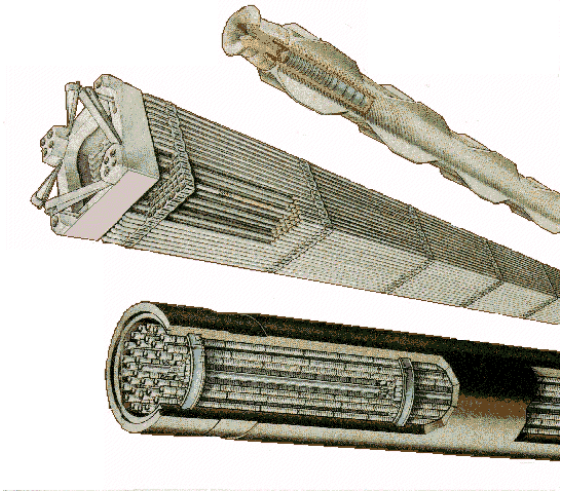
ENV-5022B Low Carbon Energy 2018

http://www2.env.uea.ac.uk/energy/energy.htm
http://www.uea.ac.uk/~e680/energy/energy.htm

Sizewell B Nuclear Power Station – the UK's only Pressurised Water Reactor



Nuclear Fuel Assemblies

Top: MAGNOX
Middle: PWR
Bottom AGR

Section 0: Background for Nuclear Power in UK Electricity Generation
Section 1: Nuclear Power – The basics
Section 2: Nuclear Reactors
Section 3: Nuclear Fuel Cycle
Section 4: Nuclear Fusion
Section 5: Notes written relating to Fukushima Incident in March 2011 [from 2017 this is incorporated as a separate file – see Website above]

This handout is based on the handouts used in previous years when Nuclear Power issues were covered in more depth and thus covers a fuller account of the topic over and above that covered explicitly in the lectures.
Copies of this handout and also the actual PowwerPoint Presentations may be found on the WEB Site

https://archive.uea.ac.uk/~e680/energy/ENV-5022B/env-5022B_nuclear_power_2018.pdf

There are also links on that WEBSITE to the recent Government White Papers including the very recent NUCLEAR POWER WHITE PAPER.

Another WEBSITE of relevance is http://www2.env.uea.ac.uk/energy/energy.htm

Background for Nuclear Power in UK Electricity Generation

The Paris Agreement on Climate Change in December 2015 set a target limiting the increase in global temperatures to 2°C and to achieve this significant changes in the way energy is extracted, converted, and used will be required over te next 30 years, While several countries are making noticeable strides in reducing carbon emissions associated with electricity, much less progress has been made in reducing carbon emissions in the transport and heat sectors and to decarbonise the overall economy it will be necessary to tackle these other fuel vectors through fuel witching etc. Thus deployment of electric heat pumps for space and industrial heating applications would reduce energy demand and also the consequential carbon emissions even though the demand for electricity generation could increase significantly. Similarly the development of electric vehicles or vehicles power directly (or indirectly) via hydrogen would reduce carbon emissions and reduce pollution, but would also see an increase in electricity demand including the situation if hydrogen is used as an intermediate energy vector.

The UK Electricity Generating sector reached severable notable milestones in 2016 – 17 and in particular there has been a significant reduction in the electricity generation carbon factor from over 500 gm/kWh in 2012 to under 250 gm/kWh.

The carbon factor for electricity generation depends on 1) the fuel used and in particular its carbon content, and (2) the efficiency of the plant and 3) the technology used.. For stations using steam as te intermediate vector, the maximum practical thrermodynamic efficiency is approximately 35 – 40% although can be lower if pollution combating facilities uch as flue gas desulpurisatuin are included. The current generation of cola fired stations has had an average efficiency of 34.1% over the last 20 years. Table 1 illustrates the approximate carbon emission factors for different fuels.

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Table 1. Operational Carbon Emission Factors for electricity Generation by different fuels.

Generation	gms CO / kWH[2]	Comments
Coal	900 – 1100	750 – 900 with supercritical coal
Coal with CCS	~ 100	
Gas (Steam)	~ 600	
Gas CCGT	360 – 440	
GAS CCGT with CCS	40	Latest information suggests that CH_4 pipe line leakages increases impact to around 80+ gms/kWh
Nuclear	5 - 20	Depending on reactor type and enrichment needed.
Renewables	<10	Biomass will significantlybe higher

The overall carbon emission factor for electricity generation in the UK in 2010 was 540 gms/kWh but with the significant closure of coal stations in the last few years, the figure has fallen to below 250gm/ kWh. This significant reduction has been achieved with the reduced use of coal which is a high carbon fuel and is limited in thermodynamic efficiency..

In the future low carbon generation is needed for all generation and options include:

i). Carbon Capture nd Sequestration,
ii). Nuclear
iii). Renewables

To date, despite £1billion incentives from Government there has been no development of CCS for coal, and there has been no discussion at all for CCS with Gas.

Figure 1 shows the historic carbon factors since 1970 and projected future one to 2030. There are two principle scenarios for future generation with and without nuclear generation or new CCS coal. Aas explained further in Figure 3. The projections follow current government Policy and plans not to consider CCS with gas but to expand renewables significantly. Without new nuclear, the carbon emission factor will only slightly fall in future as without nuclear increased gas use will occur.

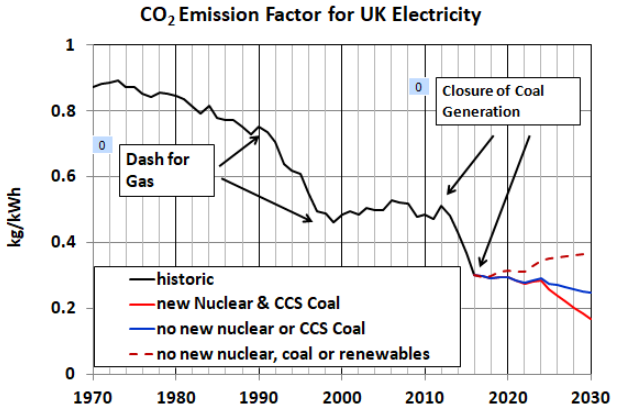

Figure 1. Historic and projected overall carbon emission factors for electricity generation in the UK. Without new nuclear or substantially increased renewable energy, further reduction in carbon factor below 2017 level is limited.

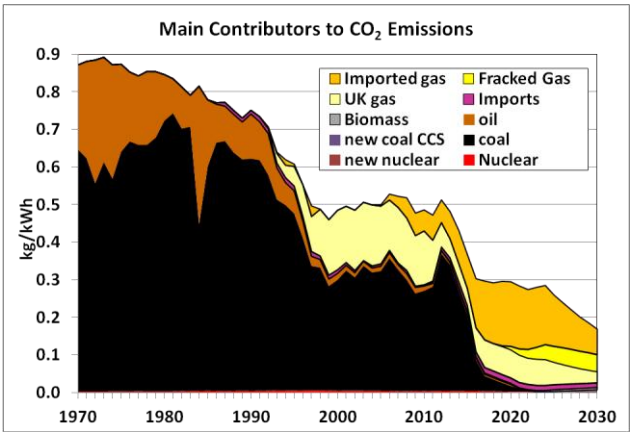

Figure 2. Component parts of the carbon emission factor showing dominance of coal until 2012.

While there has been a significant reduction in CO_2 emissions associated with electricity generation in the last 4 – 5 years, and the UK has one of the highest reductions in CO_2 over all sectors since the Paris Agreement, changes in government policy and the current reluctance to consider CCS for gas generation will mean that future reductions will be limited and the UK is likely to loose its position as one of the leading nations combating climate change.

Figure 3 shows the historic and projected contributions to fuelling electricity generation up to 2030 based on current trends. It is these projections that are also used in Figures 1 and 2.

The following used for projected generation are:

i). The completion of one new nuclear reactor and one new coal station with CCS each year after 2025.
ii). Equivalent of one million homes fitted with PV each year from 2020 or 40% of homes fitted by 2030
iii). 19 GW of onshore wind by 2030 compared to 11 GW in 2016 and 20GW of offshore compared to 5.3 GW
iv). Projected future demand follows projections of Climate Chhange Committee and sees increased deployment of heat pumps and electric vehicles.
v). The proections for use of "Fracked Gas" aare based on projections of Cuadrillla

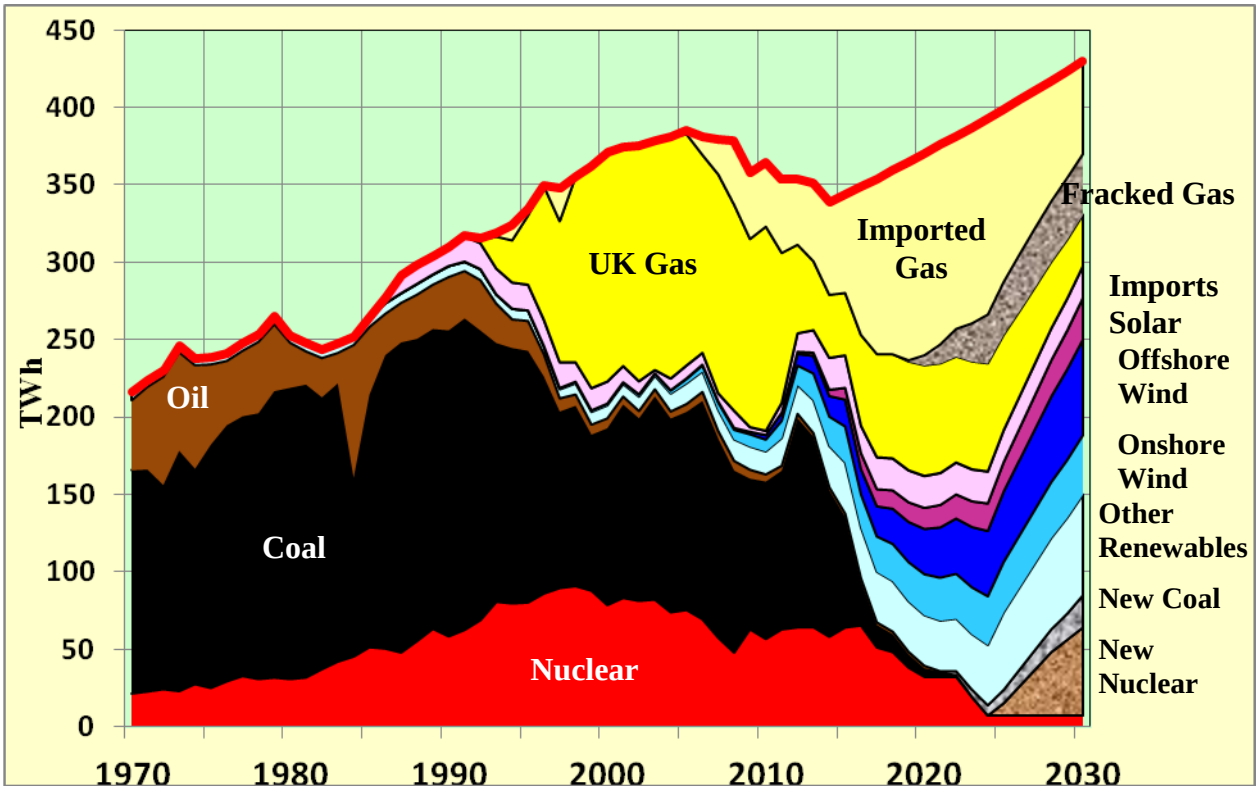

Figure 3. Historic and Projected generation mix for electricity production in the UK. Historic Data abstracted from Digest of UK Energy Statistics. Future generation according to text above.

1. NUCLEAR POWER – The Basics

1.0 General information

Copies of this handout and also the actual PowwerPoint Presentations may be found on the WEB Site

http://www2.env.uea.ac.uk/energy/nbs-m018/nbs-m018.htm

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1.1 NATURE OF RADIOACTIVITY - Structure of Atoms.

Matter is composed of atoms which consist primarily of a nucleus of positively charged **PROTONS** and (electrically neutral) **NEUTRONS.** This nucleus is surrounded by a cloud of negatively charged **ELECTRONS** which balance the charge from the **PROTONS.**

PROTONS and NEUTRONS have approximately the same mass, but **ELECTRONS** are about 0.0005 times the mass of the **PROTON.**

A NUCLEON refers to either a **PROTON or a NEUTRON**

Different elements are characterised by the number of **PROTONS** present thus the **HYDROGEN** nucleus has **1 PROTON** while **OXYGEN** has **8 PROTONS** and **URANIUM** has **92.** The number of **PROTONS** is known as the **ATOMIC NUMBER (Z),** while **N** denotes the number of **NEUTRONS.**

The number of neutrons present in any element varies. Thus it is possible to have a number of ISOTOPES of the same element. Thus there are 3 isotopes of hydrogen all of which have 1 PROTON:-

- **HYDROGEN i**tself with NO NEUTRONS
- **DEUTERIUM** (heavy hydrogen) with 1 NEUTRON
- **TRITIUM** with 2 NEUTRONS.

Of these only **TRITIUM** is radioactive.

UNSTABLE or radioactive isotopes arises if the Z differs significantly from N. For the heavy elements e.g. Z > 82, most nuclei become unstable and will decay by the emission of various particles or radiation into a more stab**le nucleus.**

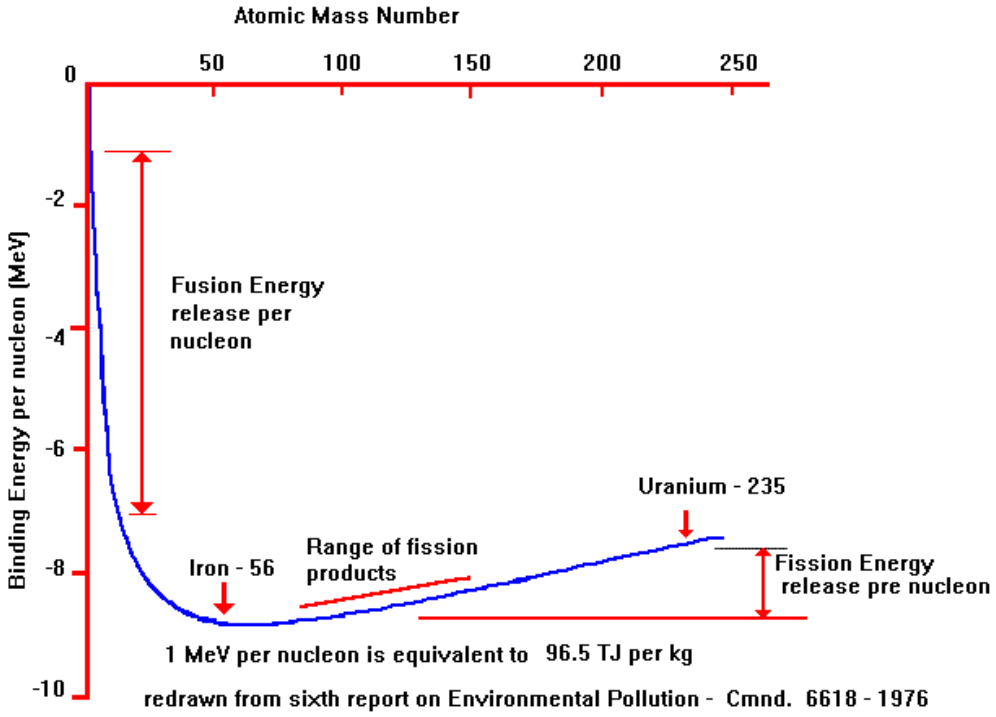

Fig. 1.1 Energy Binding Curve

- **The energy released per fusion reaction is much greater than the corresponding fission reaction.**
- **In fission there is no single fission product but a broad range as indicated.**

1.2 NATURE OF RADIOACTIVITY - Radioactive emissions.

There are **FOUR t**ypes of radiation to consider:-

1) **ALPHA** particles - large particles consisting of **2 PROTONS and 2 NEUTRONS**
   i.e. the nucleus of a **HELIUM atom.**
2) **BETA** particles which are **ELECTRONS**
3) **GAMMA - RAYS.** These arise when the kinetic energy of Alpha and Beta particles is lost passing through the electron clouds of other atoms. Some of this energy may be used to break chemical bonds while some is converted into **GAMMA -RAYS** which are similar to **X -RAYS,** but are usually of a shorter wavelength.
4) **X - RAYS.** Alpha and Beta particles, and also gamma-rays may temporarily dislodge ELECTRONS from their normal orbits. As the electrons jump back they emit X-Rays which are characteristic of the element which has been excited.

UNSTABLE nuclei emit Alpha or Beta particles in an attempt to become more stable. When an ALPHA particle is emitted, the new element will have an ATOMIC NUMBER two less than the original. While if an ELECTRON is emitted as a result of a NEUTRON transmuting into a PROTON, an isotope of the element ONE HIGHER in the PERIODIC TABLE will result. Thus ^{235}U consisting of 92 PROTONS and 143 NEUTRONS is one of SIX isotopes of URANIUM decays as follows:-

$$^{235}\mathbf{U} \xrightarrow{\text{alpha}} {}^{231}\mathbf{Th} \xrightarrow{\text{beta}} {}^{231}\mathbf{Pa} \xrightarrow{\text{alpha}} {}^{227}\mathbf{Ac}$$

URANIUM THORIUM PROTACTINIUM ACTINIUM

Thereafter the ACTINIUM - 227 decays by further alpha and beta particle emissions to LEAD - 207 (^{207}**Pb**) which is stable. Similarly two other naturally occurring radioactive decay series exist. One beginning with ^{238}**U**, and the other with ^{232}**Th**. Both of these series also decay to stable (but different) isotopes of LEAD.

1.3 HALF LIFE.

Time taken for half the remaining atoms of an element to undergo their first decay e.g.:-

^{238}**U** 4.5 billion years
^{235}**U** 0.7 billion years
^{232}**Th** 14 billion years

All of the daughter products in the respective decay series have much shorter half - lives some as short as 10^{-7} seconds.

When 10 half-lives have expired, the remaining number of atoms is less than 0.1% of the original.

1.4 FISSION

Some very heavy UNSTABLE elements exhibit FISSION where the nucleus breaks down into two or three fragments accompanied by a few free neutrons and the release of very large quantities of energy. Other elements may be induced to FISSION by the capture of a neutron. The fragments from the fission process usually have an atomic mass number (i.e. N+Z) close to that of iron.

Elements which undergo FISSION following capture of a neutron such as URANIUM - 235 are known as FISSILE.

Diagrams of Atomic Mass Number against binding energy per NUCLEON show a minimum at about IRON - 56 and it is possible to estimate the energy released during FISSION from the difference in the specific binding energy between say URANIUM - 235 and its FISSION PRODUCTS.

All Nuclear Power Plants currently exploit FISSION reactions, and the FISSION of 1 kg of URANIUM produces as much energy as burning 3000 tonnes of coal.

[The original atomic weapons were Fission devices with the Hiroshima device being a ^{235}**U** device and the Nagasaki bomb being a ^{239}**Pu** device.]

1.5 FUSION

If two light elements e.g. DEUTERIUM and TRITIUM can be made to fuse together then even greater quantities of energy per nucleon are released (see diagram).

The sun's energy is derived from FUSION reactions, and despite extensive research no FUSION reactor has yet been a net producer of power in a commercial sense. Vast quantities of energy are needed to initiate fusion. 10 years ago, the input energy was around 10 000 times that output. Recent developments at the JET facility in Oxfordshire have achieved the break even point.

[The current generation of nuclear weapons are FUSION devices.]

1.6 CHAIN REACTIONS

FISSION of URANIUM - 235 yields 2 - 3 free neutrons. If exactly ONE of these triggers a further FISSION, then a chain reaction occurs, and contiguous power can be generated. **UNLESS DESIGNED CAREFULLY, THE FREE NEUTRONS WILL BE LOST AND THE CHAIN REACTION WILL STOP.**

If more than one neutron creates a new fission the reaction would be super-critical (or in layman's terms a bomb would have been created).

It is very difficult to sustain a chain reaction, and to create a bomg, the Uranium-235 must be highly enriched > 93%, and be larger than a critical size otherwise neutrons are lost.

Atomic weapons are made by using a conventional explosive to bring two sub-critical masses of a fissile material together for sufficient time for a super critical reaction to take place.

NUCLEAR POWER PLANTS <u>CANNOT</u> EXPLODE LIKE AN ATOMIC BOMB.

1.7 FERTILE MATERIALS

Some elements like URANIUM - 238 are not FISSILE, but can transmute as follows:-

$$^{238}U + n \xrightarrow{} {}^{239}U \xrightarrow{\text{beta}} {}^{239}Np \xrightarrow{\text{beta}} {}^{239}Pu$$

Uranium - 238	Uranium - 239	Neptunium - 239	Plutonium - 239

The last of these PLUTONIUM - 239 is FISSILE and may be used in place of URANIUM - 235.

Materials which can be converted into FISSILE materials are FERTILE. URANIUM - 238 is such a material as is THORIUM - 232 which can be transmuted into URANIUM - 233 which is FISSILE. FISSION REACTORS. Naturally occurring URANIUM consists of 99.3% ^{238}U which is FERTILE and NOT FISSILE, and 0.7% of ^{235}U which is FISSILE. Normal reactors primarily use the FISSILE properties of ^{235}U.

