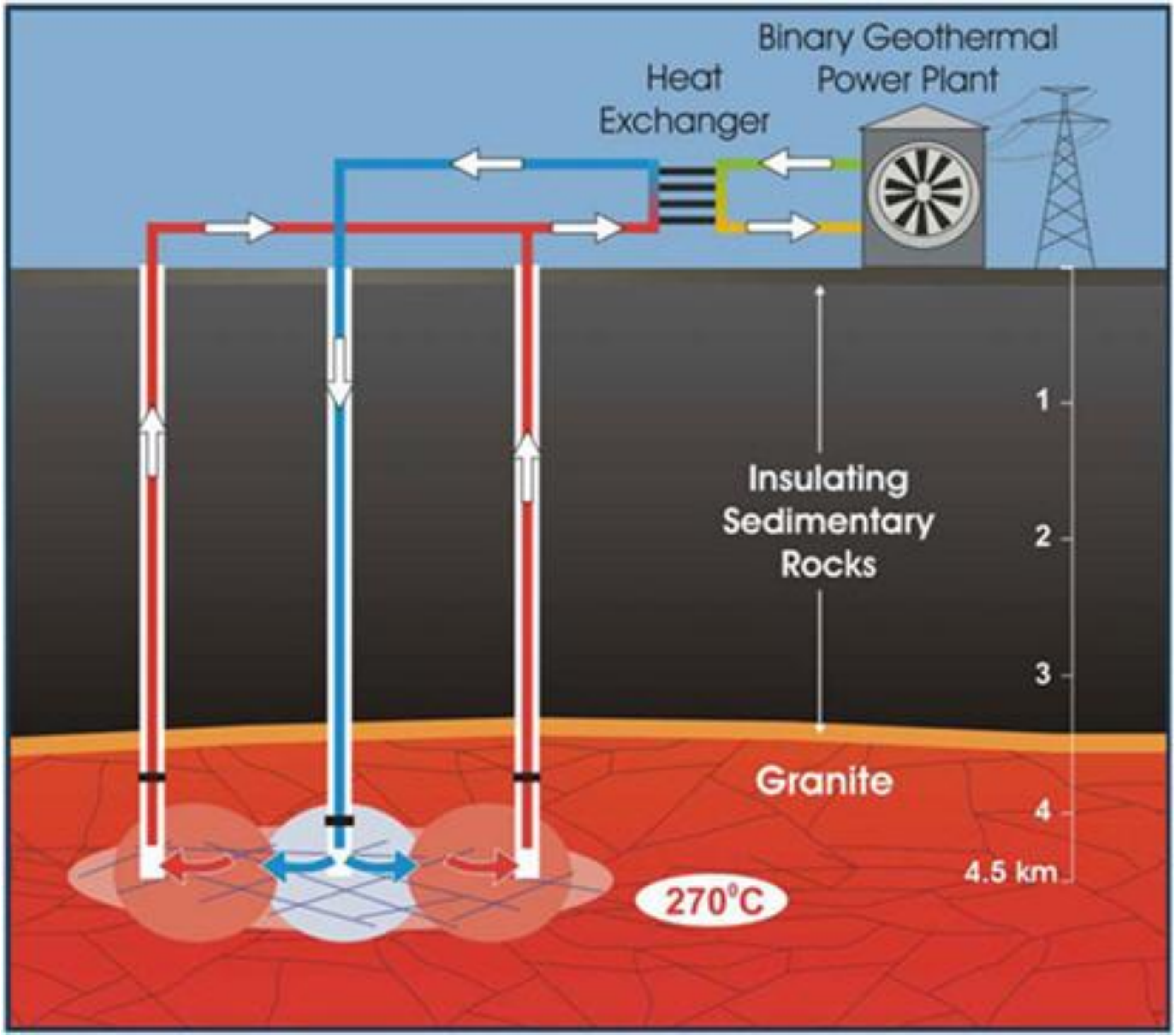
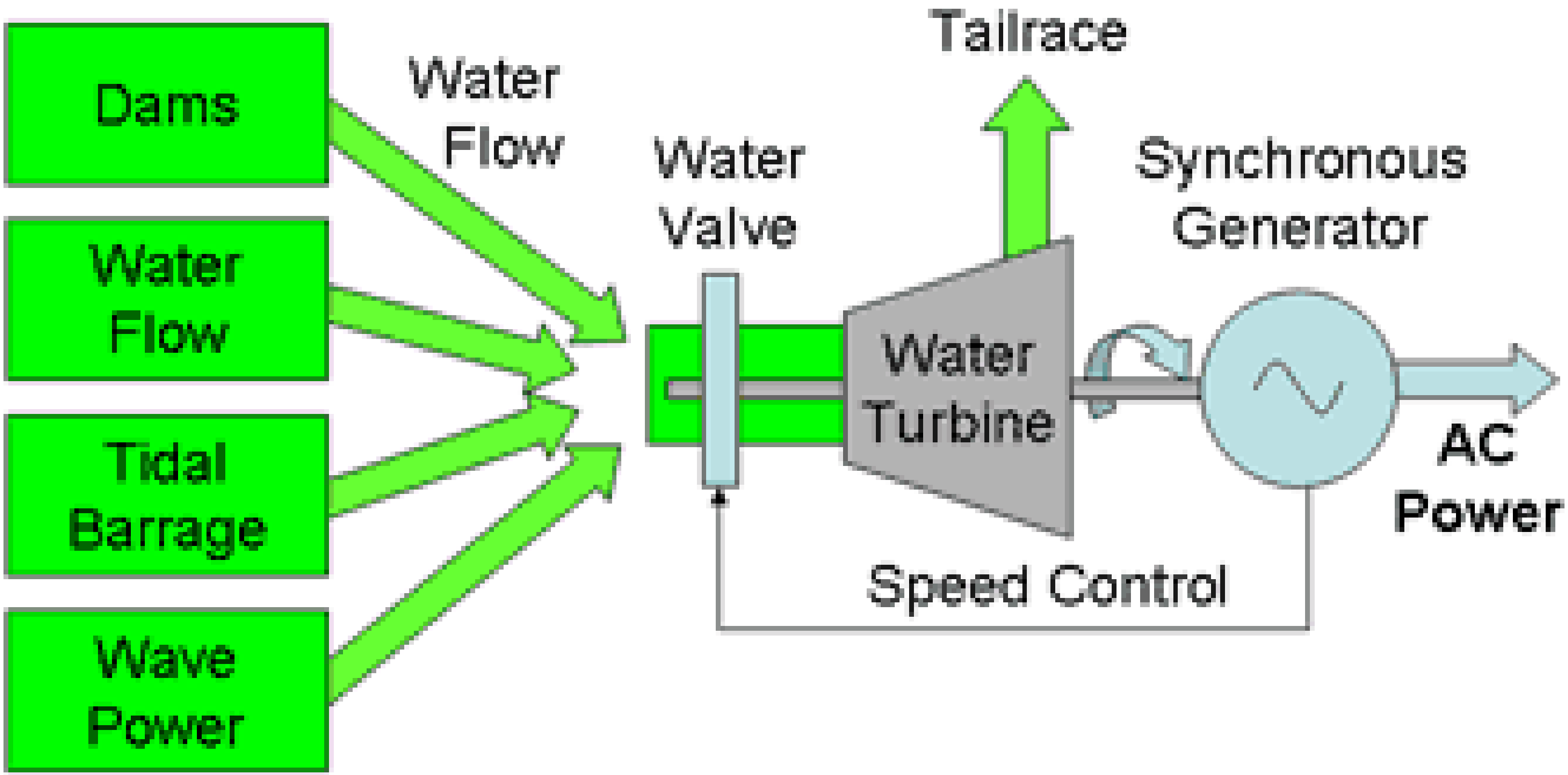
Geothermal Power Plant

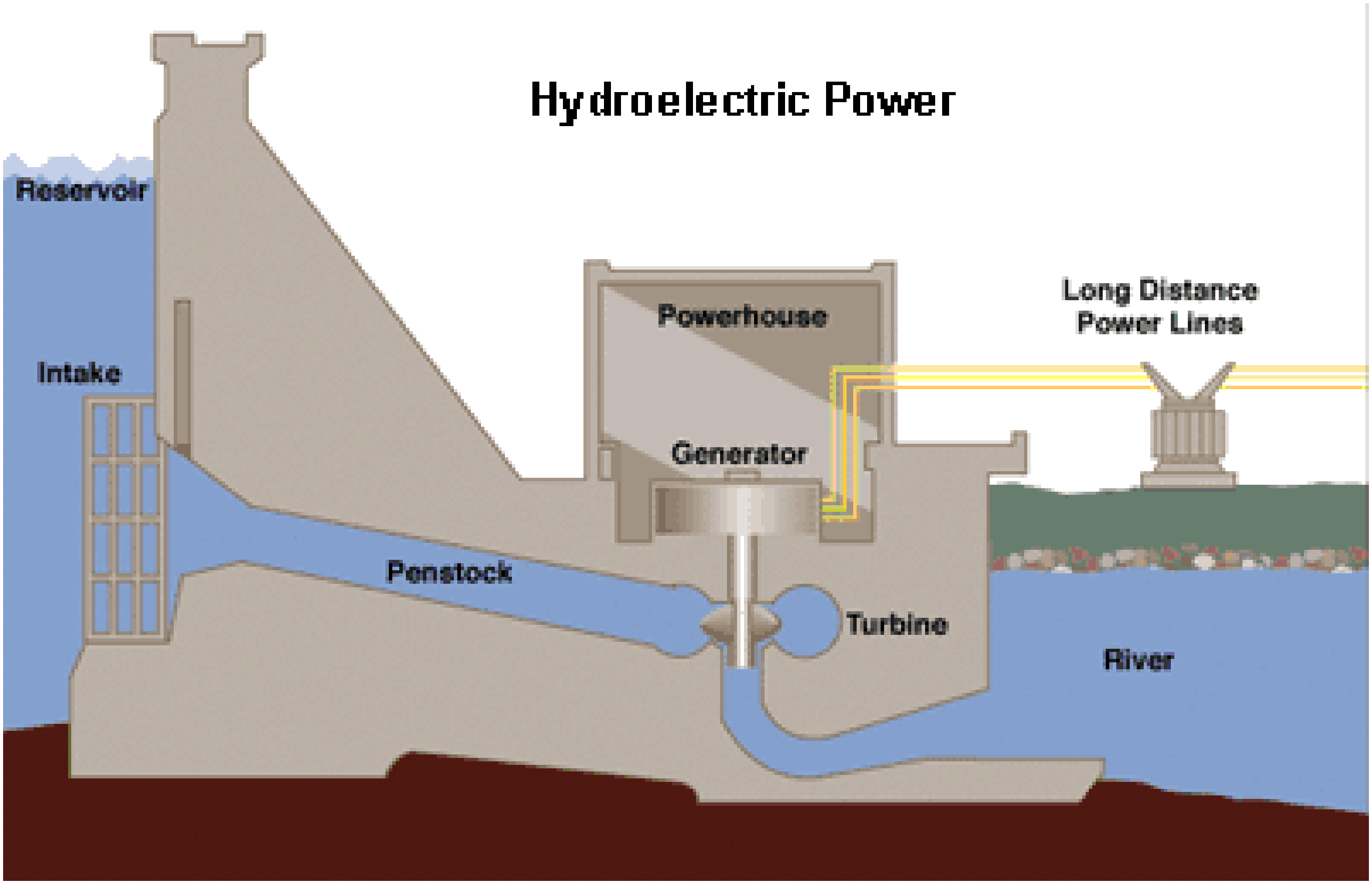


How Power Plants Work? Momentum Sources!



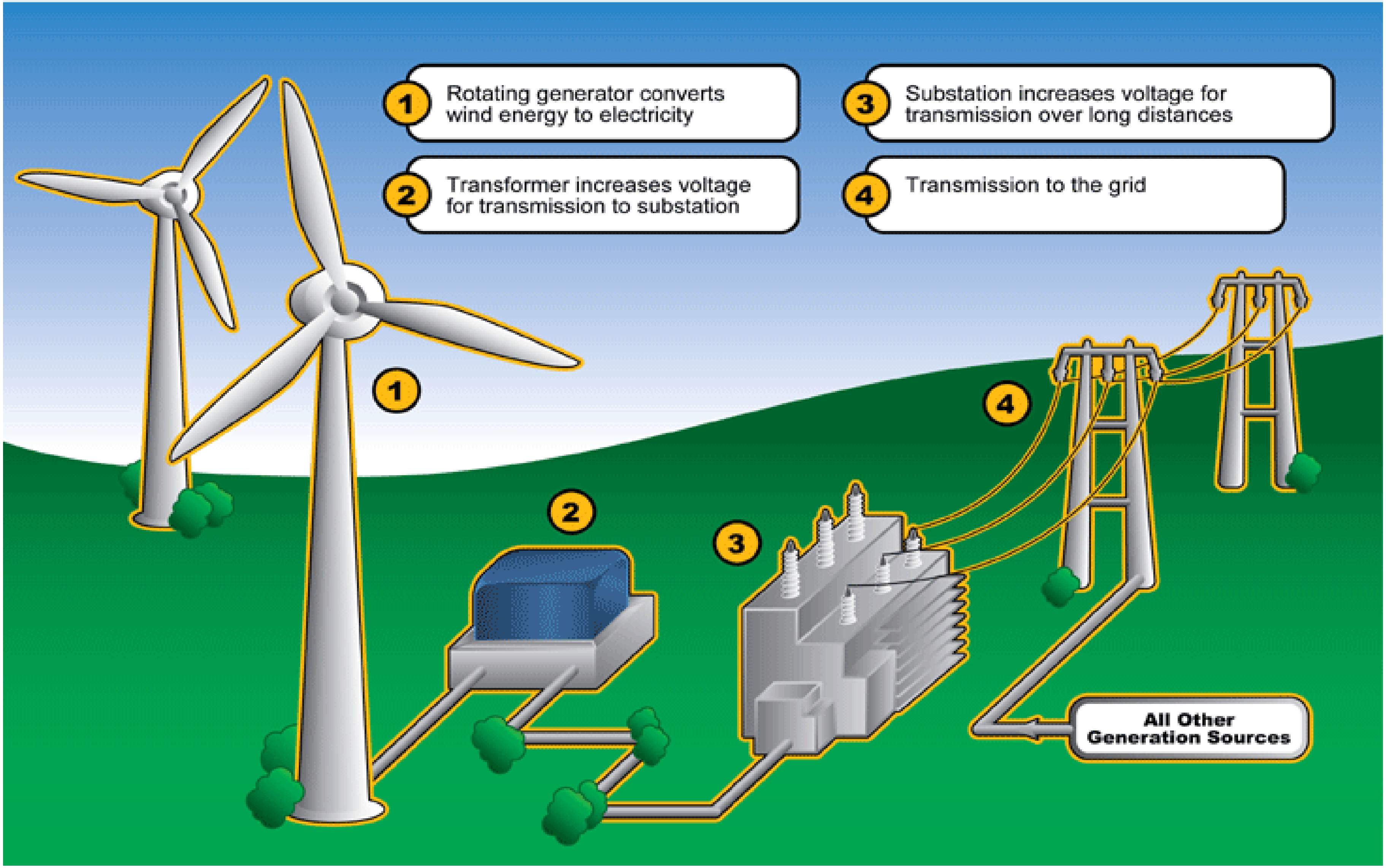
Hydro Electric Power Generation

How Power Plants Work? Momentum Sources!

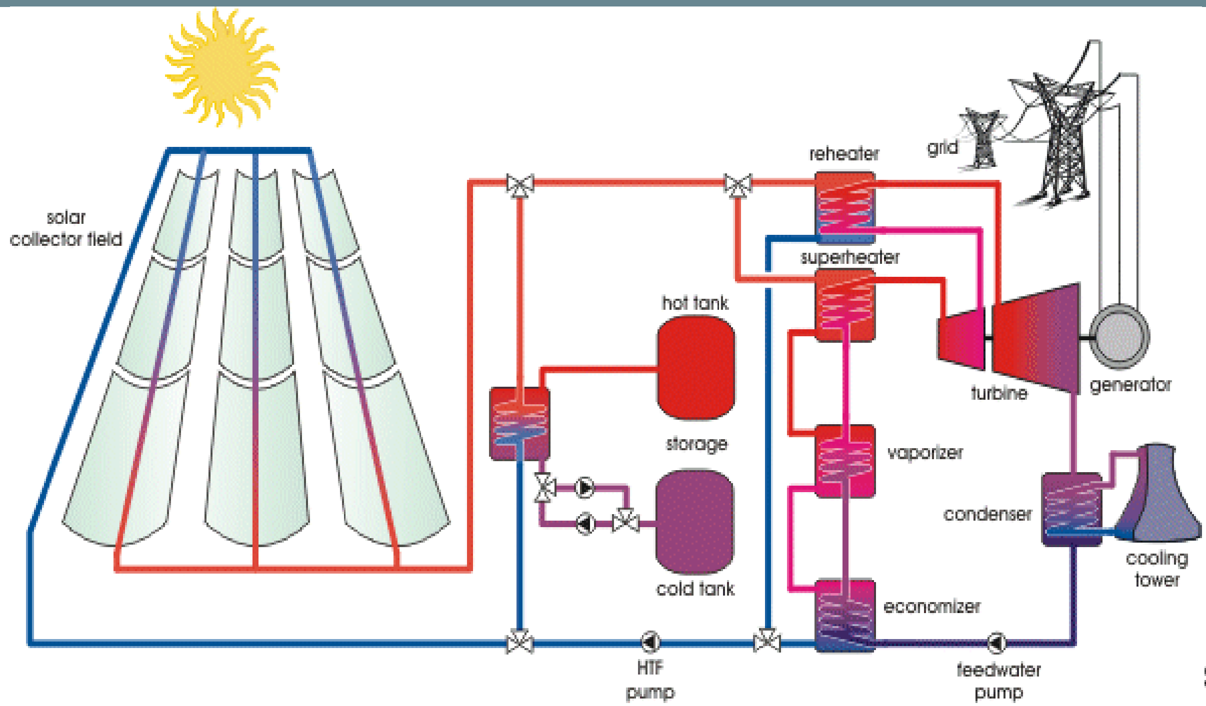


How Power Plants Work? Momentum Sources!

