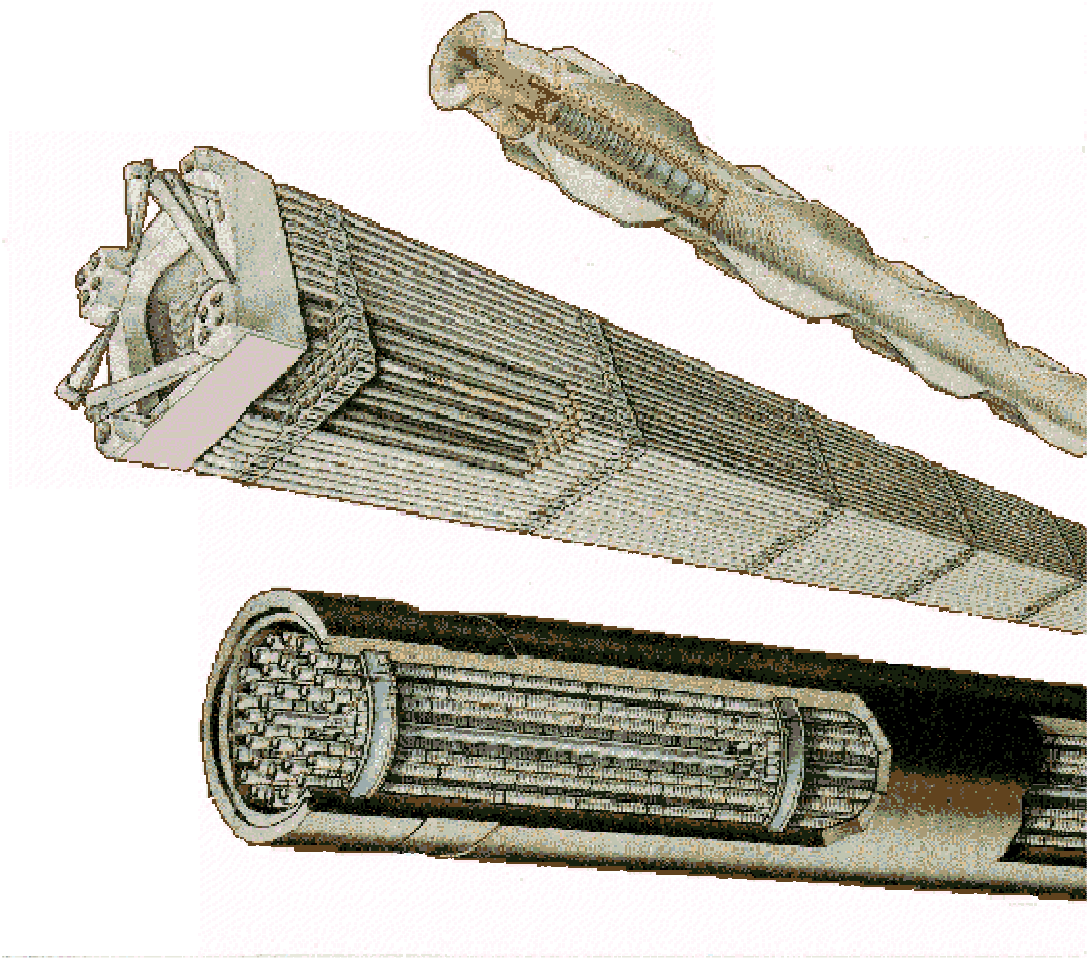
ENV-2A36 Low Carbon Energy Technology 2010



Section 5: Nuclear Power

Section 6: Nuclear Reactors

Section 7: Nuclear Fuel Cycle

- **the waste disposal aspects of thsis topic will be covered more fully by Alan Kendall**

Section 8: Nuclear Fusion

Section 9: Introduction to Hazards of Radiation

- **additional aspects to be covered separately by Alan Kendall**

5. NUCLEAR POWER

5.0 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/gmmc/energy/env-2e36\env-2e36.htm

