Nuclear Energy

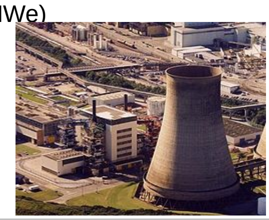
Nuclear Power - timelines

1933 - Concept of nuclear chain reaction – Hungarian Leo Szilard

1942 – First nuclear reactor built by Enrico Fermi – Chicago Pile-1

1954 – First civil nuclear reactor – AM-1 Obninsk Nuclear Power Plant (5MWe)

1956 – First "commercial" nuclear plant – Calder Hall, Sellafield (50 MWe, later 200 MWe)

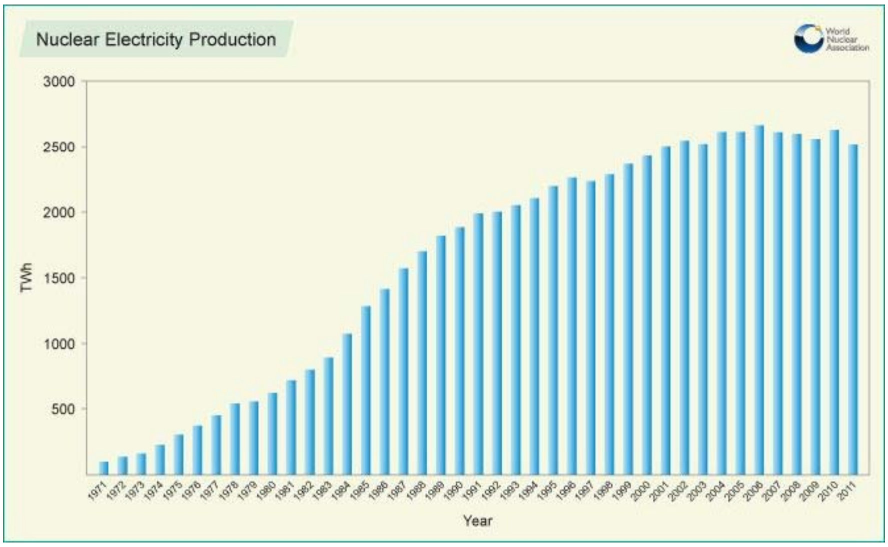


Nuclear Power in the World

- The first commercial nuclear power stations started operation in the 1950s
- There are now some 430 commercial nuclear power reactors operating in 31 countries, with 372,000 MWe of total capacity
- Mean age of reactors 27 years
- They provide about 13.5% of the world's electricity as continuous, reliable base-load power, and their efficiency is increasing
- 56 countries operate a total of about 240 research reactors reactors
- 180 reactors power ships and submarines

EG5066 Energy Technologies: current issues & future directions

Nuclear Electricity Production



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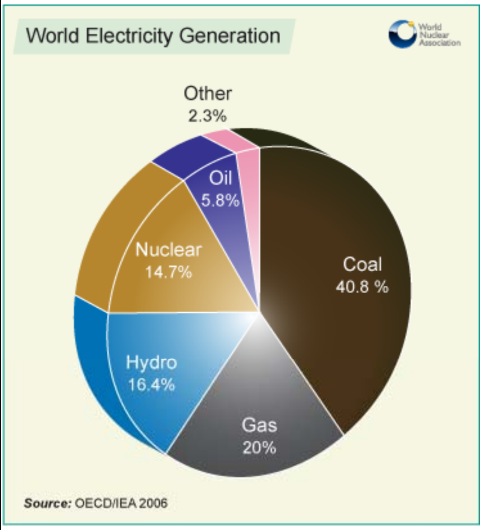
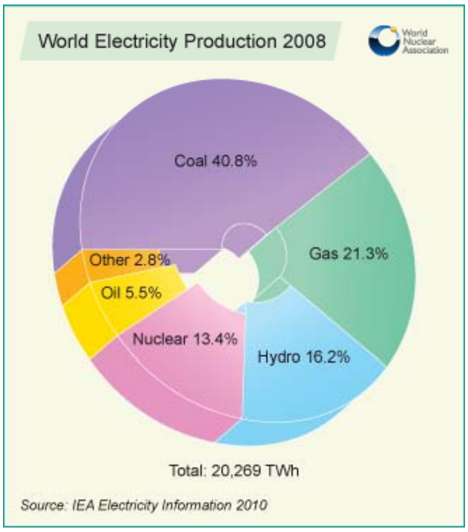
World Nuclear Electricity





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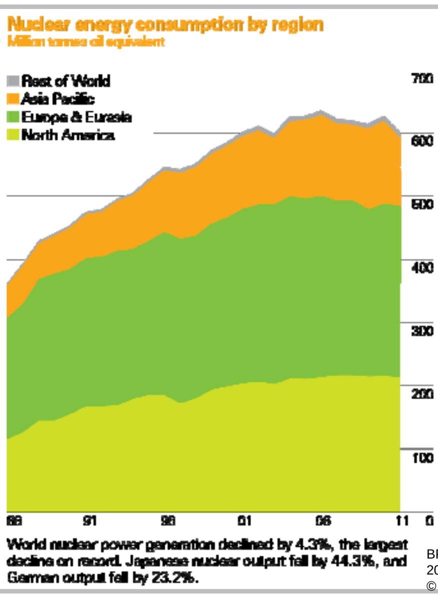
Nuclear energy consumption by region 2011