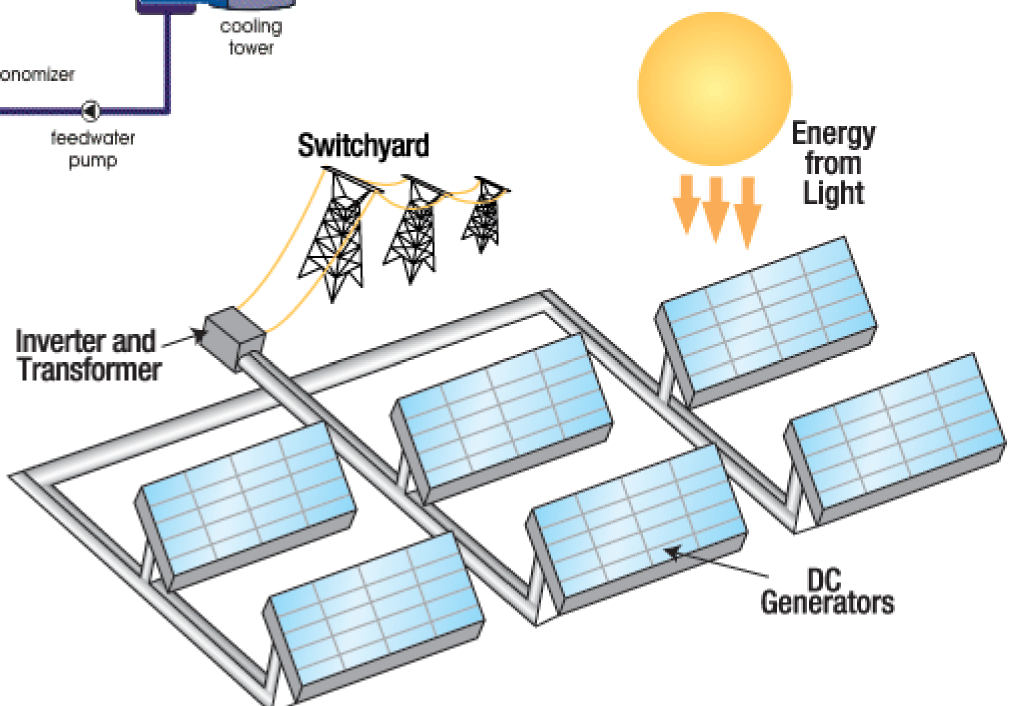
WIND



How Power Plants Work? And Solar?



- Heat Source: thermal radiation to boil water or;



- Photovoltaic (solar cells): direct conversion of the electromagnetic radiation from the Sun to electricity.

How Power Plants Work?

- The vast majority of power plants work based on elements of the following workflow:
  1. Generate heat;
  2. Boil water;
  3. Produced steam is used to turn a (set of) turbine(s);
  4. Turbines are linked with generator to;
  5. Produce electricity.
- We saw that:
  - Fossil fuels and nuclear: 1-5;
  - Hydro and wind: based on momentum transfer + 4-5;
  - Geothermal: undergrounded heated water + 2-5;
  - Solar: Either (a) solar radiation + 2-5 or photovoltaic cells + 5.

How Power Plants Work?

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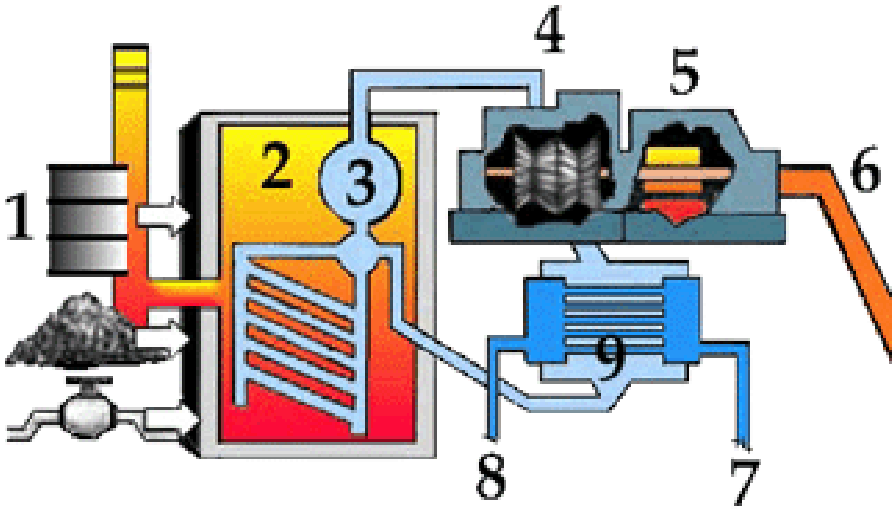
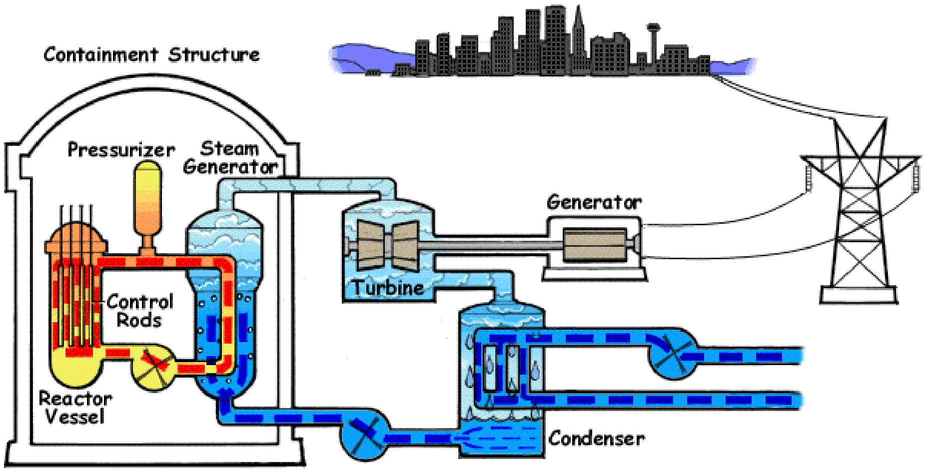
1. Energy Source (coal, oil, NG, nuclear, etc) is 'burnt' generating heat in the;
2. Boiler. Heat is transferred into the water-steam cycle (3-4-9-3);
3. Steam (at high temperature and pressure) produced by the water vaporisation is driven towards a;
4. Steam turbine that promotes an isentropic expansion and produces **work**;
5. The **work** is transferred to a generator responsible to produce;
6. Electricity that is linked to the power grid;
7. After the expansion (in the turbine), steam (low temperature and pressure) is driven into the condenser (9), where it is transformed in water and returns to the Boiler (2);

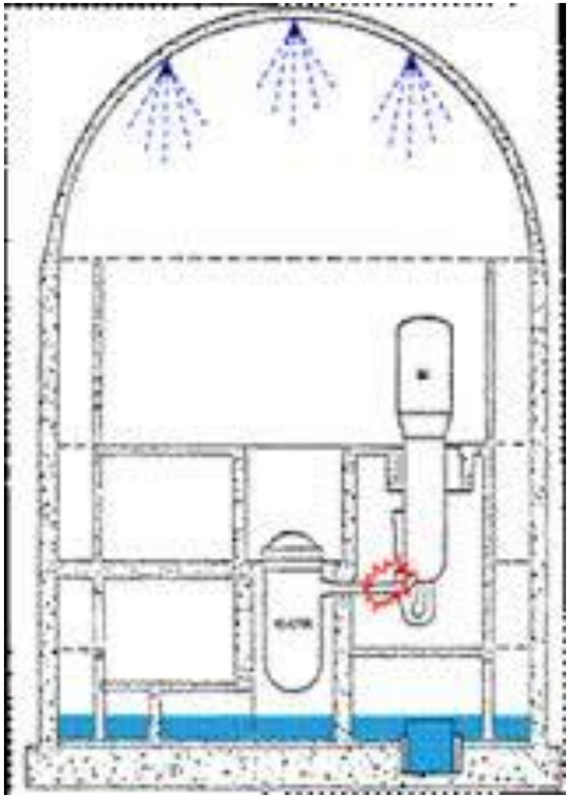


- System 7-8-9 comprises condenser and cooling waste water.

Nuclear Power Plants (NPP)

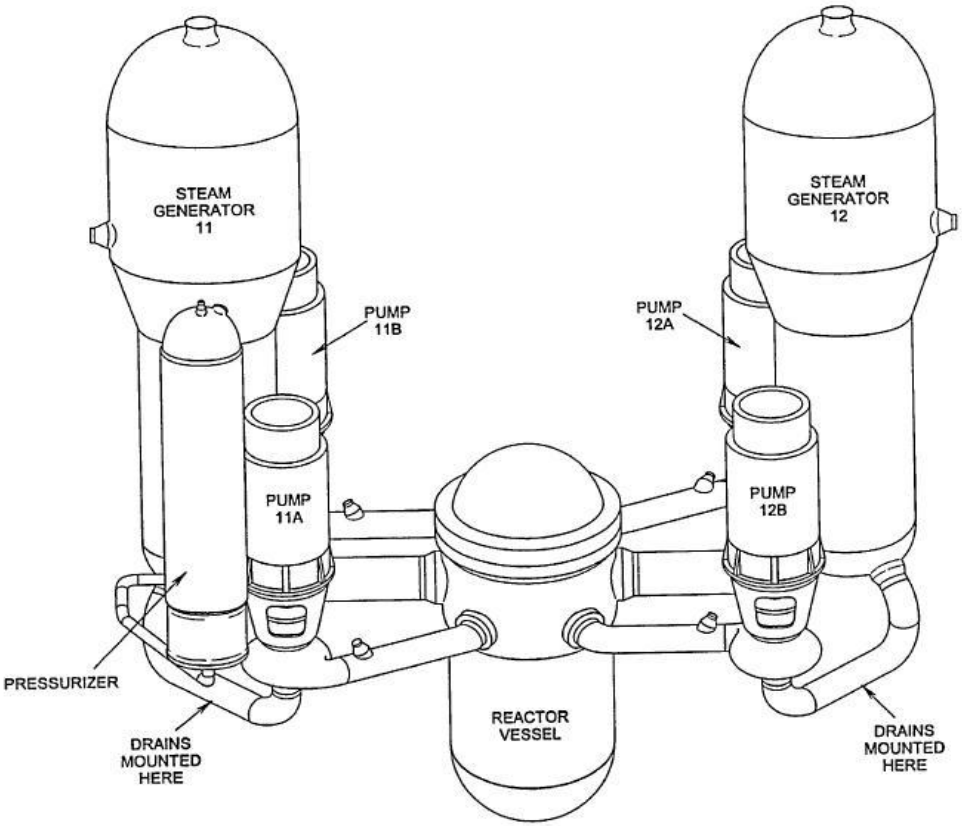


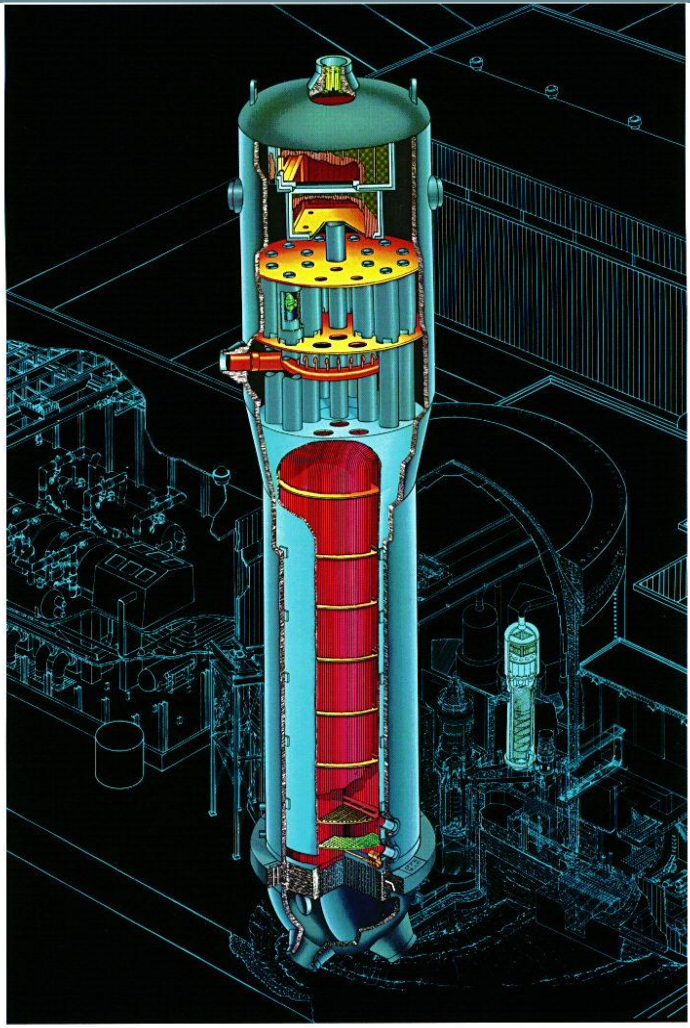
Nuclear Power Plants: Containment Building



- Structure around the reactor core designed to protect from outside intrusion and, it is the last protection in case of accidents;
- Typically a metre-thick concrete and steel building.

Nuclear Power Plants: Steam Generator





Westinghouse STEAM GENERATOR

- Heat from the reactor is extracted through a coolant fluid (water, steam, CO_2, Helium etc);
- The coolant fluid is then used vaporise water from the external cycle (→ high pressure and temperature steam).
- The resulting steam is driven towards the turbines.

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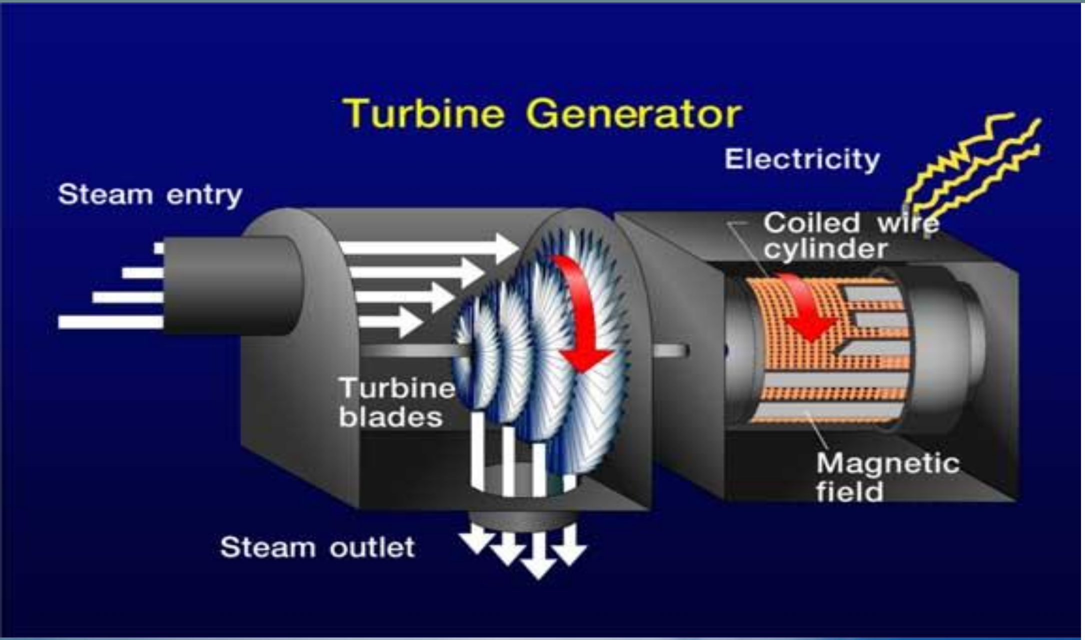
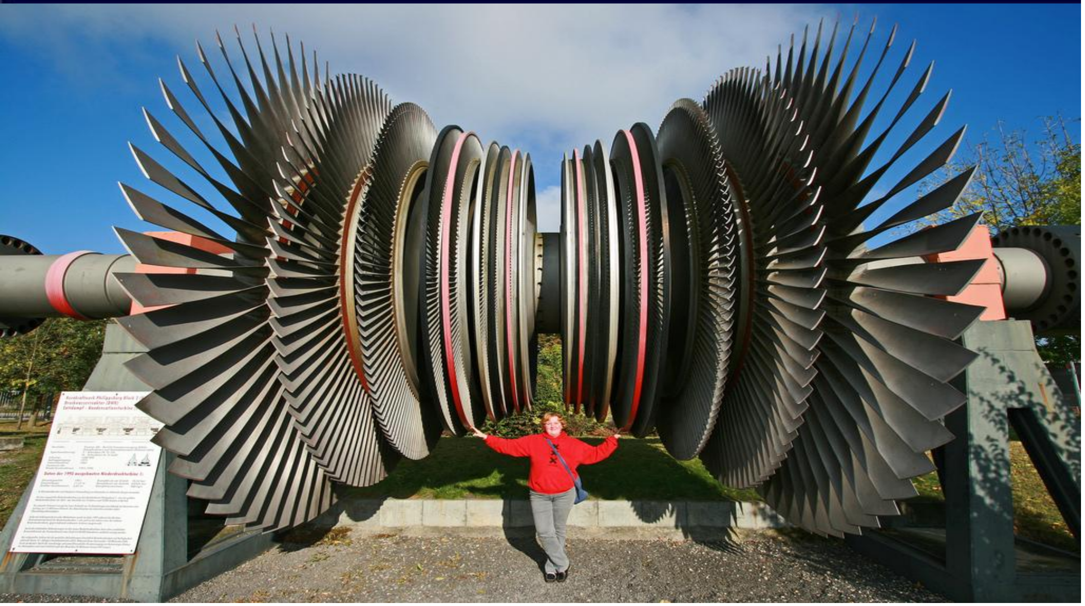
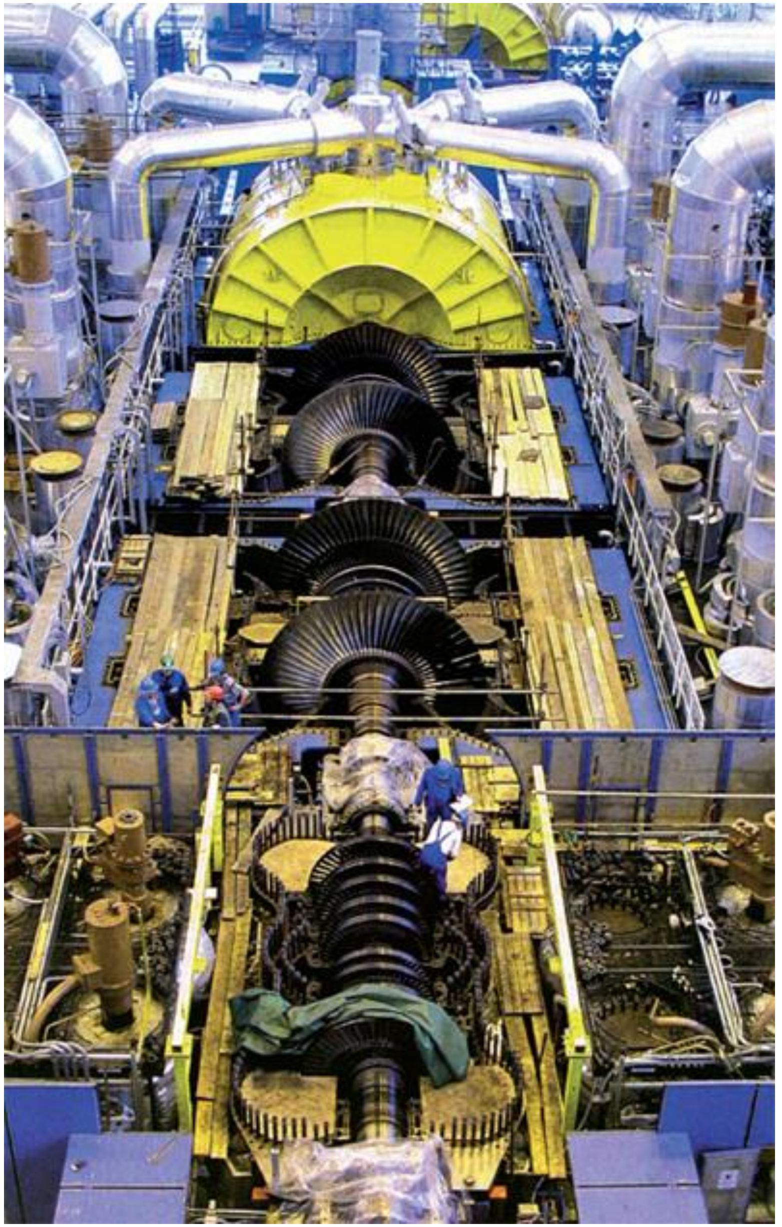
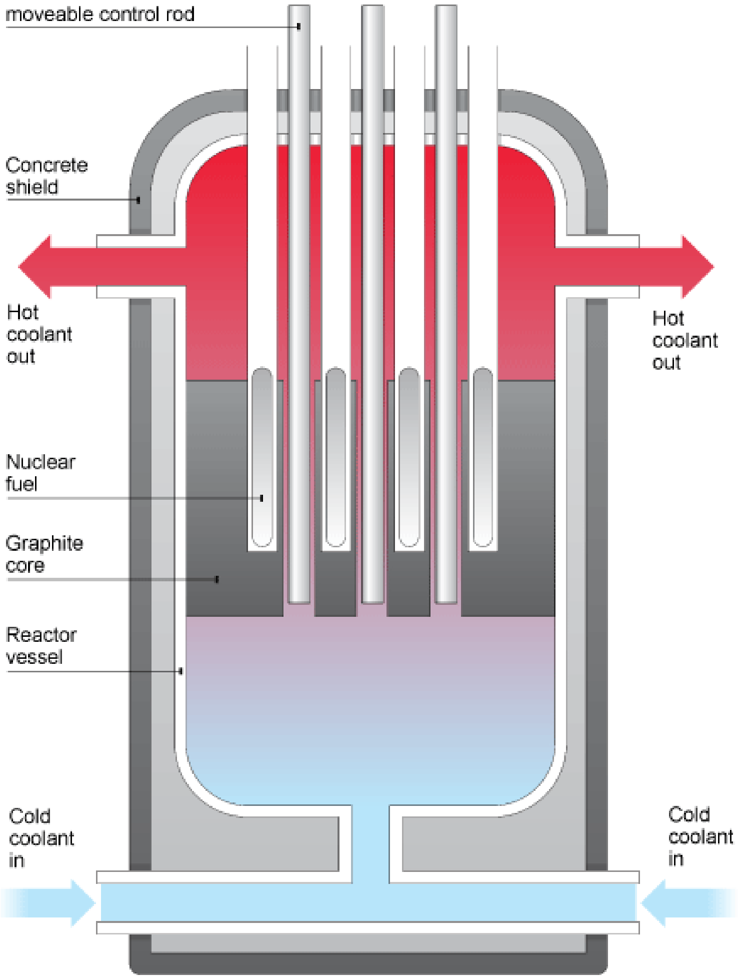
Nuclear Power Plants: Turbine & Generator