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

5.1 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.**

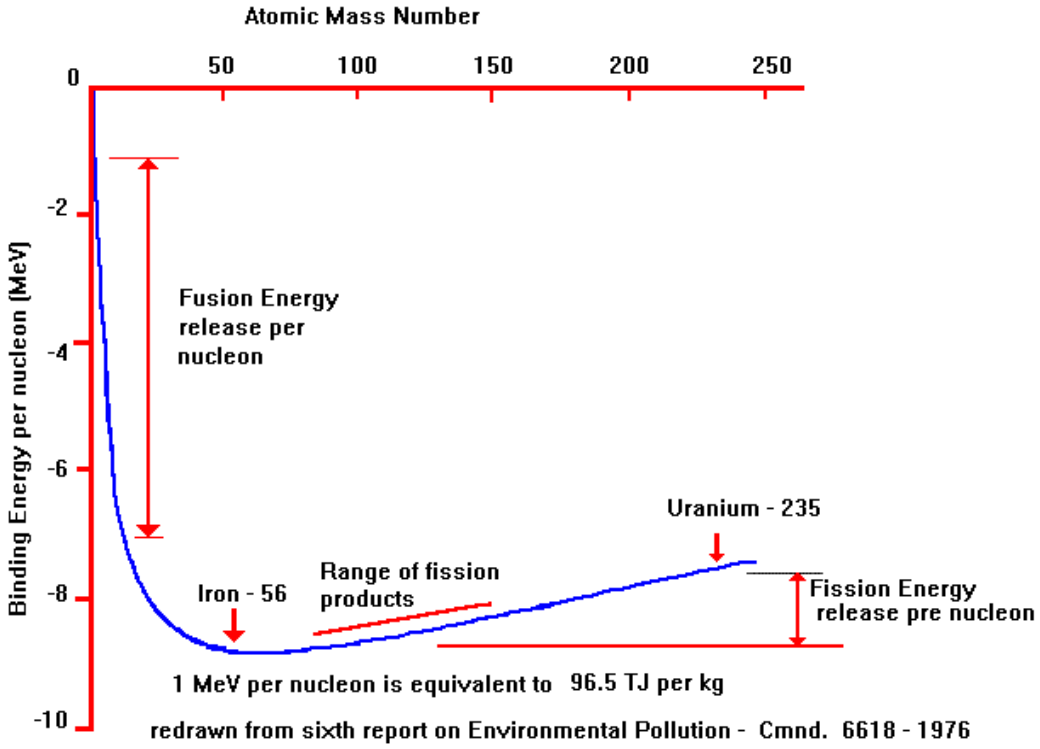


Fig. 5.1 Energy Binding Curve

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

5.2 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.

5.3 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.

5.3 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.]

5.4 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.]

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 BOMB, THE URANIUM - 235 MUST BE HIGHLY ENRICHED > 93%, AND BE LARGER THAN A CRITICAL SIZE OTHERWISE NEUTRONS ARE LOST.

ATOMIC BOMBS 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.

5.5 FERTILE MATERIALS

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

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

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.

6. FISSION REACTORS

6.1 NORMAL FISSION REACTORS THUS 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 1987 there were a total of 374 reactors world-wide in operation having a combined output of nearly 250 GW. A further 157 reactors were then under construction with a combined output of 142 GW. i.e. the total output of about 400 GW is about 8 times the total UK generating capacity.

6.2 REACTOR TYPES – summary

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 6.3.10)

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.

TABLE 1. NUCLEAR POWER REACTORS IN OPERATION AND UNDER CONSTRUCTION, 31 DEC. 2005

	Redactors in Operation		Reactors under Construction		Electricity Generated in 2005		Reactor Experience	
Country	No of Units	Total MW(e)	No of Units	Total MW(e)	TW(e).h	% of Total	Years	Months
ARGNTINA	2	935	1	692	6.37	6.92	54	7
ARMENIA	1	376			2.50	42.74	38	3
BELGIUM	7	5801			45.34	55.63	205	7
BRAZIL	2	1901			9.85	2.46	29	3
BULGARIA	4	2722	2	1906	17.34	44.10	137	3
CANADA	18	12599			86.83	14.63	534	7
CHINA	9	6572	3	3000	50.33	2.03	56	11
CZECH REP	6	3368			23.25	30.52	86	10
FINLAND	4	2676	1	1600	22.33	32.91	107	4
FRANCE	59	63363			430.90	78.46	1464	2
GERMANY	17	20339			154.61	30.98	683	5
HUNGARY	4	1755			13.02	37.15	82	2
INDIA	15	3040	8	3602	15.73	2.83	252	0
IRAN			1	915	0	0		
JAPAN	56	47839	1	866	280.67	29.33	1231	8
KOREA	20	16810			139.29	44.67	259	8
LITHNIA	1	1185			10.30	69.59	39	6
MEXICO	2	1310			10.80	5.01	27	11
NETHERLANDS	1	449			3.77	3.91	61	0
PAKISTAN	2	425	1	300	2.41	2.80	39	10
ROMANIA	1	655	1	655	5.11	8.58	9	6
RUSSIA	31	21743	4	3775	137.27	15.78	870	4
S.AFRICA	2	1800			12.24	5.52	42	3
SLOVAKIA	6	2442			16.34	56.06	112	6
SLOVENIA	1	656			5.61	42.36	24	3
SPAIN	9	7588			54.70	19.56	237	2
SWEDEN	10	8910			70.00	46.67	332	6
SWITZERLAND	5	3220			22.11	32.09	153	10
UK	23	11852			75.17	19.86	1377	8
UKRAINE	15	13107	2	1900	83.29	48.48	308	6
USA	104	99210			780.47	19.33	3079	8
Total	443	369552	27	21811	2626.35	19.28	12086	2

Note: The total includes the following data in Taiwan, China: — 6 units, 4904 MW(e) in operation; 2 units, 2600 MW(e) under construction; — 38.4 TW(e).h of nuclear electricity generation, representing 20.25% of the total electricity generated there; — 146 years 1 month of total operating experience.