In natural form, URANIUM CANNOT sustain a chain reaction as the free neutrons are travelling at too high a speed to successfully cause another FISSION, or are lost to the surrounds. This is why it is impossible to construct an atomic bomb from natural uranium.

MODERATORS are thus needed to slow down/and or reflect the neutrons.

2. FISSION REACTORS

2.1. Basic Requiremenst of Fission reactors

Normal fission reactors consist of:-

i) a FISSILE component in the fuel

ii) a MODERATOR

iii) a COOLANT to take the heat to its point of use.

Some reactors use unenriched URANIUM - i.e. the ^{235}U remains at 0.7% - e.g. **MAGNOX** and **CANDU** reactors, others use slightly enriched **URANIUM** - e.g. **AGR, SGHWR** (about 2.5 - 2.7%), **PWR** and **BWR** (about 3.5%), while some experimental reactors - e.g. **HTRs** use highly enriched URANIUM (>90%).

The nuclear reactor replaces the boiler in a conventional power station and raises steam which is passed to a steam turbine. Most the plant is identical to a conventional power station consisting of large turbines, often incorporating superheating and reheating facilities, large condensers, huge cooling water pumps, and a set of auxiliary gas turbines for frequency control and emergency use. The land area covered by a nuclear power plant is much smaller than that for an equivalent coal fired plant for two reasons:-

1) There is no need for the extensive coal handling plant.
2) In the UK, all the nuclear power stations are sited on the cost (except Trawsfynydd which is situated beside a lake), and there is thus no need for cooling towers.

In most reactors there are three fluid circuits:-

1) The reactor coolant circuit
2) The steam cycle
3) The cooling water cycle.

The cooling water is passed through the station at a rate of tens of millions of litres of water and hour, and the outlet temperature is raised by around $10^{o}C$.

In 2009 there were a total of 437 reactors world-wide in operation (374 in 1990) having a combined output of nearly 370 GW (250 GW in 199). In 2009, a further 55 reactors were then under construction with a combined output of 50 GW.

The total current capacity of about 370 GW is about 6 times the maximum peak demand in the UK.

2.2 REACTOR TYPES

2.2.1 Summary of Reactor TYpes

MAGNOX - Original British Design named after the magnesium alloy used as fuel cladding. Four reactors of this type were built in France, One in each of Italy, Spain and Japan. 26 units were in use in UK but all but 4 (in 2 stations) have now been closed..

AGR - ADVANCED GAS COOLED REACTOR - solely British design. 14 units are in use. The original Windscale AGR is now being decommissioned. The last two stations Heysham II and Torness (both with two reactors), were constructed to time and have operated to expectations.

SGHWR - STEAM GENERATING HEAVY WATER REACTOR - originally a British Design which is a hybrid between the CANDU and BWR reactors. One experimental unit at Winfrith, Dorset. Tony Benn ruled in favour of AGR for Heysham II and Torness Labour Government in late 1970s. More recently JAPAN has been experimenting with a such a reactor known as an ATR or Advanced Thermal Reactor.

PWR - Originally an American design, but now the most common reactor type. The PRESSURISED WATER REACTOR (also known as a Light Water Reactor LWR) is the type at Sizewell B, the only such reactor in the UK at present. After a lull of many years, a new generation PWR is being builtin in Finland and due for completion around 2011. Another of the type has just started construction in Flammanville in France. Currently there are two variants of this reactor type being considered around the world.

BWR - BOILING WATER REACTOR - a derivative of the PWR in which the coolant is allowed to boil in the reactor itself. Second most common reactor in use:-

RMBK - LIGHT WATER GRAPHITE MODERATING REACTOR - a design unique to the USSR which figured in the CHERNOBYL incident. 28 units including Chernobyl were operating on Jan 1st 1986 with a further 7 under construction.

CANDU - A reactor named initially after CANadian DeUterium moderated reactor (hence CANDU), alternatively known as PHWR (pressurised heavy water reactor). 41 in use in CANADA, INDIA, ARGENTINA, S. KOREA, PAKISTAN and ROMANIA, with 14 further units under construction in the above countries.

HTGR - HIGH TEMPERATURE GRAPHITE REACTOR - an experimental reactor. The original HTR in the UK started decommissioning in 1975, while West Germany (2), and the USA (1) have operational units. None are under construction. Variants of this design are under development as the PBMR (see section 2.3.10)

FBR - FAST BREEDER REACTOR - unlike all previous reactors, this reactor 'breeds' PLUTONIUM from FERTILE ^{238}**U** to operate, and in so doing extends resource base of URANIUM over 50 times. Mostly experimental at moment with FRANCE, W. GERMANY and UK each having 1 unit, and the USSR having 3. France is building a commercial reactor, and JAPAN and W. Germany experimental ones.

2.2.2 Reactors under Constructuction

Throughout the 1990,s there were relatively few reactors under construction, but since 2005 the number in this category has increased significantly now totalling 50GW (see Table 1.)

TABLE 1. POWER OF NUCLEAR REACTORS UNDER CONSTRUCTION, 08 JAN 2016

	PWR		BWR		PHWR		LWGR		HTGR		FBR		TOTAL	
	No	MW(e)	No	MW(e)	No	MW(e)	No	MW(e)	No	MW(e)	No	MW(e)	No	MW(e)
ARGENTINA	1	25											1	25
BELARUS	2	2218											2	2218
BRAZIL	1	1245											1	1245
CHINA	23	23928							1	200			24	24128
FINLAND	1	1600											1	1600
FRANCE	1	1600											1	1600
INDIA	1	917	4	2520							1	470	6	3907
JAPAN			2	2650									2	2650
KOREA,	4	5360											4	5360
PAKISTAN	2	630											2	630
RUSSIA	8	6582											8	6582
SLOVAKIA	2	880											2	880
UKRAINE	2	1900											2	1900
UAE	4	5380											4	5380
USA	5	5633											5	5633
TOTAL	57	57898	6	5170	0	0	0	0			1	470	64	63538

During 2014 – the latest year for which data are available, four nuclear power plants with a total capacity of 4540 MW were commissioned.

WEBSITE: http://www.iaea.org/programmes/a2 follow link to publications – it is hoped to have a copy on the UEA WEBSITE accessible from the Energy Home Page

2.2.3 Operational Reactors.

The number, type and capacity of nuclear reactors in each country is shown in Table 2, while Table 3 gives more specific details of Reactors in the UK. This last table provides a direct link to the performance of each Reactor in each year of operation which can be reached by clicking on the appropriate link in the on-line version of this handout. Which may be accessed from the course WEBSITE – see section 1.0.

TABLE 2. REACTOR TYPES AND NET ELECTRICAL POWER, REACTORS CONNECTED TO THE GRID, 8th January 2016

	PWR		BWR		MAGNOX		AGR		PHWR		LWGR		FBR		TOTAL	
	No	MW(e)	No	MW(e)	No	MW(e)	No	MW(e)	No	MW(e)	No	MW(e)	No	MW(e)	No	MW(e)
ARGENTINA									3	1627					3	1627
ARMENIA	1	376													1	376
BELGIUM	7	5913													7	5913
BRAZIL	2	2520													2	2520
BULGARIA	2	1926													2	1926
CANADA									19	13524					19	13524
CHINA	28	25315							2	1354			1	20	31	26689
CZECH REP.	6	3907													6	3907
FINLAND	2	992	2	1760											4	2752
FRANCE	58	63130													58	63130
GERMANY	6	8227	2	2572											8	10799
HUNGARY	4	1889													4	1889
INDIA	1	917	2	300					18	4091					21	5308
IRAN, ISL. REP.	1	915													1	915
JAPAN	21	17965	22	22325											43	40290
KOREA,	20	19078							4	2643					24	21721
MEXICO			2	1445											2	1445
NETHERLANDS	1	482													1	482
PAKISTAN	2	600							1	90					3	690
ROMANIA									2	1300					2	1300
RUSSIA	18	13875									15	10219	2	1349	35	25443
SLOVAKIA	4	1818													4	1818
SLOVENIA	1	688													1	688
SOUTH AFRICA	2	1860													2	1860
SPAIN	6	6057	1	1064											7	7121
SWEDEN	3	2985	7	6663											10	9648
SWITZERLAND	3	1740	2	1593											5	3333
UK	1	1198			0	0	14	7685							15	8883
UKRAINE	15	13107													15	13107
USA	65	64741	34	33967											99	98708
TOTAL	394	378017	86	82029	0	0	14	7685	50	24829	17	11159	132	128645	435	377812

Note: The totals include 6 units, 5018 MW in Taiwan, China. The last MAGNOX reactor was shutdown on 30th December 2015.

Table derived from PRIS WEbsite: Note for UK, data has been divided between GCR (MAGNOX) and GCR (AGR)

WEBSITE: http://www.iaea.org/programmes/a2 follow link to publications – it is hoped to have a copy on UEA WEBSITE accessible for the Energy Home Page.

TABLE 3: United Kingdom of Great Britain and Northern Ireland: Nuclear Power Reactors

Operational	15	Shutdown	30

Annual Electrical Power Production for 2014 – data for 2015 will become available in Summer 2016		
Total UK Power Production (including Nuclear)	Nuclear Power Production	% Nuclear generation
337,030 **GWh(e)**	57918.48 **GWh(e)**	17.18%

Click on the name of a reactor to view its full details including annual operation experience.

				Capacity (MWe)		Date	Date
Name	**Type**	**Status**	**Location**	**Net**	**Gross**	**Connected**	**Closed**
BERKELEY-1	MAGNOX	Shutdown	RIVER SEVERN	138	166	12/06/1962	31/03/1989
BERKELEY-2	MAGNOX	Shutdown	RIVER SEVERN	138	166	24/06/1962	26/10/1988
BRADWELL-1	MAGNOX	Shutdown	BRADWELL	123	146	01/07/1962	31/03/2002
BRADWELL-2	MAGNOX	Shutdown	BRADWELL	123	146	06/07/1962	30/03/2002
CALDER HALL-1	MAGNOX	Shutdown	SEASCALE	49	60	27/08/1956	31/03/2003
CALDER HALL-2	MAGNOX	Shutdown	SEASCALE	49	60	01/02/1957	31/03/2003
CALDER HALL-3	MAGNOX	Shutdown	SEASCALE	49	60	01/03/1958	31/03/2003
CALDER HALL-4	MAGNOX	Shutdown	SEASCALE	49	60	01/04/1959	31/03/2003
CHAPELCROSS-1	MAGNOX	Shutdown	ANNAN	48	60	01/02/1959	29/06/2004
CHAPELCROSS-2	MAGNOX	Shutdown	ANNAN	48	60	01/07/1959	29/06/2004
CHAPELCROSS-3	MAGNOX	Shutdown	ANNAN	48	60	01/11/1959	29/06/2004
CHAPELCROSS-4	MAGNOX	Shutdown	ANNAN	48	60	01/01/1960	29/06/2004
DOUNREAY DFR	FBR	Shutdown	DOUNREAY	11	15	01/10/1962	01/03/1977
DOUNREAY PFR	FBR	Shutdown	DOUNREAY	234	250	10/01/1975	31/03/1994
DUNGENESS A-1	MAGNOX	Shutdown	ROMNEY MARSH	225	230	21/09/1965	31/12/2006
DUNGENESS A-2	MAGNOX	Shutdown	ROMNEY MARSH	225	230	01/11/1965	31/12/2006
DUNGENESS B-1	AGR	Operational	ROMNEY MARSH	520	615	03/04/1983	
DUNGENESS B-2	AGR	Operational	ROMNEY MARSH	520	615	29/12/1985	
HARTLEPOOL A-1	AGR	Operational	HARTLEPOOL	595	655	01/08/1983	
HARTLEPOOL A-2	AGR	Operational	HARTLEPOOL	585	655	31/10/1984	
HEYSHAM A-1	AGR	Operational	HEYSHAM	580	625	09/07/1983	
HEYSHAM A-2	AGR	Operational	HEYSHAM	575	625	11/10/1984	
HEYSHAM B-1	AGR	Operational	HEYSHAM	610	680	12/07/1988	
HEYSHAM B-2	AGR	Operational	HEYSHAM	610	680	11/11/1988	
HINKLEY POINT A-1	MAGNOX	Shutdown	HINKLEY POINT	235	267	16/02/1965	23/05/2000
HINKLEY POINT A-2	MAGNOX	Shutdown	HINKLEY POINT	235	267	19/03/1965	23/05/2000
HINKLEY POINT B-1	AGR	Operational	HINKLEY	475	655	30/10/1976	
HINKLEY POINT B-2	AGR	Operational	HINKLEY	470	655	05/02/1976	
HUNTERSTON A-1	MAGNOX	Shutdown	HUNTERSTON	150	173	05/02/1964	13/03/1990
HUNTERSTON A-2	MAGNOX	Shutdown	HUNTERSTON	150	173	01/06/1964	31/12/1989
HUNTERSTON B-1	AGR	Operational	HUNTERSTON	475	644	06/02/1976	
HUNTERSTON B-2	AGR	Operational	HUNTERSTON	485	644	31/03/1977	
OLDBURY A-1	MAGNOX	Shutdown	OLDBURY	217	230	07/11/1967	29/02/2012
OLDBURY A-2	MAGNOX	Shutdown	OLDBURY	217	230	06/04/1968	30/06/2011
SIZEWELL A-1	MAGNOX	Shutdown	SIZEWELL	210	245	21/01/1966	31/12/2006
SIZEWELL A-2	MAGNOX	Shutdown	SIZEWELL	210	245	09/04/1966	31/12/2006
SIZEWELL B	PWR	Operational	SIZEWELL	1198	1250	14/02/1995	
TORNESS-1	AGR	Operational	DUNBAR	590	682	25/05/1988	
TORNESS-2	AGR	Operational	DUNBAR	595	682	03/02/1989	
TRAWSFYNYDD-1	MAGNOX	Shutdown	MERIONETHSHIRE	195	235	14/01/1965	06/02/1991
TRAWSFYNYDD-2	MAGNOX	Shutdown	MERIONETHSHIRE	195	235	02/02/1965	04/02/1991
WINDSCALE AGR	AGR	Shutdown	WINDSCALE	24	36	01/02/1963	03/04/1981
WINFRITH SGHWR	SGHWR	Shutdown	DORCHESTER	92	100	01/12/1967	11/09/1990
WYLFA-1	MAGNOX	Shutdown	ANGLESEY	490	530	24/01/1971	30/12/2015
WYLFA-2	MAGNOX	Shutdown	ANGLESEY	490	540	21/07/1971	25/04/2012

Information downloaded from following WEBSITE on 9th January 2016
http://www.iaea.org/programmes/a2/. It is possible to get operational experience of each reactor individuallyfor each year by clicking on the appropriate reactor in the online version of this document or alternatively searching in the full PRIS website database.

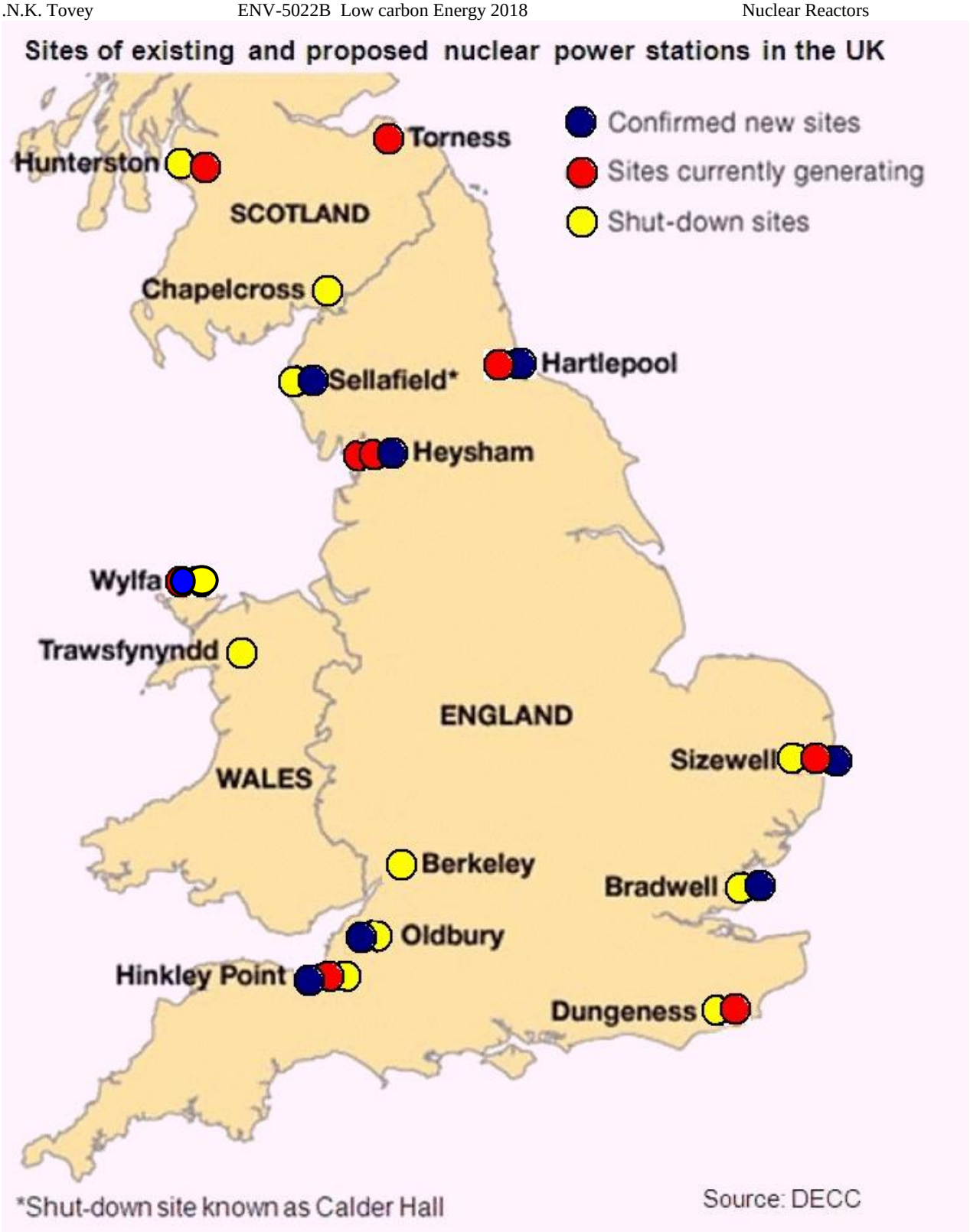

Figure 1.2 Nuclear Power Stations in the UK

The map shows locations of the civil nuclear power plant used for generating electricity for Public Supply. It does not include the experimental reactors such as the SGHWR at Winfrith in Dorest, the demonstration AGR at Sellafield or the two FBRs at Dounreay.

WYLFA had the last operating MAGNOX reactors and was finally shut down on December 31st 2015. The only PWR in the UK is at Sizewell, while all otherones listed are AGRs. New construction nuclear reactors are likely to be PWRs of the EPR1300 or AP1000 type..

2.3.1 MAGNOX REACTORS.

FUEL TYPE - unenriched URANIUM METAL clad in Magnesium alloy
MODERATOR - GRAPHITE
COOLANT - CARBON DIOXIDE
DIRECT RANKINE CYCLE - no superheat or reheat
Efficiency varies from 20% to 28% depending on reactor

ADVANTAGES:-

- LOW POWER DENSITY - 1 MW/m^3. Thus very slow rise in temperature in fault conditions.
- UNENRICHED FUEL - no energy used in enrichment.
- GASEOUS COOLANT - thus under lower pressure than water reactors (28 - 40 bar cf 160 bar for PWRs). Slow drop in pressure in major fault conditions - thus cooling not impaired significantly. Emergency circulation at ATMOSPHERIC PRESSURE would suffice.
- ON LOAD REFUELLING
- MINIMAL CONTAMINATION FROM BURST FUEL CANS - as defective units can be removed without shutting down reactor.
- VERTICAL CONTROL RODS which can fall by gravity in case of emergency.

DISADVANTAGES:-

- CANNOT LOAD FOLLOW - Xe poisoning prevents increasing load after a reduction without shutting reactor down to allow poisons to decay sufficiently.
- OPERATING TEMPERATURE LIMITED TO ABOUT 250^{o}C - in early reactors and about 360^{o}C in later designs thus limiting CARNOT EFFICIENCY to about 40 - 50%, and practical efficiency to about 28-30%.
- LOW BURN-UP - (about 400 TJ per tonne) thus requiring frequent fuel replacement, and reprocessing for effective URANIUM use.
- EXTERNAL BOILERS ON EARLY DESIGNS make them more vulnerable to damage. LATER designs have integral boilers within thick pre-stressed concrete biological shield (see also AGRs).

On December 31st 2006, two further Magnox Reactors were closed after 40 years of service. Oldbury was scheduled to close at the end of 2008, but continued operation until 2014 while the final reactor at Wylfa was finally closed on 30th December 2015.