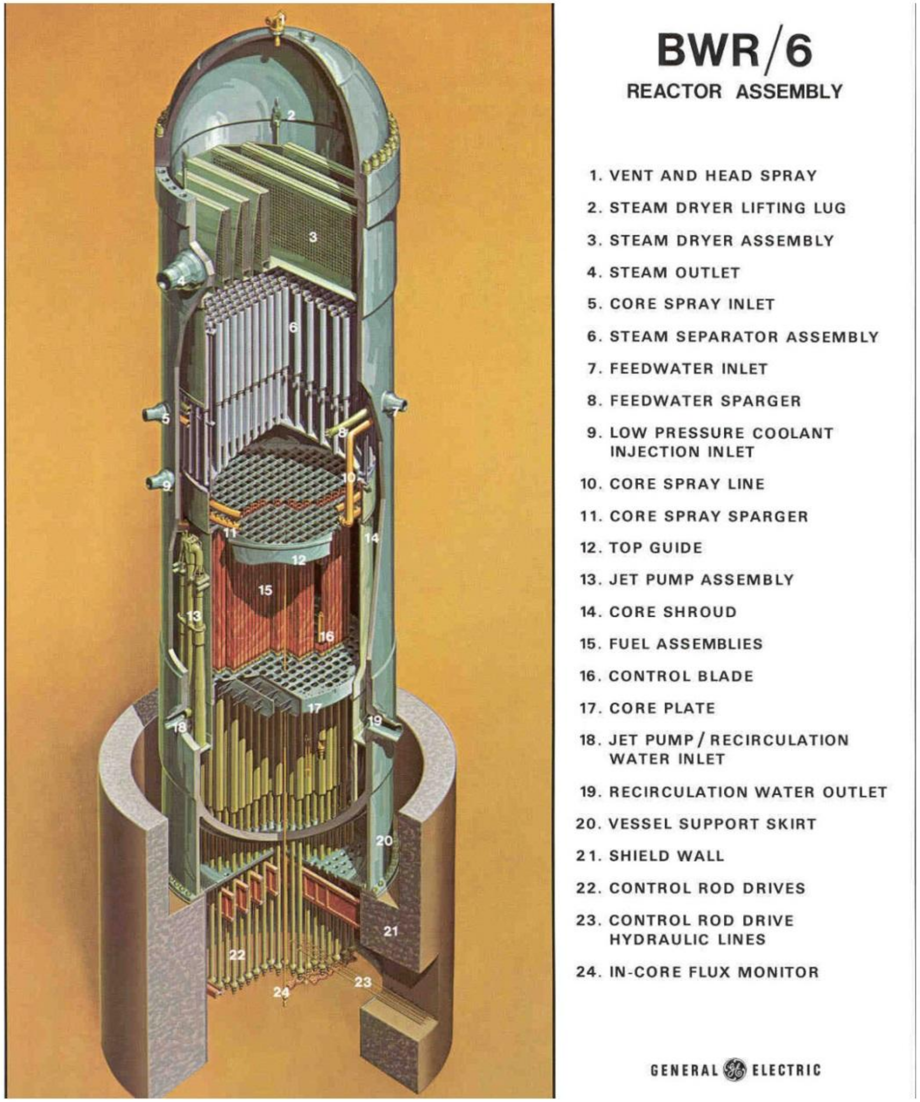




Nuclear Power Plants: Elements of the Reactor

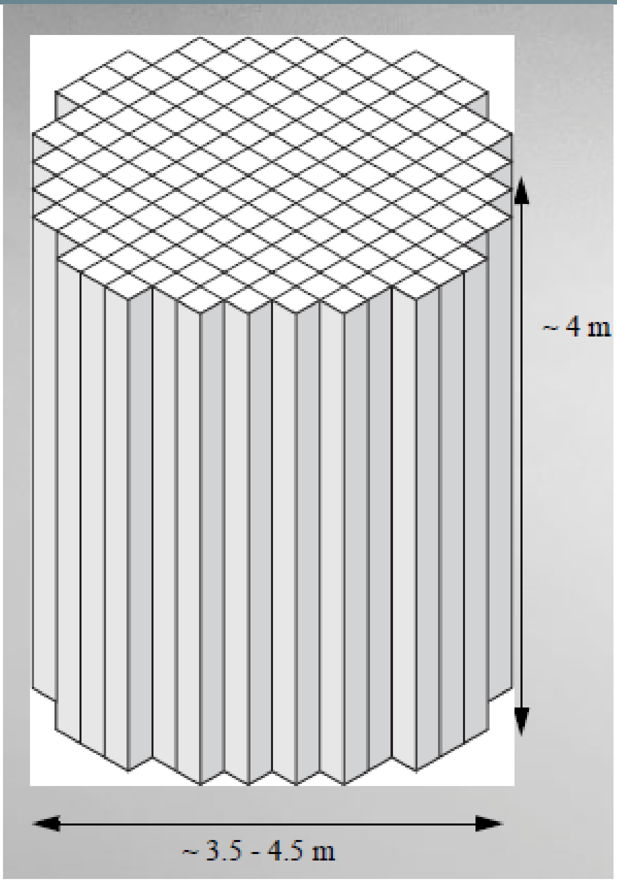


1. Nuclear Fuel
2. Graphite Core
3. Control Rods
4. Cooling Fluid Flows



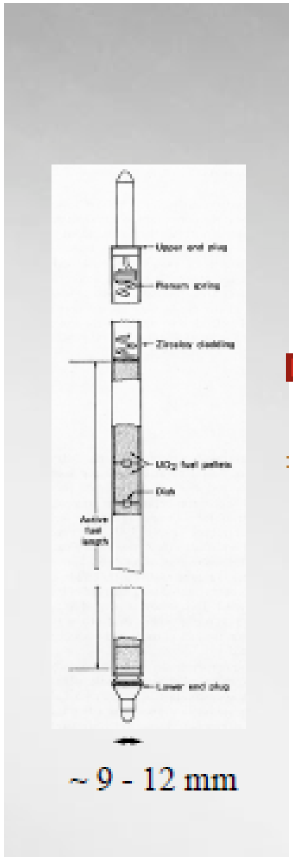
Captioned diagram of a General Electric Boiling Water Reactor presumably similar to those in the Fukushima I plant, from http://www.nrc.gov/reading-rm/basic-ref/teachers/03.pdf 2011-03-15 7:00 UTC http://www.firstpr.com.au/jncrisis/

Nuclear Power Plants: Elements of the Reactor



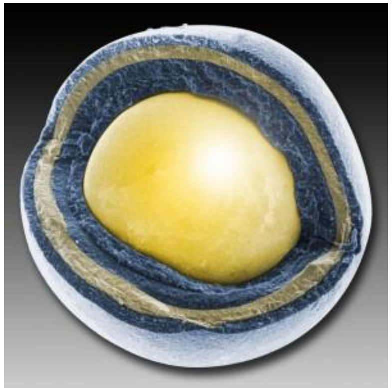
Nuclear core

Fuel assembly



Fuel rods

Fuel pellets



TRISO particles
Uranium coated with graphite): ~ 1mm

Current Commercial Nuclear Reactor Designs

- Pressurized Water Reactor (PWR)
- Boiling Water Reactor (BWR)
- Advanced Gas-Cooled Reactor (AGR)
- Pressurized Heavy Water Reactor (CANDU)
- Light Water Graphite Reactor (RBMK)
- Fast Neutron Reactor (FBR)

Current Commercial Nuclear Reactor Designs

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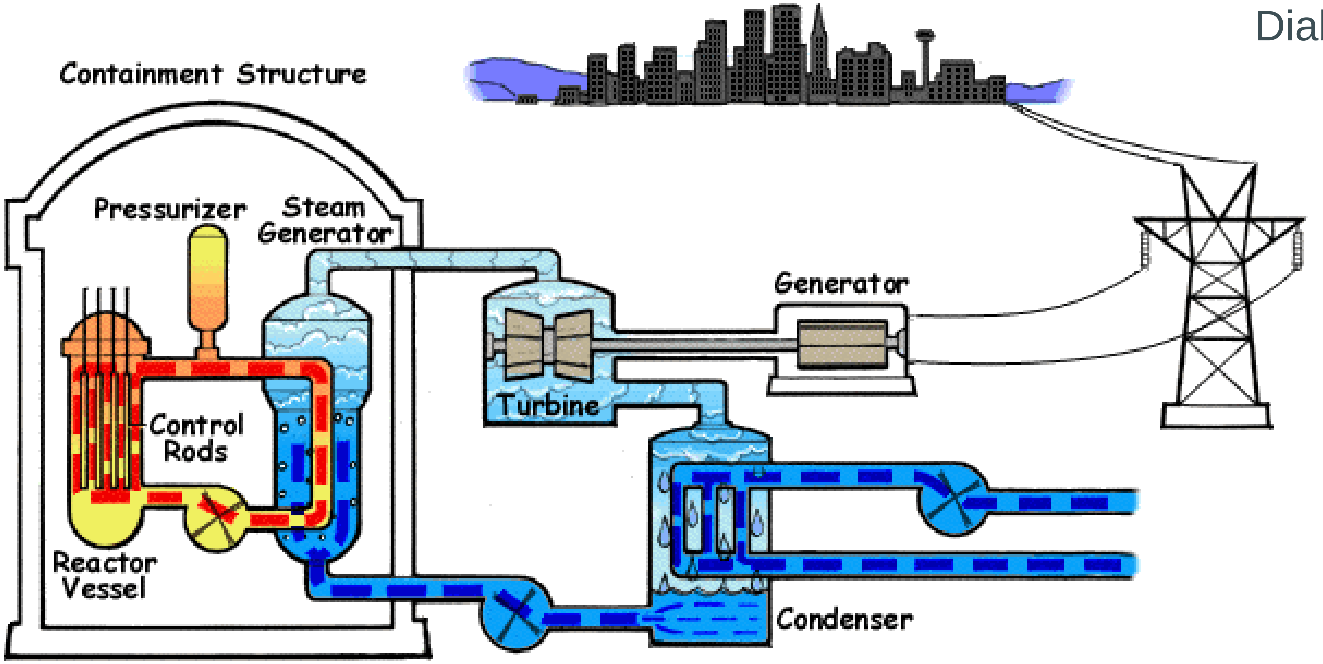
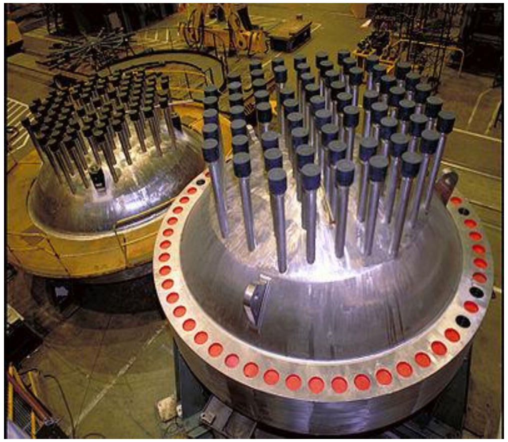
Reactor	Fuel	Moderator	Coolant
PWR	Enriched Uranium	Light water	Light water
BWR	Enriched Uranium	Light water	Light water/steam
Magnox	Natural Uranium	Graphite	CO_2 gas
AGR	Enriched Uranium	Graphite	CO_2 gas
CANDU	Natural Uranium	Heavy water	Heavy water
RBMK	Enriched Uranium	Graphite	Light water/steam
LMFBR	Highly Enriched Uranium	None	Liquid sodium

Pressurized Water Reactor (PWR)

- Main nuclear reactor type;
- Primary coolant fluid is **superheated water** under high pressure;
- Light water is used as both coolant & moderator

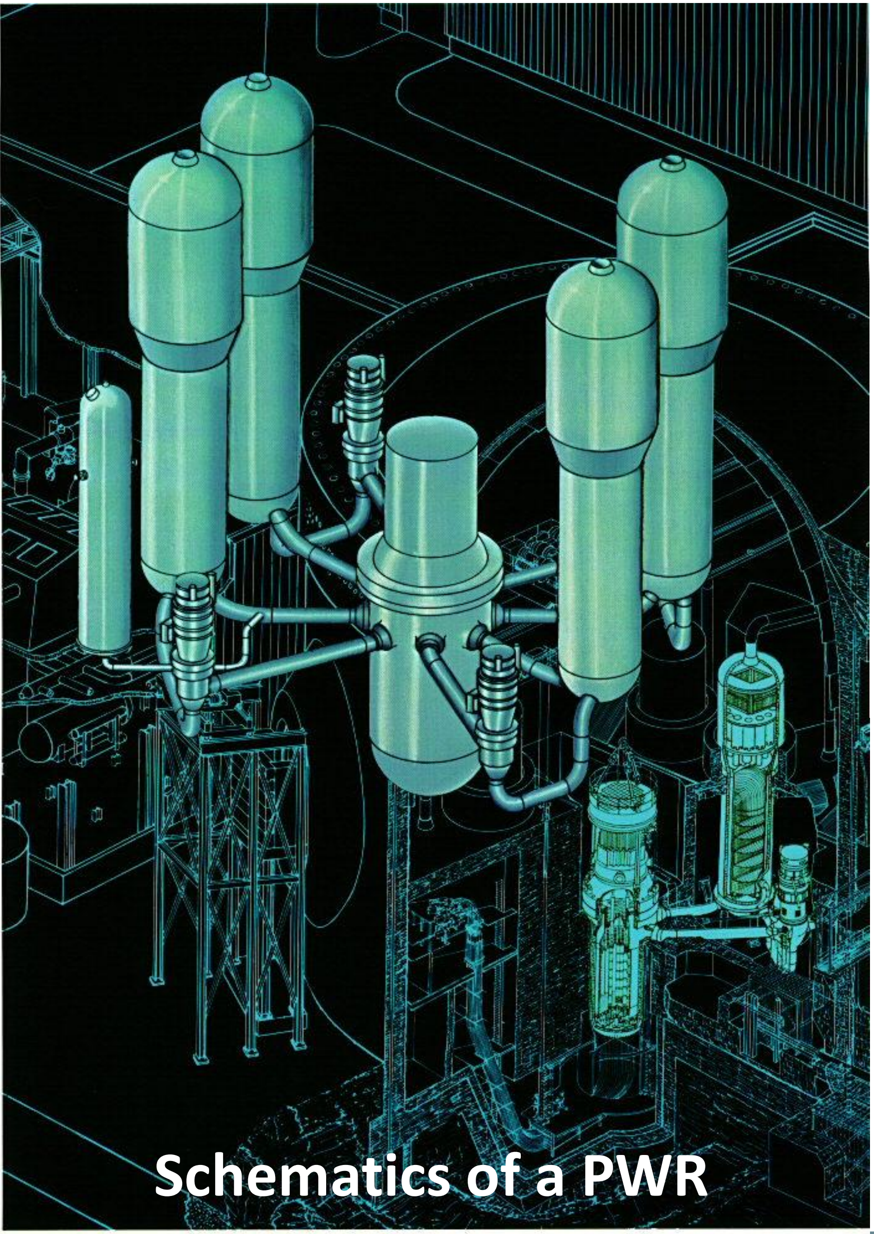
Diablo Canyon Power Plant





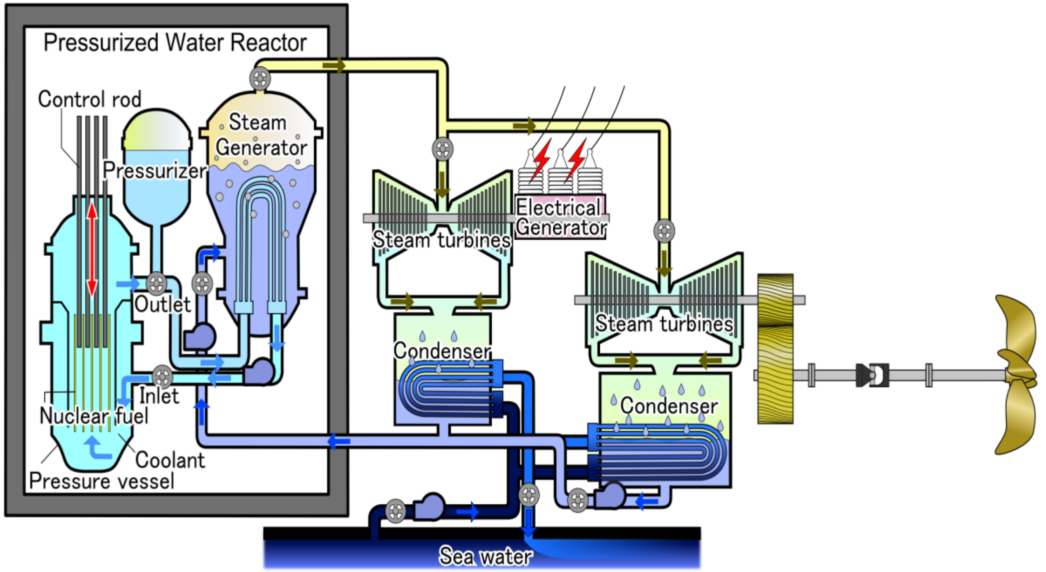
PWR Reactor Vessel heads

Pressurised Water Reactor (PWR)