BP Statistical Review of World Energy 2012

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Nuclear Consumption (Mtoe)

	1965	1975	1985	1995	2005	2010
North America	0.9	43.8	105.1	184.5	209.2	213.8
S & C America	-	0.5	2.1	2.2	3.7	4.9
Europe & Eurasia	4.9	32.6	181.1	243.7	286.3	272.9
Middle East	-	-	-	-	-	-
Africa	-	-	1.3	2.7	2.9	3.1
Asia Pacific	-	5.5	45.8	93.0	125.0	131.7
World	**5.8**	**82.4**	**335.3**	**526.1**	**627.2**	**626.3**

Source: BP 2012

Nuclear Consumption (TWh)

	1970	1980	1990	2000	2010
North America	23.0	300.1	682.6	874.1	945.0
S & C America	-	2.3	9.5	12.2	21.6
Europe & Eurasia	49.8	312.2	1013.0	1181.7	1205.9
Middle East	-	-	-	-	-
Africa	-	-	8.9	13.7	13.5
Asia Pacific	4.6	96.8	288.3	500.7	582.1
World	**77.3**	**711.4**	**2002.3**	**2582.4**	**2768.1**

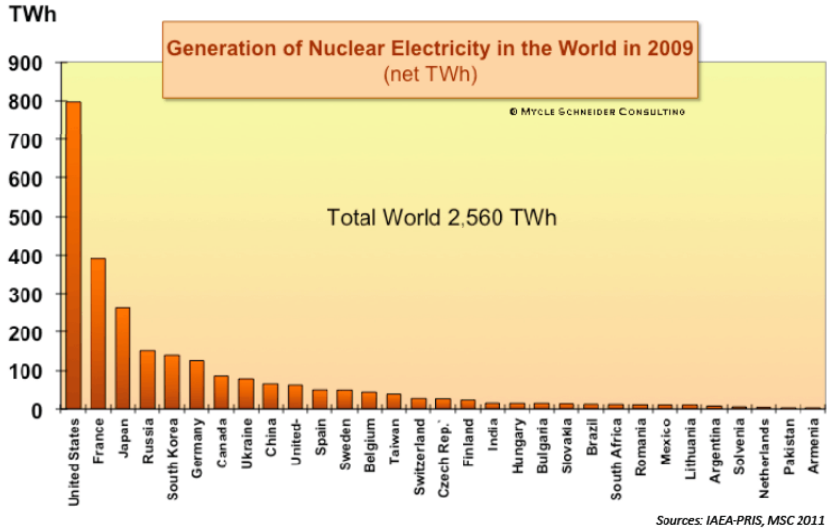
Source: BP 2012

Nuclear Consumption (Mtoe)

	1965	1975	1985	1995	2005	2010
USA	0.9	41.1	91.4	160.4	185.9	192.2
France	0.2	4.1	50.7	85.4	102.4	96.9
S Africa	-	-	1.3	2.7	2.9	3.1
China	-	-	-	2.9	11.8	16.7
India	-	0.5	1.0	1.7	4.0	5.2
Japan	-	4.9	34.4	65.1	66.3	66.2
S Korea	-	-	3.8	12.7	33.2	33.6

Source: BP 2012

Nuclear Electricity Production



Nuclear

Big 6 countries provide 70% of generation

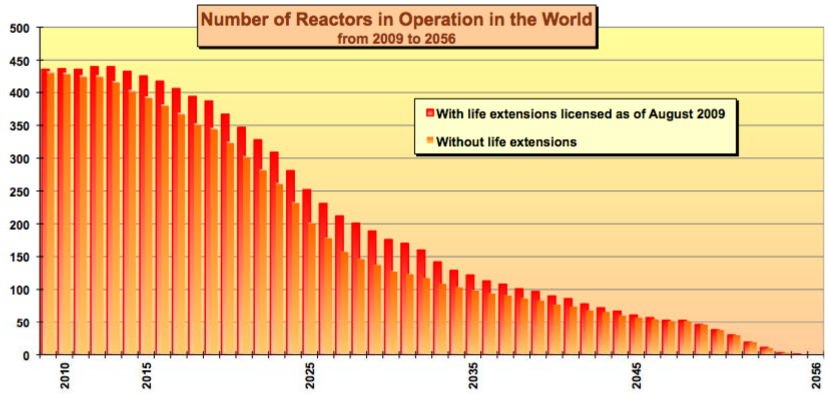
	No Reactors	Capacity (Mwe)	Average age (y)	Share Electricity	Share Energy
France	58	63130	27	78	41
Germany	9	12068	27	18	8
Japan	44	38120	25	18	8
Russia	33	23643	29	18	6
S Korea	21	18657	17	35	13
USA	104	101465	33	19	8