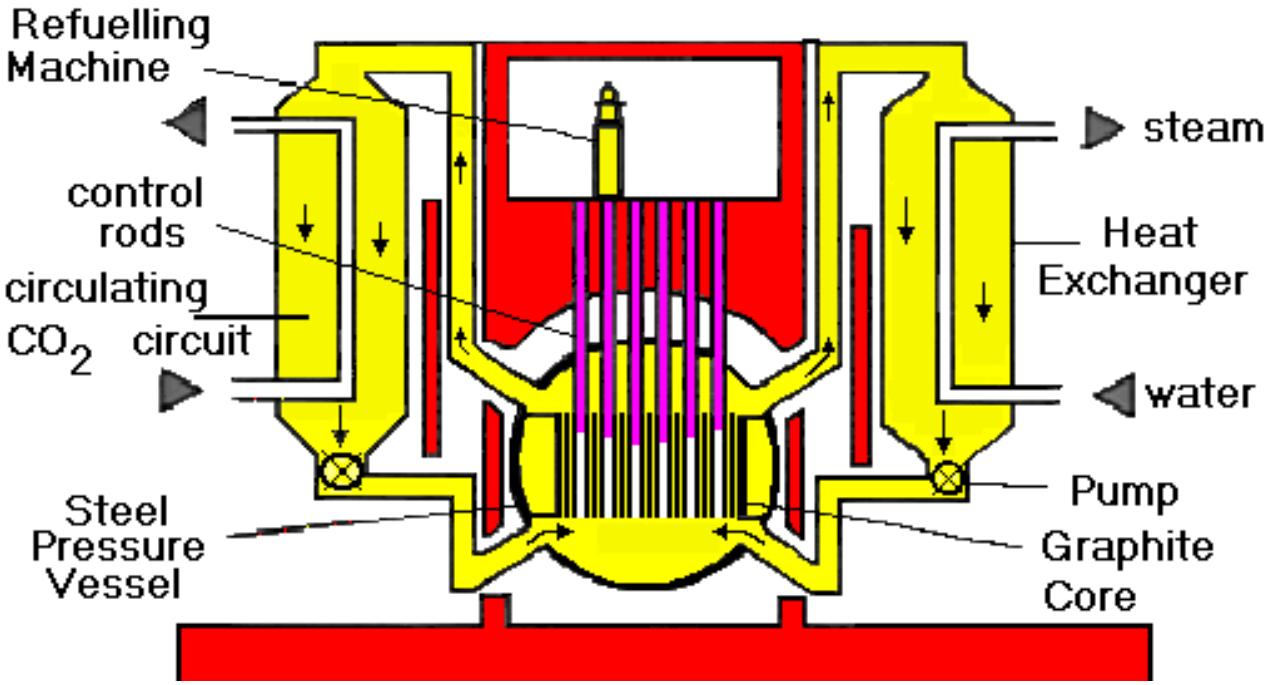

Fig. 2.1 Schematic section of an early Magnox Reactor. Later versions had a pressurised concrete vessel which also enclosed the boilers as with the AGRs. This reactor was developed in the UK and France. The 2 French reactors were closed in the late 1980s. There were originally 24 such reactors in operation in the UK, but as of 31st December 2006 there are only 4 remaining in two stations, Oldbury and Wylfa. Their original design life was 25 years, and all reactors exceeded this with several achieving 40 years services and Calder Hall and Chapel Cross over 45 years of operation.

2.3.2 AGR REACTORS.

FUEL TYPE - enriched URANIUM OXIDE - 2.3% clad in stainless steel
MODERATOR - GRAPHITE
COOLANT - CARBON DIOXIDE
SUPERHEATED RANKINE CYCLE (with reheat) - efficiency 39 - 30%

ADVANTAGES:-

- MODEST POWER DENSITY - 5 MW/m^3. Thus slow rise in temperature in fault conditions.
- GASEOUS COOLANT - thus under lower pressure than water reactors (40 - 45 bar cf 160 bar). Slow drop in pressure in major fault conditions - thus cooling not impaired significantly. [Emergency circulation at ATMOSPHERIC PRESSURE might suffice.]
- ON LOAD REFUELLING - but only operational at part load at present.
- MINIMAL CONTAMINATION FROM BURST FUEL CANS - as defective units can be removed without shutting down reactor.
- SUPERHEATING AND REHEATING AVAILABLE - thus increasing thermodynamic efficiency well above any other reactor.
- VERTICAL CONTROL RODS which can fall by gravity in case of emergency.

DISADVANTAGES:-

- ONLY MODERATE LOAD FOLLOWING CHARACTERISTICS
- SOME FUEL ENRICHMENT NEEDED. - 2.3%

OTHER FACTORS:-

- MODERATE FUEL BURN-UP - about 1800TJ/tonne (c.f. 400TJ/tonne for MAGNOX, 2900TJ/tonne for PWR, and 2600TJ/tonne for BWR)
- SINGLE PRESSURE VESSEL with pre-stressed concrete walls 6m thick. Pre-stressing tendons can be replaced if necessary.

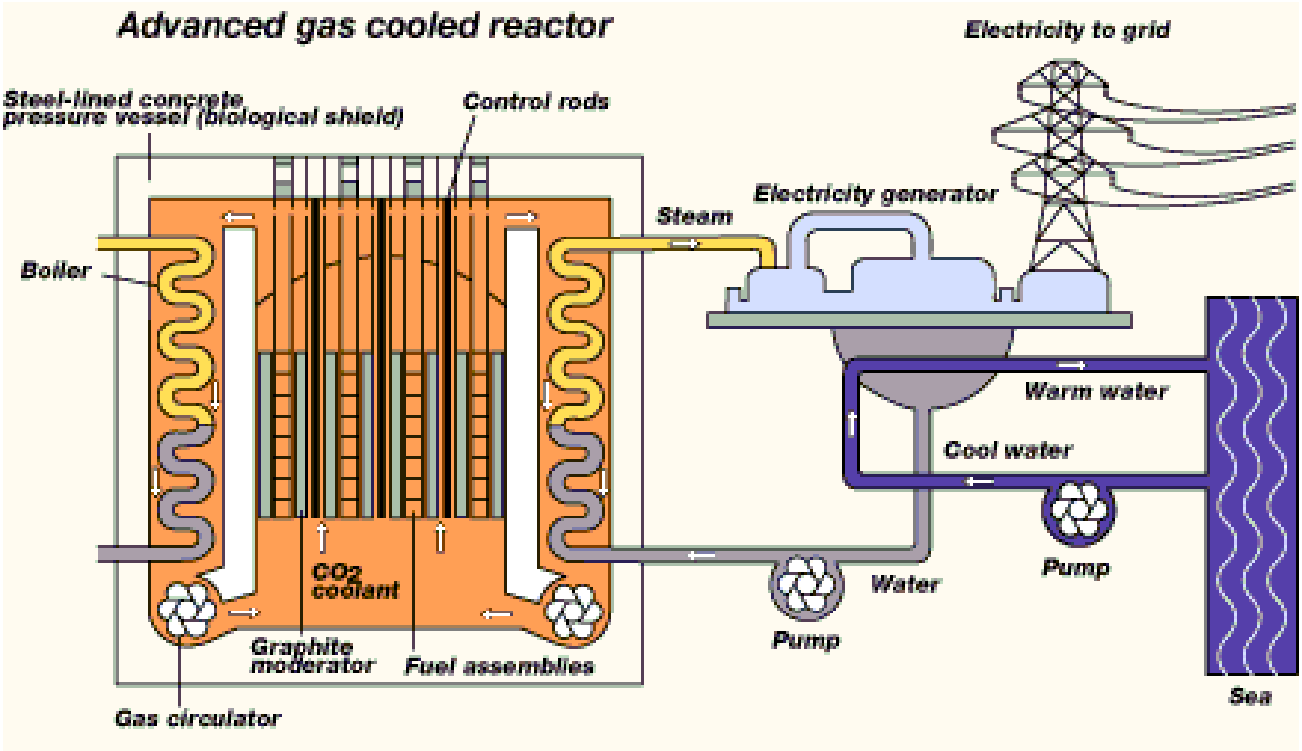

Fig. 2.2 Section of an Advanced Gas Cooled Reactor. This reactor was only developed in the UK. There are currently 14 such reactors in 7 stations in the UK.

2.3.3 CANDU REACTORS.

FUEL TYPE - unenriched URANIUM OXIDE clad in Zircaloy
MODERATOR - HEAVY WATER
COOLANT - HEAVY WATER

ADVANTAGES:-

- MODERATE POWER DENSITY - 11 MW/m^3. Thus fairly slow rise in temperature in fault conditions.
- HEAVY WATER COOLANT - low neutron absorber hence no need for enrichment.
- ON LOAD REFUELLING - and very efficient indeed permits high load factors.
- MINIMAL CONTAMINATION FROM BURST FUEL CANS - as defective units can be removed without shutting down reactor.
- NO FUEL ENRICHMENT NEEDED.
- is modular in design and can be made to almost any size

DISADVANTAGES:-

- POOR LOAD FOLLOWING CHARACTERISTICS
- CONTROL RODS ARE HORIZONTAL, and therefore cannot operate by gravity in fault conditions.
- MAXIMUM EFFICIENCY about 28%

OTHER FACTORS:-

- MODEST FUEL BURN-UP - about 1000TJ/tonne (c.f. 400TJ/tonne for MAGNOX, 2900TJ/tonne for PWR, and 2600TJ/tonne for BWR)
- FACILITIES PROVIDED TO DUMP HEAVY WATER MODERATOR from reactor in fault conditions
- MULTIPLE PRESSURE TUBES (stainless steel) instead of one pressure vessel

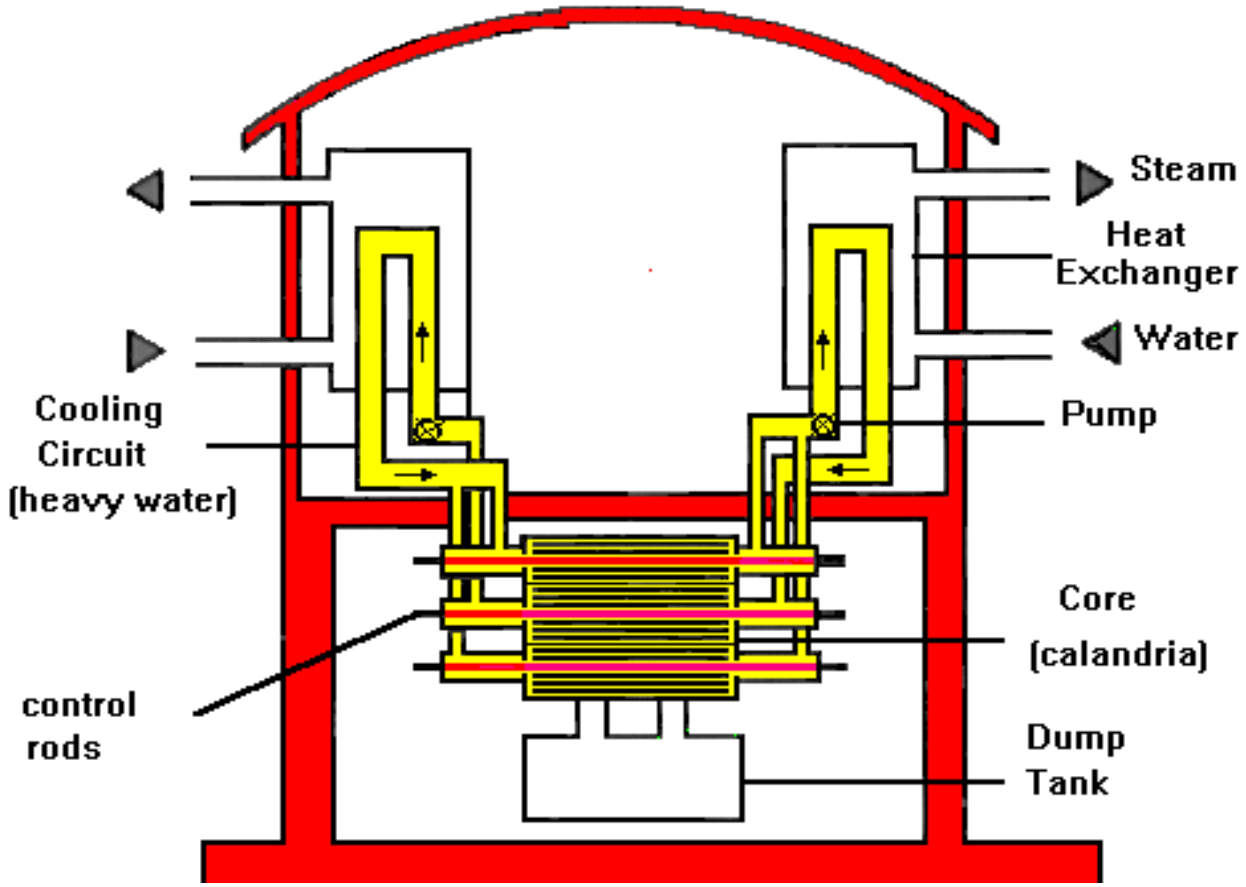

Fig. 2.3 A section of a CANDU reactor. This design was developed in Canada, and has the advantage that it is modular and can be built to any size. The British Steam Generating Heavy Water Reactor (SGHWR) was of similar design except the cooling circuit was ordinary water. The space surrounding the fuel elements in the calandria in a SGHWR was heavy water as in the CANDU design.

2.3.4 PWR REACTORS (WWER are equivalent Russian Reactors).

FUEL TYPE - enriched URANIUM OXIDE - 3 - 4% clad in Zircaloy
MODERATOR - WATER
COOLANT - WATER

ADVANTAGES:-

- Good Load Following Characteristics - claimed for SIZEWELL B. - although most PWR are NOT operated as such. **[update September 2006 – the load following at Sizewell is not that great]**
- HIGH FUEL BURN-UP- about 2900 TJ/tonne - VERTICAL CONTROL RODS which can drop by gravity in fault conditions.

DISADVANTAGES:-

- ORDINARY WATER as COOLANT - pressure must be high to prevent boiling (160 bar). If break occurs then water will flash to steam and cooling will be less effective.
- ON LOAD REFUELLING NOT POSSIBLE - reactor must be completely closed down.
- SIGNIFICANT CONTAMINATION OF COOLANT CAN ARISE FROM BURST FUEL CANS - as defective units cannot be removed without shutting down reactor.
- FUEL ENRICHMENT NEEDED. - 3 - 4%.
- MAXIMUM EFFICIENCY ABOUT 31 - 32%

OTHER FACTORS:-

- LOSS OF COOLANT also means LOSS OF MODERATOR so reaction ceases - but residual decay heat can be large.
- HIGH POWER DENSITY - 100 MW/m^3, and therefore compact. HOWEVER temperature could rise very rapidly indeed in fault conditions. NEEDS Emergency Core Cooling Systems (ECCS) which are ACTIVE SYSTEMS - thus power must be available in fault conditions.
- SINGLE STEEL PRESSURE VESSEL 200 mm thick.

Sizewell B is the only PWR in the UK, but unlike other such plant it incorporates several other safety features, such as the double containment. Further more, unlike other plant it feed two turbines each of 594MW capacity rather than having a single turbine as in other cases – e.g. Flammanville in France. The consequence of this is that in the event of a turbine trip one turbine would still be reunning providing good cooling ot the reactor.

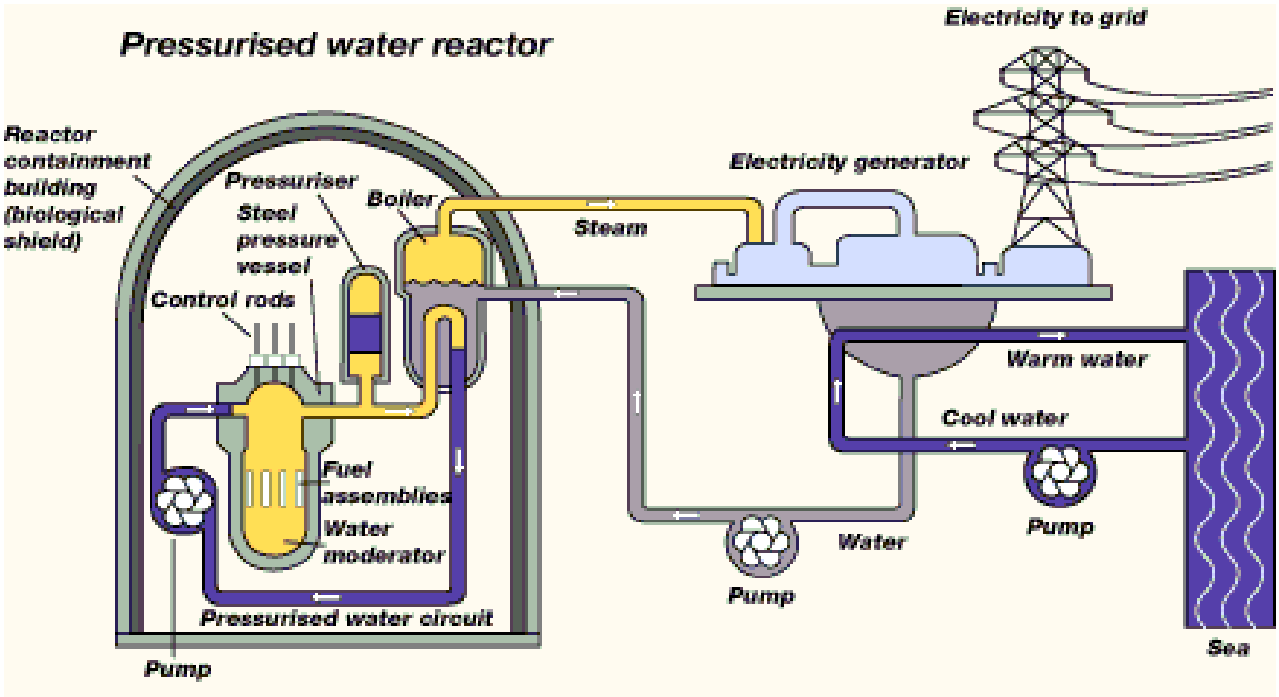

Fig. 2.4 A section of a PWR. This shows the safer design having the cold and hot legs entering the reactor vessel at the top. the reactor at Sizewell has a secondary dome outside the primary containment building. This is the only one in the world that has a double skin. One of the new designs being considered for a possible new UK nuclear program (the AP1000) has a large water tank on the top of the reactor. This would provide cooling by gravity in the event of an emergency unlike the positive response needed from pumps in all current designs.

For more information on PWRs see http://www2.env.uea.ac.uk/energy/energy_links/nuclear.htm#concepts

2.3.5 BWR REACTORS

FUEL TYPE - enriched URANIUM OXIDE - 3% clad in Zircaloy about 4% for PWR)
MODERATOR - WATER
COOLANT - WATER

ADVANTAGES:-

- HIGH FUEL BURN-UP - about 2600TJ/tonne
- STEAM PASSED DIRECTLY TO TURBINE therefore no heat exchangers needed. BUT SEE DISADVANTAGES.

DISADVANTAGES:-

- ORDINARY WATER as COOLANT - but designed to boil therefore pressure about 75 bar
- ON LOAD REFUELLING NOT POSSIBLE - reactor must be completely closed down.
- SIGNIFICANT CONTAMINATION OF COOLANT CAN ARISE FROM BURST FUEL CANS - as defective units cannot be removed without shutting down reactor. ALSO IN SUCH CIRCUMSTANCES RADIOACTIVE STEAM WILL PASS DIRECTLY TO TURBINES.
- CONTROL RODS MUST BE DRIVEN UPWARDS - SO NEED POWER IN FAULT CONDITIONS. Provision made to dump water (moderator in such circumstances).
- FUEL ENRICHMENT NEEDED. - 3%
- MAXIMUM EFFICIENCY ABOUT 31 - 32%

OTHER FACTORS:-

- MODERATE LOAD FOLLOWING CHARACTERISTICS?
- HIGH POWER DENSITY - 50 - 100 MW/m^3. Therefore compact core, but rapid rise in temperature in fault conditions. NEEDS Emergency Core Cooling Systems (ECCS) which are ACTIVE SYSTEMS - thus power must be available in fault conditions.
- SINGLE STEEL PRESSURE VESSEL 200 mm thick.