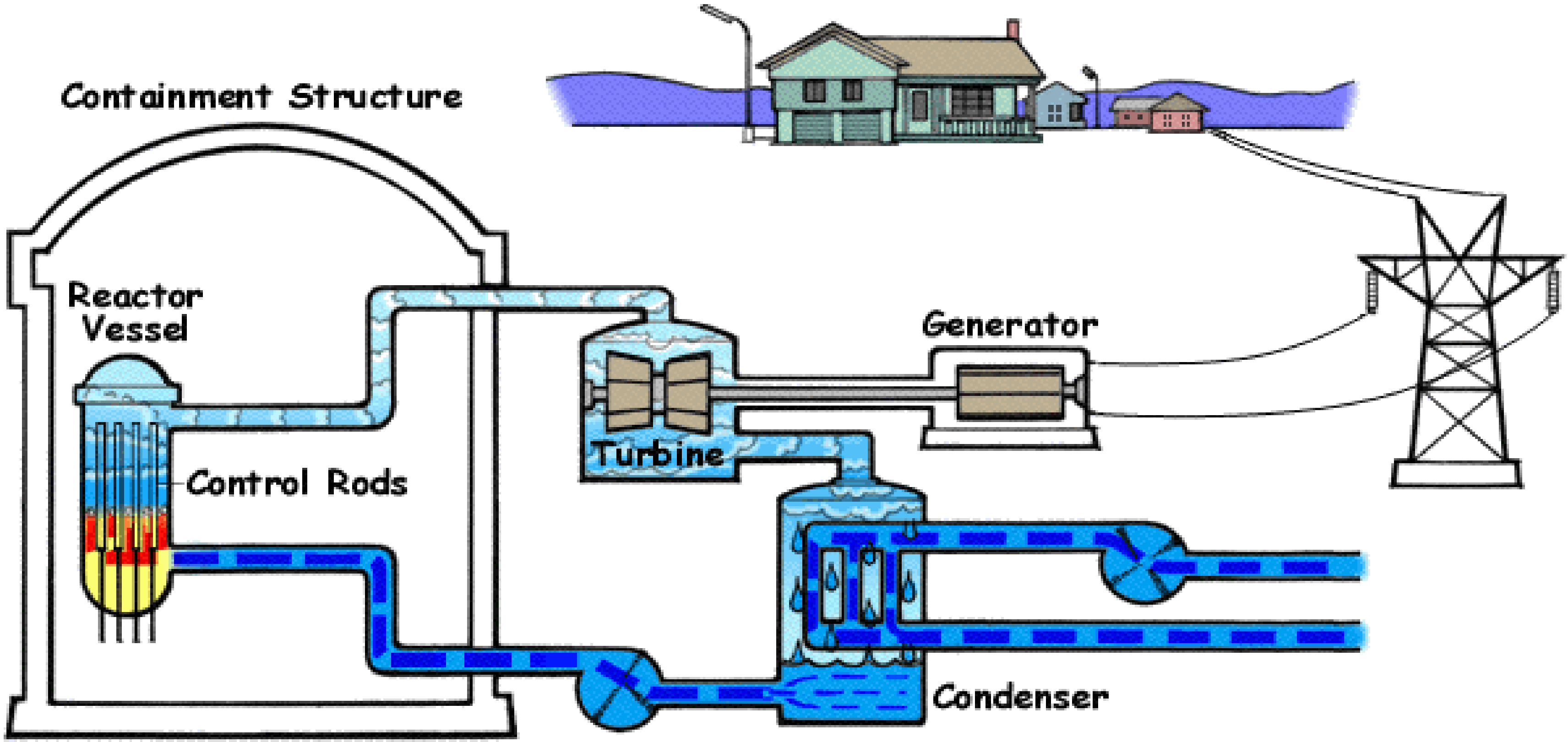
Westinghouse NUCLEAR STEAM SUPPLY SYSTEM

Schematics of a Naval PWR



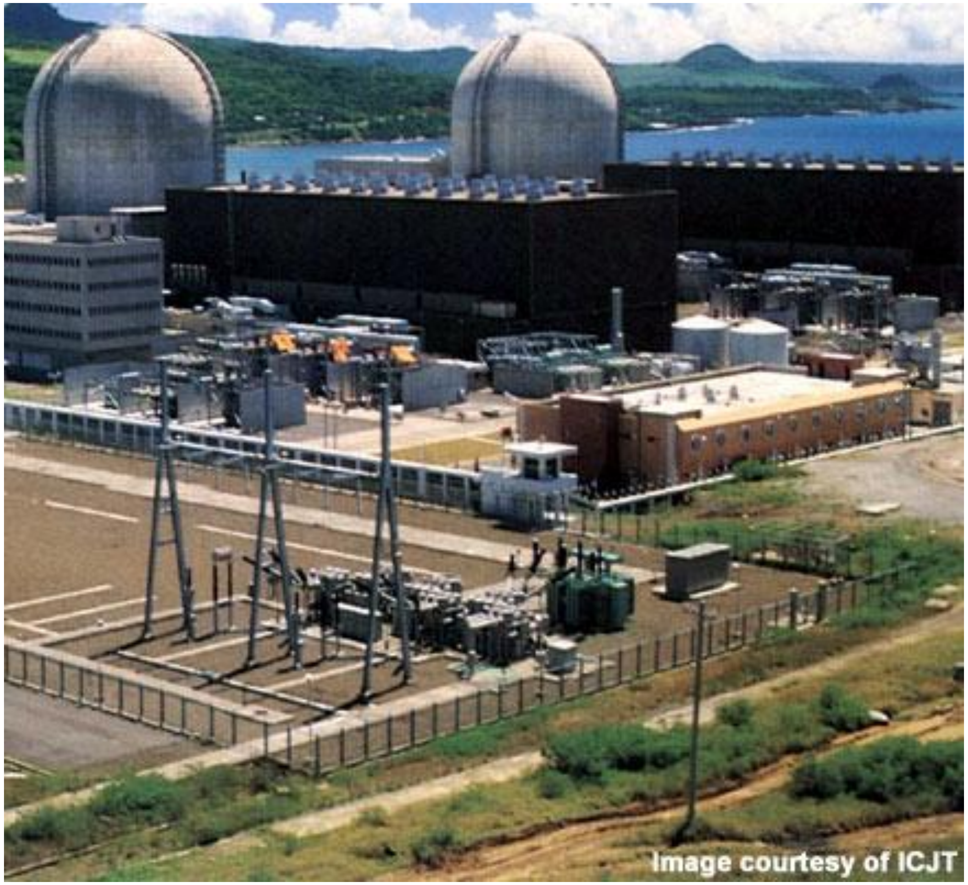
- Reactor is contained in a steel pressure vessel;
- Pressure vessel, boilers and connecting pipe-work form a sealed primary pressurised circuit, which is contained within a steel-lined pre-stressed concrete containment building.

Boiling Water Reactor (BWR)

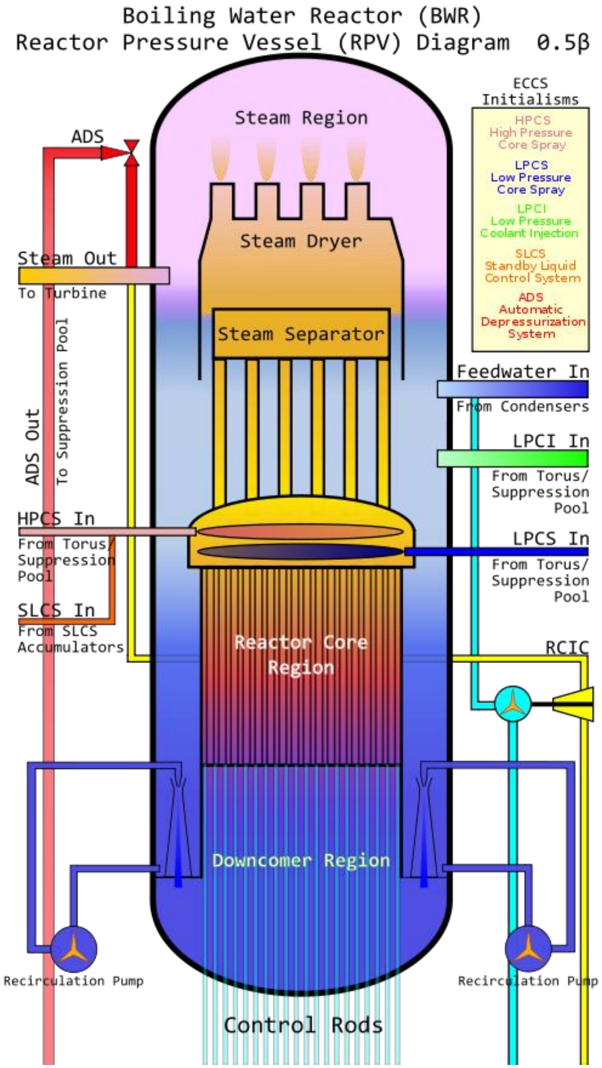


- 2nd most common reactor;
- Ordinary water used as moderator & coolant;
- Operates at low pressure which allows water to boil.

Boiling Water Reactor (BWR)



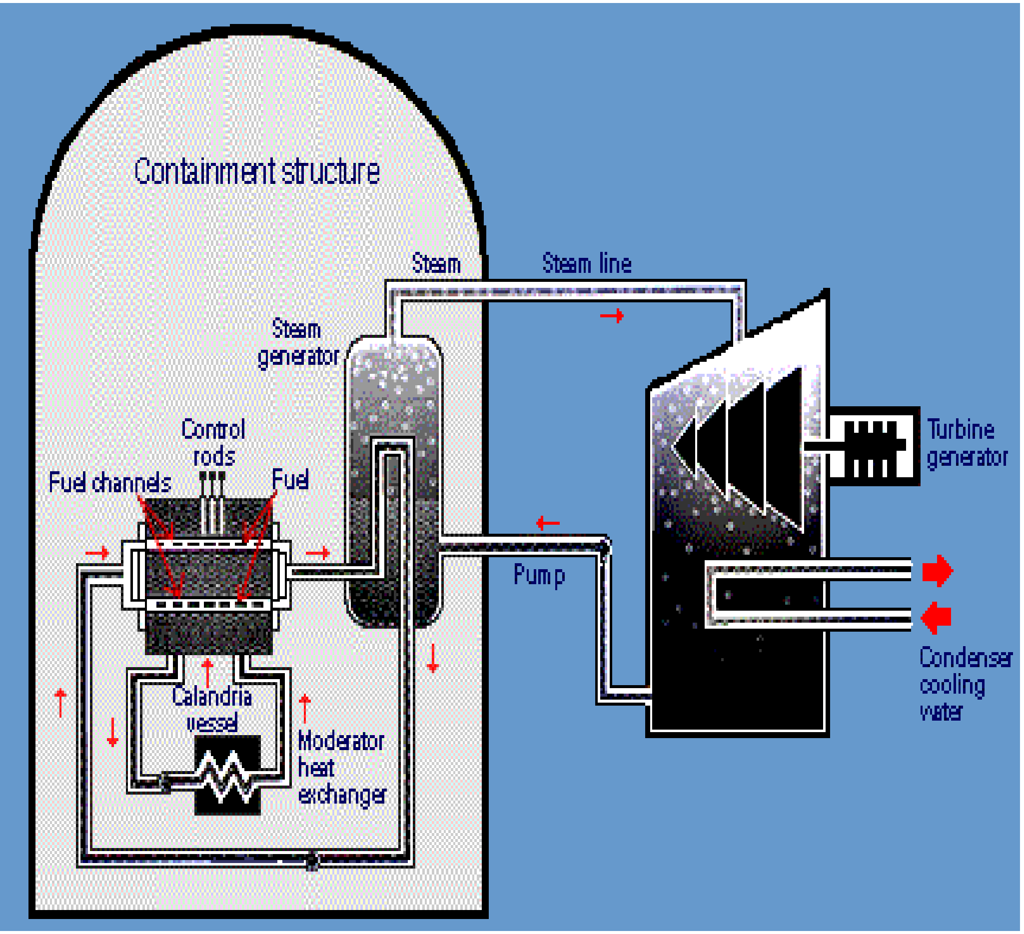
Chin Shan NPP (Taiwan): two 604MWe BWRs.



- No separate secondary steam cycle;
- Water from reactor converted to steam & used to directly drive the generator turbine.

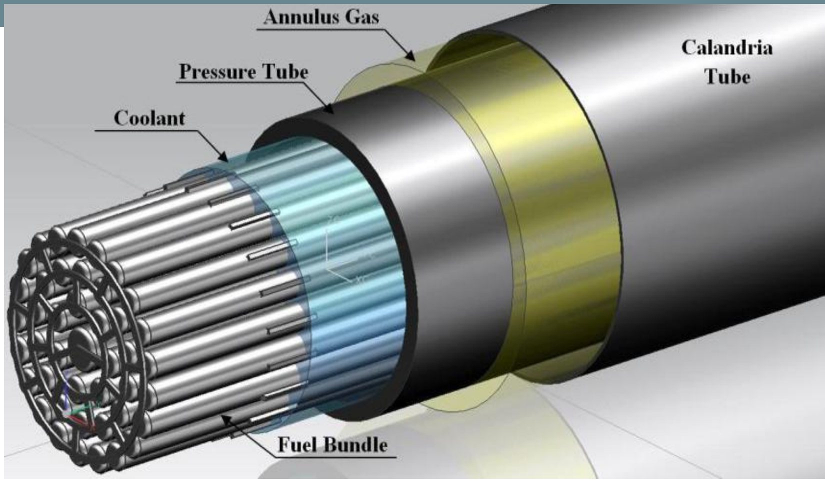
Pressurized Heavy Water Reactors (PHWR-Candu)

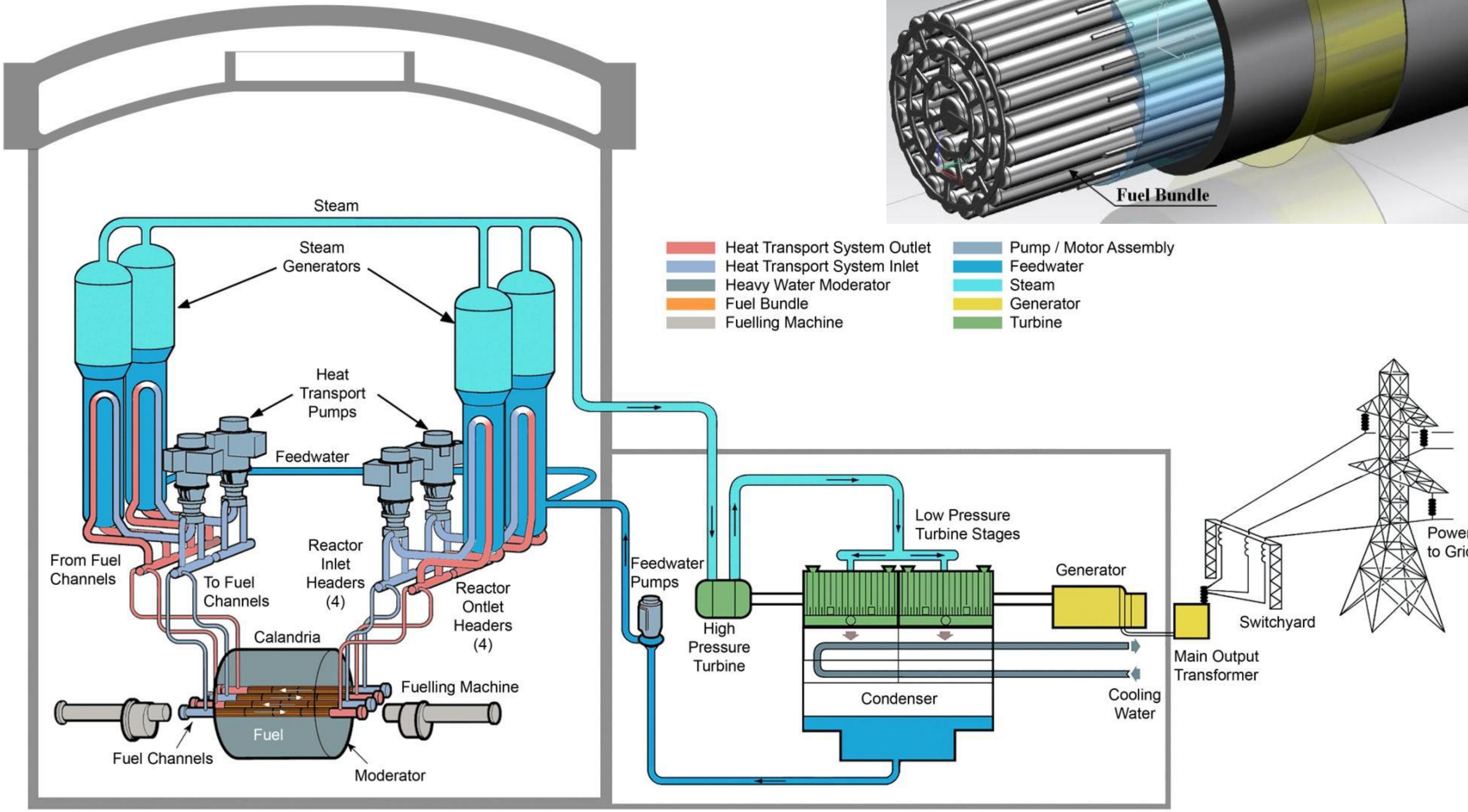
- Canadian invented pressurized heavy water reactor late 1950s & 1960s
- **CAN**ada **D**euterium **U**ranium: deuterium-oxide (i.e., heavy water) moderator and Uranium



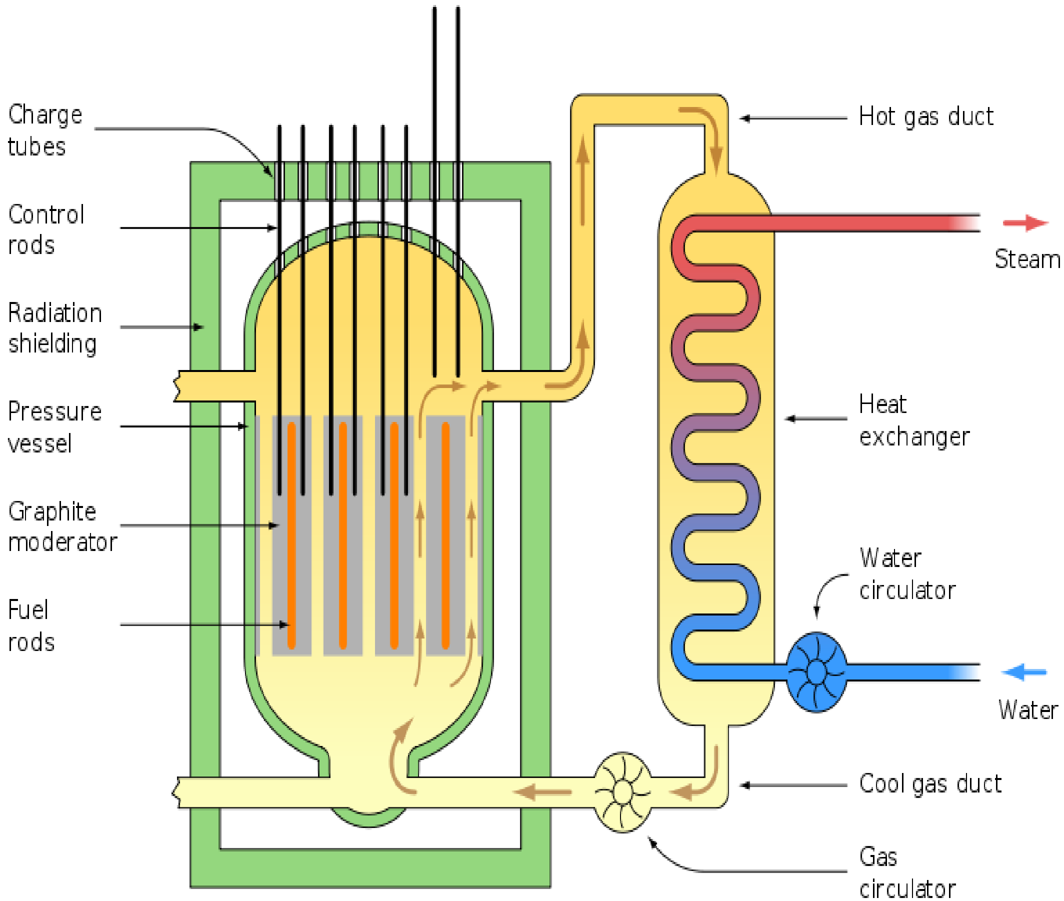
CANDU Bruce Nuclear Reactor
Second largest plant in the world.