World Nuclear Power September 2012

Reactors	No	Production (MWe)
Operable	433	372,010
Under construction	65	64, 979
Planned	160	177,915
Proposed	323	366,415

Tonnes of Uranium required in 2012 **67,990**

World Nuclear Power to 2056

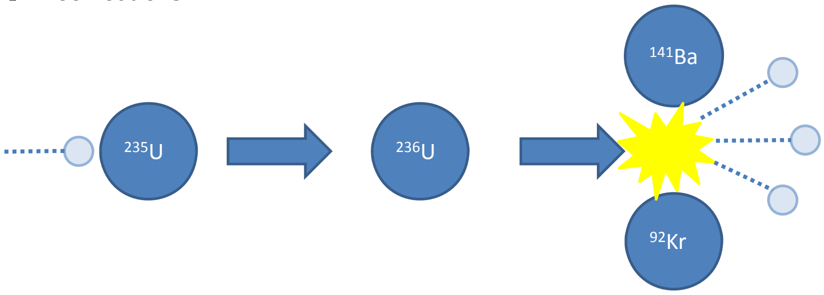


Fission

When a relatively large fissile atomic nucleus (uranium-235, plutonium-239 or plutonium-241) absorbs a neutron it is likely to undergo nuclear fission

The original heavy nucleus splits into two or more lighter nuclei, releasing fission products:

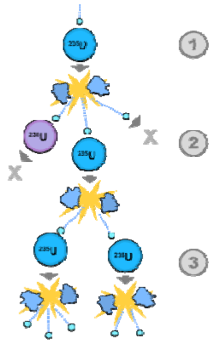
- Kinetic energy
- Gamma radiation
- Free neutrons



Chain reaction

Chain reaction controlled by:

- Neutron poisons – e.g. control rods
- Neutron moderators – e.g. heavy water



Cooling system

- Removes heat from reactor core and used to produce heat of other useful work
- Hot coolant used as heat source for a boiler and pressurised steam drives electrical generators

Common Components of Reactors

Fuel

- Usually pellets of uranium oxide arranged in tubes to form fuel rods
- Rods arranged into fuel assemblies in the reactor core

Moderator

- Material in the core which slows neutrons released from fission
- Usually water, sometimes heavy water or graphite

Control rods

- Neutron absorbing material e.g. cadmium, hafnium, boron
- Inserted or withdrawn from the core to control the rate of reaction or to halt it

Common Components of Reactors

Coolant

- A liquid or gas circulating through the core to transfer heat from it
- In light water reactors the water moderator functions also as primary coolant
- Except in BWRs there is a secondary coolant circuit where the steam is made

Pressure vessel or pressure tubes

- Usually a robust steel vessel containing the reactor core & moderator/coolant
- May be a series of tubes holding the fuel and conveying the coolant through the moderator

Common Components of Reactors

Steam generator

- Part of the cooling system where the primary coolant bringing heat from the reactor is used to make steam for the turbine

Containment

- Structure around the reactor core designed to protect it from outside intrusion and protect those outside from effects of radiation in case of a malfunction
- typically a metre-thick concrete and steel structure

Fission

Nuclear chain reaction controlled by neutron poisons and neutron moderators:

Poisons:

- Control rods
- Boron

Moderators:

- Light water (75% of world's reactors)
- Solid graphite (20% of reactors)
- Heavy water (5%)

Types of Reactor

- Pressurized water reactors (PWR)
- Boiling Water Reactor (BWR)
- Pressurized Heavy Water Reactor (PHWR)
- Advanced Gas-cooled Reactor (AGR)
- High Power Channel Reactor (RBMK)
- Fast Neutron Reactor (FBR)

Types of Fission Reactor

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

Nuclear Power Plant in Commercial Operation (2008)

Reactor Type	Main Countries	Number	GWe	Fuel	Coolant	Moderator
Pressurised water reactor (PWR)	US, France, Japan, Russia, China	265	251.6	Enriched UO_2	Water	Water
Boiling Water Reactor (BWR)	US, Japan, Sweden	94	86.4	Enriched UO_2	Water	Water
Pressurised heavy water reactor “Candu”	Canada	44	24.3	Natural UO_2	Heavy water	Heavy Water
Gas cooled reactor (AGR & Magnox)	UK	18	10.8	Natural U Enriched UO_2	CO_2	Graphite
Light water graphite reactor (RBMK)	Russia	12	12.3	Enriched UO_2	Water	Graphite
Fast neutron reactor (FBR)	Japan, France, Russia	4	1	PuO_2 & UO_2	Liquid Sodium	None

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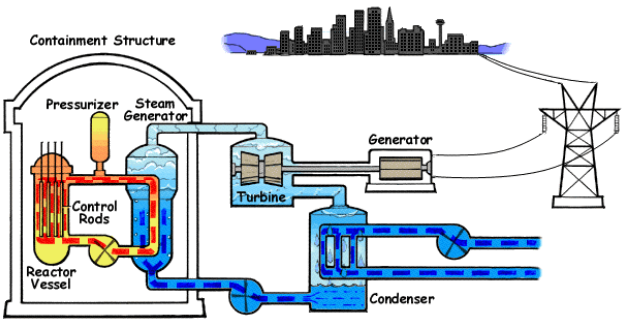
Reactor Type	Thermal Power (MW/m³)	Yield (%)
Magnox	1	30
AGCR	2	41
PWR, VVER	100	33
BWR	50	33
Candu	12	29
FBR	500	40
HTR*	8	>45