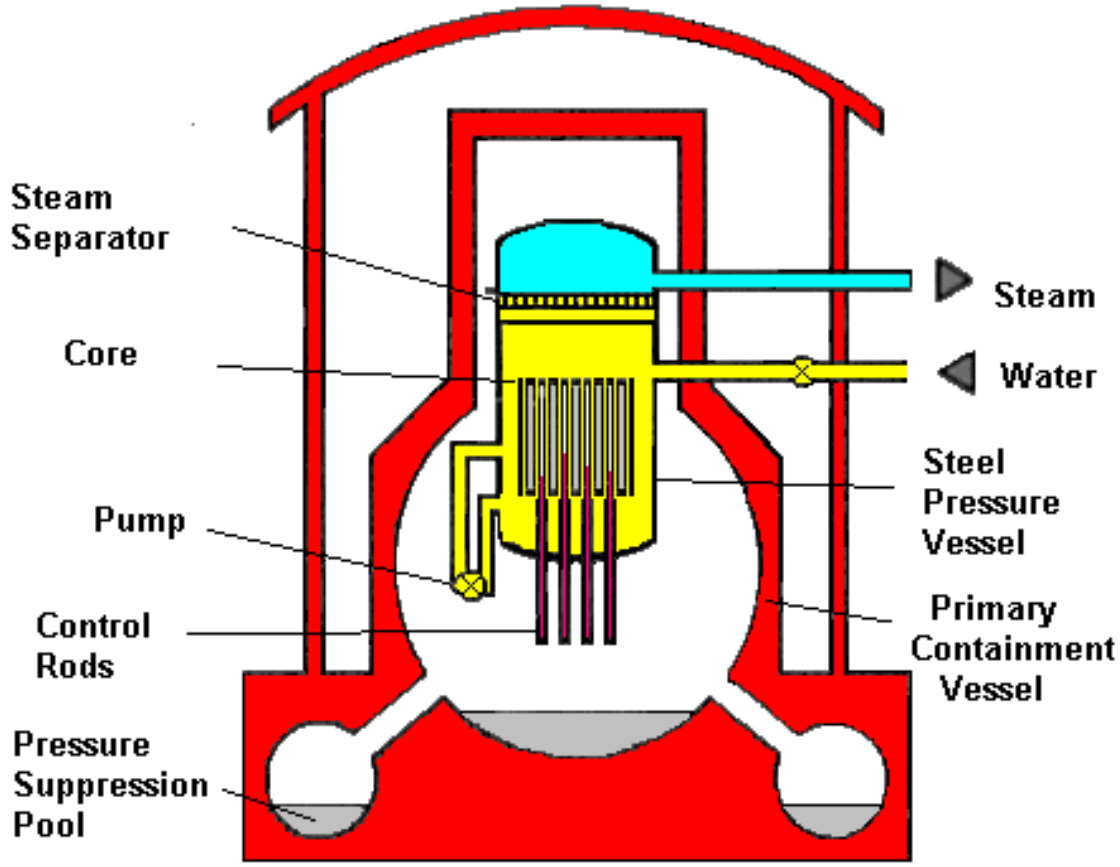

Fig. 2.5 A Boiling Water Reactor. Notice that the primary circuit steam is passed directly to the turbines.

For more information on PWRs see http://www2.env.uea.ac.uk/energy/energy_links/nuclear.htm#concepts

See next page for further information relating to Fukushima.

Technical Information on Fukushima BWRs Supplementary Information added since 2012

Unlike a Pressurised water reactor, a Boiling Water Reactor actually allows the water in the primary cooling (i.e. reactor cooling circuit) to boil and as a result operates at a pressure of around 70 bar rather than around 160 bar in a normal PWR. However, there are major differences.

2. Basic operation of a BWR

BWRs are the second most common reactor in the world although in Japan it is the most common reactor with 30 units in operation as opposed to 17 PWRs (see table below)

Thus unlike in a PWR, the primary coolant passes directly through the turbines rather than relying on heat exchangers to raise steam for the secondary turbine circuit. As a result the BWR has the potential of being a little more efficient thermodynamically than a PWR.

In all nuclear power plants there is the possibility of a burst fuel can – usually no more than a small pin prick which may allow gaseous and/or liquid daughter products from the nuclear reaction to circulate in the primary circuit. In the case of the British Design (MAGNOX and Advanced Gas Cooled reactors) and the Canadian design (CANDU), such defective fuel elements can be removed while the reactor is still on line and generally any contamination within the primary coolant is very minimal.

In the case of the PWR and BWR reactors, however, refuelling can only be done at routine maintenance shutdown – typically up to 21months apart, and so the primary coolant will tend to become radioactive from any fuel cladding issues. In the case of the PWR, such mildly radioactive cooling water is kept within the containment building and the water passing through the turbines is not radioactive. In the case of a BWR as at Fukushima-Daiichi-1 the slightly radioactive cooling water will pass through as steam through the turbines such that the turbine hall may be an area of slightly raised radiation levels.

3. Fukushima Nuclear Power Plants

At Fukushima there are ten separate reactors in two groups making it one of the highest concentration of nuclear plant in the world. The Daiichi group has six separate reactors which were commissioned between March 1971 and April 1979 whereas the Daini group located some kilometres to the north has four commissioned between 1981 and 1986. Both groups of reactors were affected, although the Daini group were in a stable condition within a few days of the earthquake. Several issues have occurred at Fukushima-Daiichi, the first being Fukushima-Daiichi-1 which is the oldest and scheduled to reach 40 years of operation later this month. This reactor is the third oldest reactor still operating in Japan and would have been scheduled to close shortly. It has a gross capacity of 460 MW and a net output of 439 MW (i.e. after power has been taken for pumps etc). Most of the other reactors are larger at 760MW each for Daiichi -2 to 5 and 1067MW for the other five reactors.

The performance of Daiichi-1 has been fairly poor with an average annual load factor of just 53% compared with several at the Daini complex at well over 70% and Sizewell B with a load factor of 86%

Further information on the events which occurred at Fukushima Daiichi at units 2, 3, and 4 in the early days of the incident may be found in Section 6. None of the reactors in units 4, 5, and 6 were operating at the time of the earthquake and their reactor cores are in cold shut down, although there are issues with the Spent Fuel Pond in unit 4.

2.3.6 RBMK or LWGR REACTORS.

FUEL TYPE - enriched URANIUM OXIDE - 2% clad in Zircaloy about 4% for PWR)
MODERATOR - GRAPHITE
COOLANT - WATER

ADVANTAGES:-

- ON LOAD REFUELLING POSSIBLE
- VERTICAL CONTROL RODS which can drop by GRAVITY in fault conditions.

NO THEY CANNOT!!!!

DISADVANTAGES:-

- ORDINARY WATER as COOLANT - which can flash to steam in fault conditions thereby further hindering cooling.
- POSITIVE VOID COEFFICIENT !!! - positive feed back possible in some fault conditions all other reactors have negative voids coefficient in all conditions.
- if coolant is lost moderator will keep reaction going.
- FUEL ENRICHMENT NEEDED. - 2%
- primary coolant passed directly to turbines. This coolant can be slightly radioactive.
- MAXIMUM EFFICIENCY ABOUT 30% ??

OTHER FACTORS:-

- MODERATE FUEL BURN-UP - about 1800TJ/tonne
- LOAD FOLLOWING CHARACTERISTICS UNKNOWN
- POWER DENSITY probably MODERATE?
- MULTIPLE STEEL TUBE PRESSURE VESSEL

This type of reactor was involved in the Chernobyl incident in April 1986. See the following video for an eye-witness account of what happened together with an assessment of exactly how it happened.

https://www.youtube.com/watch?v=5WGUbfzr31s

The video is 47 minutes long.

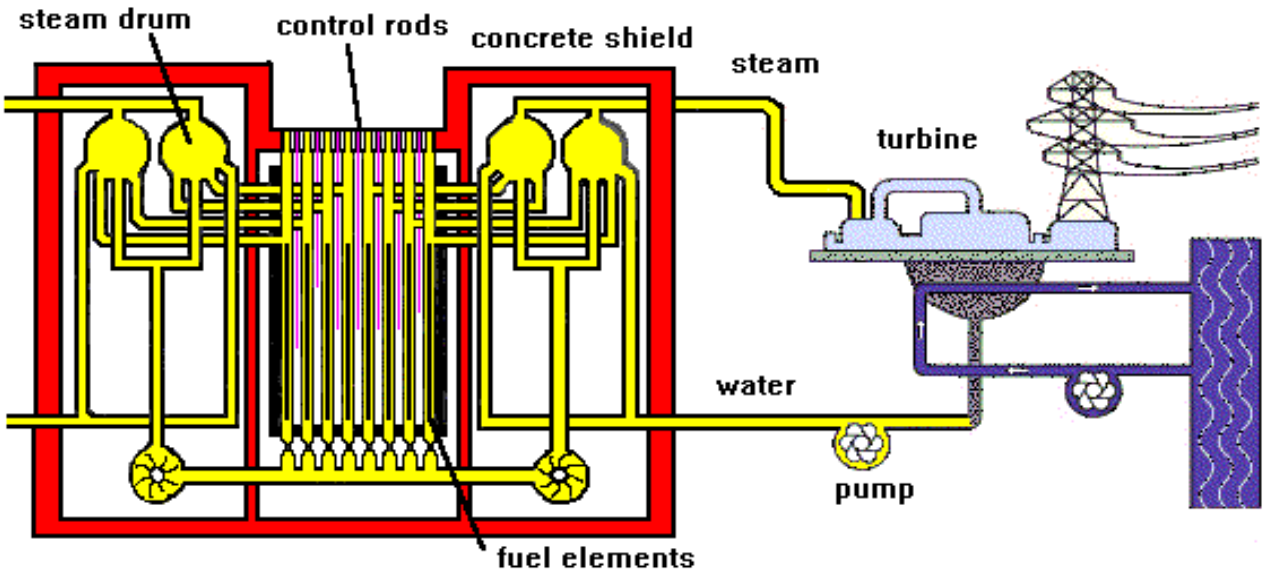

Fig. 2.6 The Russian Light Water - Graphite Moderated Reactor. This reactor was of the type involved in the Chernobyl incident in 1986.

2.3.7 Summary of key parameters for existing reactors.

Table 2.1 summarises the key differences between the different reactors currently in operation. Newer design reactors now being built or proposed are generally derivatives of the earlier models, usually with simplicity of design and safety feature in mind. In many cases in the newer designs, slightly higher fuel enrichments are used to improve the burn up and also the potential overall efficiency of the plant..

Table 2.1 Summary of Existing Reactor Types

REACTOR	COUNTRY of origin	FUEL	Cladding	Moderator	Coolant	BURN-UP (TJ/tonne)	Enrichment	POWER DENSITY MW m^{-3}
MAGNOX	UK/ FRANCE	Uranium Metal	MAGNOX	graphite	CO_2	400	unenriched (0.7%)	1
AGR	UK	Uranium Oxide	Stainless Steel	graphite	CO_2	1800	2.5-2.7%	4.5
SGHWR	UK	Uranium Oxide	Zirconium	Heavy Water	H_2O	1800	2.5-3.0%	11
PWR	USA	Uranium Oxide	Zircaloy	H_2O	H_2O	2900	3.5-4.0%	100
BWR	USA	Uranium Oxide	Zircaloy	H_2O	H_20 (water/steam)	2600	3%	50
CANDU	CANADA	Uranium Oxide	Zircaloy	Heavy Water	Heavy Water	1000	unenriched (0.7%)	16
RMBK	USSR	Uranium Oxide	Zirconium/ Niobium	graphite	H_2O	1800	1.8%	2
HTGR/ PBMR	several	Uranium Oxide	Silicon Carbide	graphite	Helium	8600	9%	6
FBR	several	depleted Uranium metal or oxide surrounding inner area of plutonium dioxide	Stainless Steel	none	liquid sodium	?	-	600

2.3.8 Closure of Existing UK Nuclear Reactors.

The original Magnox Reactors were typically designed with a life of 20 years, but most exceeded that duration significantly as indicated in Table 4. All these reactors are now undergoing decommissioning beginning initial wi th removal of the fuel from the Reactor. See section 2.3.19 regarding the decommissioning of the experimental Windscale AGR which is being used as a test bed for decommissioning reactors.

Table 4. Closure of MAGNOX Stations

	Net MWe	Date of operation of first unit	Closure	Comments
Berkeley	2 x 138	1962-6	1988-6 (unit 1) 1989-3 (unit 2)	
Bradwell	2 x 123	1962-7	2002-3	
Calder Hall	4 x 50	1956-8	2003-1	
Chapel Cross	4 x 50	1959-2	2004-6	
Dungeness A	2 x 225	1965-9	2006-12	
Hinkley Point A	2 x 235	1965-2	2000-5	
Hunterston A	2 x 150	1964-2	1990-03 (unit 1) 1989-12 (unit 2)	
Sizewell A	2 x 210	1966-1	2006 – 12	
Trawsfynydd	2 x 195	1965-1	1991-02	
Oldbury	2 x 217	1967-11	Original schedule 2008	Unit 1 2011 - 6 Unit 2 2012 -2
Wylfa	2 x 490	1971-1	Original Schedule 2010	Unit 1 2015 - 12 Unit 2 2012 - 4

Exact date of closure of Wylfa Reactor 1 during 2014 has yet to be decided. Data on actual output of this sole remaining Magnox Reactor (andn all other power stations) can be found by consulting the BM Unit Data at www.bmreports.com

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AGR STATIONS – scheduled Closure

In Feb 2005 it was announced in Parliament that the estimated closure dates for the Advanced Gas Cooled Reactors Stations would be as shown in Table 5. Each Station has two reactors. Subsequently some of the Reactors have been given extended lives and there is a general plan that consideration for a life extension will be given typically 3 years before the current scheduled date. Thus on Dec 17th 2010 EDF, the current operators of all AGRs indicated that the life of Hartlepool and Heysham 1 Stations had been extended to 2019.

It is noteworthy that both Hinkley Poitn and Hunterston now have scheduled life of 40 years whereas even with the extension Hartlepool and Heysham 1 are currently scheduled for 30 years.

Currently the only PWR in the UK at Sizewell is scheduled from closure in 2035.

Table 5. Scheduled Closure Dates of Advanced Gas Cooled Reactors.

	Net MWe	Construction started	Connected to grid	Full operation	Initial Closing published in 2005	Revised Closing date	Latest Closing dates
Dungeness B	1110	1965	1983	1985	2008	2018	2018
Hartlepool	1210	1968	1983	1989	2014	2019	2019
Heysham 1	1150	1970	1983	1989	2014	2019	2019
Heysham 2	1250	1980	1988	1989	2023		2023
Hinkley Point B	1220	1967	1976	1976	2011	2016	2023
Hunterston B	1190	1967	1976	1976	2011	2016	2023
Torness	1250	1980	1988	1988	2023		2023

Based on Hansard (Feb 2005) and subsequently updated.

2.3.9 Third Generation Reactors

These reactors are developments from the 2nd Generation PWR reactors. There are basically two main contenders – the AP1000 which is a Westinghouse design in which there is strong UK involvement and the EPR1300 with major backing from France and Germany. More recently two further reactors have come to the forefront following the Nuclear White Paper in January 2008. These are the ACR1000 (Advanced Candu Reactor) and the ESBWR (Econmically Simple Boiling Water Reactor0

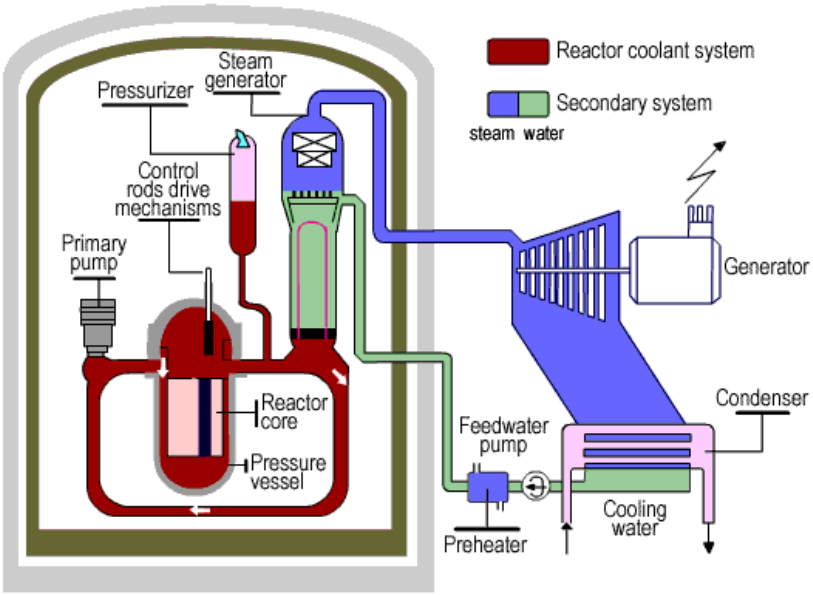


Fig.2.7 [From the AREVA WEB SITE]. This diagram is very similar to the PWR above.

2.3.10 European Pressurised Reactor (EPR)

The EPR1300 has a plant under construction in Finland at Olkiluoto. This is expected to be operational in 2012/3. A second reactor is under construction at Flammanville in France while tow more are now under construction at Taishan in China,

Provisional Data

FUEL TYPE - enriched URANIUM OXIDE – up to 5% or equivalent MOX clad in Stainless SteelZircaloy
MODERATOR - WATER
COOLANT - WATER

In the UK the EPR 1300 is one of two remaining reactors now going through the Generic Design Assessment (GDA). It is the favoured reactor for EDF who in partnership with Rolls Royce are seeking to construct two reactors at Hinkley Point and two at Sizewell. All reactors of this type will have an output of around 1600MW

Generally, the EPR1300 appears to be very similar to Sizewell B which was the reactor with the highest safety design consideration, but has some advanced features. Like Sizewell it has 4 steam generator loops. However, the Reactor Vessel is larger and the power density is probably between 25 and 50% that of a conventional PWR. The efficiency is likely to be slightly higher than fro a conventional PWR at around 33-35%. The company promoting this type of reactor is AREVA and further information may be found in their WEB site at:

www.areva-np.com

One development of the EPR 1300 over previous designs is that it incorporates a neutron reflector around the core which minimises neutron loss leading to a more efficient operation.

Further technical information on the EPR 1300 may be found via links from the WEBSITE under Generation 3 Reactors.

2.3.11. AP1000 REACTOR

The AP1000 Reactor has been certified in USA, is under construction at several sites in China who are developing their own version CAP-1400. It is currently undergoing the Generic Design Assessment in the UK, but delays mean that this will not be complete until around 2017. It develops the AP600 design but with bigger components and a design output of 1120 – 1150 MW. It hasseveral inherent advantages such as not requiring active provision of cooling (i.e. using gravity to spray water). This is achieved by having a large water tank on top of the containment building (Fig. 2.8). Furthermore natural convection within gthe containment vessel will also help to dissipate decay heat even if there is a leak. The AP 1000 will have two turbogenerators which will mean there will always be signigicant cooling even if one generator trips.

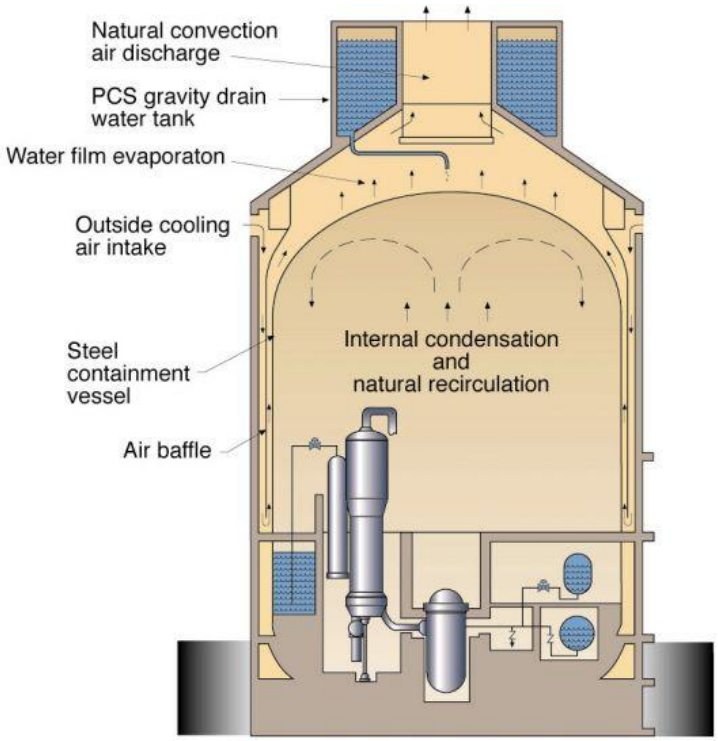


Fig. 2.8 Cross section of AP1000 Reactor and Containment Building showing passive cooling

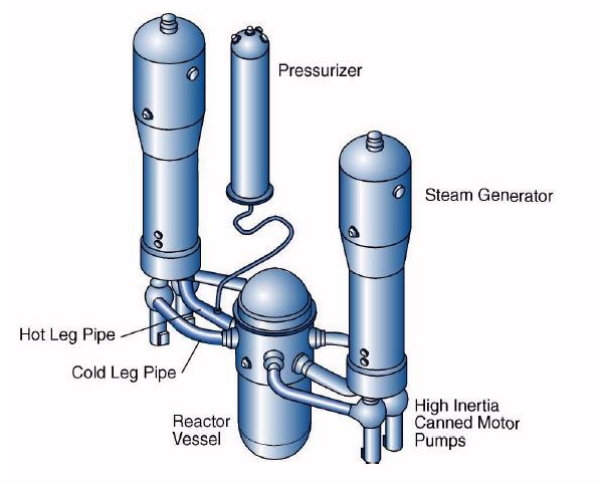


Fig. 2.9 Diagram showin two loops in AP1000 design. The EPR1300 has four separate steam generators. Both Reactors have just one Pressuriser.

Futhermore it uses less than 50% of many of the components such as pumps, pipework which leads to a simplicity in design with less to go wrong. However, unlike the EPR1300 it has only 2 steam generator legs (Fig. 2.9) The efficiency is likely to be margingally higher than a normal PWR at around 35% which is less than that achieved by the AGRs. It is claimed that the safety of an AP1000 would be at least 100 times better than a comparable Reactor.

A unique aspect of the AP1000 is that the basic design CANNOT be changed. This is seen as a significant economic advantage as costly appraisals are not needed for each reactor built.