Pressurized Heavy Water Reactors (PHWR-Candu)



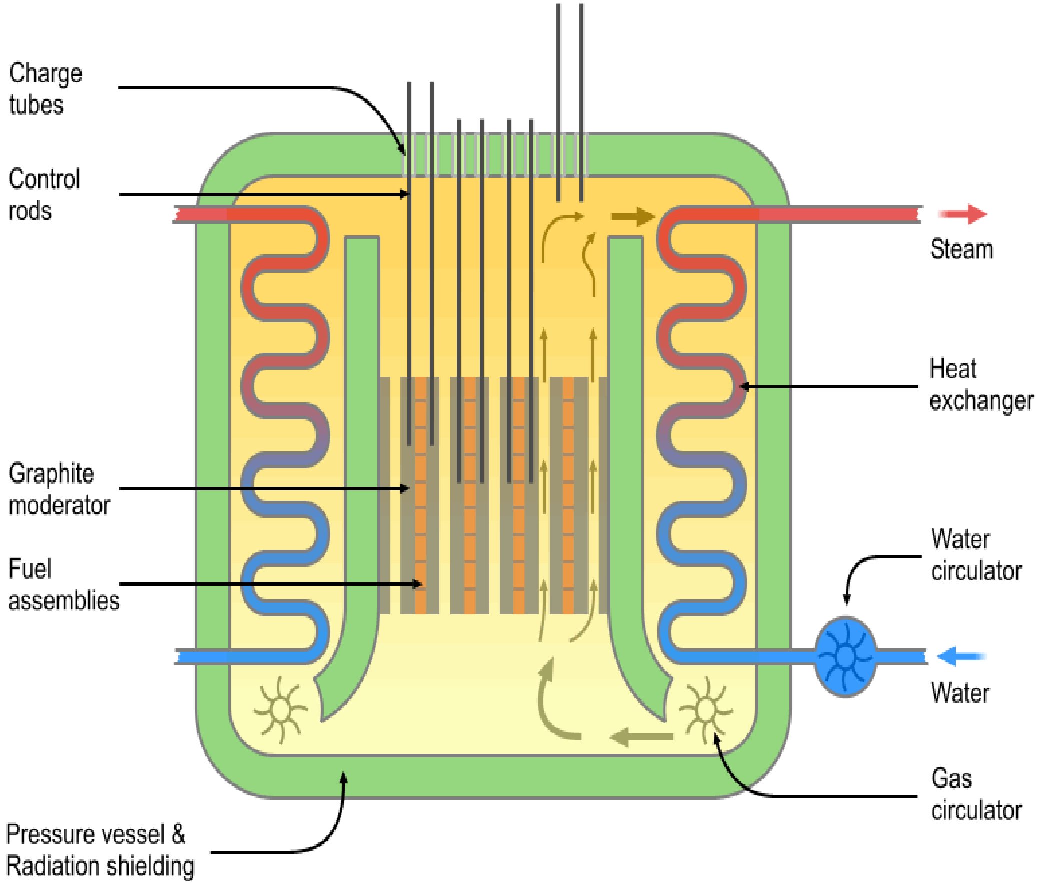


Magnox Reactors



- The first commercial nuclear stations in the UK;
- Named after the magnesium alloy used to make the fuel can containing the uranium fuel
- Use natural uranium metal as the fuel
- Graphite moderator
- **Pressurised CO_2 as the coolant**

Advanced Gas-cooled Reactor (AGR)

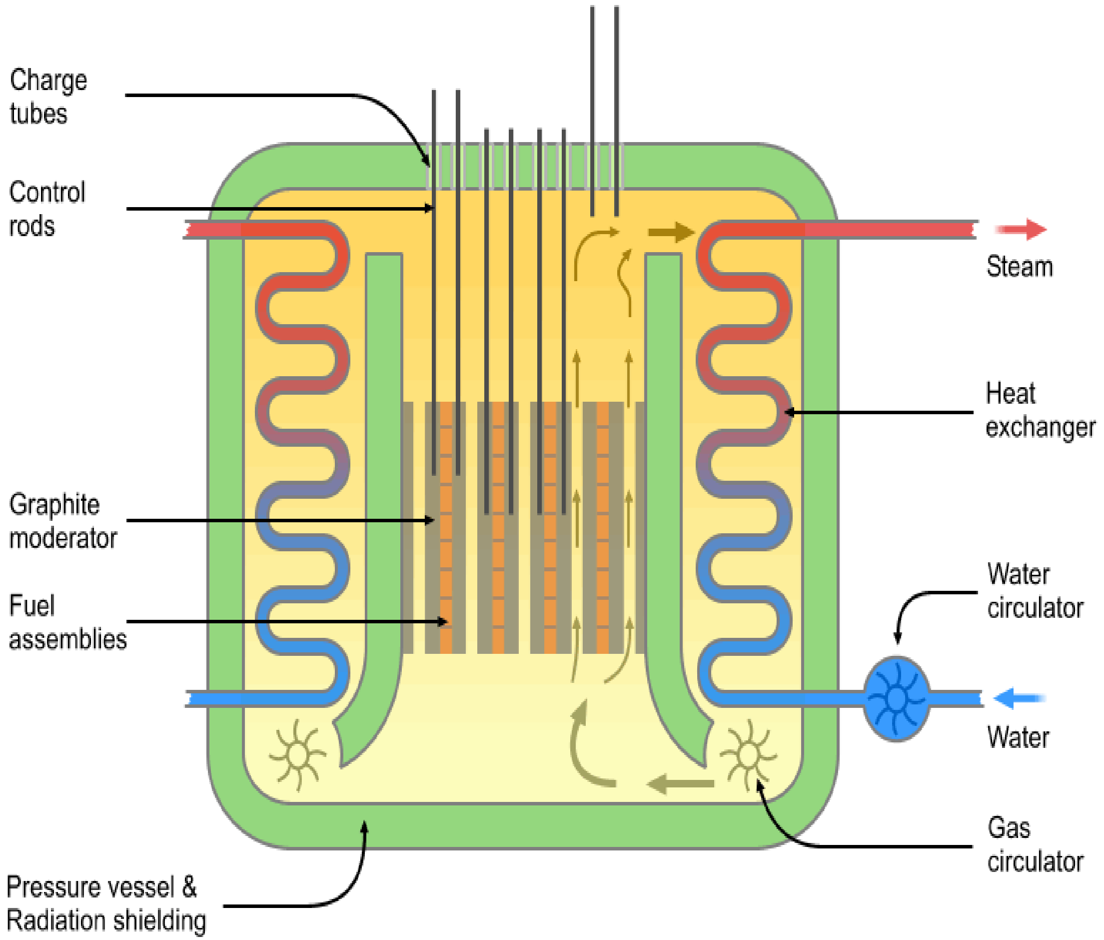


- 2^{nd} generation of British gas-cooled reactors – developed from Magnox
- Uses graphite as the neutron moderator and CO_2 as coolant
- Configured with 2 reactors in single building

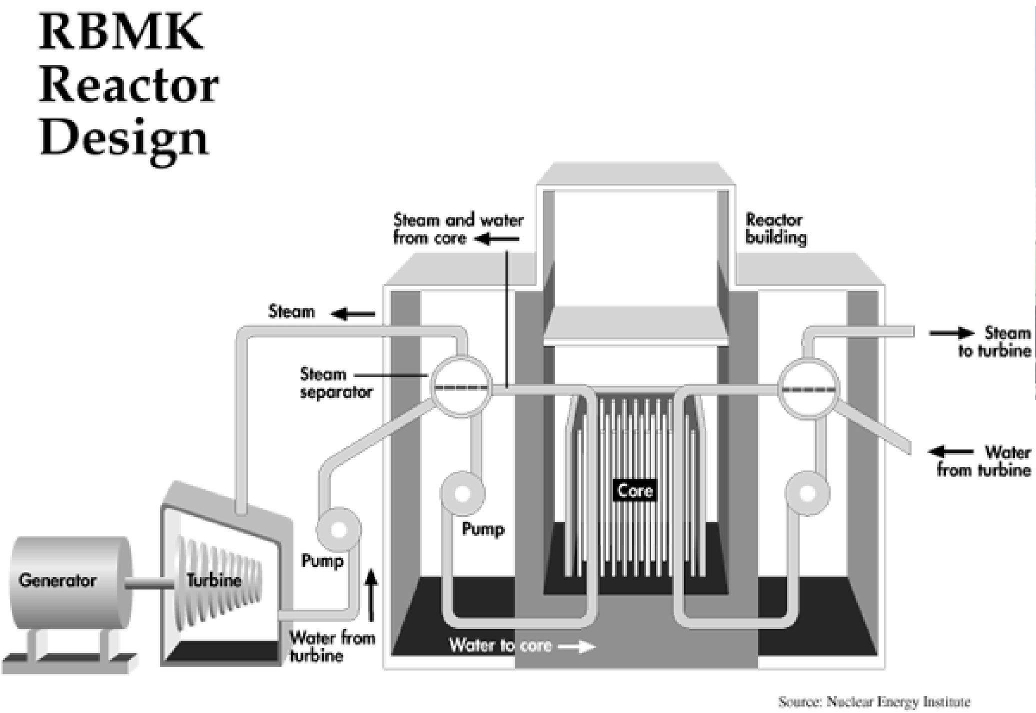
- **Windscale Advanced Gas-cooled reactor (WAGR) :** built in the 1960s and decommissioned in 2011. It produced approximately 3257500 MWh during operation life .

Advanced Gas-cooled Reactor (AGR)

- Use enriched uranium clad stainless steel cans;
- Also have a **graphite moderator** and use **pressurised CO_2 as the coolant**;
- AGRs are able to operate at a higher temperature than the Magnox reactor;
- Coolant conveys heat from the reactor to the boilers which, in turn, heats water in an isolated steam circuit which is then used to turn the turbines.



High-Power Channel Reactor (RBMK)



Chernobyl

- Russian design;
- Class of graphite-moderated nuclear power reactor;
- Type involved in Chernobyl accident;
- Uses light water for cooling and graphite for moderation;
- Uses natural uranium for fuel.

Ignalina Nuclear Power Plant, Lithuania

Fast Neutron Reactor

- Fission chain reaction sustained by fast neutrons;
- Needs no neutron moderator;
- Needs fuel rich in fissile material;
- **All current fast reactors are liquid metal cooled (lead or sodium);**
- Fuel – enriched **uranium or plutonium.**

Shevchenko BN350 nuclear-heated desalination plant

Superphenix power plant, France

Dounreay

Current Commercial Nuclear Reactor Designs

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Reactor Type	Main Countries	Number	GWe	Fuel	Coolant (Temp in °C)	Moderator
Pressurised water reactor (PWR)	US, France, Japan, Russia, China	265	251.6	Enriched UO_2	Water (300)	Water
Boiling Water Reactor (BWR)	US, Japan, Sweden	94	86.4	Enriched UO_2	Water (300)	Water
Pressurised heavy water reactor "Candu"	Canada	44	24.3	Natural UO_2	Heavy water (300)	Heavy Water
Gas cooled reactor	UK, Russia	18	10.8	Natural U Enriched UO_2	He, CO_2 (600)	Graphite
Light water graphite reactor (RBMK)	Russia	12	12.3	Enriched UO_2	Water (300)	Graphite
Liquid Metal-Cooled (LMFBR)	Japan, France, Russia, China	4	1	PuO_2 & UO_2	Liquid Sodium,Lead and Lead-Bismuth (600)	None

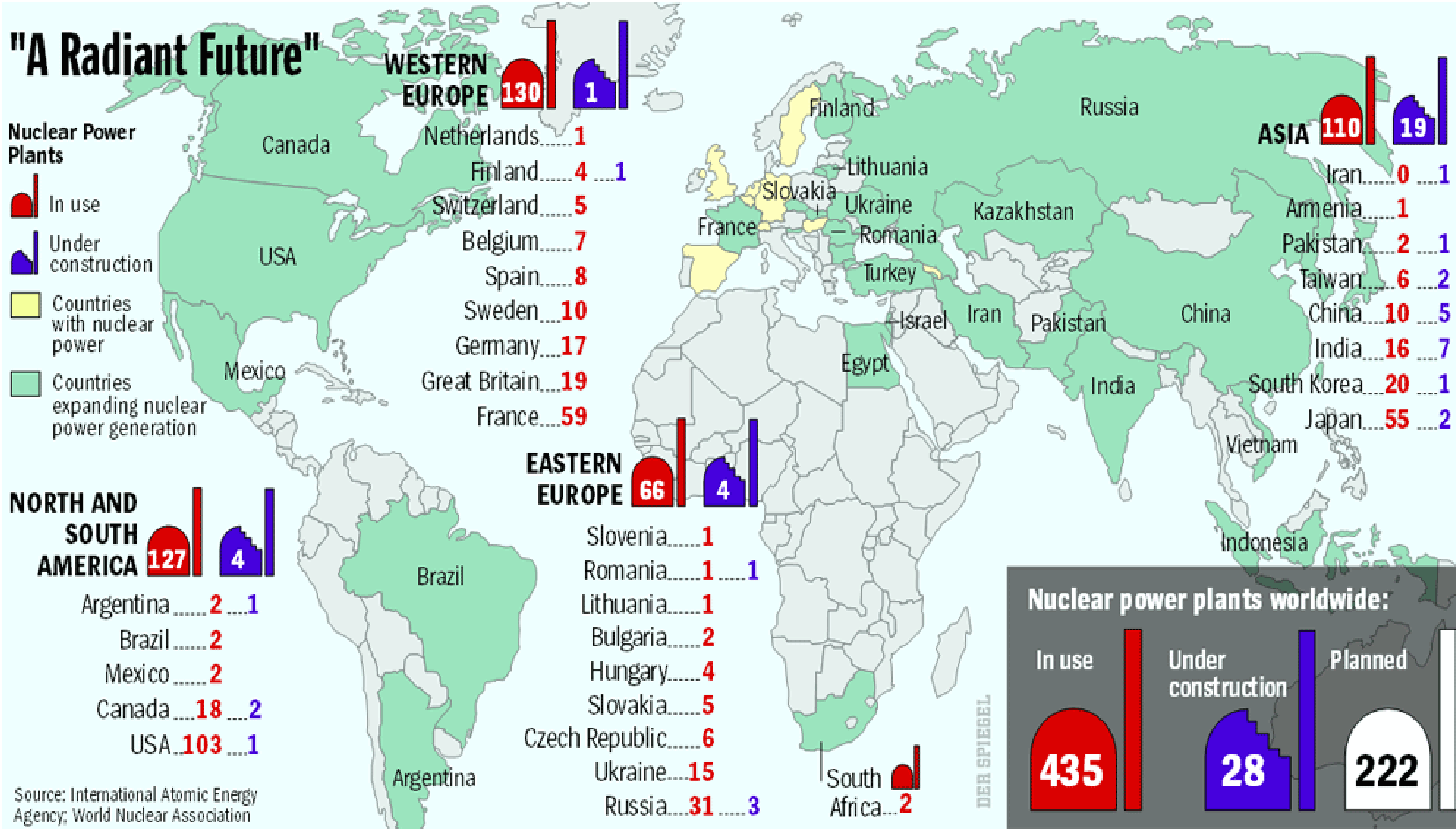
(2008)

Current Commercial Nuclear Reactor Designs

Country	Fraction of Electricity	Units Under Construction	Operating Units
France	75.2	1	59
Belgium	51.7	0	7
Bulgaria	35.9	0	2
S. Korea	34.8	6	21
Switzerland	39.5	0	5
Japan	28.9	2	55
UK	17.9	0	19
USA	20.2	1	104
Russia	17.8	10	32
S. Africa	4.8	0	2
Netherlands	3.7	0	1
China	1.9	23	13

Sources: World Nuclear Association (2010)