* High temperature reactor, a generation IV prototype

Source: Ngo & Natowitz, 2009

Pressurized Water Reactor

- Main type of Light Water Reactor
- In contrast to boiling water reactor the primary coolant loop is superheated water under high pressure
- Use ordinary light water as both coolant & moderator




Diablo Canyon Power Plant


PWR Reactor Vessel heads

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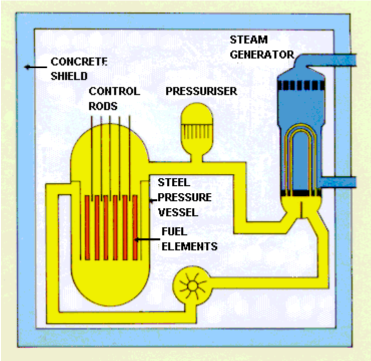
Pressurised Water Reactors (PWRs)

- Based on US technology
- Most common reactor type used in the world
- Reactor is contained in a steel pressure vessel
- Pressurised water (moderator & coolant) pumped around reactor & through boilers
- 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, which also acts as a biological shield.
- Remainder of the generation process is similar to that for other power stations.



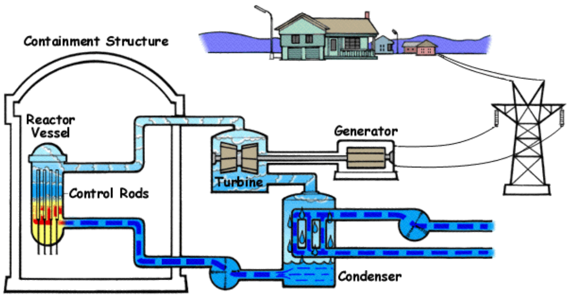
Source: DECC

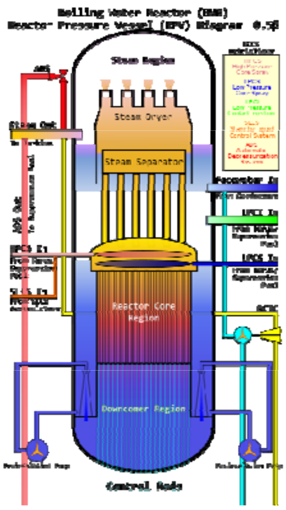
Boiling Water Reactor

- 2nd most common reactor
- Ordinary water used as moderator & coolant
- Operates at low pressure which allows water to boil
- No separate secondary steam cycle
- Water from reactor converted to steam & used to directly drive the generator turbine

Laguna Verde Nuclear power plant, Mexico

Boiling Water Reactor





Pressurized Heavy Water Reactors (PHWR)

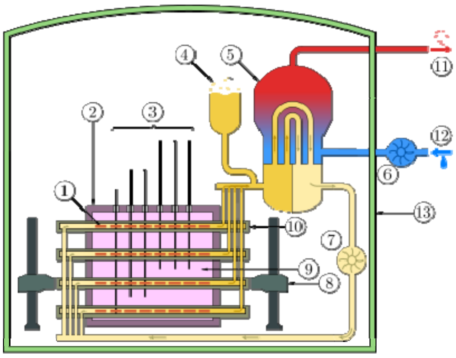
CANDU Reactor

- Canadian invented pressurized heavy water reactor late 1950s & 1960s
- CANada Deuterium Uranium – deuterium-oxide (heavy water) moderator and Uranium

CANDU Bruce Nuclear Reactor
Second largest plant in the world.

Fuel bundles

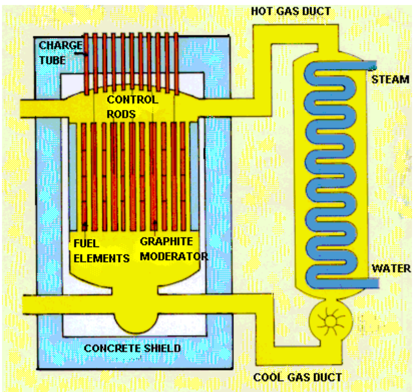
CANDU Reactor



1 - Fuel bundle
2 - Calandria (reactor core)
5 - Steam generator
9 - Heavy water moderator