Table derived from IAEA(2006) Nucelar Reactors around the World

Data from WNA 17/10/ 2007

	NUCLEAR ELECTRICITY GENERATION 2006		REACTORS OPERABLE October 2007		REACTORS UNDER CONSTRUCTION October 2007		REACTORS PLANNED October 2007		REACTORS PROPOSED October 2007		URANIUM REQUIRED 2007
	TWh	% e	No.	MWe	No.	MWe	No.	MWe	No.	MWe	tonnes U
Argentina	7.2	6.9	2	935	1	692	1	740	1	740	135
Armenia	2.4	42	1	376	0	0	0	0	1	1000	51
Bangladesh	0	0	0	0	0	0	0	0	2	2000	0
Belarus	0	0	0	0	0	0	2	2000	0	0	0
Belgium	44.3	54	7	5728	0	0	0	0	0	0	1079
Brazil	13	3.3	2	1901	0	0	1	1245	4	4000	338
Bulgaria	18.1	44	2	1906	0	0	2	1900	0	0	255
Canada*	92.4	16	18	12595	2	1540	4	4000	2	2200	1836
China	51.8	1.9	11	8587	5	4540	30	32000	86	68000	1454
Czech Republic	24.5	31	6	3472	0	0	0	0	2	1900	550
Egypt	0	0	0	0	0	0	0	0	1	1000	0
Finland	22	28	4	2696	1	1600	0	0	1	1000	472
France	428.7	78	59	63473	1	1630	0	0	1	1600	10368
Germany	158.7	32	17	20339	0	0	0	0	0	0	3486
Hungary	12.5	38	4	1826	0	0	0	0	2	2000	254
India	15.6	2.6	17	3779	6	2976	10	8560	9	4800	491
Indonesia	0	0	0	0	0	0	2	2000	0	0	0
Iran	0	0	0	0	1	915	2	1900	1	300	143
Israel	0	0	0	0	0	0	0	0	1	1200	0
Japan	291.5	30	55	47577	2	2285	11	14945	1	1100	8872
Kazakhstan	0	0	0	0	0	0	0	0	1	300	0
Korea DPR (North)	0	0	0	0	0	0	1	950	0	0	0
Korea RO (South)	141.2	39	20	17533	2	2000	6	7600	0	0	3037
Lithuania	8	69	1	1185	0	0	0	0	2	3200	134
Mexico	10.4	4.9	2	1310	0	0	0	0	2	2000	257
Netherlands	3.3	3.5	1	485	0	0	0	0	0	0	112
Pakistan	2.6	2.7	2	400	1	300	2	600	2	2000	64
Romania	5.2	9	2	1310	0	0	2	1310	1	655	92
Russia	144.3	16	31	21743	7	4920	8	9600	20	18200	3777
Slovakia	16.6	57	5	2064	2	840	0	0	0	0	299
Slovenia	5.3	40	1	696	0	0	0	0	1	1000	145
South Africa	10.1	4.4	2	1842	0	0	1	165	24	4000	332
Spain	57.4	20	8	7442	0	0	0	0	0	0	1473
Sweden	65.1	48	10	9086	0	0	0	0	0	0	1468
Switzerland	26.4	37	5	3220	0	0	0	0	1	1000	575
Thailand	0	0	0	0	0	0	0	0	4	4000	0
Turkey	0	0	0	0	0	0	0	0	3	4500	0
Ukraine	84.8	48	15	13168	0	0	2	1900	20	27000	2003
United Kingdom	69.2	18	19	11035	0	0	0	0	0	0	2021
USA	787.2	19	104	99049	0	0	7	10180	25	32000	20050
Vietnam	0	0	0	0	0	0	0	0	2	2000	0
WORLD**	**2658**	**16**	**439**	**372,002**	**33**	**26,838**	**94**	**101,595**	**222**	**193,095**	**66,529**

Operational **19** Shutdown **26**

Annual Electrical Power Production for 2008

Total Power Production (including Nuclear)	Nuclear Power Production	% Nuclear generation
390322 GWh(e)	**52486 GWh(e)**	13.45%

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

				Capacity (MWe)		Date
Name	**Type**	**Status**	**Location**	**Net**	**Gross**	**Connected**
BERKELEY 1	Magnox	Shutdown	Gloucestershire	138	166	12/06/1962
BERKELEY 2	Magnox	Shutdown	Gloucestershire	138	166	24/06/1962
BRADWELL 1	Magnox	Shutdown	Essex	123	146	01/07/1962
BRADWELL 2	Magnox	Shutdown	Essex	123	146	06/07/1962
CALDER HALL 1	Magnox	Shutdown	Cumbria	50	60	27/08/1956
CALDER HALL 2	Magnox	Shutdown	Cumbria	50	60	01/02/1957
CALDER HALL 3	Magnox	Shutdown	Cumbria	50	60	01/03/1958
CALDER HALL 4	Magnox	Shutdown	Cumbria	50	60	01/04/1959
CHAPELCROSS 1	Magnox	Shutdown	Dumfriesshire	50	60	01/02/1959
CHAPELCROSS 2	Magnox	Shutdown	Dumfriesshire	50	60	01/07/1959
CHAPELCROSS 3	Magnox	Shutdown	Dumfriesshire	50	60	01/11/1959
CHAPELCROSS 4	Magnox	Shutdown	Dumfriesshire	50	60	01/01/1960
DOUNREAY DFR	FBR	Shutdown	Caithness	14	15	01/10/1962
DOUNREAY PFR	FBR	Shutdown	Caithness	234	250	10/01/1975
DUNGENESS-A1	Magnox	Shutdown	Kent	225	230	21/09/1965
DUNGENESS-A2	Magnox	Shutdown	Kent	225	230	01/11/1965
DUNGENESS-B1	AGR	Operational	Kent	520	615	03/04/1983
DUNGENESS-B2	AGR	Operational	Kent	520	615	29/12/1985
HARTLEPOOL-A1	AGR	Operational	Durham	595	655	01/08/1983
HARTLEPOOL-A2	AGR	Operational	Durham	595	655	31/10/1984
HEYSHAM-A1	AGR	Operational	Lancashire	585	625	09/07/1983
HEYSHAM-A2	AGR	Operational	Lancashire	575	625	11/10/1984
HEYSHAM-B1	AGR	Operational	Lancashire	615	680	12/07/1988
HEYSHAM-B2	AGR	Operational	Lancashire	620	680	11/11/1988
HINKLEY POINT-A1	Magnox	Shutdown	Somerset	235	267	16/02/1965
HINKLEY POINT-A2	Magnox	Shutdown	Somerset	235	267	19/03/1965
HINKLEY POINT-B1	AGR	Operational	Somerset	410	655	30/10/1976
HINKLEY POINT-B2	AGR	Operational	Somerset	410	655	05/02/1976
HUNTERSTON-A1	Magnox	Shutdown	Ayrshire	150	173	05/02/1964
HUNTERSTON-A2	Magnox	Shutdown	Ayrshire	150	173	01/06/1964
HUNTERSTON-B1	AGR	Operational	Ayrshire	410	644	06/02/1976
HUNTERSTON-B2	AGR	Operational	Ayrshire	410	644	31/03/1977
OLDBURY-A1	Magnox	Operational	Gloucestershire	217	230	07/11/1967
OLDBURY-A2	Magnox	Operational	Gloucestershire	217	230	06/04/1968
SIZEWELL-A1	Magnox	Shutdown	Suffolk	210	245	21/01/1966
SIZEWELL-A2	Magnox	Shutdown	Suffolk	210	245	09/04/1966
SIZEWELL-B	PWR	Operational	Suffolk	1188	1250	14/02/1995
TORNESS 1	AGR	Operational	East Lothian	615	682	25/05/1988
TORNESS 2	AGR	Operational	East Lothian	615	682	03/02/1989
TRAWSFYNYDD 1	Magnox	Shutdown	Wales	195	235	14/01/1965
TRAWSFYNYDD 2	Magnox	Shutdown	Wales	195	235	02/02/1965
WINDSCALE AGR	AGR	Shutdown	Cumbria	32	41	01/02/1963
WINFRITH SGHWR	SGHWR	Shutdown	Dorset	92	100	01/12/1967
WYLFA 1	Magnox	Operational	Wales	490	540	24/01/1971
WYLFA 2	Magnox	Operational	Wales	490	540	21/07/1971