Nuclear Reactors across the World



Source: IAEA

Environmental Impacts of Energy Matrix

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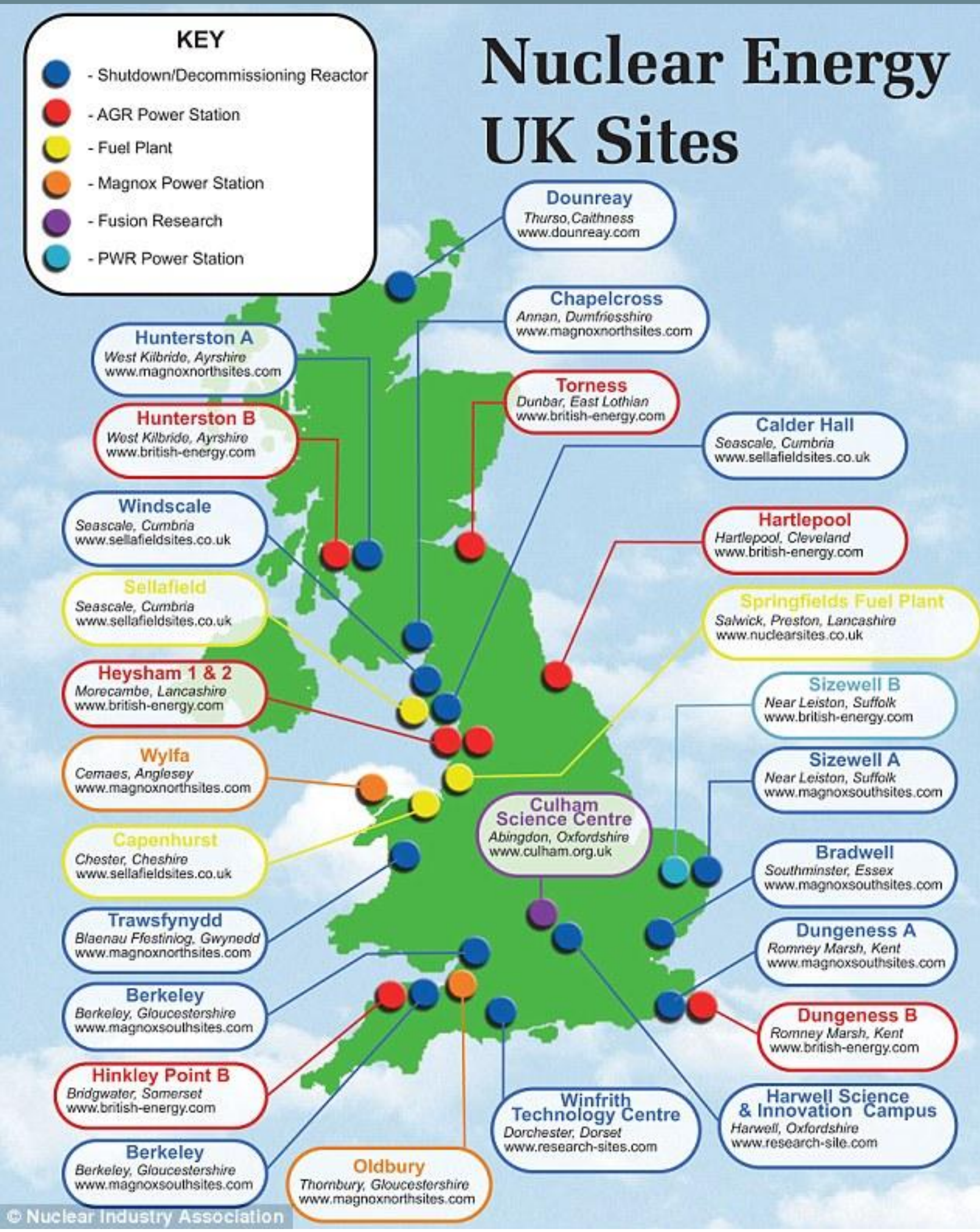
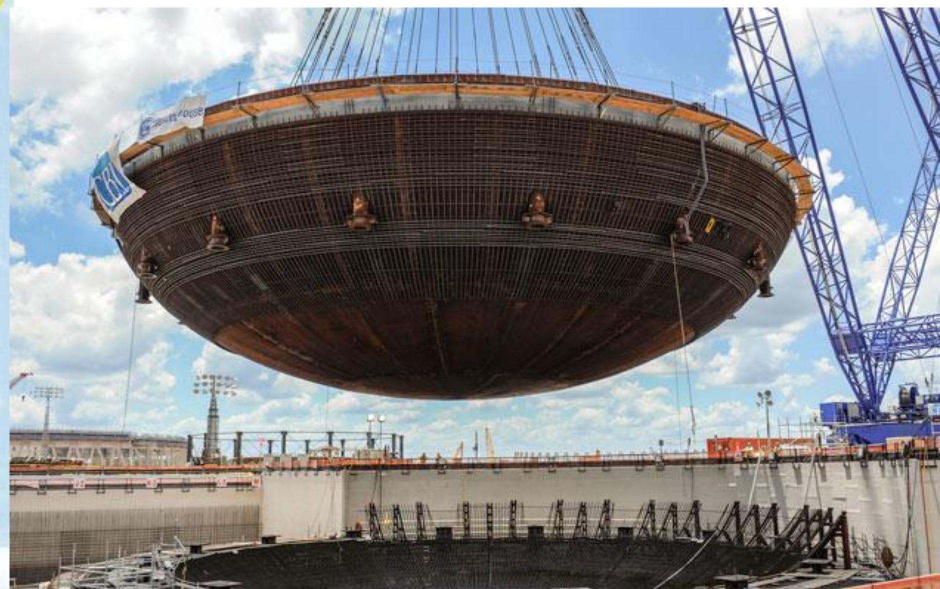
FUEL PHASE	Coal	Petroleum	Natural Gas	Nuclear	Hydro	Solar Terrestrial Photovoltaic	Solar Power Tower	Wind	Fusion	Geothermal
Extraction	Mining Accidents Lung Damage	Drilling-Spills (off-shore)	Drilling	Mining Accidents Lung Damage	Construction	Mining Accidents	- -	- -	He, H_2, Li Production	- -
Refining	Refuse Piles	Water Pollu- tion	- -	Milling Tails	- -	- -	- -	- -	- -	- -
Transportation	Collision	Spills	Pipeline Explosion	- -	- -	- -	- -	- -	- -	- -
On-Site										
Thermal	High Efficiency	High Efficiency	High Efficiency	Low Efficiency	- -	Low Efficiency Ecosystem Change	Ecosyste m Change	- -	- -	Low Efficiency
Air	Particulates - SO_2, NO_x	SO_2, NO_x	NO_x	BWR Radia- tion Releases	- -	- -	- -	- -	- -	H_2S
Water	Water Treat- ment Chemi- cals	Water Treat- ment Chemi- cals	Water Treat- ment Chemi- cals	Water Treat- ment Chemi- cals	Destroys Prior Ecosystems	Water Treat- ment Chemi- cals	Water Treat- ment Chemi- cals	- -	Tritium in Cooling Water	Brine in Streams
Aesthetic	Large Plant Transmission Lines	Large Plant Transmission Lines	Large Plant Transmission Lines	Small Plant Transmission Lines	Small Plant Transmission Lines	Poor Large Area	Poor Large Area	Large Area Large Towers Noise?	Small Area	Poor Large Area
Wastes	Ash, Slag	Ash	- -	Spent Fuel Transportation Reprocessing Waste Storage	- -	Spent Cells	- -	- -	Irradiated Struc- tural Material	Cool Brine
Special Problems	- -	- -	- -	- -	- -	Construction Accidents	- -	Bird, Human Injuries	Occupational Radiation Doses	- -
Major Accident	Mining	Oil Spill	Pipeline Explosion	Reactor Cooling	Dam Failure	Fire	- -	- -	Tritium Release	- -

Source: MITOpenCourseWare

Current- and Next-Generation of Nuclear Reactors





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Evolution of Nuclear Power Plants

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Generation I	Generation II	Generation III	Generation III+	Gen IV
Early prototype reactors	Commercial power reactors	Advanced LWRs	Near-term deployment	Economic Safe Min waste

Generation I	Generation II	Generation III	Generation III+	Gen IV
Shippingport Dresden Fermi Magnox	LWR-PWR, BWR CANDU VVER/RBMK	ABWR System 80+ AP600 EPR	Evolutionary designs with improved economics	

1950 1960 1970 1980 1990 2000 2010 2020 2030

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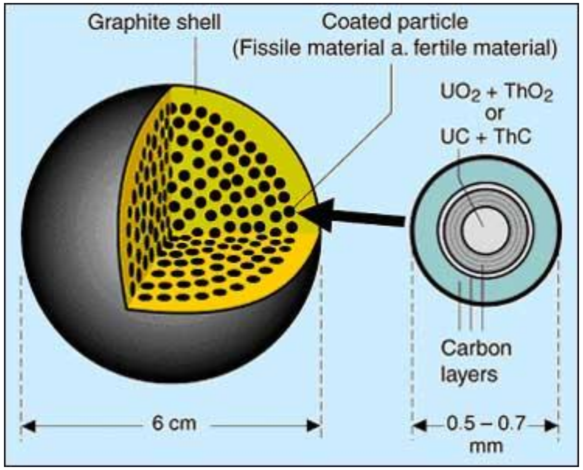
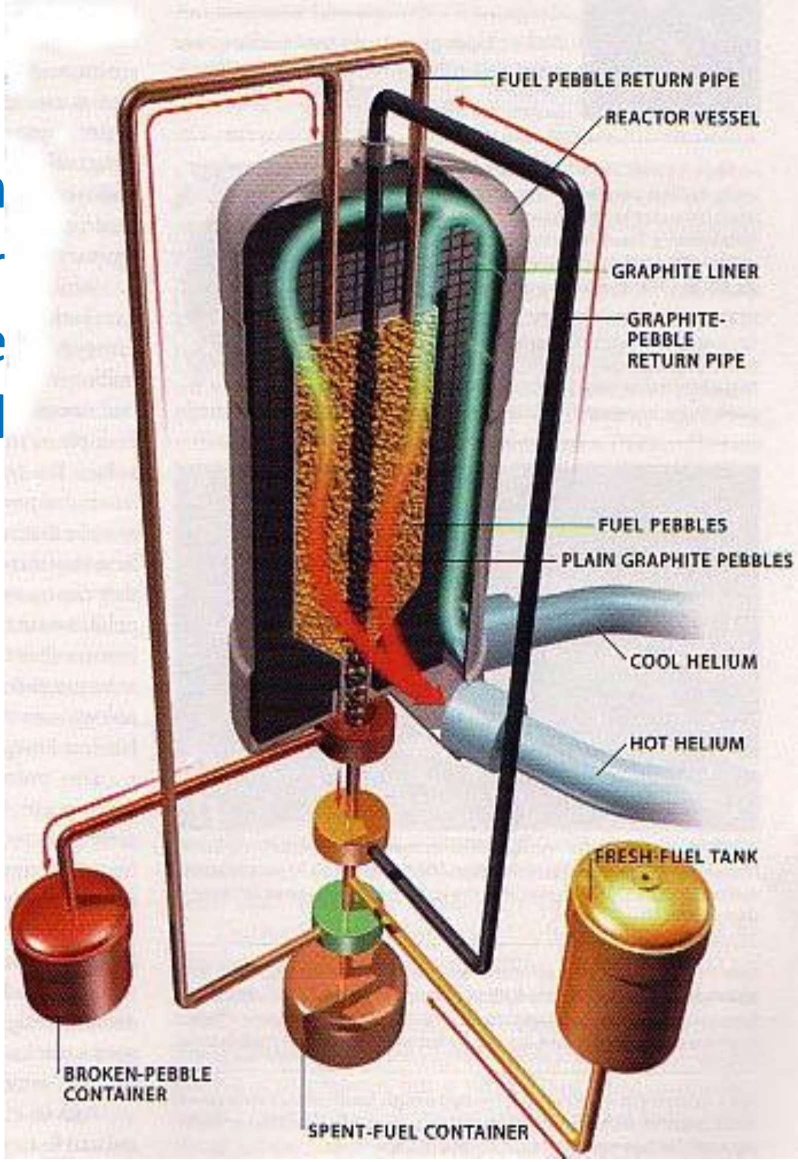
Pebble Bed Reactor

- Use pebbles containing fissile materials;
- These are based on TRISO particles with either UO_2+PuO_2 (i.e., MOX) or UO_2+ThO_2 core with layers of graphite for material integrity and thermal homogenisation;
- No control rods;
- Cooled with Helium gas (>400°C).





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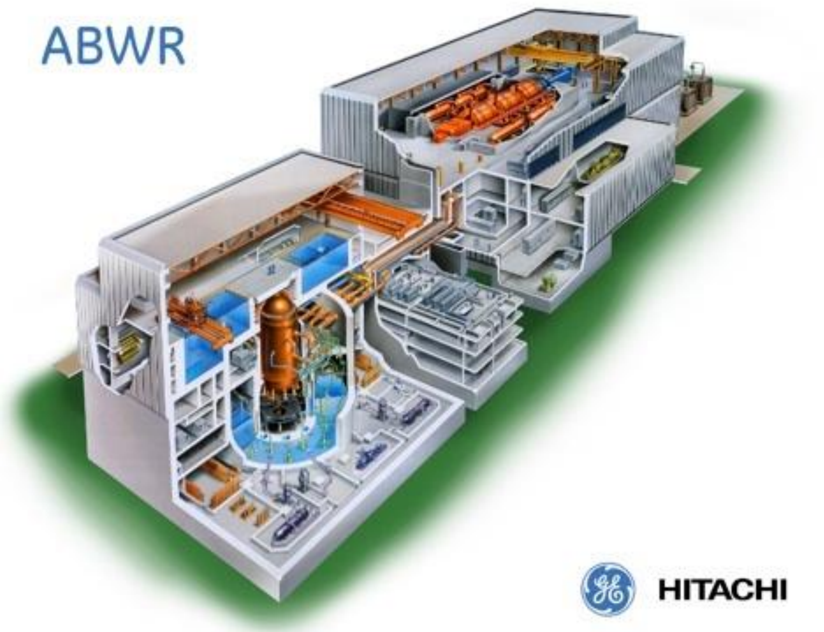
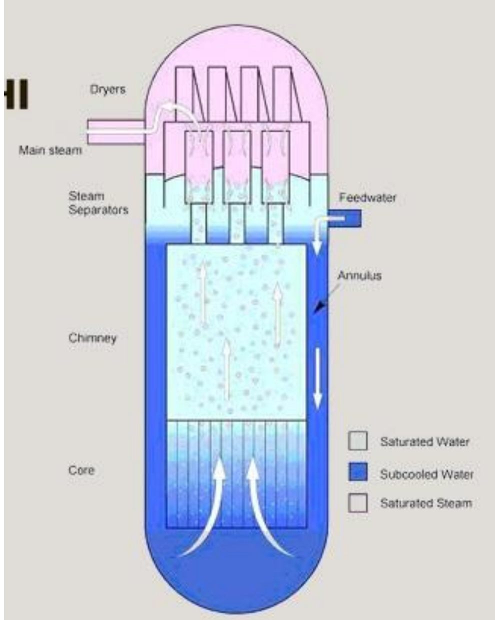
Advanced Boiling Water Reactor (ABWR)

- More compact design → cuts construction costs and increases safety.
- Additional control rod power supply improves reliability;
- Equipment and components designed for ease of maintenance.





Selected Generation III+ Reactors

- Advanced BWR -- Hitachi-GE (Japan-USA) and Toshiba (only Generation III+ reactor design already implemented in the industry): **Kashiwazaki-Kariwa NPP** Units 6 & 7 (first ABWRs in the world, 1996 & 1997); **Hamaoka**#5 (2005); **Shika**#2 (2006); also 2 units planned to be built in USA and another 2 in Taiwan;
- Advanced CANDU Reactor (ACR-1000);
- Advanced PWR: Toshiba-Westinghouse AP-1000, 6 are being constructed in China, another 12 are planned to be built in China and USA;
- Advanced PWR: 4 AP-1400 are being built in South Korea and another 4 in the United Arab Emirates;
- European Pressurized-water Reactor (EPR) - AREVA, France: 1 will be in operation in Finland (2014), 1 is under construction in France and 2 in China;
- VVER (Russian design PWR with ~1200 MWel): 6 under construction in Russia and 4 planned to be built in Turkey.

Fuel Type and Assemblies

Type of Reactor (% fraction):

- PWR (66%)
- BWR (22%)
- Candu (6%)
- RBMK (3%)
- AGR (2.7%)

Type of Fuel:

- UO_2
- MOX (UO_2 + PuO_2)
- U Metal
- Thorium/Uranium
- (enrichment levels)

Generation IV (GenIV) Reactors: Goals

- More efficient use of U and/or Th → long fuel cycle (refuelling 15-20 years);
- Higher burn up (i.e., Actinide burning);
- More economical (relative small capacity) → production of H_2 as by-product;
- Production of minimal amount of waste;
- Less long-lived waste;
- **Inheritably safe;**
- More proliferation resistant (misuse of nuclear elements);
- Ability to burn weapons grade fuel.

Generation IV (GenIV) Reactors

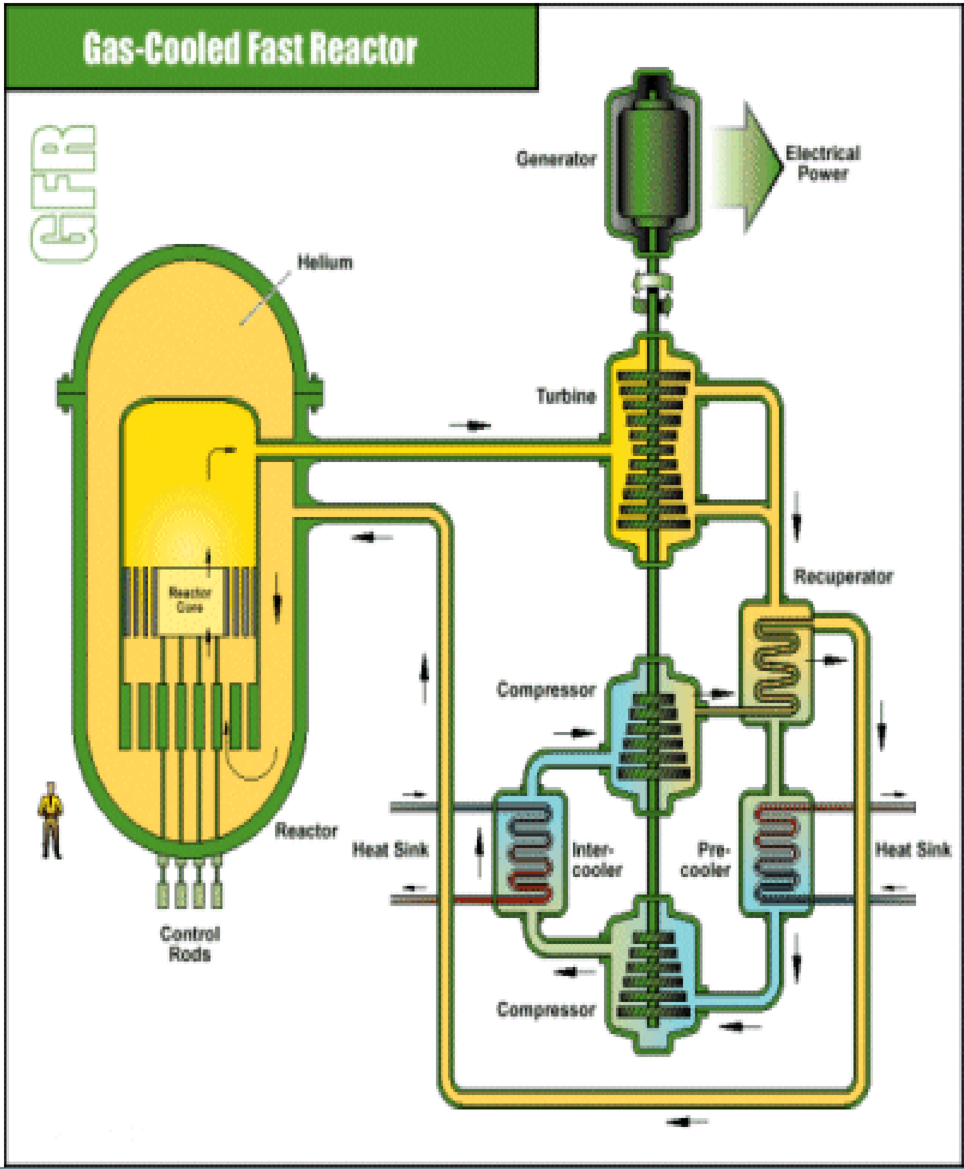
- Gas Cooled Fast Reactor (GFR)
- Very High Temperature Reactor (VHTR)
- Supercritical Water Cooled Reactor (SCWR)
- Sodium Cooled Fast Reactor (SFR)
- Lead Cooled Fast Reactor (LFR)
- Molten Salt Reactor (MSR)