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

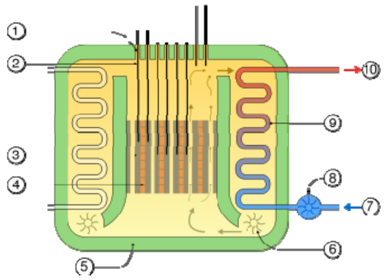


Source: DECC

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

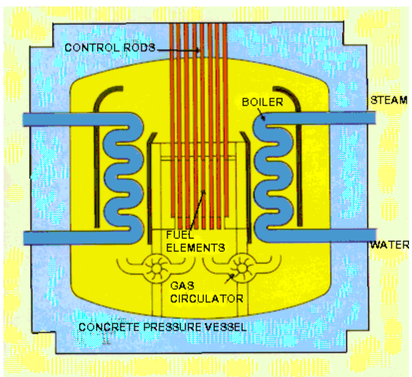
Torness



1. Charge tubes
2. Control rods
3. Graphite moderator
4. Fuel assemblies
5. Concrete pressure vessel & radiation shielding
6. Gas circulator
7. Water
8. Water circulator
9. Heat exchanger
10. Steam

Advanced gas-cooled reactor (AGR)

- Successor to the Magnox reactors & unique to the UK
- Use enriched uranium clad stainless steel cans
- Also have a graphite moderator and use pressurised CO_2 as the coolant.
- These allow the AGRs to operate at a higher temperature than the Magnox reactor.
- Reactor is encased in a steel-lined pre-stressed concrete pressure vessel several metres thick which acts as the biological shield, with the boilers inside.
- 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.

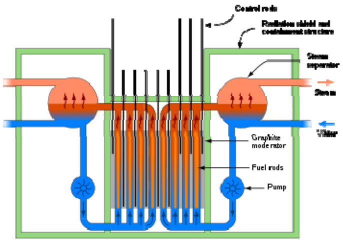


Source: DECC

RBMK Reactors

- Russian High Power Channel Type Reactor
- 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



Chernobyl

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

Generations of Nuclear Plants

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

Shippingport
Dresden
Fermi
Magnox

LWR-PWR, BWR
CANDU
WER/RBMK

ABWR
System 80+
AP600
EPR

Evolutionary designs with improved economics

Generation I | Generation II | Generation III | Generation III+ | Gen IV

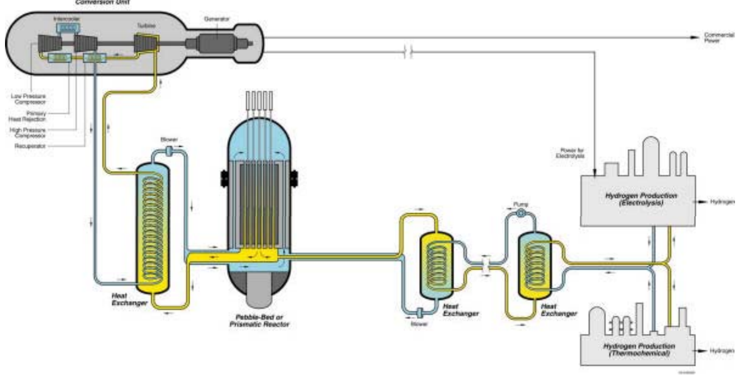
1950 1960 1970 1980 1990 2000 2010 2020 2030

Generation IV Nuclear Energy Systems

- Very High Temperature Reactor (VHTR)
- Super Critical Water Cooled Reactor (SCWCR)
- Gas Cooled Fast Reactor (GCFR)
- Lead Cooled Fast Reactor (LCFR)
- Sodium Cooled Fast Reactor (SCFR)
- Molten Salt Reactor (MSR)

Very-High-Temperature Reactor (VHTR)

- Graphite-moderated
- Helium-cooled
- Once-through uranium fuel cycle.
- Supplies heat with high core outlet temperatures which enables applications such as hydrogen production or process heat for the petrochemical industry or others



Source: Idaho National Laboratory

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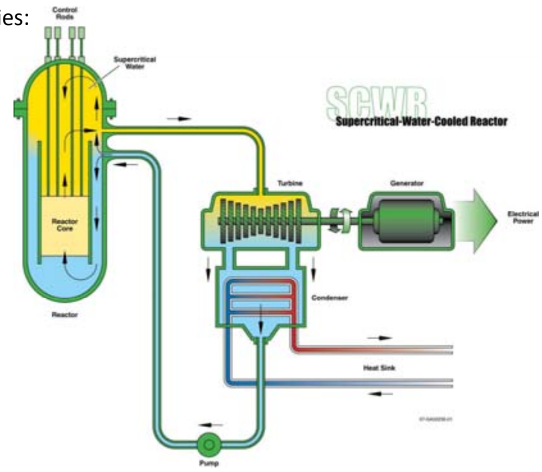
Supercritical-Water-Cooled Reactor (SCWR)

- High-temperature, high-pressure water cooled reactor that operates above the thermodynamic critical point of water (374Â°C, 22 MPa)
- Built upon two proven technologies:
- Light Water Reactors (LWRs)
- Supercritical fossil-fired boilers