Above data from PRIS database.

Comments to Project Officer

This page was automatically created on 11 Jan 2010, 10:45:37

TABLE 2. REACTOR TYPES AND NET ELECTRICAL POWER, REACTORS CONNECTED TO THE GRID, 31 DEC. 2005

Country	PWR		PWR-WWER		BWR		ABWR		GCR		AGR		PHWR		LWGR/RBMK		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)	No	MW(e)	No	MW(e)
ARGNTINA													2	935					2	935
ARMENIA			1	376															1	376
BELGIUM	7	5801																	7	5801
BRAZIL	2	1901																	2	1901
BULGARIA			4	2722															4	2722
CANADA													18	12599					18	12599
CHINA	7	5272											2	1300					9	6572
CZECH R.			6	3368															6	3368
FINLAND			2	976	2	1700													4	2676
FRANCE	58	63130															1	233	59	63363
GERMANY	11	13968			6	6371													17	20339
HUNGARY			4	1755															4	1755
INDIA					2	300							13	2740					15	3040
JAPAN	23	18425	28	23909	4	5259	(*)1	246	56	47839										
KOREA	16	14231											4	2579					20	16810
LITHUANIA															1	1185			1	1185
MEXICO					2	1310													2	1310
NETHERLANDS	1	449																	1	449
PAKISTAN	1	300											1	125					2	425
ROMANIA	1	655	1	655									1	655					1	655
RUSSIA			15	10964											15	10219	1	560	31	21743
S.AFRICA	2	1800																	2	1800
SLOVAKIA			6	2442															6	2442
SLOVENIA	1	656																	1	656
SPAIN	7	6078			2	1510													9	7588
SWEDEN	3	2692			7	6218													10	8910
SWITZRLD	3	1700			2	1520													5	3220
UK	1	1188							8	2284	14	8380							23	11852
UKRAINE			15	13107															15	13107
USA	69	65984			35	33226													104	99210
TOTAL	214	205375	53	35710	90	79168	4	5259	8	2284	14	8380	41	20933	16	11404	3	1039	443	369552

*** Long Term Shut Down**

Table derived from IAEA(200) Nucelar Reactors around the World

6.3.1 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. Shortly there will only be two such reactors left in service at Oldbury and Wylfa.