❖ **Reactors planned to be deployed in 2030s.**

Generation IV (GenIV) Reactors

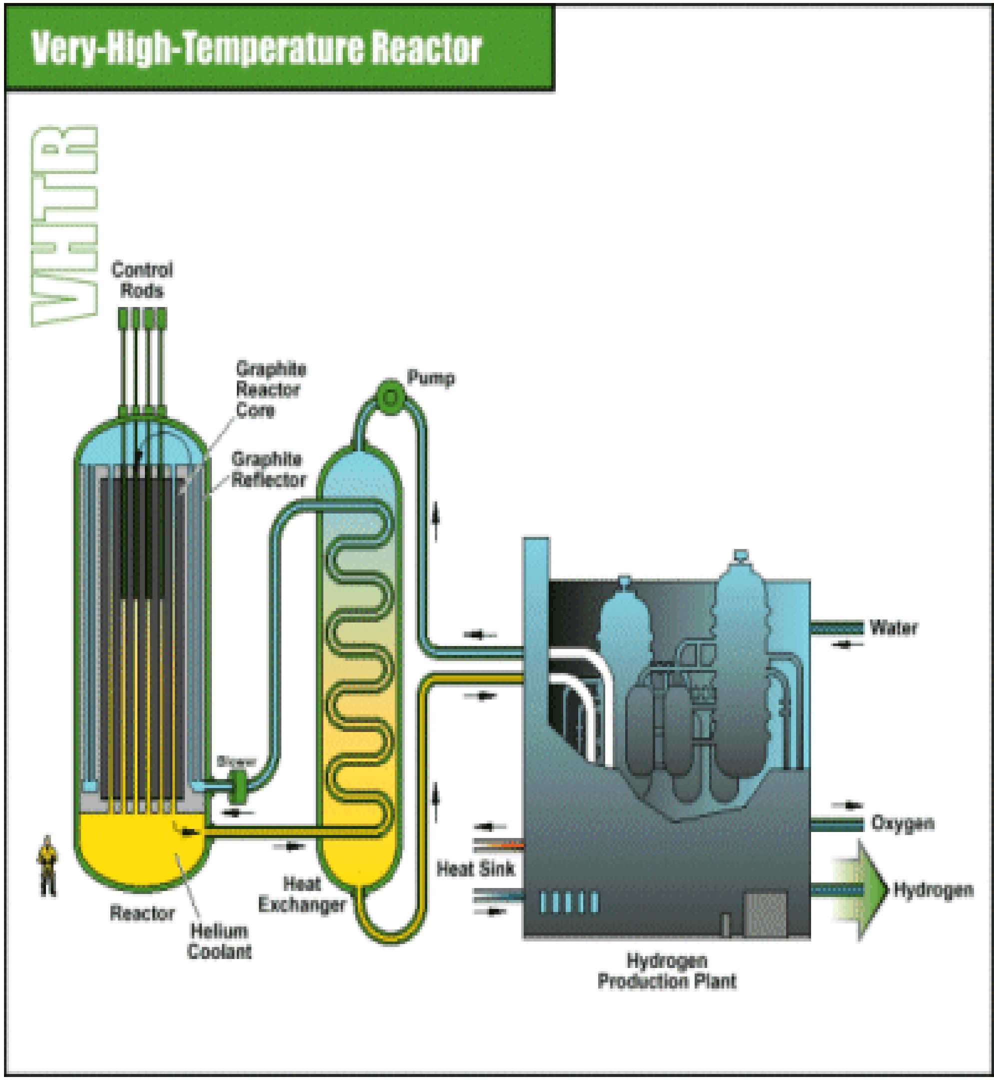
Gas Cooled Fast Reactor (GFR)

- Or High-Temperature Reactors (HTRs);
- Fast-neutron spectrum;
- Helium-cooled reactor (Brayton thermal cycle);
- The high output temperature of the helium coolant (485-850ºC and 7MPa) makes it possible to:
  - deliver electricity (288 MWe);
  - produce hydrogen;
  - process heat with high efficiency.
- Closed fuel cycle;
- Robust refractory fuel.



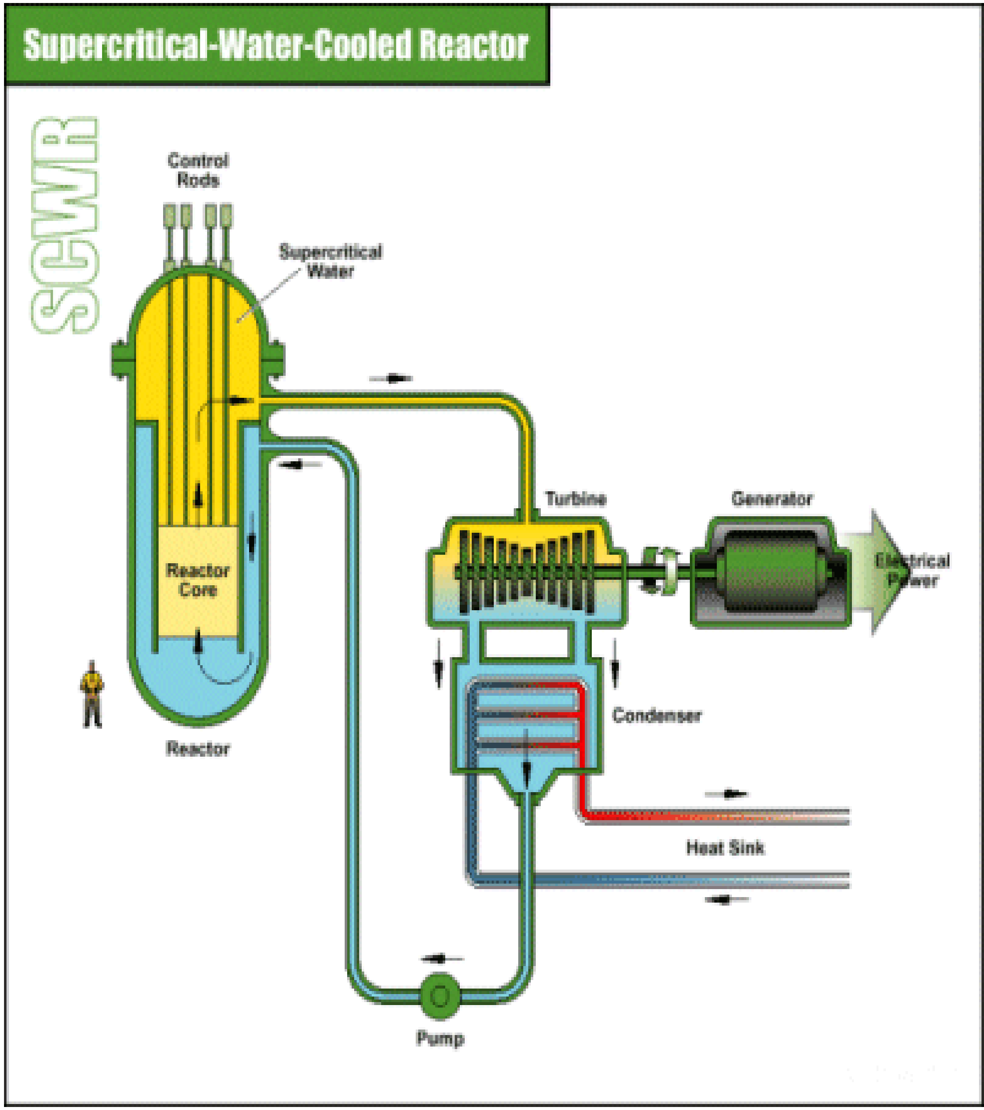
Very High Temperature Reactor (VHTR)

- Graphite-moderated (thermal spectrum)
- Helium-cooled reactor
- No reprocessing;
- Core outlet temperatures of coolant (500-1000°C and 9MPa);
- The cycle is operated with a combined Brayton cycle (gas-turbine cycle) and a Rankine steam cycle through heat exchangers.



Supercritical Water-Cooled Reactor (SCWR)

- High-temperature and high-pressure water-cooled reactor;
- Reactor is operated above the thermodynamic critical point of water (<625°C and 25MPa);
- Built upon two proven-technologies:
  - Light water reactors (LWRS) and;
  - Supercritical fossil-fired boilers;



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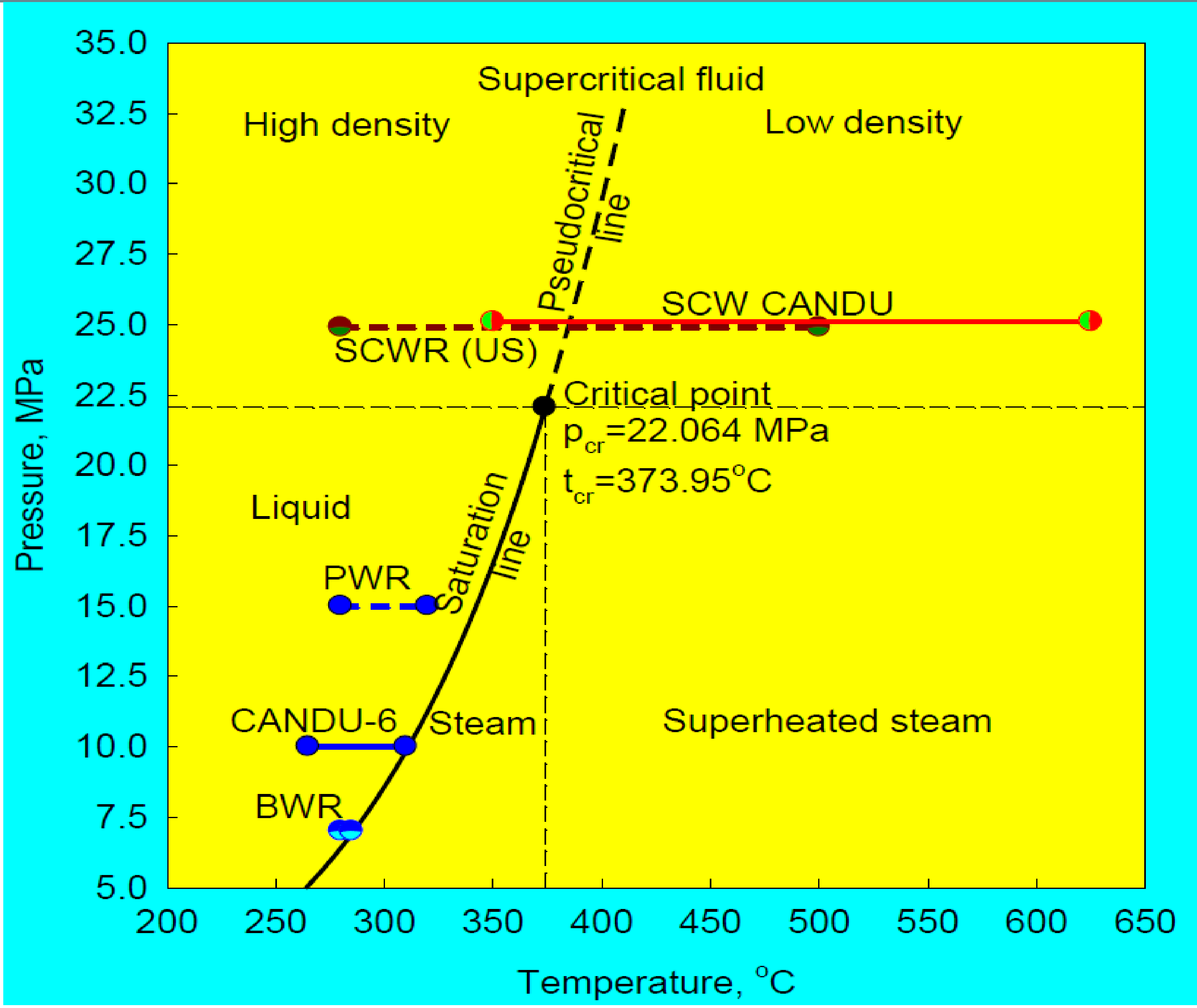
Supercritical Water-Cooled Reactor (SCWR)



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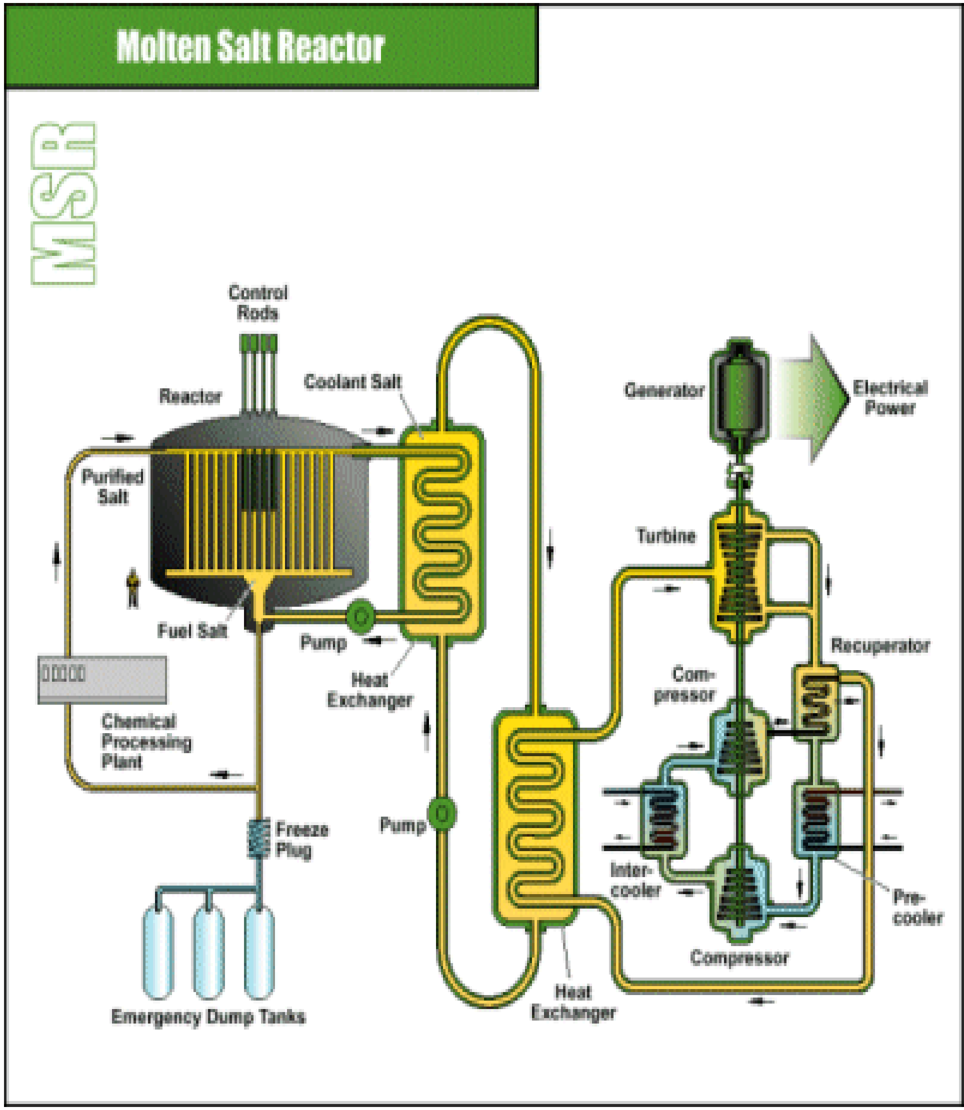
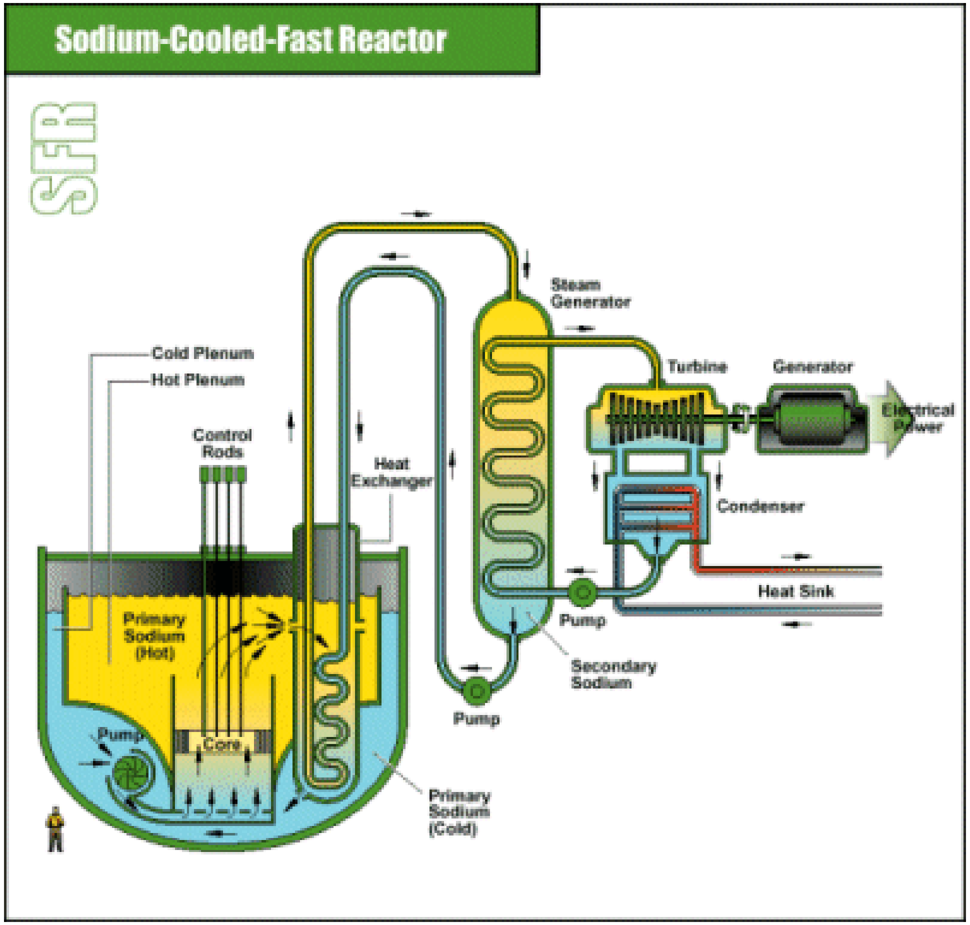
Molten Salt Reactor (MSR)

- Produces fission power in a circulating molten salt fuel mixture:
  - epithermal-spectrum reactor;
  - full actinide recycle fuel cycle.
  - Brayton cycle;
- Molten fluoride salts have excellent heat transfer characteristics and a very low vapor pressure, which reduce stresses on the vessel and piping.