Source: Idaho National Laboratory

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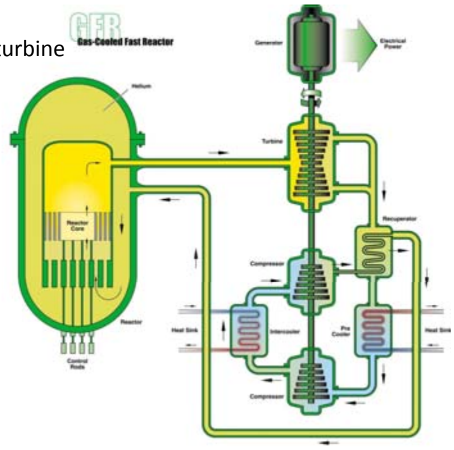
Gas-Cooled Fast Reactor (GFR)

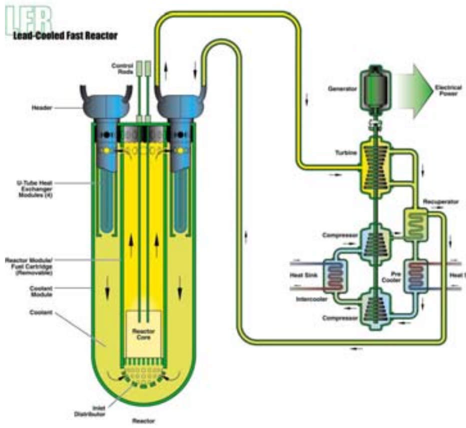
- Features a fast-spectrum, helium-cooled reactor and closed fuel cycle.
- Main characteristics:
  - a self-generating core (i.e., conversion ratio = 1) with a fast neutron spectrum
  - robust refractory fuel
  - high operating temperature
  - direct energy conversion with a gas turbine
  - full actinide recycling



Source: Idaho National Laboratory

Lead-Cooled Fast Reactor (LFR)

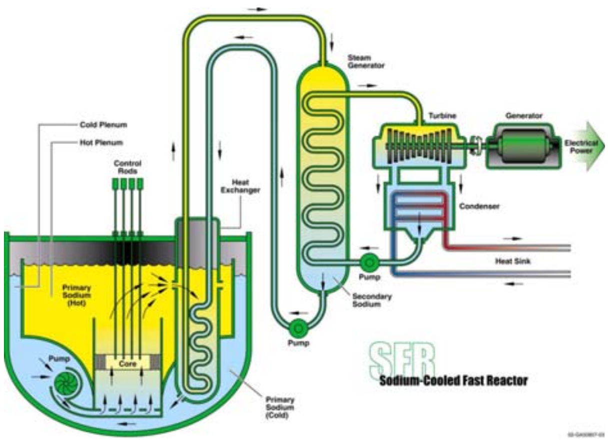
Features a fast-spectrum lead or lead/bismuth eutectic liquid metal-cooled reactor and a closed fuel cycle for efficient conversion of fertile uranium and management of actinides.



Source: Idaho National Laboratory

Sodium-Cooled Fast Reactor (SFR)

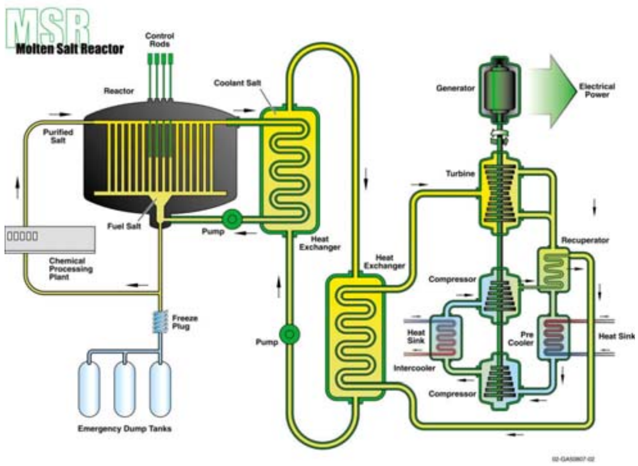
Features a fast-spectrum, sodium-cooled reactor and a closed fuel cycle for efficient management of actinides and conversion of fertile uranium.



Source: Idaho National Laboratory

Molten Salt Reactors (MSRs)

Liquid-fueled reactors that can be used for production of electricity, actinide burning, production of hydrogen, and production of fissile fuels.



Source: Idaho National Laboratory

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

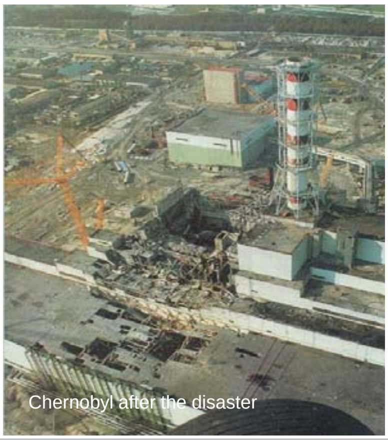

Windscale Fire


Three Mile Island

Issues for Nuclear Power

Safety

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



Chernobyl after the disaster

Fukushima Daiichi Nuclear Disaster

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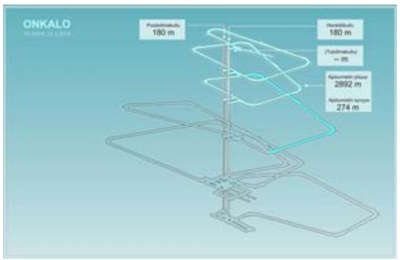
Issues for Nuclear Power