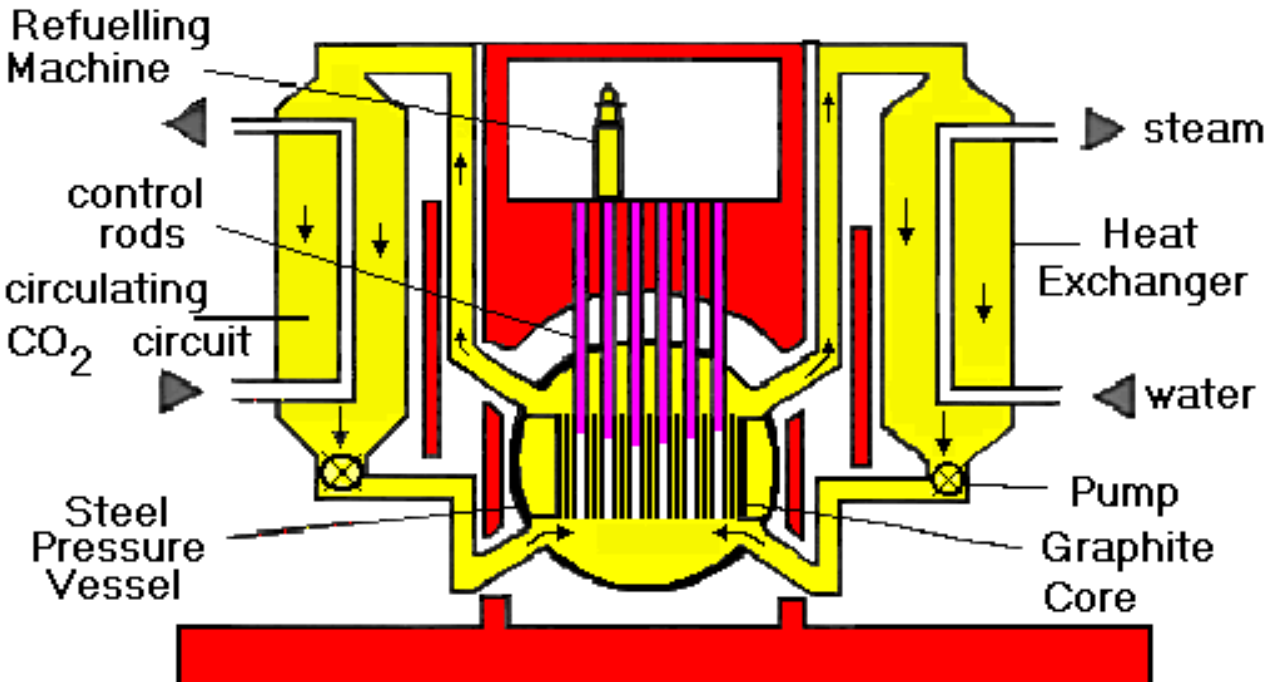


Fig. 6.1 Schematic section of an early Magnox Reactor. Later versions had a pressurised concrete vessel which also enclosed the boilers as with the AGRs. This reactor was developed in the UK and France. The 2 French reactors were closed in the late 1980s. There were originally 24 such reactors in operation 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.

6.3.2 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.

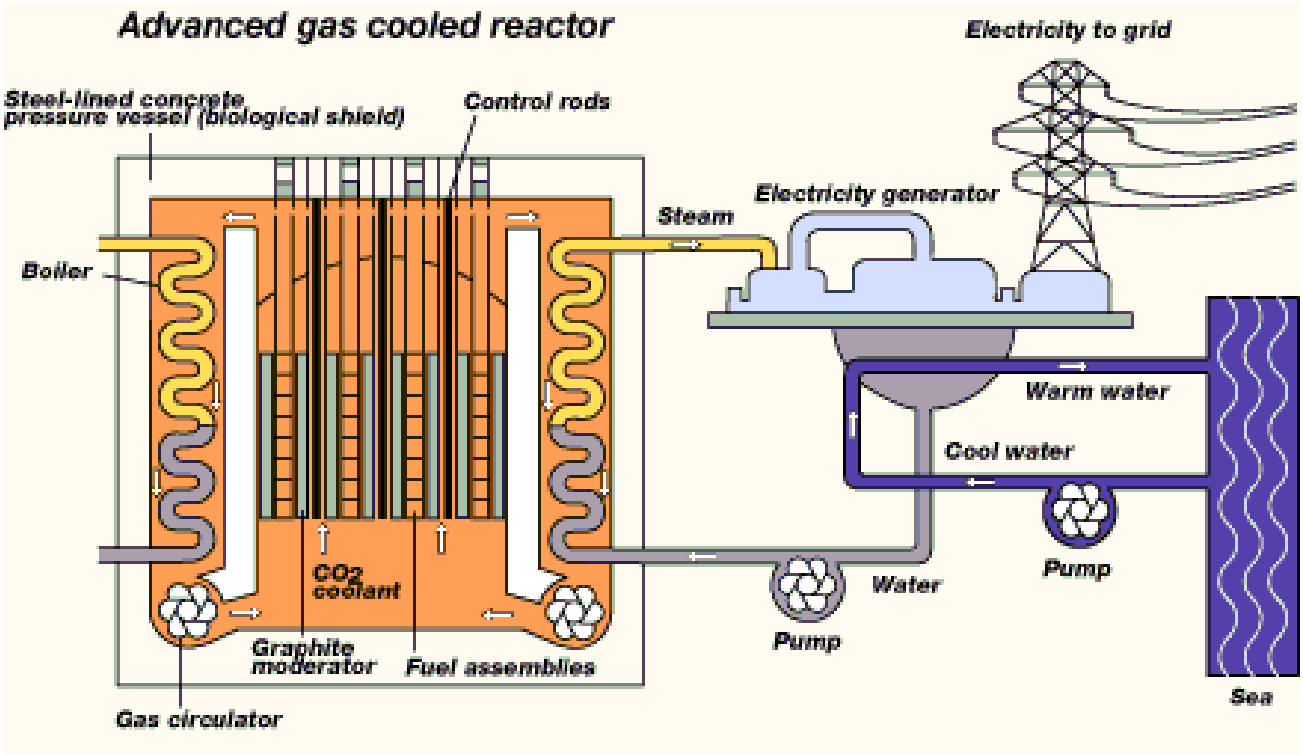


Fig. 6.2 Section of an Advanced Gas Cooled Reactor. This reactor was only developed in the UK. There are currently 14 such reactors in 7 stations in the UK.