The AP1000 is currently undergoing the Generic Design Appraisal (GDA) for use in the UK. For the latest information on the GDA process with regards to this reactor see the following WEBPAGE.
http://www.onr.org.uk/new-reactors/reports/gda-quarterly-report-jul-oct15.pdf

It is likely that construction of nuclear stations other than those by EDF may be of the AP1000 design. Currently a joint venture between RWE and E.ON are exploring the development of a nuclear power plant at both Oldbury and Wylfa – the sites of the two remaining MAGNOX stations. IBERDROLA in conjunction with Scottish and Southern have plans to construct a plant at Sellafield which also could be of this design,

Note: The Chinese are developing a derivative of the AP1000, know as the CAP 1400 which may be considered as a candidate for sites such as bradwell in the UK.

2.3.12 ACR1000 Advanced Candu Reactor

This reactor (Fig. 2.10) is being developed in Canada as a development of the Candu concept, but although unlike the earlier models will almost certainly used slightly eenriched uranium oxide as the fuel rather than the unenriched oxide.

The CANDU reactor can be built in a modular form and designs of 700 – 1200 MW are proposed. At present it has not received certification in USA, but forwarded pre-certification documents for certification in UK in May 2007. It has subsequently been temporarily withdrawn for consideration as one of the next Reactors in the UK.

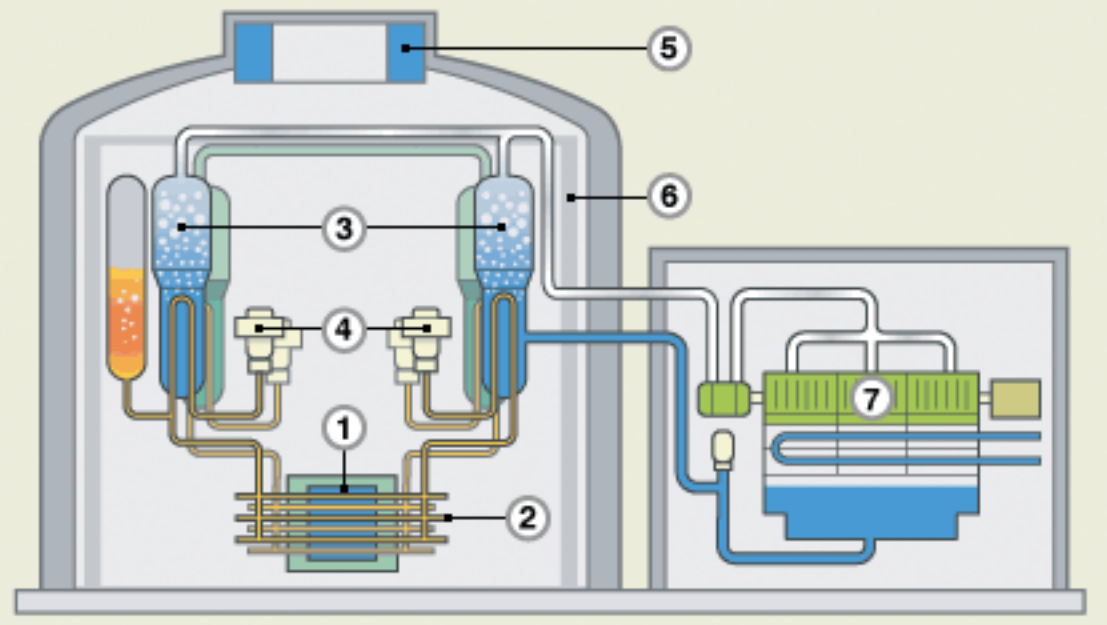


Fig. 2.10 Advanced Candu Reactor.

1. Reactor Core, 2. Horizontal Fuel Channels; 3. Steam Generators; 4. Heat transfer Pumps; 5. Passive Emergency Cooling Water; 6. Steel containment vessel; 7. turbo-generator.

FUEL TYPE – slightly enriched uranium oxide, but can handle MOX and thorium fuels as well.
MODERATOR - Heavy Water
PRIMARY COOLANT - Light Water
EFFICIENCY - designs suggest around 37% efficient.

ADVANTAGES:

- On line refuelling – a video showing how this is done can be downloaded from the WEBSITE (see section 5.0 for details). PWR's, BWR's cannot refuel on line and must be shut down. AGRs and MAGNOX can refuel on line. An existing CANDU reactor holds record for continuous operation of over 800 days.

- Like APR1000 has a large water container at top which will act by gravity in case of emergency for cooling.
- Modular over a range of sizes
- In new version burn may be as high as double that of earlier models
- Safety features include vertical control rods,
- The primary coolant is now ordinary water reducing the demand for heavy water. In this respect it has considerable similarities with the Steam Generatign Heavy Water (SGHWR(reactor formerly developed in the UK

In the Spring of 2008, the ACR1000 was temporarily withdrawn from the Generic Design Assessment Process. At present, the Canadian Designers are now planning to get design and construction experience in Canada before further development elsewhere.

2.3.13 ESBWR: Economically Simple Boiling Water Reator

This is a derivative of the Boiling Water Reactor with some added safety features and is being promoted by General Electric and Hitachi.

Like the APR1000 and ACR1000 it has a large passive cooling tank on the top of the reactors building. Fig. 6.11 shows a schematic of the design.

It is currently undergoing the Generic Design Assessment in the UK as the **ABWR** (or Advanced Boiling Water Reactor). For the latest information on the GDA process with regards to this reactor see the following WEBPAGE.

http://www.onr.org.uk/new-reactors/reports/gda-quarterly-report-jul-oct15.pdf

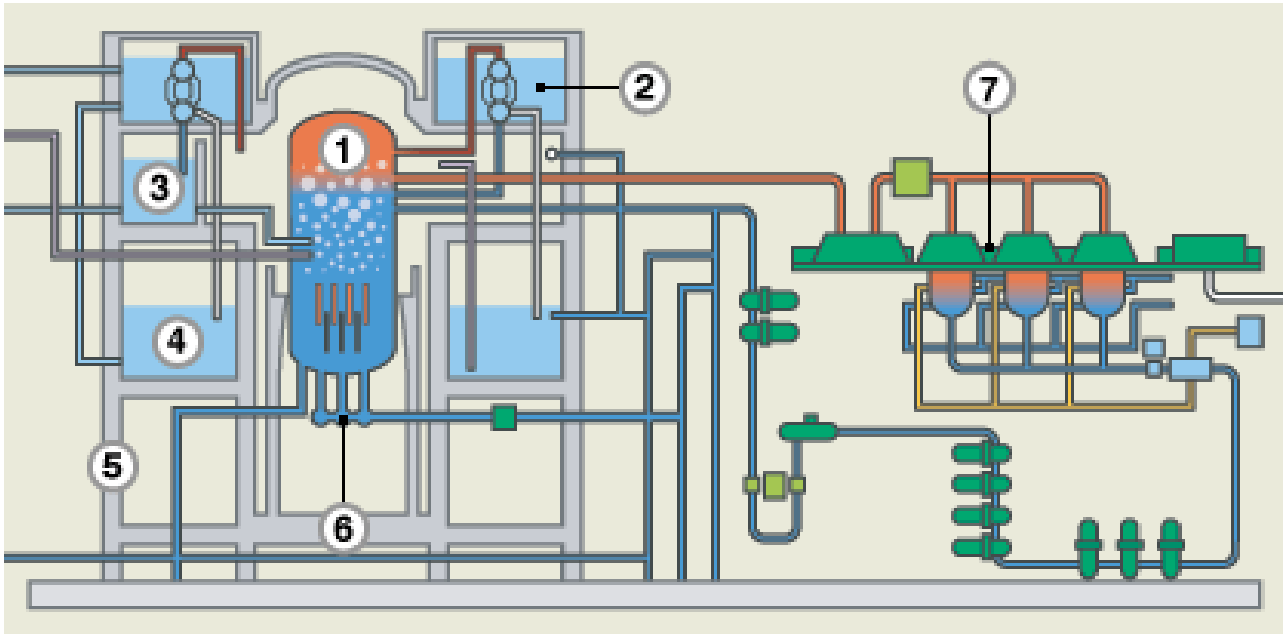


Fig. 2.11 Economic Simplified Boiling Water Reactor

1. Reactor; 2. Passive Emergency Cooling; 3. Gravity driven cooling System; 4. Supression Pool, 5. Containment Vessel, 6 control rods; 7. turbo-generator.

.A feature of this design , which would appear to be similar to AP1000 and ACR1000, at least in concept is the passive cooling system which involves initially the Passive Emergency Cooling Ponds, then the Gravity Cooling SYStem and the SAUpression Pool. The suppression Pool has the function of condensing any steam lost in a pipe leak into the containment building .

The fact sheets available on the relevant WEBSITES do not give much technical information on key operating parameters e.g. efficiency, but it is to be expected they will be similar to the standard BWR.

There is a video of the emergency cooling system accessible from the WEB site and this suggests that emergency cooling will continue for 72 hours even in the complete absence of power.

Disadvantages with the design would still seem to be the same as the basic design – i.e. the control rods having to be driven upwards rather falling by gravity, and the factor that potentially radioactive steam (arising from a burst can) circulates through the turbines

Website

http://www.gepower.com/prod_serv/products/nuclear_energy/en/new_reactors/esbwr.htm

2.3.14. Comment on Generation 3 in the context of the Nuclear White Paper.

All 4 desings listed above – i.e. the EPR1000, AP1000, ACR1000, and ESBWR submitted pre-certification documents for operation in the UK in May 2007. The Nuclear White Paper, indicated that it would use this information to shortlist three designs for certification and potential building. The reson for the reduced number is for the time required for adequate certification. During this stage the Advanced Candu Reactor withdrew from the running at this present time, although it may be reinstated later. Also as of December 2010, the two remaining reactors types under consideration are the EPR 1300 and the AP1000, although there have been issues relating to both.

2.3.15 HINKLEY POINT C and other New Reactors in the UK

Figure 2.12 shows the location of closed, operating, and potential sites for New Reactors. All the shut down sites are MAGNOX Reactors with the last one at WYLFA closing on 31st December 2015. The is also the demonstration AGR Reactor at Sellafield which is also closed. For a detailed list of closed Reactorss in the UK see Table 4.

All operating sites are AGRs except SIZEWELL B which is a PWR. All the new reactors are located in \England and Wales with the first new reactor now under construction as of Autumn 2016 at Hinkley Point C, being the third reactor at this location.

The original MAGNOX Reactor operated from 1965 until 2000, while the AGR was the first to be commissioned in the UK in 1977.

HINKLEY POINT C will consist of two 1600 MW pressurised watter reactors of the EPR design (see Figure 2.7). making the site the largest nuclear generating complex in the UK. The design has similarities with the ones under construction at Olkiluto in Finland and Flammanville in France, both of which have experienced extensive dealys and cost over-runs. Olkiluoto began construction in 2005 and was originally scheduled to start generating in 2010, but the latest completion date is now mid 2018. . Flammanville began construction in 2007 and it to has suffered similar delays that was orignaly scheduled for completion in 2012, but unlikely to be actually complete until late 2018 or early 2019. In both cases there have been significant cost over-runs.

The Government has agreed a support price of £92.5 / MWh (9.25p/kWH) under the Contract for Difference scheme for the electricity generated. This price will rise with inflation from the base year of 2012 and is thus likely to be noticeably more by the time generation starts. This figute is noticeably bove the current support price for onshore wind at around £80 / MWh (8p/kWH) which is falling year on year.

Whiile experience gained from the difficulties encountered fvrom Olkiluto and Flammanville, will shorten the construction time, it is unlikely that the plant will be operating before 2026 at the earliest.

The next nuclear station of an EPR in the UK will be at Sizewell adjacent to the existing PWR. Once again it will be a twin reactor station, but the go ahead for construction is unlikely before late 2018/ early 2019 at he earliest meaning that generation will not start until around 2030.

Both Hinkley Point C and Sizewell C are part financed by a consortium including EdF (Electricity de France) and China General Nuclear (CGN).

As part of the financial package for Hinkley Point C, CGN has been given the opportunity to develop a Chinese deign of PWR the HPR1000 (Hualong Pressurised Reactor) which has an electrical capacity of 1150 MW. This design is a contender for a new station at Bradwell, on a site adjoining the closed MAGNOX Reactor. On 10th January 2017, the Parliamentary Under-Secretary (Department for Business, Energy and Industrial Strategy) announced that this of Nuclear Regulation had been instructed to begin Generic Design Assessment of the design.

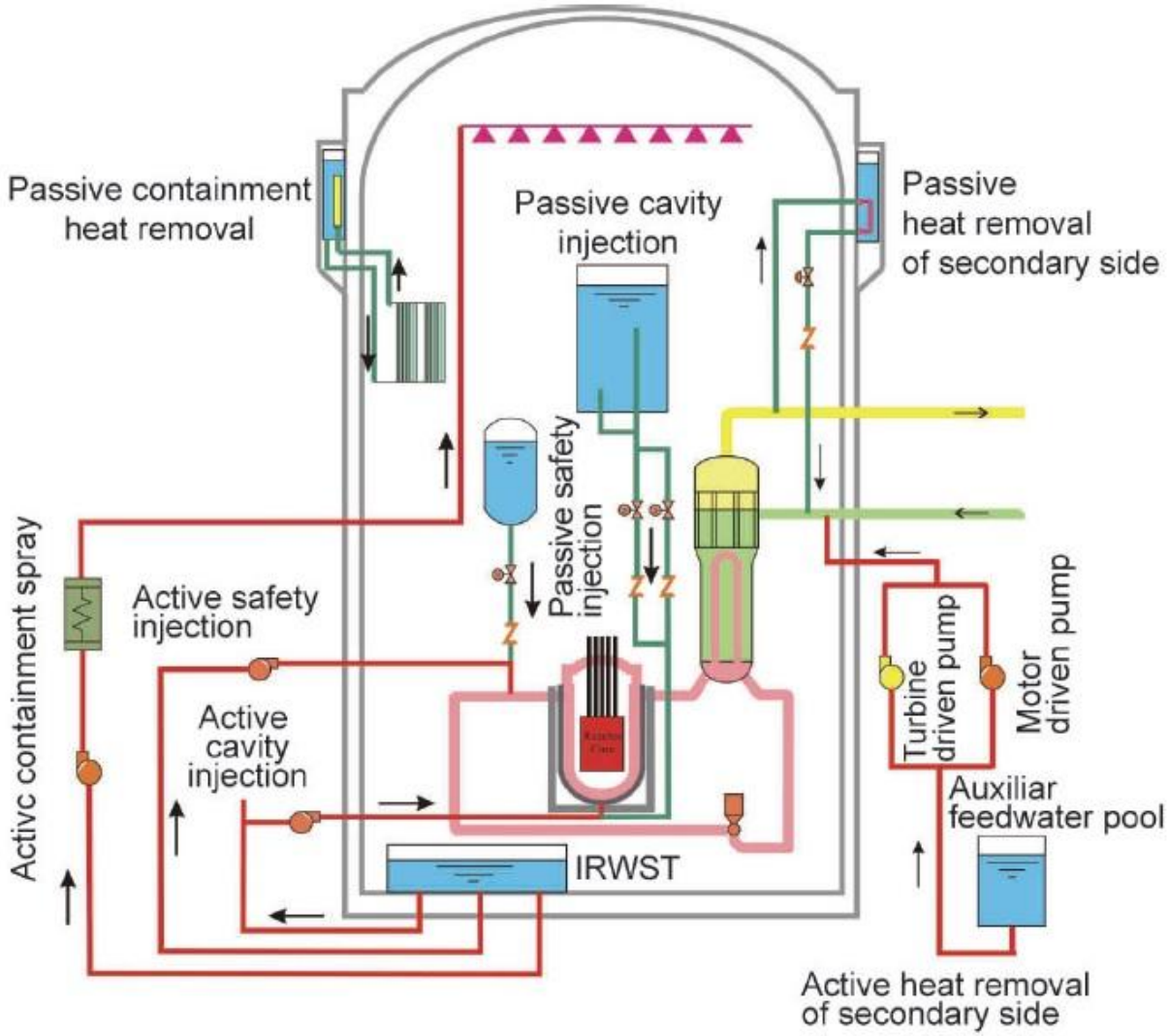


Figure 2.12 HPR1000 Reactor designed by CGN as a possible contender for a new station at Bradwell.

IRWST – In Containment Refuelling Water Storage Tank

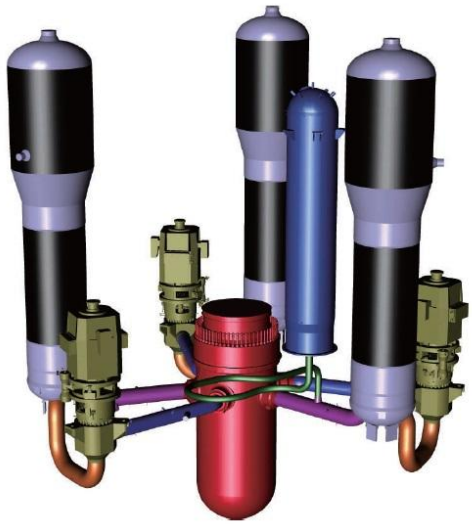


Figure 2.13 HPR1000 schematic showing relationships between the 3 loops and the reactor (red)

2.3.16. GENERATION 3+ REACTORS.

Many of the Generation 3+ reactors are developments for the types list above, but with new constructors entering the market at regular intervals – see the following WEBSITE for latest developments:

http://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/advanced-nuclear-power-reactors.aspx

One of the moreThe most advanced design of 3+ Genertaion Reactor are those developed on the Pebble Bed Modulating Reactor concept. This is a High Temperature Gas cooled Reactor using helium as the core coolant. It also has other similarities with the Gas Cooled Reactors with graphite as the moderator. A 3D view of such a Reactor is shown in Fig. 2.14, while the novel method of producing fuel elements is shown in Fig. 2.15. South Africa was pionerring this technology until 2010. There has been some interest shown since by China and also as smaller inherently safe nuclear reactors such as the U2 Battery concept..

FUEL TYPE - enriched URANIUM OXIDE - 9% clad in specially created sand sized particles (see Fig. 2.13)
MODERATOR - GRAPHITE
PRIMARY COOLANT - HELIUM

EFFICIENCY is likely to be 40% or more with possible opportunities of using Super Critical Steam Cycles. Would use the Superheated RANKINE cycle with REHEAT and even possible the supercritical version

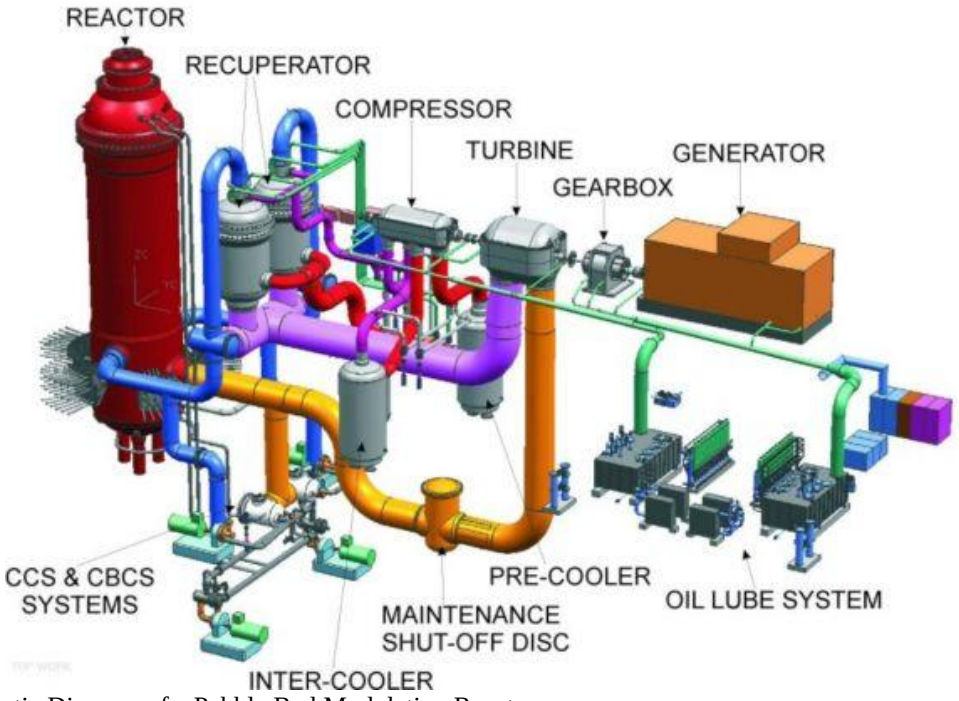


Fig. 2.14 Schematic Diagram of a Pebble Bed Modulating Reactor

Fuel pellets for a PBMR are novel. The inner kernel is prepared by spraying uranyl nitrate to form small pellets 0.5mm in diameter. These are baked to produce Uranium Dioxide. Four layers are then deposited on the fuel particle:
a) a porous graphite (which allows the fisiion products space to accumulate),
b) a heat teated layer of pyrolitic dense carbon,
c) a layer of silicon carbide, and
d) another layer of pyrolitic carbon to form a particle around 0.9mm in diameter.
Around 15000 of these particles are then packed together with graphite and finally coated with 5mm of graphite to form a pebble 60 mm in diameter. The reactor would have around 450 000 pebbles in total. For further information on the PMBR see: http://www.pbmr.com

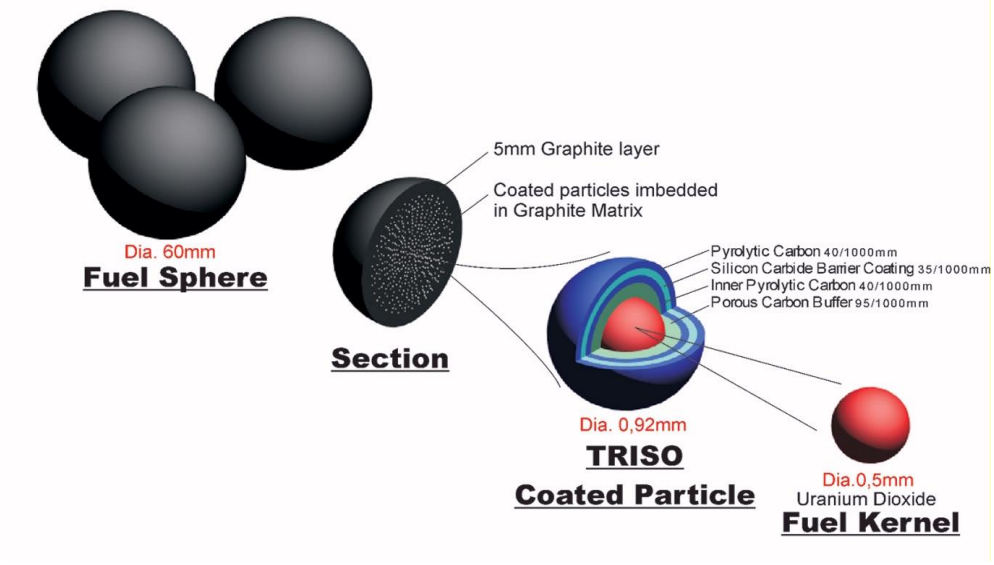


Fig. 2.15 Fuel pellets for a PBMR.