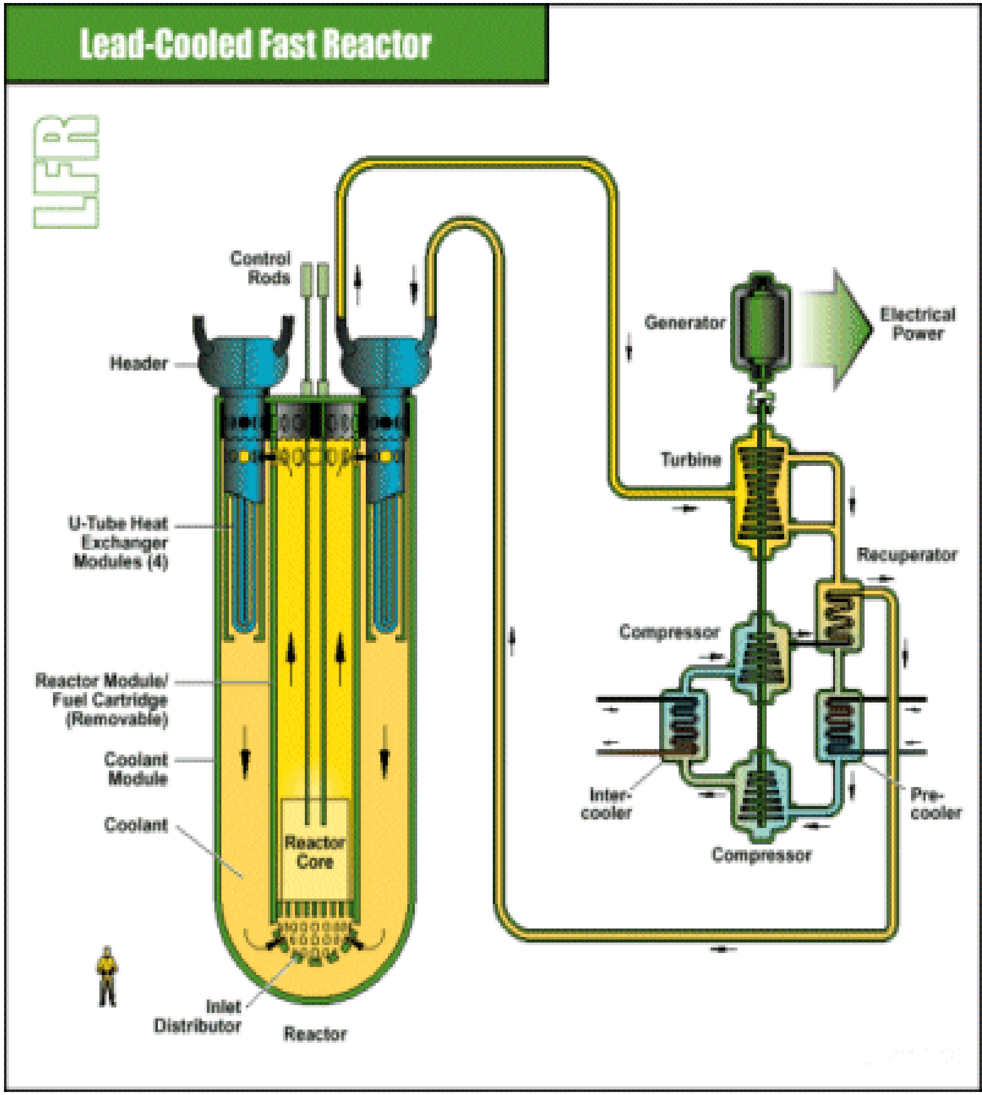
Sodium Cooled Fast Reactor (SFR)

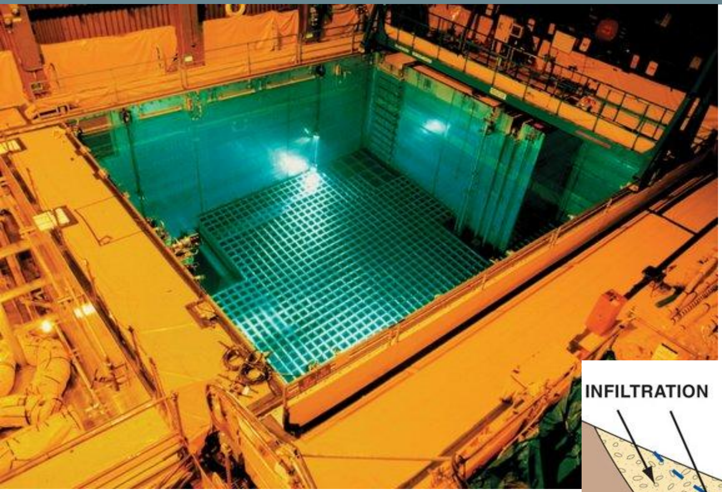
- Fast-spectrum (facilitates breeding) ➔ sodium does not moderate neutrons as water does!
- Sodium-cooled reactor;
- Closed fuel cycle (reprocessing) for efficient management of actinides and conversion of fertile uranium.;
- Rankine Cycle with power output of 500-1500 MWe (~550ºC).

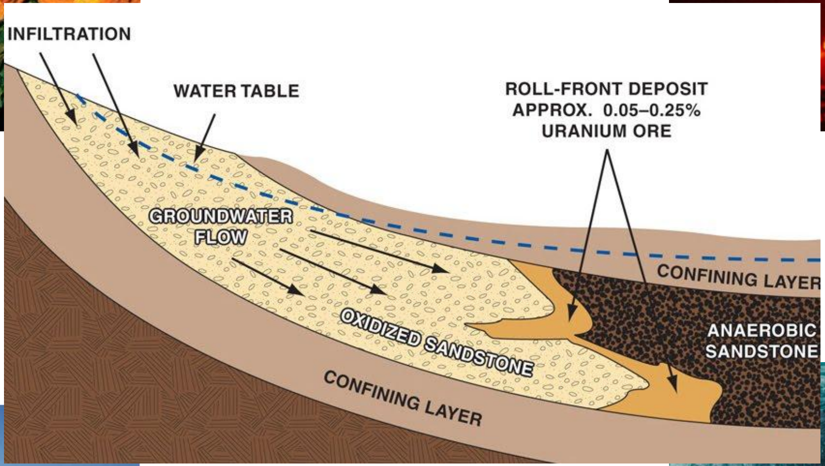


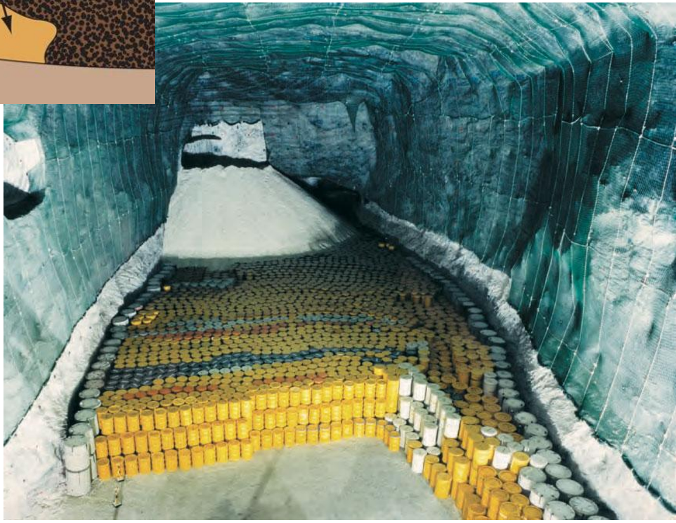
Lead Cooled Fast Reactor (LFR)

- Fast-spectrum lead or lead/bismuth eutectic liquid metal-cooled reactor
- Closed fuel cycle (reprocessing) for efficient conversion of fertile uranium and management of actinides.;
- Brayton Cycle;
- Higher temperature (550-800ºC) enables the production of hydrogen by thermochemical processes.
- Very long refueling interval (15 to 20 years) (proliferation resistant) ;









Issues for Nuclear Power

Issues for Nuclear Power

Safety

- Windscale , UK 1957
- Three Mile Island, USA, 1979
- Chernobyl, Ukraine, 1986
- Fukushima-Daiichi, Japan, 2011

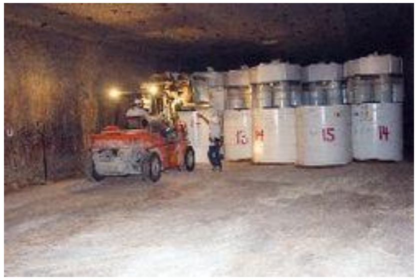
Costs

- More expensive than gas-fired power stations
- Not “too cheap to meter”
- Increasing in response to concerns over safety

Weapons proliferation/terrorism

Wastes

- Need to find long-term storage solution that satisfies concerns of public



Availability of Uranium

- Is there more than 50 years supply left?

Issues for Nuclear Power

Safety

- Windscale , UK 1957 - fire at plutonium production pile releases 1000TBq of radioactive iodine

- Three Mile Island, USA, 1979 – loss of coolant, partial meltdown of the fuel in the reactor core

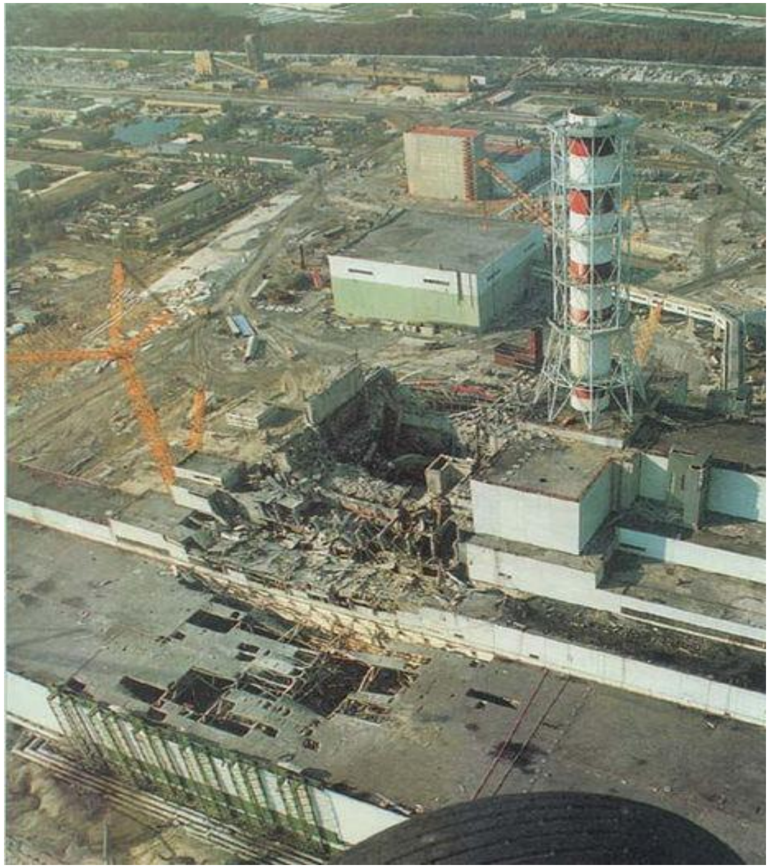
Windscale Fire

Three Mile Island

Issues for Nuclear Power

Safety

- Chernobyl, Ukraine, 1986
- Fukushima-Daiichi, Japan, 2011



Fukushima Daiichi Nuclear Disaster

Chernobyl after the disaster

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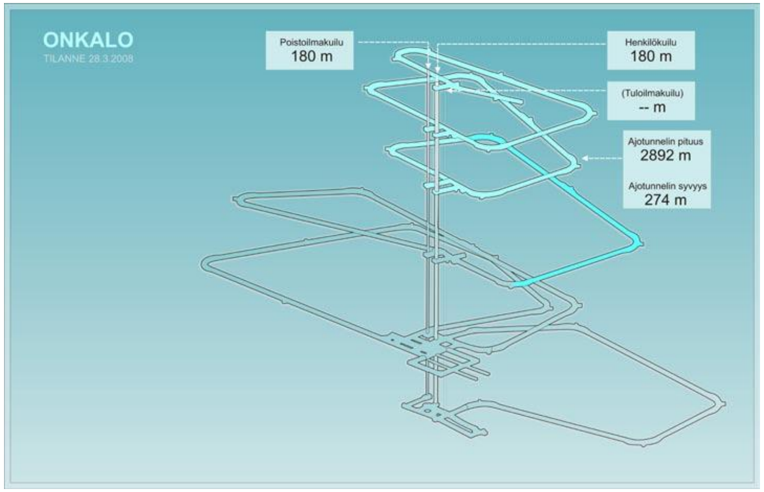
Wastes

- Need to find long-term storage solution that satisfies concerns of public

Swedish KBS-3 capsule for nuclear waste



Geologic Depository at Olkiluoto Nuclear Power Plant in Finland

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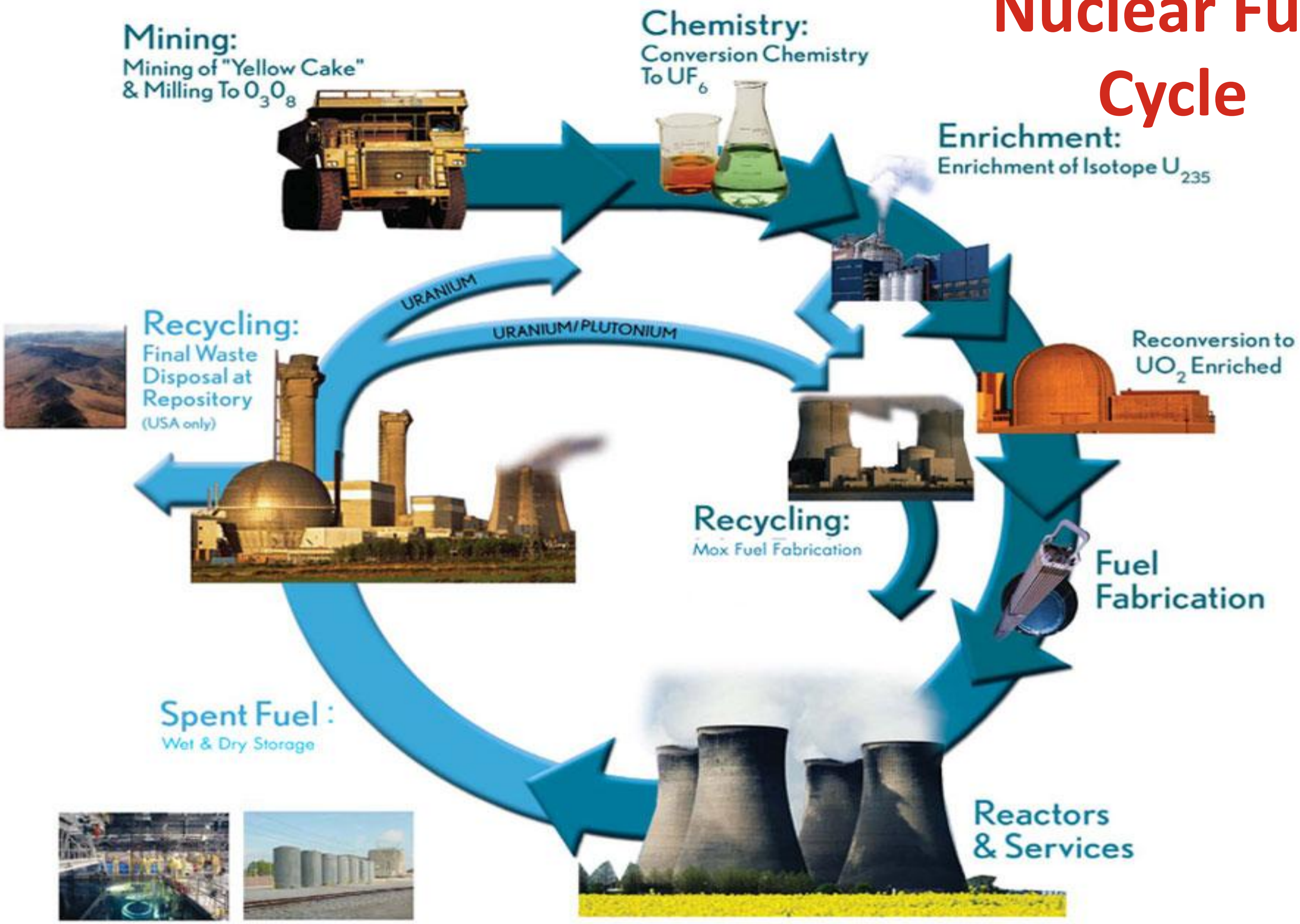
Nuclear Fuel Cycle



MATERIAL BALANCE IN THE NUCLEAR FUEL CYCLE (based on annual operation of a 1000 MWe reactor)

Mining	**20000** tonnes of 1% uranium core
Milling	230 tonnes of uranium oxide concentrate (~ 195 tU)
Conversion	288 tonnes UF_6 (~ 195 tU)
Enrichment	35 tonnes enriched UF_6 (~ 24 tU)
Fuel fabrication	**27** tonnes UO_2 (~24 tU enriched)
Reactor operation	8.76 TWh of electricity at full output (**22.3 tonnes of natural U per TWh**)
Used fuel	27 tonnes: 240 kg transuranics (e.g., Pu), 23 tU (0.8% U^{235}), 1.1 tonnes of fission products

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Issues for Nuclear Power: Uranium Availability

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	tonnes U	percentage of world
Australia	1,673,000	31%
Kazakhstan	651,000	12%
Canada	485,000	9%
Russia	480,000	9%
South Africa	295,000	5%
Namibia	284,000	5%
Brazil	279,000	5%
Niger	272,000	5%
USA	207,000	4%
China	171,000	3%
Jordan	112,000	2%
Uzbekistan	111,000	2%
Ukraine	105,000	2%
India	80,000	1.5%
Mongolia	49,000	1%
other	150,000	3%
World total	**5,404,000**	

Recoverable Resources of Uranium

Source: OECD NEA & IAEA, *Uranium 2009: Resources, Production and Demand* ("Red Book")

Factors to Affect the Use of Nuclear Energy Technologies

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- Operational safety record;
- Degree if nuclear weapons proliferation;
- Nuclear waste disposal success;
- Global warming and air pollution;
- Nuclear power to produce electricity and heat more efficiently;
- New technologies for medical isotopes and food irradiation;
- Cost and safety policies;
- Public concern.

Summary

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- Multiple energy sources: fossil-fuel, uranium-plutonium-thorium, wind, solar, tides, wave etc;
- Demand and production of energy mix;
- Thermal and momentum energy sources;
- Current nuclear reactor technologies;
- GenIV reactors.

Additional Reading

- **BP Statistical Review 2012:** http://www.bp.com/content/dam/bp/pdf/Statistical-Review-2012/statistical_review_of_world_energy_2012.pdf
- **International Energy Outlook 2013 (DoE/EIA-0484):** http://www.eia.gov/forecasts/ieo/pdf/0484(2013).pdf
- **Annual Energy review 2011 (DoE/EIA-0384):** http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf
- **Energy for a Sustainable Future: Reports and Recommendations (2010), The Secretary-General's Advisory Group on Energy and Climate Change (AGECC):** http://www.un.org/wcm/webdav/site/climatechange/shared/Documents/AGECC%20summary%20report%5B1%5D.pdf
- **The Economics of the Back End of the Nuclear Fuel Cycle, NEA Report No 7061:** http://www.oecd-nea.org/ndd/pubs/2013/7061-ebenfc.pdf

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