6.3.3 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

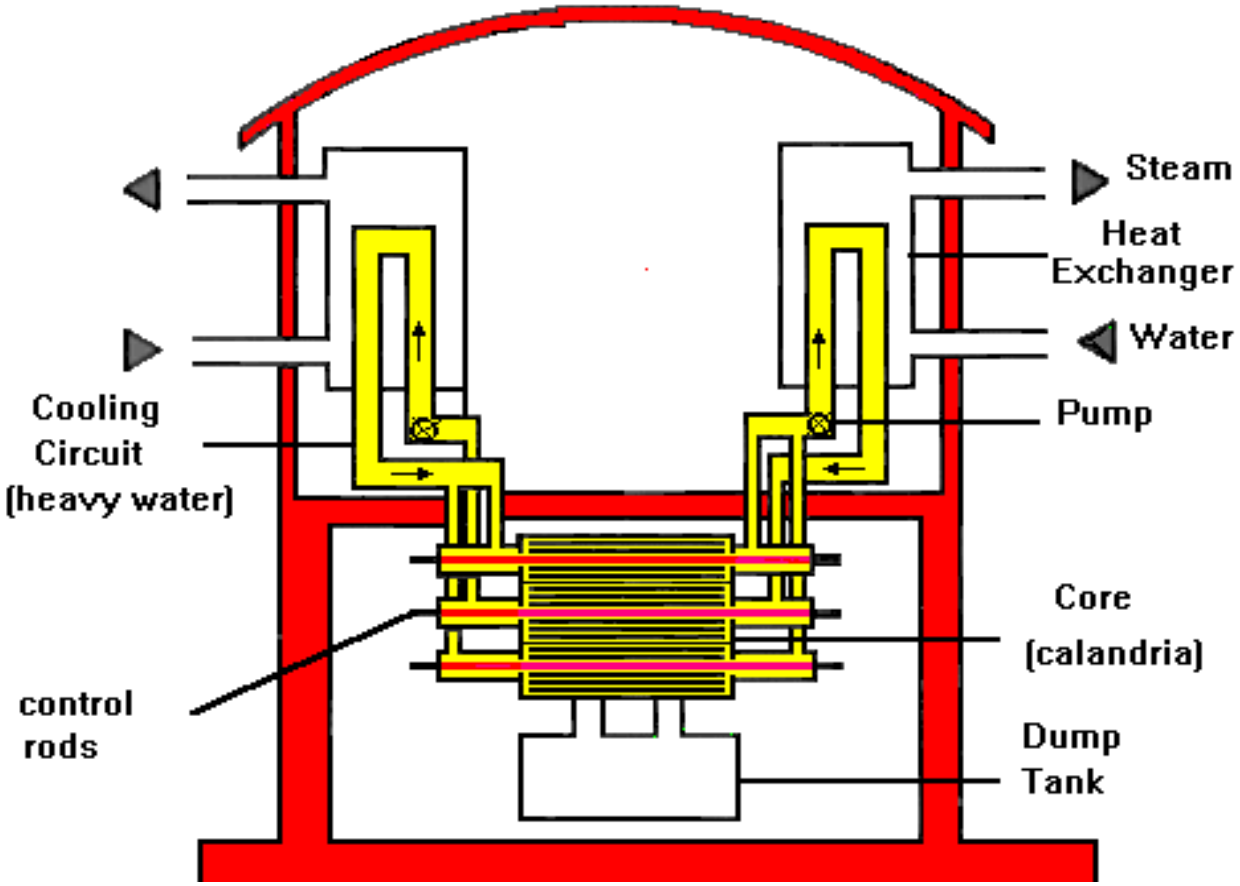


Fig. 6.3 A section of a CANDU reactor. This design was developed in Canada, and has the advantage that it is modular and can be built to any size. The British Steam Generating Heavy Water Reactor (SGHWR) was of similar design except the cooling circuit was ordinary water. The space surrounding the fuel elements in the calandria in a SGHWR was heavy water as in the CANDU design.

6.3.4 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.