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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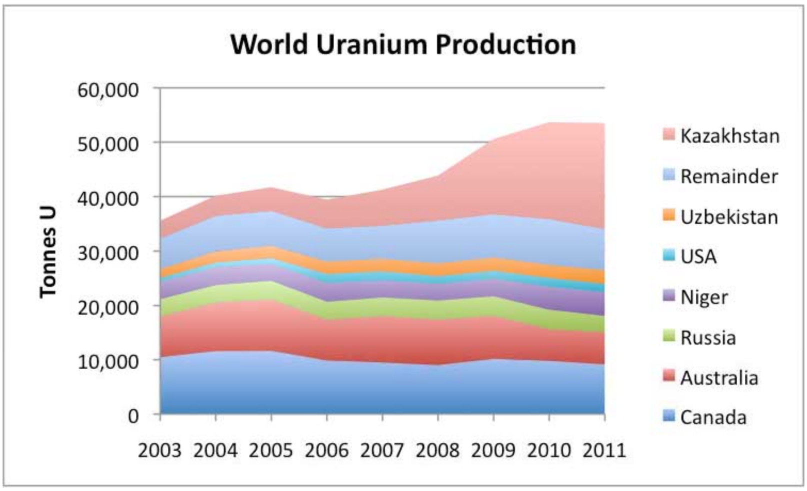
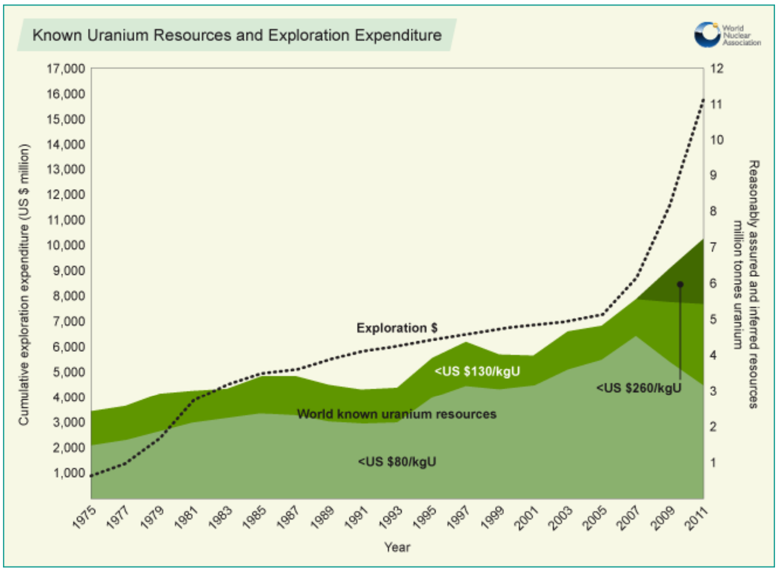
Known Recoverable Resources of Uranium

- Uranium is abundant in the earth's crust as tin or zinc
- Uranium occurs in many kinds of chemical compounds, minerals & rocks
- Uranium ore is an uranium containing deposit from which uranium can be extracted economically
- Known amount of ore depends on market prices
- Known recoverable = RAR + EAR
  - RAR = Reasonable Assured Resources
  - EAR = Estimated Additional Resources
- Figures on next slide based on 130US$/kgU
- Current Fleet is 372 GW which uses 6800 tonnes uranium per annum
- Estimates indicate that exploitable reserves of uranium will have been depleted by 2070

Resources of Uranium



Resources of Uranium



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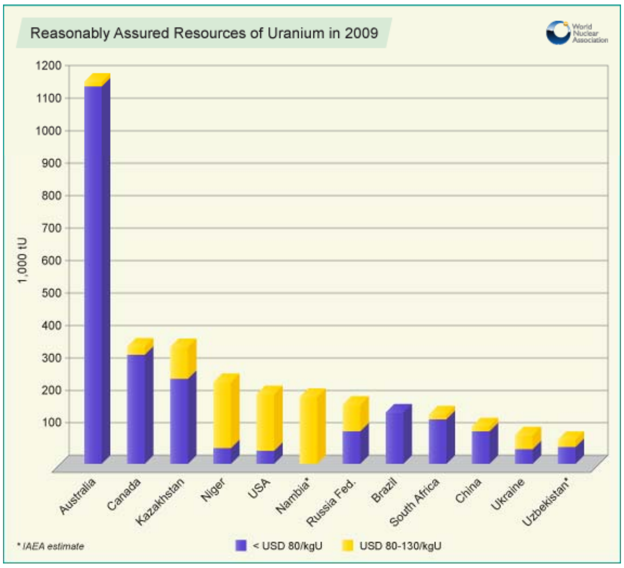
Resources of Uranium



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Known Recoverable Resources of Uranium 2011