ADVANTAGES:-

- High Fuel Burn Up
- Low Power Density~ 3 MW/m^3
- Can be built in modular form from ~200MW upwards – for a large plant several modules would be located.
- Slow temperature rise under fault conditions
- On Load Refuelling.
- As fuel is enclosed in very small pellets it would be very difficult to divert fuel for other purposes.

DISADVANTAGES:-

- Only experimental at present there is no full commercial scale plant in operation although moderate scale ones may soon be operating in China.
- Higher fuel enrichment needed

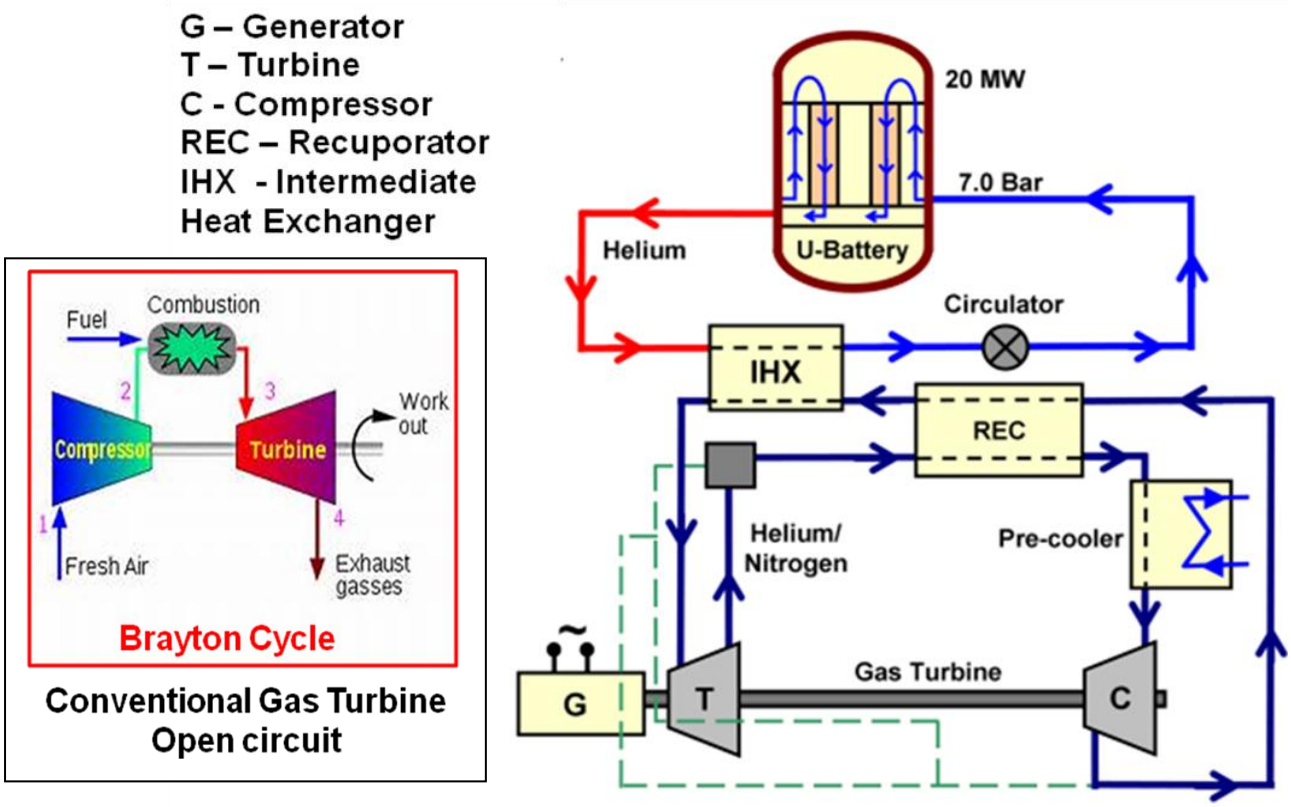


Figure 2.16 A Small Modular Generation 4 Reactor wwhich might be deployed from 2030

2.3.17 Small Modular Nuclear Reactors

In recent years several novel designs have been developed for small reactors with an electrical capacity someties as low as 10 MW. Such as device could be portable and be suitable for power a remote town or village. An example is the U2 Battery which has a small reactor using fuel similar to the TRISO fuel from a pebble bed Moderating Reactor, and importantly running at higher temperatures than conventional reactors sso that closed cicuit gas turbines working on the Brayton Cycle may be used.

2.3.18 FBR REACTORS (sometimes also known as LMFBR - Liquid Metal Fast Breeder Reactor).

FUEL TYPE - depleted URANIUM METAL or URANIUM DIOXIDE in outer regions of core surrounding PLUTONIUM DIOXIDE fuel elements in centre. All fuel elements clad in Stainless steel.
MODERATOR - NONE
COOLANT - LIQUID SODIUM PRIMARY COOLANT.

This type of reactor has depleted Uranium - 238 in a blanket around the fissile core material (of enriched U-235 or Plutonium). Fast neutrons can be captured by the fertile U - 238 to produce more Plutonium. Typically one kilogram of fissile Plutonium could produce as much a 3/4 kg of Plutonium from U-238 and would thus provide enough fuel not only for itself but also 2/3 other reactors.

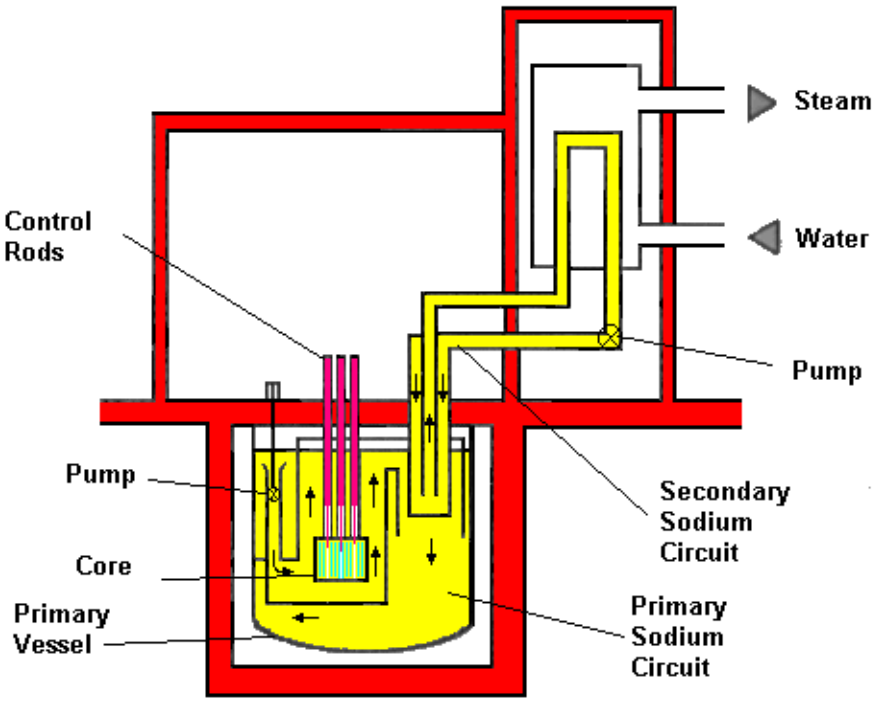


Fig. 2.14 A Fast Breeder Reactor.

ADVANTAGES:-

- LIQUID METAL COOLANT - at ATMOSPHERIC PRESSURE under normal operation. Will even cool by natural convection in event of pump failure. - BREEDS FISSILE MATERIAL from non-fissile ^{238}U and can thus recover 50+ times as much energy as from a conventional 'THERMAL' nuclear power plant.
- HIGH EFFICIENCY (about 40%) and comparable with that of AGRs, and much higher than other reactors.
- VERTICAL CONTROL RODS which can fall by gravity in case of emergency.

DISADVANTAGES:-

- DEPLETED URANIUM FUEL ELEMENTS MUST BE REPROCESSED to recover PLUTONIUM and hence sustain the breeding of more plutonium for future use.
- CURRENT DESIGNS have SECONDARY SODIUM CIRCUIT
  heating water and raising steam EXTERNAL to reactor. If water and sodium mix a significant CHEMICAL explosion may occur which might cause damage to reactor itself.

OTHER FACTORS

VERY HIGH POWER DENSITY - 600 MW/m^3. However, rise in temperature in fault conditions is limited by natural circulation of sodium. very slow rise in temperature in fault conditions.

The first FBR was at Dounreay in Scotland which was followed by the Prototype Fast reactor, bioth of which worked well. Subsequently France built a full size FBR at Marcoule. Currently, 2010, both India and Russia are reputed to be building FBRs.

A derivative of the Fast Breeder reactor is the Travelling Wave Reactor concept being developed by TERRAPOWER and which first came to prominence in a TED lecture given by Bill Gates. Details of this novel concept may be accessed from the WEBPAGE.

2.3.18 REPROCESSING and FAST BREEDER REACTORS.

Reprocessing of nuclear fuel is essential with a Fast Breeder Programme unless the Travelling Wave Reactor becomes a reality..

- For each FBR, approximately FOUR times as much fuel as in the reactor will be in the various stages of cooling, transportation to and from reprocessing, and the reprocessing itself. The time taken to produce TWICE this total inventory is known as the doubling time and will affect the rate at which FBRs can be developed. Currently the doubling time is about 20 years.

- PLUTONIUM is produced in 'THERMAL REACTORS' but at a much slower rate than in FBRs. The PLUTONIUM itself also undergoes FISSION, and this helps to reduce the rate at which the FISSILE URANIUM - 235 is used.

- In theory there is nothing to stop reprocessing the spent fuel, extract the plutonium and enrich the depleted uranium for reuse as a fuel in 'THERMAL REACTORS'. The plutonium may also be consumed in such reactors, or the fuel may be MOX - mixed oxides of uranium and plutonium.

- TEXTBOOKS often state that this is what happens in UK, but in practice the URANIUM and PLUTONIUM are stockpiled for future possible use in FBRs

2.3.19 CONCLUDING COMMENTS ON FISSION REACTORS:-

- A summary of the differences between in the different reactors is given in 'Nuclear Power' by Walter Patterson - chapter 2, and especially pages 72-73, and 'Nuclear Power, Man and the Environment' by R.J. Pentreath - sections 4.1 and 4.2.

- The term 'THERMAL REACTOR' applies to all FISSION REACTORS other than FBRs which rely on slow or 'THERMAL NEUTRONS' to sustain the fission chain reaction. FAST NEUTRONS are used in FBRs to breed more FISSILE plutonium from FERTILE URANIUM - 238. This process extends the resource base of URANIUM by a factor of 50 or more, i.e. a FBR will produce MORE fuel than it consumes.

- REPROCESSING IS NOT ESSENTIAL for THERMAL REACTORS, although for those such as **MAGNOX** which have a low burn up it becomes a sensible approach as much of the URANIUM - 235 remains unused. Equally in such reactors, it is believed that degradation of the fuel cladding may make the long term storage of used fuel elements difficult or impossible.

- IAEA figures suggest that for **PWR** (and **BWR**?) fuel elements it is marginally UNECONOMIC to reprocess the fuel - although many assumptions are made e.g. the economic value of PLUTONIUM which make definite conclusions here difficult.

- DECISIONS on whether to reprocess hinge on:-
  - the Uranium supplies available to Country in question,
  - whether FBRs are to be built.

- **FOR AGR and CANDU** reactors it becomes more attractive economically to reprocess, although the above factors may be overriding - e.g. CANADA which has large uranium reserves IS NOT reprocessing.

- There are now developments with Third Generation Reactors and also 3+ Generation Reactors. A debate is ranging as to whether the AP1000 is safer than the EPR1300. Evidence suggests that it might be and that the EPR is little more than a small improvememtn on Sizewell B.

- **It is** expected, that following the Nuclear White Paper (Jan 2008), that one or more of the Generation 3 designs may be certified for use in the UK. This certification process started in late 2008.

2.3.20 NUCLEAR POWER -DECOMMISSIONING REACTORS

- The WINDSCALE experimental AGR was shut down in 1981 after 17 years of operation.

- TWO YEARS of testing then occurred, followed by removal of the entire spent fuel.

- In 1985 a start was made on removing the reactor entirely.

PHASE 1

- construction of a waste packaging unit with remote handling facilities to check waste for radioactivity as it is removed from reactor.

provision of an access tunnel through steel outer dome and removal of 1 (possibly 2) of four boilers.

PHASE 2 - dismantling of reactor itself using a specially designed robotic arm.

Decommissioning is scheduled to take about 20 years as there is no urgency for completion of task some time will be spent in experimentation.

Site will be returned to a greenfield site.

NOTE: British Energy prefer a solution where reactor is entombed and covered with soil rather than removing reactor completely.

TABLE 4. Details of Reactors which were Grid Connected but are now Shutdown

Country	Reactor Code and Name	Type	Capacity (MW)				Timeline (Year – Month)			
			Thermal	Electrical		Operator NSSS Supplier	Start of Construction	Grid Connection	Start Commercial Operation	Shutdown
				Gross	Net					
ARMENIA	AM-18 ARMENIA-1	PWR	1375	408	376	ANPPJSC FAEA	1969-7	1976-12	1977-10	1989-2
BELGIUM	BE-1 BR-3	PWR	41	12	10	CEN SCK WH	1957-11	1962-10	1962-10	1987-6
BULGARIA	BG-1 KOZLODUY-1	PWR	1375	440	408	KOZNPP AEE	1970-4	1974-7	1974-10	2002-12
	BG-2 KOZLODUY-2	PWR	1375	440	408	KOZNPP AEE	1970-4	1975-8	1975-11	2002-12
	BG-3 KOZLODUY-3	PWR	1375	440	408	KOZNPP AEE	1973-10	1980-12	1981-1	2006-12
	BG-4 KOZLODUY-4	PWR	1375	440	408	KOZNPP AEE	1973-10	1982-5	1982-6	2006-12
CANADA	CA-2 DOUGLAS POINT	PHWR	704	218	206	OH AECL	1960-2	1967-1	1968-9	1984-5
	CA-3 GENTILLY-1	HWLWR	792	266	206	OH AECL	1966-9	1971-4	1972-5	1977-6
	CA-1 ROLPHTON NPD	PHWR	92	25	22	OH CGE	1958-1	1962-6	1962-10	1987-8
FRANCE	FR-9 BUGEY-1	GCR-MAGNOX	1954	555	540	EDF FRAM	1965-12	1972-4	1972-7	1994-5
	FR-2 CHINON-A1	GCR-MAGNOX	300	80	70	EDF LEVIVIER	1957-2	1963-6	1964-2	1973-4
	FR-3 CHINON-A2	GCR-MAGNOX	800	230	180	EDF LEVIVIER	1959-8	1965-2	1965-2	1985-6
	FR-4 CHINON-A3	GCR-MAGNOX	1170	480	360	EDF GTM	1961-3	1966-8	1966-8	1990-6
	FR-5 CHOOZ-A (ARDENNES)	PWR	1040	320	305	SENA AFW	1962-1	1967-4	1967-4	1991-10
	FR-6 EL-4 (MONTS D'ARREE)	HWGCR	250	75	70	EDF GAAA	1962-7	1967-7	1968-6	1985-7
	FR-1B G-2 (MARCOULE)	GCR-MAGNOX	260	43	39	COGEMA SACM	1955-3	1959-4	1959-4	1980-2
	FR-1 G-3 (MARCOULE)	GCR-MAGNOX	260	43	40	COGEMA SACM	1956-3	1960-4	1960-4	1984-6
	FR-7 ST. LAURENT-A1	GCR-MAGNOX	1650	500	390	EDF FRAM	1963-10	1969-3	1969-6	1990-4
	FR-8 ST. LAURENT-A2	GCR-MAGNOX	1475	530	465	EDF FRAM	1966-1	1971-8	1971-11	1992-5
	FR-24 SUPER-PHENIX	FBR	3000	1242	1200	EDF ASPALDO	1976-12	1986-1	1986-12	1998-12
GERMANY	DE-4 AVR JUELICH (AVR)	HTGR	46	15	13	AVR BBK	1961-8	1967-12	1969-5	1988-12
	DE-502 GREIFSWALD-1 (KGR 1)	PWR	1375	440	408	EWN AtEE	1970-3	1973-12	1974-7	1990-2
	DE-503 GREIFSWALD-2 (KGR 2)	PWR	1375	440	408	EWN AtEE	1970-3	1974-12	1975-4	1990-2
	DE-504 GREIFSWALD-3 (KGR 3)	PWR	1375	440	408	EWN AtEE	1972-4	1977-10	1978-5	1990-2
	DE-505 GREIFSWALD-4 (KGR 4)	PWR	1375	440	408	EWN AtEE	1972-4	1979-9	1979-11	1990-7
	DE-506 GREIFSWALD-5 (KGR 5)	PWR	1375	440	408	EWN AtEE	1976-12	1989-4	1989-11	1989-11
	DE-3 GUNDREMMINGEN-A (KRB A)	BWR	801	250	237	KGB AEG,GE	1962-12	1966-12	1967-4	1977-1
	DE-7 HDR GROSSWELZHEIM	BWR	100	25	25	HDR AEG, KWU	1965-1	1969-10	1970-8	1971-4
	DE-8 KNK II	FBR	58	21	17	KBG IA	1974-9	1978-4	1979-3	1991-8
	DE-6 LINGEN (KWL)	BWR	520	268	183	KWL AEG	1964-10	1968-7	1968-10	1979-1
	DE-22 MUELHEIM-KAERLICH (KMK)	PWR	3760	1302	1219	KGG BBR	1975-1	1986-3	1987-8	1988-9
	DE-2 MZFR	PHWR	200	57	52	KBG SIEMENS	1961-12	1966-3	1966-12	1984-5
	DE-11 NIEDERAICHBACH (KKN)	HWGCR	321	106	100	KKN SIEM,KWU	1966-6	1973-1	1973-1	1974-7

TABLE 4 (contd). Details of Reactors which were Grid Connected but are now Shutdown