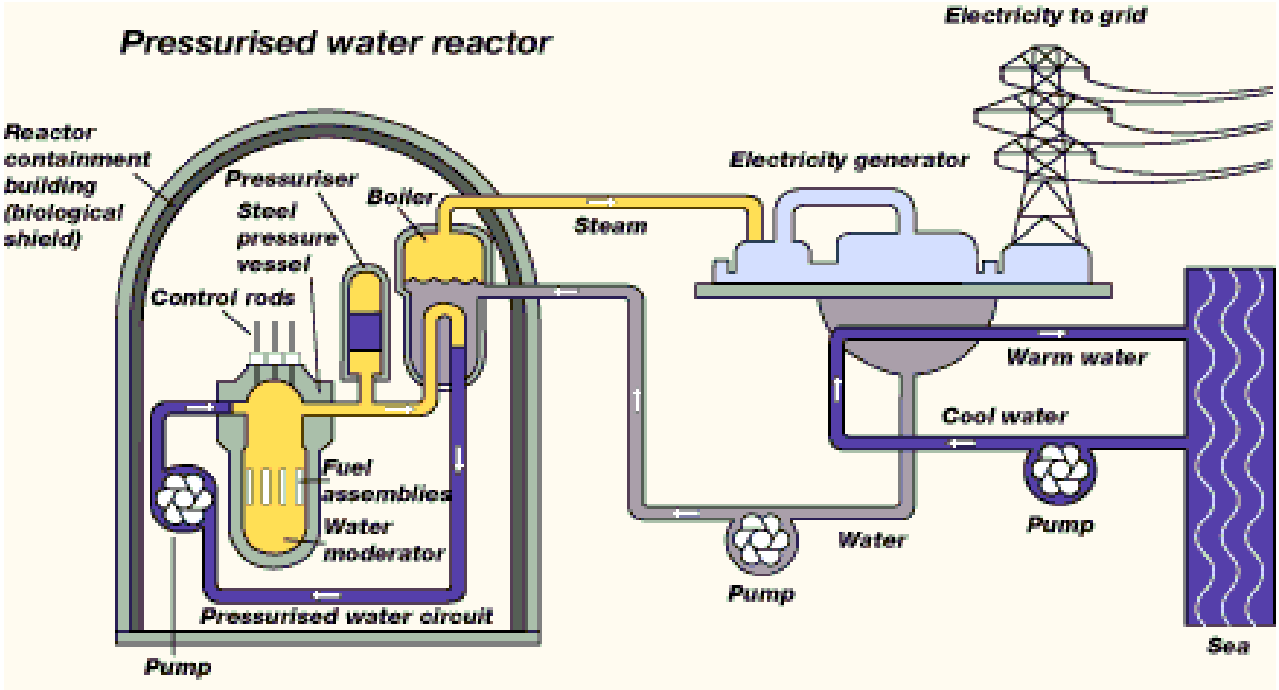


Fig. 6.4 A section of a PWR. This shows the safer design having the cold and hot legs entering the reactor vessel at the top. the reactor at Sizewell has a secondary dome outside the primary containment building. This is the only one in the world that has a double skin. One of the new designs being considered 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

6.3.5 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.

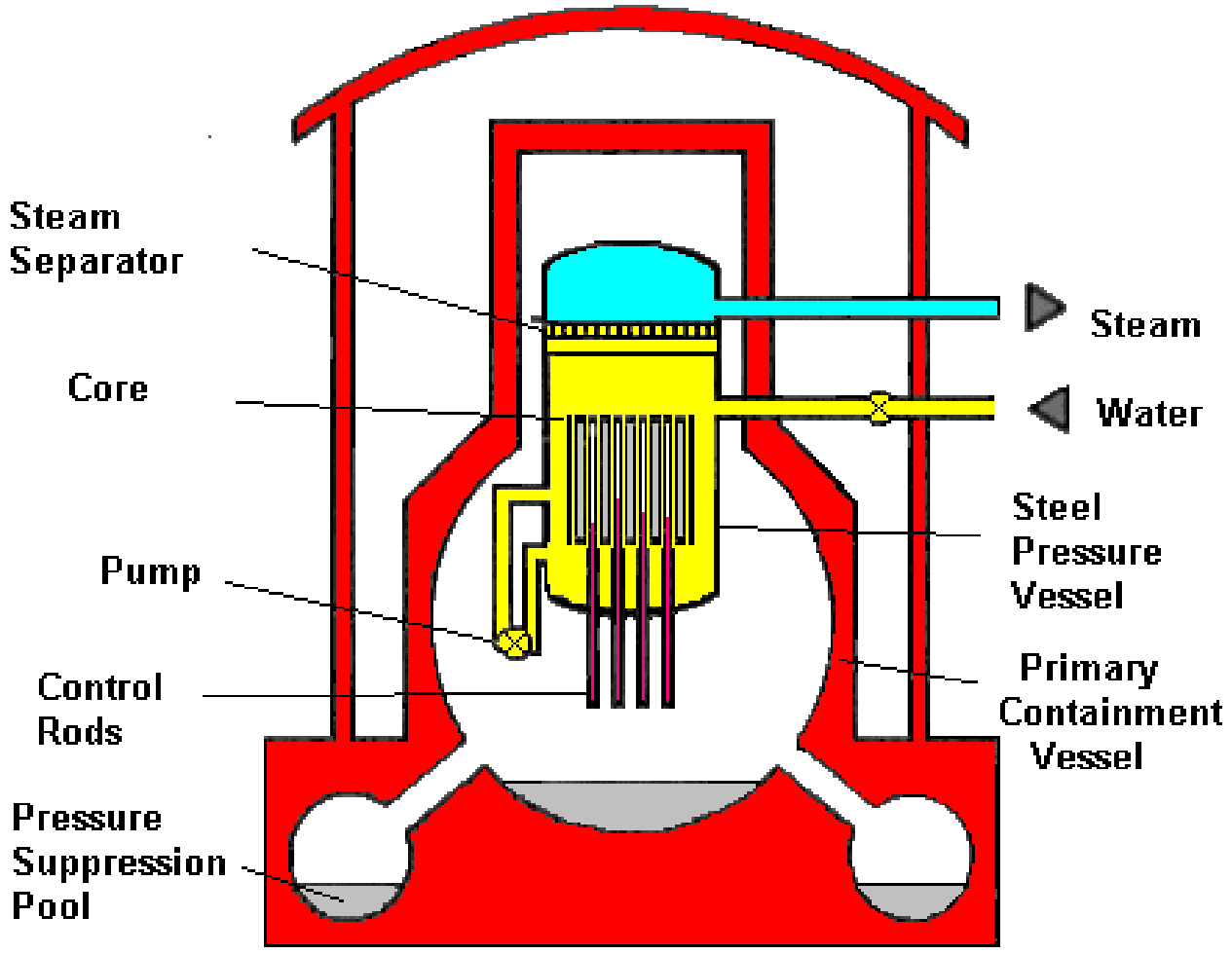


Fig. 6.5 A Boiling Water Reactor. Notice that the primary circuit steam is passed directly to the turbines.