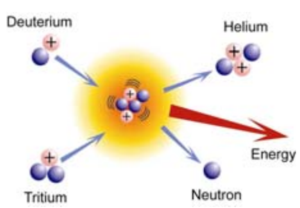
Country	K tonnes	%
Australia	1,661	31
Kazakhstan	629	12
Russia	487	9
Canada	469	9
Niger	421	8
South Africa	279	5
Nambia	261	5
Brazil	263	5
USA	207	4
China	166	3
Ukraine	120	2
Uzbekistan	96	2
World	**5327**	

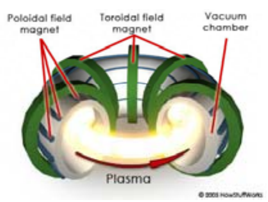
EG5066 Energy Technologies: current issues & future directions

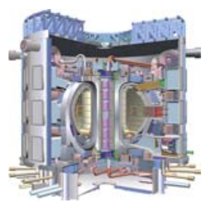
Nuclear fusion

Fusion power offers the prospect of an almost inexhaustible source of energy for future generations, but it also presents so far insurmountable scientific and engineering challenges.

The main hope is centred on tokamak reactors which confine a deuterium-tritium plasma magnetically.







EG5066 Energy Technologies: current issues & future directions

Thorium Cycle

- Naturally occurring, slightly radioactive metal discovered in 1828 by Swedish chemist Jons Jakob Berzelius
- 3 times more abundant than uranium
- Mainly obtained from monazite sands (a rare earth phosphate mineral)
- Single isotope – ^{232}Th
- In reactor captures a neutron and converted to ^{233}U
- ^{233}U undergoes fission like ^{235}U and ^{239}Pu but releases more neutrons
- Amount of transuranic waste vastly decreased *cf* uranium/plutonium-based reactors

- Used in India's nuclear programme
  - Have 25% of world's thorium reserves
  - Kakrapar-1 first thorium reactor
  - Developing a 3 stage thorium fuel cycle
  - Developing a 300MWe thorium-based Advanced Heavy Water Reactor (AHWR)

Thorium

Advantages

- An abundant resource
- Production of power with few long-lived transuranic elements in the waste
- Reduced radioactive wastes generally

Problems

- High cost of fuel fabrication, due partly to the high radioactivity of ^{233}U chemically separated from the irradiated thorium fuel
- Similar problems in recycling thorium due to highly radioactive ^{228}Th (an alpha emitter with a 2 year half life) present
- Concern over weapons proliferation risk of ^{233}U
- Technical problems in reprocessing solid fuels but may disappear with development of molten salt reactor (MSR)
- Long-lived actinides produced that constitute a long-term radiological impact (eg ^{231}Pa)

Thorium

Country	Reserves (k tonnes)	Percentage
India	846	16
Turkey	744	14
Brazil	606	11
Australia	521	10
USA	434	8
Egypt	380	7
Norway	320	6
Venezuela	300	6
World	5385	

Source: NEA 2011

Nuclear Power in the UK

- The UK has 16 reactors at 9 plants generating 16% of its electricity and all but 2 will be retired by 2023
- 14 AGRs, 1 Magnox & 1 PWR operating
- At peak in 1997 generated 26% of electricity
- First commercial nuclear power reactor in 1956
- Has full fuel cycling facilities, including major reprocessing plants
- UK Government commitment to the future of nuclear energy is firm
- New generation plants expected to be on line about 2017?
- Scottish Government is strongly anti-nuclear

Nuclear Power Reactors Operating in UK

Reactor	Operator	Type	Net Capacity	Start	Shutdown
Wylfa 1&2	Magnox	Magnox	980	1972	End 2012
Dungeness B 1&2	EDF	AGR	1110	1985	2018
Hartlepool 1&2	EDF	AGR	1210	1989	2019
Heysham 1	EDF	AGR	1150	1989	2019
Heysham 2	EDF	AGR	1250	1989	2023
Hinkley Point B 1&2	EDF	AGR	1220	1976	2016
Hunterson B	EDF	AGR	1190	1976	2016
Torness 1&2	EDF	AGR	1250	1988	2023
Sizewell B	EDF	PWR	1188	1995	2035

Nuclear Power Reactors Retired in UK

Power Station	Type	Net MWe	Start	Close
Calder Hall	Magnox	200	1959	2003
Chapelcross	Magnox	240	1960	2004
Berkeley	Magnox	276	1962	2004
Bradwell	Magnox	246	1962	1989
Hunterston A	Magnox	300	1964	1990
Hinkley Point A	Magnox	470	1965	2000
Trawsfynydd	Magnox	390	1965	1991
Dungeness A	Magnox	450	1965	2006
Sizewell A	Magnox	420	1966	2006
Oldbury	Magnox	434	1968	2012

Future of Nuclear Power in UK

November 2009 UK government identified 10 nuclear sites for future reactors, reduced to 8 in 2010:

- Bradwell in Essex
- Sellafield in Cumbria
- Hartlepool ion County Durham
- Heysham in Lancashire
- Hinkley Point in Somerset
- Oldbury in Gloucestershire
- Sizewell in Suffolk
- Wyfla in North Wales