Country	Reactor Code and Name	Type	Capacity (MW)				Timeline (Year – Month)			
			Thermal	Electrical		Operator NSSS Supplier	Start of Construction	Grid Connection	Start Commercial Operation	Shutdown
				Gross	Net					
GERMANY	DE-5 OBRIGHEIM (KWO)	PWR	1050	357	340	EnBW SIEM,KWU	1965-3	1968-10	1969-3	2005-5
	DE-501 RHEINSBERG (KKR)	PWR	265	70	62	EWN AtEE	1960-1	1966-5	1966-10	1990-6
	DE-10 STADE (KKS)	PWR	1900	672	640	E.ON KWU	1967-12	1972-1	1972-5	2003-11
	DE-19 THTR-300	HTGR	750	308	296	HKG HRB	1971-5	1985-11	1987-6	1988-4
	DE-1 VAK KAHL	BWR	60	16	15	VAK GE, AEG	1958-7	1961-6	1962-2	1985-11
	DE-9 WUERGASSEN (KWW)	BWR	1912	670	640	PE AEG,KWU	1968-1	1971-12	1975-11	1994-8
ITALY	IT-4 CAORSO	BWR	2651	882	860	SOGIN AMN GETS	1970-1	1978-5	1981-12	1990-7
	IT-3 ENRICO FERMI (TRINO)	PWR	870	270	260	SOGIN EL WEST	1961-7	1964-10	1965-1	1990-7
	IT-2 GARIGLIANO	BWR	506	160	150	SOGIN GE	1959-11	1964-1	1964-6	1982-3
	IT-1 LATINA	GCR-MAGNOX	660	160	153	SOGIN TNPG	1958-11	1963-5	1964-1	1987-12
JAPAN	JP-20 FUGEN ATR	HWLWR	557	165	148	JAEA HITACHI	1972-5	1978-7	1979-3	2003-3
	JP-11 HAMAOKA-1	BWR	1593	540	515	CHUBU TOSHIBA	1971-6	1974-8	1976-3	2009-1
	JP-24 HAMAOKA-2	BWR	2436	840	806	CHUBU TOSHIBA	1974-6	1978-5	1978-11	2009-1
	JP-1 JPDR	BWR	90	13	12	JAEA GE	1960-12	1963-10	1965-3	1976-3
	JP-2 TOKAI-1	GCR-MAGNOX	587	166	137	JAPCO GEC	1961-3	1965-11	1966-7	1998-3
KAZAKHSTAN	KZ-10 BN-350	FBR	1000	90	52	MAEC-KAZ MAEC-KAZ	1964-10	1973-7	1973-7	1999-4
LITHUANIA**	LT-46 IGNALINA-1	LWGR	4800	1300	1185	INPP MAEP	1977-5	1983-12	1984-5	2004-12
	LT-47 IGNALINA-2	LWGR	4800	1300	1185	INPP MAEP	1978-1	1987-8	1987-8	2009-12
NETHERLANDS	NL-1 DODEWAARD	BWR	183	60	55	BV GKN RDM	1965-5	1968-10	1969-3	1997-3
RUSSIA	RU-1 APS-1 OBNINSK	LWGR	30	6	5	MSM MSM 1951-1	1951-1	1954-6	1954-12	2002-4
	RU-3 BELOYARSKY-1	LWGR	286	108	102	MSM MSM 1958-6	1958-6	1964-4	1964-4	1983-1
	RU-6 BELOYARSKY-2	LWGR	530	160	146	MSM MSM 1962-1	1962-1	1967-12	1969-12	1990-4
	RU-4 NOVOVORONEZH-1	PWR	760	210	197	MSM MSM 1957-7	1957-7	1964-9	1964-12	1988-2
	RU-8 NOVOVORONEZH-2	PWR	1320	365	336	MSM MSM 1964-6	1964-6	1969-12	1970-4	1990-8
SLOVAKIA	SK-1 BO-A1	HWGCR	560	143	93	JAVYS SKODA	1958-8	1972-12	1972-12	1977-2
	SK-2 BOHUNICE-1	PWR	1375	440	408	JAVYSAEE	1972-4	1978-12	1980-4	2006-12
	SK-3 BOHUNICE-2	PWR	1375	440	408	JAVYSAEE	1972-4	1980-3	1981-1	2008-12
SPAIN	ES-1 JOSE CABRER A-1 (ZORITA)	PWR	510	150	141	UFG WH	1964-6	1968-7	1969-8	2006-4
	ES-3 VANDELLOS-1	GCR-MAGNOX	1670	500	480	HIFRENSA CEA	1968-6	1972-5	1972-8	1990-7
SWEDEN	SE-1 AGESTA	PHWR	80	12	10	BKAB ABBATOM	1957-12	1964-5	1964-5	1974-6
	SE-6 BARSEBACK-1	BWR	1800	615	600	BKAB ASEASTAL	1971-2	1975-5	1975-7	1999-11
	SE-8 BARSEBACK-2	BWR	1800	615	600	BKAB ABBATOM	1973-1	1977-3	1977-7	2005-5

TABLE 4 (contd). Details of Reactors which were Grid Connected but are now Shutdown

Country	Reactor Code and Name	Type	Capacity (MW)				Timeline (Year – Month)			
			Thermal	Electrical		Operator NSSS Supplier	Start of Construction	Grid Connection	Start Commercial Operation	Shutdown
				Gross	Net					
UK	GB-3A BERKELEY 1	GCR-MAGNOX	620	166	138	MEL TNPG	1957-1	1962-6	1962-6	1989-3
	GB-3B BERKELEY 2	GCR-MAGNOX	620	166	138	MEL TNPG	1957-1	1962-6	1962-10	1988-10
	GB-4A BRADWELL 1	GCR-MAGNOX	481	146	123	MEL TNPG	1957-1	1962-7	1962-7	2002-3
	GB-4B BRADWELL 2	GCR-MAGNOX	481	146	123	MEL TNPG	1957-1	1962-7	1962-11	2002-3
	GB-1A CALDER HALL 1	GCR-MAGNOX	268	60	49	MEL UKAEA	1953-8	1956-8	1956-10	2003-3
	GB-1B CALDER HALL 2	GCR-MAGNOX	268	60	49	MEL UKAEA	1953-8	1957-2	1957-2	2003-3
	GB-1C CALDER HALL 3	GCR-MAGNOX	268	60	49	MEL UKAEA	1955-8	1958-3	1958-5	2003-3
	GB-1D CALDER HALL 4	GCR-MAGNOX	268	60	49	MEL UKAEA	1955-8	1959-4	1959-4	2003-3
	GB-2A CHAPELCROSS 1	GCR-MAGNOX	260	60	48	MEL UKAEA	1955-10	1959-2	1959-3	2004-6
	GB-2B CHAPELCROSS 2	GCR-MAGNOX	260	60	48	MEL UKAEA	1955-10	1959-7	1959-8	2004-6
	GB-2C CHAPELCROSS 3	GCR-MAGNOX	260	60	48	MEL UKAEA	1955-10	1959-11	1959-12	2004-6
	GB-2D CHAPELCROSS 4	GCR-MAGNOX	260	60	48	MEL UKAEA	1955-10	1960-1	1960-3	2004-6
	GB-14 DOUNREAY DFR	FBR	60	15	11	UKAEA UKAEA	1955-3	1962-10	1962-10	1977-3
	GB-15 DOUNREAY PFR	FBR	600	250	234	UKAEA TNPG	1966-1	1975-1	1976-7	1994-3
	GB-9A DUNGENESS-A1	GCR-MAGNOX	840	230	225	MEL TNPG TNPG	1960-7	1965-9	1965-10	2006-12
	GB-9B DUNGENESS-A2	GCR-MAGNOX	840	230	225	MEL TNPG TNPG	1960-7	1965-11	1965-12	2006-12
	GB-7A HINKLEY POINT-A1	GCR-MAGNOX	900	267	235	MEL EE B&W T	1957-11	1965-2	1965-3	2000-5
	GB-7B HINKLEY POINT-A2	GCR-MAGNOX	900	267	235	MEL EE B&W T	1957-11	1965-3	1965-5	2000-5
	GB-6A HUNTERSTON-A1	GCR-MAGNOX	595	173	150	MEL GEC	1957-10	1964-2	1964-2	1990-3
	GB-6B HUNTERSTON-A2	GCR-MAGNOX	595	173	150	MEL GEC	1957-10	1964-6	1964-7	1989-12
	GB-10A SIZEWELL-A1	GCR-MAGNOX	1010	245	210	MEL EE B&W T	1961-4	1966-1	1966-3	2006-12
	GB-10B SIZEWELL-A2	GCR-MAGNOX	1010	245	210	MEL EE B&W T	1961-4	1966-4	1966-9	2006-12
	GB-8A TRAWSFYNYDD-1	GCR-MAGNOX	850	235	195	MEL APC	1959-7	1965-1	1965-3	1991-2
	GB-8B TRAWSFYNYDD-2	GCR-MAGNOX	850	235	195	MEL APC	1959-7	1965-2	1965-3	1991-2
	GB-5 WINDSCALE	GCR-AGR	120	36	24	UKAEA UKAEA	1958-11	1963-2	1963-3	1981-4
	GB-12 WINFRITH	SGHWR	318	100	92	UKAEA ICL EE	1963-5	1967-12	1968-1	1990-9
UKRAINE	UA-25 CHERNOBYL-1	LWGR	3200	800	740	MTE FAEA	1970-3	1977-9	1978-5	1996-11
	UA-26 CHERNOBYL-2	LWGR	3200	1000	925	MTE FAEA	1973-2	1978-12	1979-5	1991-10
	UA-42 CHERNOBYL-3	LWGR	3200	1000	925	MTE FAEA	1976-3	1981-12	1982-6	2000-12
	UA-43 CHERNOBYL-4	LWGR	3200	1000	925	MTE FAEA	1979-4	1983-12	1984-3	1986-4

TABLE 4 (contd). Details of Reactors which were Grid Connected but are now Shutdown

Country	Reactor Code and Name	Type	Capacity (MW)				Timeline (Year – Month)			
			Thermal	Electrical		Operator NSSS Supplier	Start of Construction	Grid Connection	Start Commercial Operation	Shutdown
				Gross	Net					
USA	US-155 BIG ROCK POINT	BWR	240	71	67	CPC GE	1960-5	1962-12	1963-3	1997-8
	US-014 BONUS	BWR	50	18	17	DOE PRWR GNEPRWRA	1960-1	1964-8	1965-9	1968-6
	US-144 CVTR	PHWR	65	19	17	CVPA WH	1960-1	1963-12	NA	1967-1
	US-10 DRESDEN-1	BWR	700	207	197	EXELON GE	1956-5	1960-4	1960-7	1978-10
	US-011 ELK RIVER	BWR	58	24	22	RCPA AC	1959-1	1963-8	1964-7	1968-2
	US-16 ENRICO FERMI-1	FBR	200	65	61	DETED UEC	1956-8	1966-8	NA	1972-11
	US-267 FORT ST. VRAIN	HTGR	842	342	330	PSCC GA	1968-9	1976-12	1979-7	1989-8
	US-018 GE VALLECITOS	BWR	50	24	24	GE GE	1956-1	1957-10	1957-10	1963-12
	US-213 HADDAM NECK	PWR	1825	603	560	CYAPC WH	1964-5	1967-8	1968-1	1996-12
	US-077 HALLAM	X	256	84	75	AEC NPPD GE	1959-1	1963-9	1963-11	1964-9
	US-133 HUMBOLDT BAY	BWR	220	65	63	PGE GE	1960-11	1963-4	1963-8	1976-7
	US-013 INDIAN POINT-1	PWR	615	277	257	ENTERGY B&W	1956-5	1962-9	1962-10	1974-10
	US-409 LACROSSE	BWR	165	55	48	DPC AC	1963-3	1968-4	1969-11	1987-4
	US-309 MAINE YANKEE	PWR	2630	900	860	MYAPC CE	1968-10	1972-11	1972-12	1997-8
	US-245 MILLSTONE-1	BWR	2011	684	641	DOMIN GE	1966-5	1970-11	1971-3	1998-7
	US-130 PATHFINDER	BWR	0	63	59	NMC AC	1959-1	1966-7	NA	1967-10
	US-171 PEACH BOTTOM-1	HTGR	115	42	40	EXELON GA	1962-2	1967-1	1967-6	1974-11
	US-012 PIQUA	X	46	12	12	CofPiqua GE	1960-1	1963-7	1963-11	1966-1
	US-312 RANCHO SECO-1	PWR	2772	917	873	SMUD B&W	1969-4	1974-10	1975-4	1989-6
	US-206 SAN ONOFRE-1	PWR	1347	456	436	SCE WH	1964-5	1967-7	1968-1	1992-11
	US-146 SAXTON	PWR	24	3	3	SNEC GE	1960-1	1967-3	1967-3	1972-5
	US-001 SHIPPINGPORT	PWR	236	68	60	DOE DUQU WH	1954-1	1957-12	1958-5	1982-10
	US-322 SHOREHAM	BWR	2436	849	820	LIPA GE	1972-11	1986-8	NA	1989-5
	US-320 THREE MILE ISLAND-2	PWR	2772	959	880	GPU B&W	1969-11	1978-4	1978-12	1979-3
	US-344 TROJAN	PWR	3411	1155	1095	PORTGE WH	1970-2	1975-12	1976-5	1992-11
	US-29 YANKEE NPS	PWR	600	180	167	YAEC WH	1957-11	1960-11	1961-7	1991-10
	US-295 ZION-1	PWR	3250	1085	1040	EXELON WH	1968-12	1973-6	1973-12	1998-2
	US-304 ZION-2	PWR	3250	1085	1040	EXELON WH	1968-12	1973-12	1974-9	1998-2

**** LITHUANIA no longer has any operational Reactors**

Table derived from IAEA(2010) Nuclear Reactors around the World: Note for UK, data has been divided between GCR (MAGNOX) and GCR (AGR)
WEBSITE: http://www.iaea.org/programmes/a2 follow link to publications – it is hoped to have a copy on UEA WEBSITE accessible for the Energy Home Page

3. THE NUCLEAR FUEL CYCLE.

3.1 TWO OPTIONS AVAILABLE:-

1) ONCE-THROUGH CYCLE,
2) REPROCESSING CYCLE

CHOICE DEPENDS primarily on:-
1) REACTOR TYPE IN USE,
2) AVAILABILITY OF URANIUM TO COUNTRY IN QUESTION,
3) DECISIONS ON THE POSSIBLE USE OF FBRs.

ECONOMIC CONSIDERATIONS show little difference between two types of cycle except that for PWRs, ONCE-THROUGH CYCLE appears MARGINALLY more attractive.

3.2 NUCLEAR FUEL CYCLE can be divided into two parts:-

- FRONT-END - includes MINING of Uranium Ore, EXTRACTION, CONVERSION to "Hex", ENRICHMENT, and FUEL FABRICATION.

- BACK-END -includes TRANSPORTATION of SPENT FUEL, STORAGE, REPROCESSING, and DISPOSAL.

NOTE:

1) Transportation of Fabricated Fuel elements has negligible cost as little or no screening is necessary.

2) For both ONCE-THROUGH and REPROCESSING CYCLES, the FRONT-END is identical. The differences are only evident at the BACK- END.

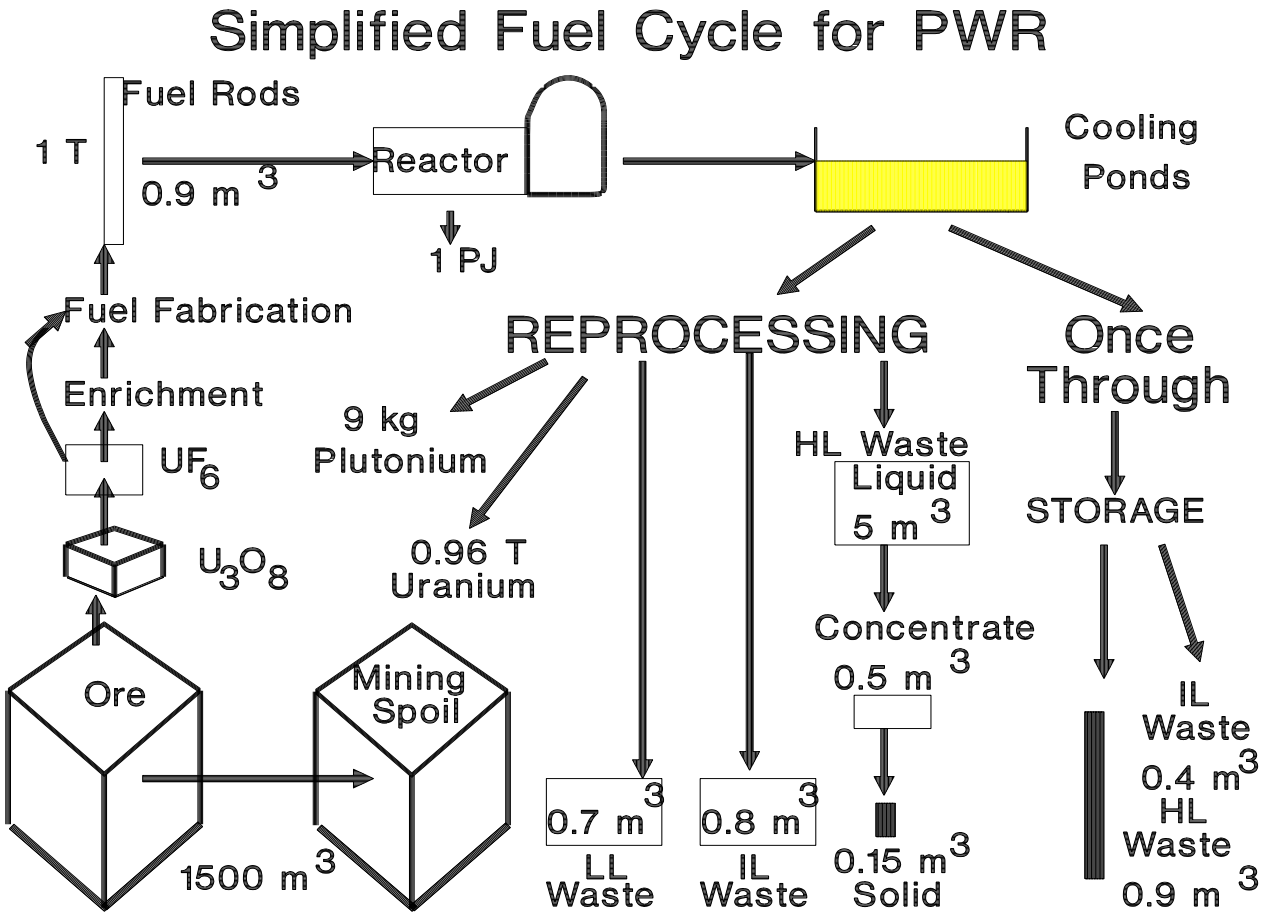


Fig. 3.1 Once through and Reprocessing Cycle for a PWR. The two cycles for an AGR are similar, although the quantities are slightly different. For the CANDU and MAGNOX reactors, no enrichment is needed at the front end.

3.3 FRONT-END of NUCLEAR FUEL CYCLE (see Fig 3.1)

1) **MINING** - ore needs to be at least 0.05% by weight of U_3O_8 to be economic. Typically at 0.5%, 500 tonnes (250 m^3) must be excavated to produce 1 tonne of U_3O_8 ("yellow-cake") which occupies about 0.1 m^3.

Ore is crushed and URANIUM is leached out chemically when the resulting powder contains about 80% yellow-cake. The 'tailings' contain the naturally generated daughter products.

2) **PURIFICATION/CONVERSION** - entails dissolving 'yellow-cake' in nitric acid and conversion to Uranium tetrafluoride which can be reduced to URANIUM METAL for use as a fuel element for MAGNOX reactors or converted into its oxide form for CANDU reactors. All other reactors require enrichment, and for these the UF_4 is converted into URANIUM HEXAFLOURIDE of "HEX".

3) **ENRICHMENT**. Most reactors require URANIUM or its oxide in which the proportion of URANIUM - 235 has been artificially increased.

Enrichment CANNOT be done chemically and the slight differences in PHYSICAL properties are exploited e.g. density. TWO MAIN METHODS OF ENRICHMENT BOTH INVOLVE THE USE OF "HEX" WHICH IS A GAS. (Fluorine has only one isotope, and thus differences arise ONLY from isotopes of URANIUM).

a) **GAS DIFFUSION** - original method still used in FRANCE. "HEX" is allowed to diffuse through a membrane separating the high and low pressure parts of a cell. ^{235}U diffuses faster the ^{238}U through this membrane. Outlet gas from lower pressure is slightly enriched in ^{235}U (by a factor of 1.0043) and is further enriched in subsequent cells. HUNDREDS or even THOUSANDS of such cells are required in cascade depending on the required enrichment. Pumping demands are very large as are the cooling requirements between stages.

Outlet gas from HIGH PRESSURE side is slightly depleted URANIUM and is fed back into previous cell of sequence.

AT BACK END, depleted URANIUM contains only 0.2 - 0.3% ^{235}U, and it is NOT economic to use this for enrichment. This depleted URANIUM is currently stockpiled, but could be an extremely value fuel resource should we decide to go for the FBR.

b) **GAS CENTRIFUGE ENRICHMENT** - this technique is basically similar to the Gas diffusion in that it requires many stages. The "HEX" is spun in a centrifuge, and the slightly enriched URANIUM is such off near the axis and passed to the next stage. ENERGY requirements for this process are only 10 - 15% of the GAS DIFFUSION method. All UK fuel is now enriched by this process.

4) **FUEL FABRICATION** - For MAGNOX reactors URANIUM metal is machined into bars using normal techniques. CARE MUST BE TAKEN not to allow water into process as this acts as a moderator and might cause the fuel element to 'go critical'. CARE MUST ALSO BE TAKEN over its CHEMICAL TOXICITY. URANIUM METAL bars are about 1m in length and about 30 mm in diameter.

Because of low thermal conductivity of oxides of uranium, fuels of this form are made as small pellets which are loaded into stainless steel cladding in the case of AGRs, and ZIRCALLOY in the case of most other reactors.

PLUTONIUM fuel fabrication presents much greater problems. Firstly, the workers require more shielding from radiation. Secondly, it is chemically toxic. Thirdly, is metallurgy is complex. FOURTHLY, AND MOST IMPORTANT OF ALL, IT CAN REACH CRITICALITY ON ITS OWN. THUS CARE MUST BE TAKEN IN MANUFACTURE AND ALL SUBSEQUENT STORAGE THAT THE FUEL ELEMENTS ARE OF A SIZE AND SHAPE WHICH COULD CAUSE CRITICALITY..

NOTE:-

1) The transport of PLUTONIUM fuel elements could present a potential hazard, as a crude atomic bomb could, at least in theory, be made without the need for vast energy as would be the case with enriched URANIUM. Some people advocate the DELIBERATE 'spiking' of PLUTONIUM with some fission products to make the fuel elements very difficult to handle.

2) 1 tonne of enriched fuel for a PWR produces 1PJ of energy. 1 tonne of unenriched fuel for a CANDU reactor produces about 0.2 PJ. However, because of losses, about 20-25% MORE ENERGY PER TONNE of MINED URANIUM can be obtained with CANDU.

3.4 NUCLEAR FUEL CYCLE (BACK END) - SPENT FUEL STORAGE.

SPENT FUEL ELEMENTS from the REACTOR contain many FISSION PRODUCTS the majority of which have SHORT HALF LIVES. During the decay process, heat is evolved so the spent fuel elements are normally stored under water - at least in the short term.

After 100 days, the radioactivity will have reduce to about 25% of its original value, and after 5 years the level will be down to about 1%.

Much of the early reduction comes from the decay of radioisotopes such as IODINE - 131 and XENON - 133 both of which have short half-lives (8 days and 1.8 hours respectively).

On the other hand elements such as CAESIUM - 137 decay to only 90% of their initial level even after 5 years. This element account for less than 0.2% of initial radioactive decay, but 15% of the activity after 5 years.

SPENT FUEL ELEMENTS are stored under 6m of water which also acts as BIOLOGICAL SHIELD. Water becomes radioactive from corrosion of fuel cladding causing leakage - so water is conditioned - kept at pH of 11 - 12 (i.e. strongly alkaline in case of MAGNOX). Other reactor fuel elements do not corrode so readily.

Should any radionucleides actually escape into the water, these are removed by ION EXCHANGE.

Subsequent handling depends on whether ONCE-THROUGH or REPROCESSING CYCLE is chosen.

Spent fuel can be stored in dry caverns, but drying the elements after the initial water cooling is a problem. Adequate air cooling must be provided, and this may make air - radioactive if fuel element cladding is defective. WYLFA power station stores MAGNOX fuel elements in this form.

3.5 ONCE-THROUGH CYCLE

ADVANTAGES:-

1) NO REPROCESSING needed - therefore much lower discharges of low level/intermediate level liquid/gaseous waste.
2) FUEL CLADDING NOT STRIPPED - therefore less solid intermediate waste created.
3) NO PLUTONIUM in transport so no danger of diversion.

DISADVANTAGES:-

1) CANNOT RECOVER UNUSED URANIUM - 235, PLUTONIUM OR URANIUM - 238. Thus fuel cannot be used again.
2) VOLUME OF HIGH LEVEL WASTE MUCH GREATER (5 - 10 times) than with reprocessing cycle.
3) SUPERVISION OF HIGH LEVEL WASTE needed for much longer time as encapsulation is more difficult than for reprocessing cycle.

3.6 REPROCESSING CYCLE

ADVANTAGES:-

1) MUCH LESS HIGH LEVEL WASTE - therefore less problems with storage
2) UNUSED URANIUM - 235, PLUTONIUM AND URANIUM - 238 can be recovered and used again, or used in a FBR thereby increasing resource base 50 fold.
3) VITRIFICATION is easier than with spent fuel elements. Plant at Sellafield now fully operation.

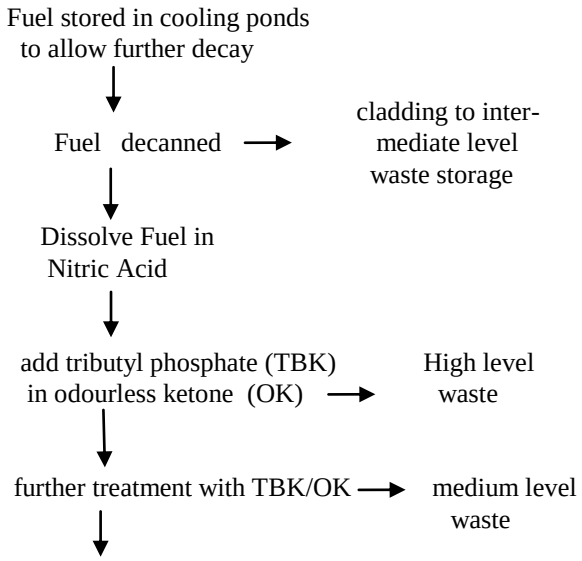
DISADVANTAGES:-

1) A MUCH GREATER VOLUME OF BOTH LOW LEVEL AND INTERMEDIATE LEVEL WASTE IS CREATED, and routine emissions from reprocessing plants have been greater than storage of ONCE-THROUGH cycle waste.

   Note: At SELLAFIELD the ION EXCHANGE plant called SIXEP (Site Ion EXchange Plant) was commissioned in early 1986, and this has substantially reduced the radioactive emissions in the effluent discharged to Irish Sea since that time. Further improvements with more advance waste treatment are under construction..

2) PLUTONIUM is stockpiled or in transport if used in FBRs. (although this can be 'spiked').

3.7 REPROCESSING CYCLE - the chemistry



reduced with ferrous sulphamate

↓ ↓

URANIUM converted to UO_3 and recycled

**PLUTONIUM converted for storage or fuel fabrication for FBR

**NOTE: PLANT MUST BE DESIGNED VERY CAREFULLY AT THIS STAGE TO PREVENT THE PLUTONIUM REACHING A CRITICAL SHAPE AND MASS. PIPES IN THIS AREA ARE THUS OF SMALL DIAMETER.

3.8 WASTE DISPOSAL

These are skeletal notes as the topic will be covered more fully by Alan Kendall in Week 10/11

1) LOW LEVEL WASTE.

LOW LEVEL WASTE contains contaminated materials with radioisotopes which have either very long half lives indeed, or VERY SMALL quantities of short lived radioisotopes. FEW SHIELDING PRECAUTIONS ARE NECESSARY DURING TRANSPORTATION.

NOTE: THE PHYSICAL BULK MAY BE LARGE as its volume includes items which may have been contaminated during routine operations. It includes items such as Laboratory Coats, Paper Towels etc. Such waste may be generated in HOSPITALS, LABORATORIES, NUCLEAR POWER STATIONS, and all parts of the FUEL CYCLE.

BURYING LOW LEVEL WASTE SURROUNDED BY A THICK CLAY BLANKET IS A SENSIBLE OPTION. The clay if of the SMECTITE type acts as a very effective ion EXchange barrier which is plastic and deforms to any ground movement sealing any cracks.

IN BRITAIN IT IS PROPOSED TO BURY WASTE IN STEEL CONTAINERS AND PLACED IN CONCRETE STRUCTURES IN A DEEP TRENCH UP TO 10m DEEP WHICH WILL BE SURROUNDED BY THE CLAY.

IN FRANCE, THE CONTAINERS ARE PILED ABOVE GROUND AND THEN COVERED BY A THICK LAYER OF CLAY TO FORM A TUMULUS.

2) INTERMEDIATE LEVEL WASTE.

INTERMEDIATE LEVEL WASTE contains HIGHER quantities of SHORT LIVED RADIOACTIVE WASTE, OR MODERATE QUANTITIES OF RADIONUCLEIDES OF MODERATE HALF LIFE - e.g. 5 YEARS - 10000 YEARS HALF LIFE.

IN FRANCE SUCH WASTE IS CAST INTO CONCRETE MONOLITHIC BLOCKS AND BURIED AT SHALLOW DEPTH.

IN BRITAIN, one proposal was to bury similar blocks at the SAME SITES to those used for LOW LEVEL WASTE.

IT IS CLEARLY UNSATISFACTORY AS CONFUSION BETWEEN THE TWO TYPES OF WASTE WILL OCCUR.

NIREX have no backed down on this proposal. SEPARATE FACILITIES ARE NOW PROPOSED.

3) HIGH LEVEL WASTE.

It is not planned to permanently dispose of HIGH LEVEL WASTE UNTIL IT HAS BEEN ENCAPSULATED. At Sellafield, high level waste is now being encapsulated and stored on site in specially constructed vaults.

MOST RADIONUCLEIDES IN THIS CATEGORY HAVE HALF LIVES OF UP TO 30 YEARS, and thus activity in about 700 years will have decayed to natural background radiation level.

PROPOSALS FOR DISPOSAL INCLUDE burial in deep mines in SALT; burial 1000m BELOW SEA BED and BACKFILLED with SMECTITE; burial under ANTARCTIC ICE SHEET, shot INTO SPACE to the sun!

4: Nuclear Fusion

4.1 Basic Reactions

Deuterium is Hydrogen with an additional neutron, and is abundant in sea water. Tritium is a third isotopes of hydrogen with 1 proton and 2 neutrons. It is radioactive having a half life of 12.8 years.

The current research is directed towards Deuterium - Tritium fusion as this the more easy to achieve. The alternative - Deuterium - Deuterium Fusion is likely not to be realised until up to 50 years after D- T fusion becomes readily available. Current estimates suggest that D - T fusion could be commercially available by 2040, although several Demonstration Commercial Reactors are likely before that time.

Tritium will have to be generated from Lithium and thus the resource base for D - T fusion is limited by Lithium recourses.

The basic reaction for D - T fusion is

$$D + T \longrightarrow He + n$$

Where is waste product is Helium and inert gas

To generate tritium, two further reactions are needed

$$^{6}Li + n = T + He$$

and $$^{7}Li + n = T + He + n$$

Since spare neutrons are generated by the fusion reaction itself, it is planned to produce the Tritium needed by placing a lithium blanket around the main reaction vessel.

4.2 The Triple Product

To achieve fusion three critical parameters must be met

i). The deuterium - tritium gas must be as a plasma - i.e. at high temperature such that the electrons are stripped from their parent atoms rather than orbit them. In a plasma, deuterium and tritium become ions and it is the central ion density which is critical. If the pressure of the gas is too high, then the plasma cannot form easily. Typical values of ion density which must be achieved are around 2 - 3 x 10^{20} ions per cubic metre.

ii). The temperature must be high typically in excess of 100 million ^{o}C. The fusion reaction rate falls off dramatically such that at 10 million ^{o}C, the reaction rate is less than 1/20000th of that at 100 million ^{o}C.

iii). The confinement time of several seconds

The triple product of the three above parameters is used as a measure to see how close to relevant reactor conditions, experiments currently achieve. This is illustrated in Fig. 4.1

4.3 Progress towards fusion (based on triple product values)

Two terms are used here

Break - even - this is where the energy released by the reaction equals the energy input to start the reaction.

Ignition is the point where the energy released is sufficient to maintain the temperature of the plasma without need for external inputs**.**

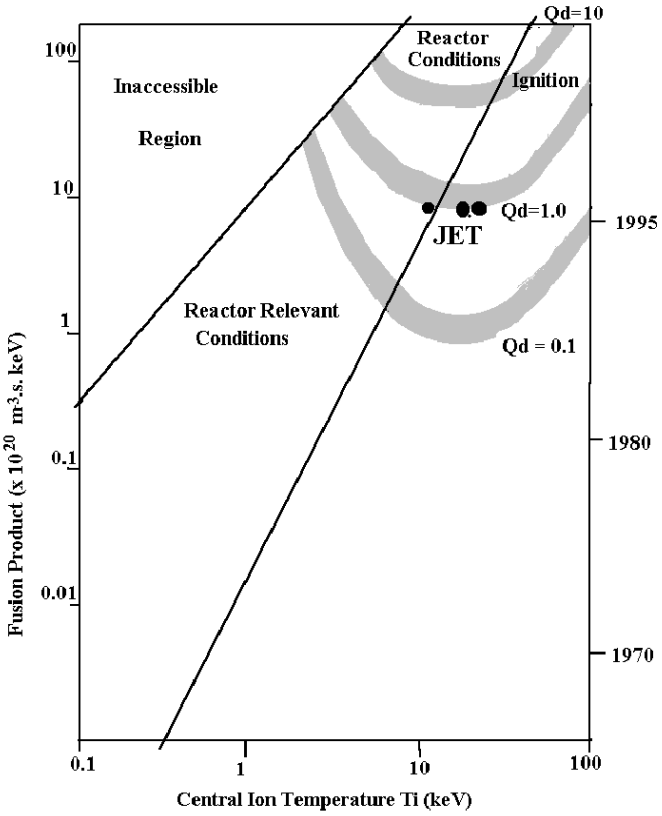


Fig. 4.1. Triple product plotted against Central Ion Temperature with a few selected data points from JET obtained during the 1990's

Date	Distance from Ignition
1970	25 000 times away
1980	700 times away
1983	100 times away
1988	20 times away
1989	10 times away
1991	Break even achieved and now about 6 times away from ignition

JET was not designed to go above about break even, and experiments are now looking at numerous aspects.

The next development ITER - International Thermonuclear Experimental Reactor will see about 10 times as much energy as is put in being produced, but that will not be until around 2020.

4.4 Basic reactor Design

Experience has shown that the most promising reactors are those which are bases on a TOKOMAK which usually takes the form of a donut The plasma must be kept away from the walls as it is so hot and this is achieved by using magnetic confinement. To do this there are two magnetic field - one the TOROIDAL one consists of regularly spaced coils in a vertical plane, the second the POLOIDAL field is generated by passing a heavy current through the plasma itself. The net result of these two field is to produce a helical field as shown in Fig. 4.2, while the actual cross section of the JET reactor is shown in Fig. 4.3.

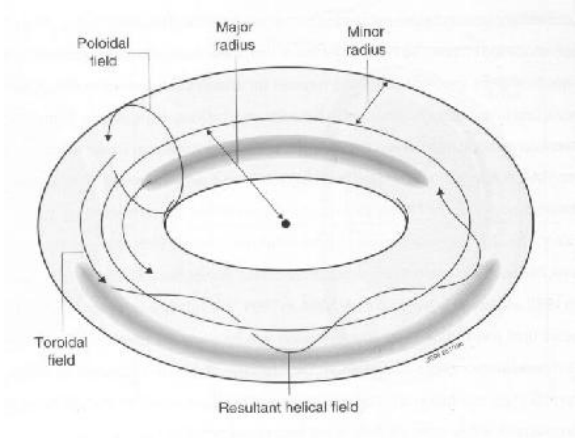


Fig. 4.2 A simplified section of a fusion device showing the helical magnetic field

4.5 A full Reactor design for commercial operation

Fig .4.4 shows a schematic of how a commercial reactor might operate. The Deuterium and Tritium are fed into the reaction chamber and the waste product is Helium. Neutrons pass through to the Lithium blanket to generate Tritium and further Helium which are separated as shown. The heat from the reaction is cooled by a cooling circuit which via a secondary circuit raise steam for generation of electricity in the normal way.

4.6 Why is it taking so long?

There are numerous technical problems to be overcome and many thousands of test runs are done each year to try to modify designs and improve performance. One of the critical issues has been the question of impurities which arise when the plasma touches the wall, causing a limited amount of vapourisation. The ions vaporise, act as impurities and lower the internal temperature making it difficult to sustain the required temperature.

Experiments in the late 1990's / early 2000s have tackled this problem by redesigning the "D" to incorporate divertors at the base. The magnetic field can be altered to cause the impurity ions to collect in the diverter area and hence be withdrawn from the system. The latest thoughts of the shape are shown in Fig. 4.5

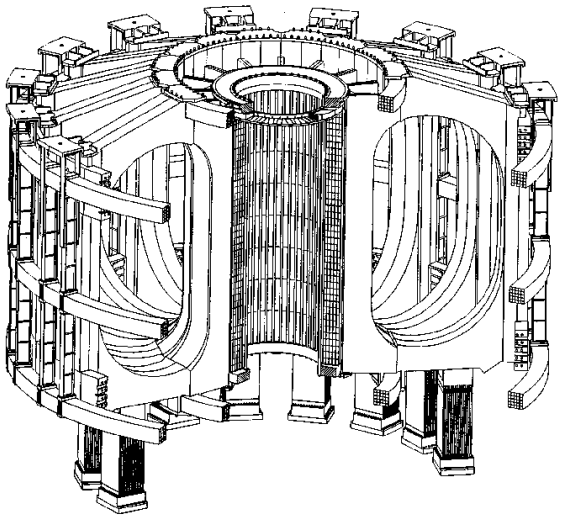


Fig. 4.3 Cross Section of the JET reactor - the Plasma chamber is "D" shaped

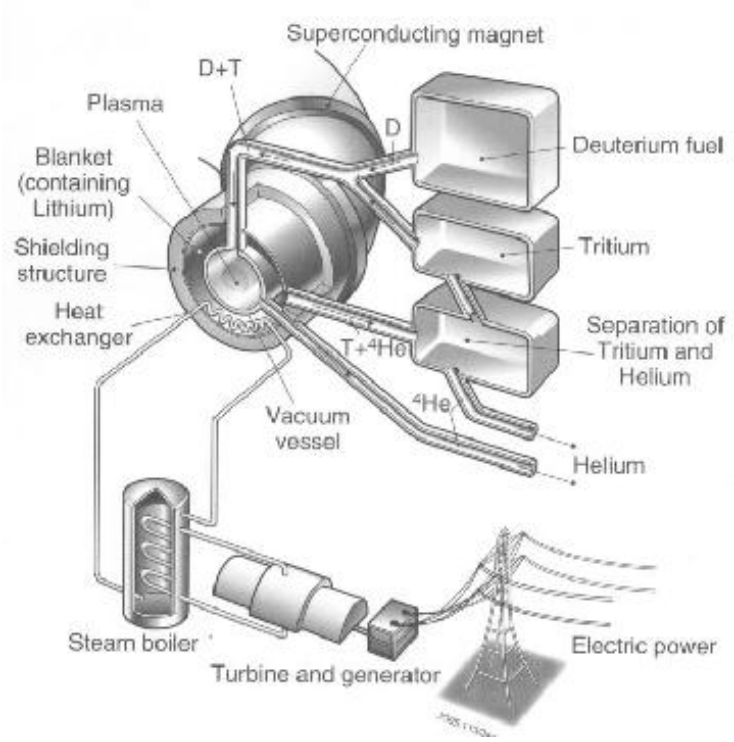


Fig. 4.4 showing a schematic of a possible commercial fusion power reactor.

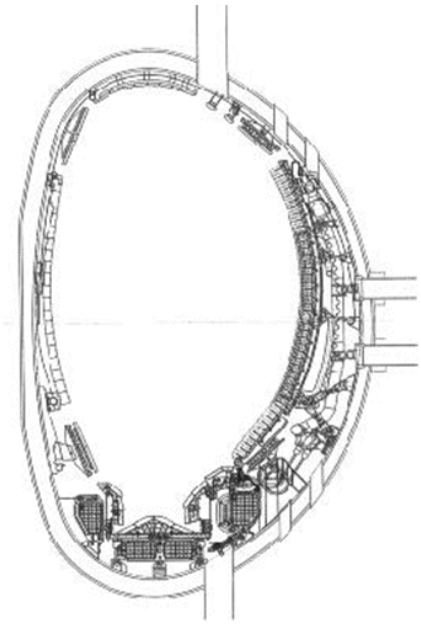


Fig. 4.5 the current shape of the "D" showing the divertor box at the base which is used to remove impurities.

4.7 The Next Stage ITER.

Following the success of JET there were plans for a larger Tokomak which would produce more power than it consumes unlike the break even achieved in JET.

ITER is a global project with the the EU, Japan, China, the United States, South Korea, India and Russia all involved. After a protacted delay it was eventually agreed in late 2007 that **ITER** should be located in Cadarache in France and construction began in 2008 with the completion date being around 2019. Tests will then start to proove the operation of the devise and provide information on how to design **DEMO** – the first commercial size reactor.

JET generated around 16 MW of power as it approached break even, but according to predictions, **ITER** should produced around 500MW of power for an input of 50MW for at least 500 seconds. Thus it should produce 10 times as much energy as it consumes. All fossil fuel power stations do consume power to drive the cooling water pumps, grind the coal etc (typically around 4 – 6%), but in the case of **ITER**, this energy will be needed to initially heat the plasma itself.

ITER will NOT produce any electricity – merely heat which will be dumped to cooling water. This is because there are numerous technical problems still to resolve.

WEB SITE: www.iter.org

4.8 The Future - DEMO

The experience from **ITER** will allow the first demonstration reactor called **DEMO** (DEMOnstration Power Plant) which will actually produce electricity to be designed and built and tested. DEMO, it is planned will produce around 2000 – 4000 MW of heat sufficient to provide up to around 1500MW of electrical power continuously comparable with a typical fossil fuel power plant.

The time scale for DEMO is tentatively potentially scheduled as:

- Basic design ~ 2020
- Full Engineering deaign based on findings of ITER 2025+
- Site selection and construction start 2028+
- Completion of construction ~ 2035+
- Pre commisioning and test 2035 – 2038
- Demonstration of commercial scale operation
- 2040_2050 design of construction of further commercial reactors – operation of a few plant by 2045-2050
- 2050 – 2060+ Fusion begins to have an impact on global electricity production

4.9. Safety

Unlike nuclear fission there are no waste products other than Helium which is inert. The reactor itself will become radioactive, but no more so than a conventional nuclear reactor, and this can be dismantled in 100 years without much difficulty. Unlike fission reactors, the inventory of fuel in the reactor at any one time is very small, and in any incident, all fuel would be used within about 1 second. There is a possible hazard from a Tritium leak from the temporary store, but once again the inventory is small