6.3.6 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

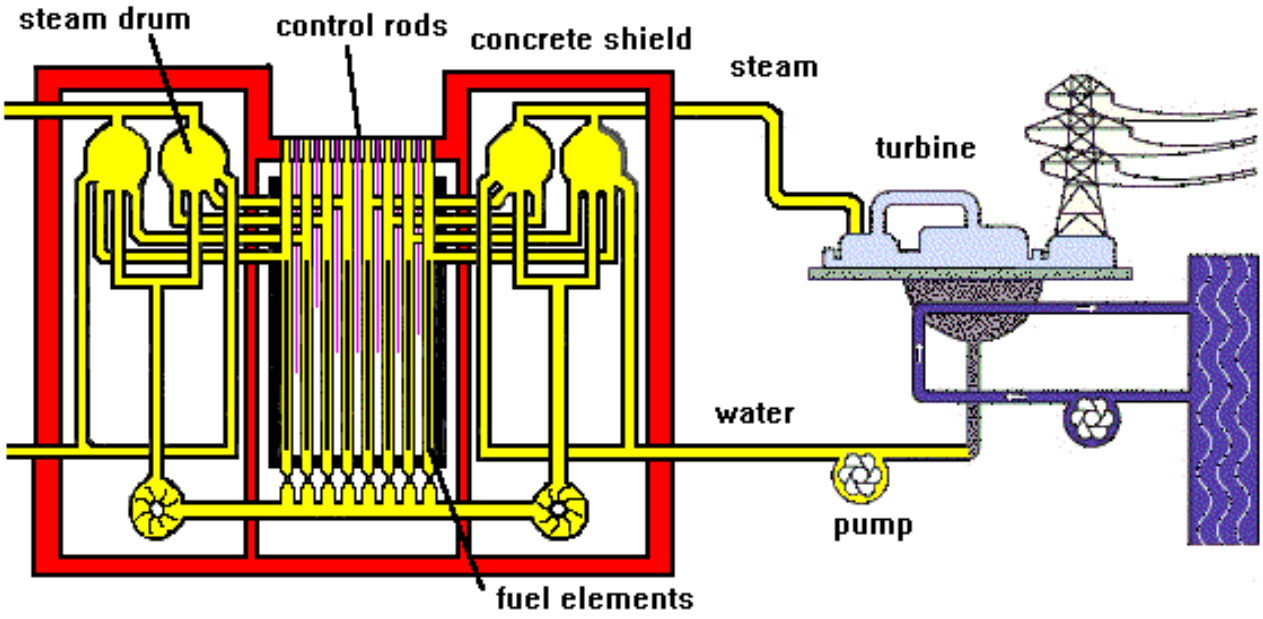


Fig. 6.6 The Russian Light Water - Graphite Moderated Reactor. This reactor was of the type involved in the Chernobyl incident in 1986.

6.3.7 Summary of key parameters for existing reactors.

Table 6.1 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 6.1 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

6.3.8 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

6.3.9 European Pressurised Reactor

Provisional Data

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

The EPR1300 has one plant under construction in Finland at Olkiluoto. This is expected to be operational in 2011. The order for the second second such reactor at Flammanville in France was signed on 24th January 2007 while the AP1000 is likely to have 4 plants built in China, and is a likely contender for any future UK development.

The digits 1300 and 1000 indicate nominal power ratings of the reactors in MW, but both types will be operated at higher ratings ~ 1600 MW in the case of the EPR1300 and 1150 MW in the case of the AP1000. Generally the fuel elements, the moderator, and the coolant are as indicated for the PWR above. The main differences come from the safety systems, and a general simplification of the componenst of the reactor.

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

The EPR1300 hopes to gain certification in the uSA in 2008.

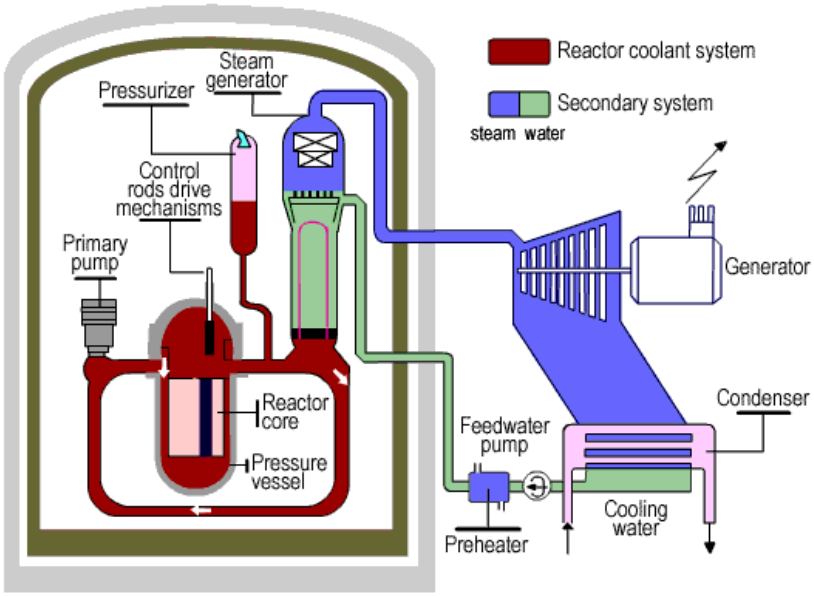


Fig.6.7 [From the AREVA WEB SITE]. This diagram is very similar to the PWR above.

6.3.10 AP1000 REACTOR

The AP1000 Reactor has been certified in USA and is a possible contender for a future Reactor in the UK. 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. 6.8).

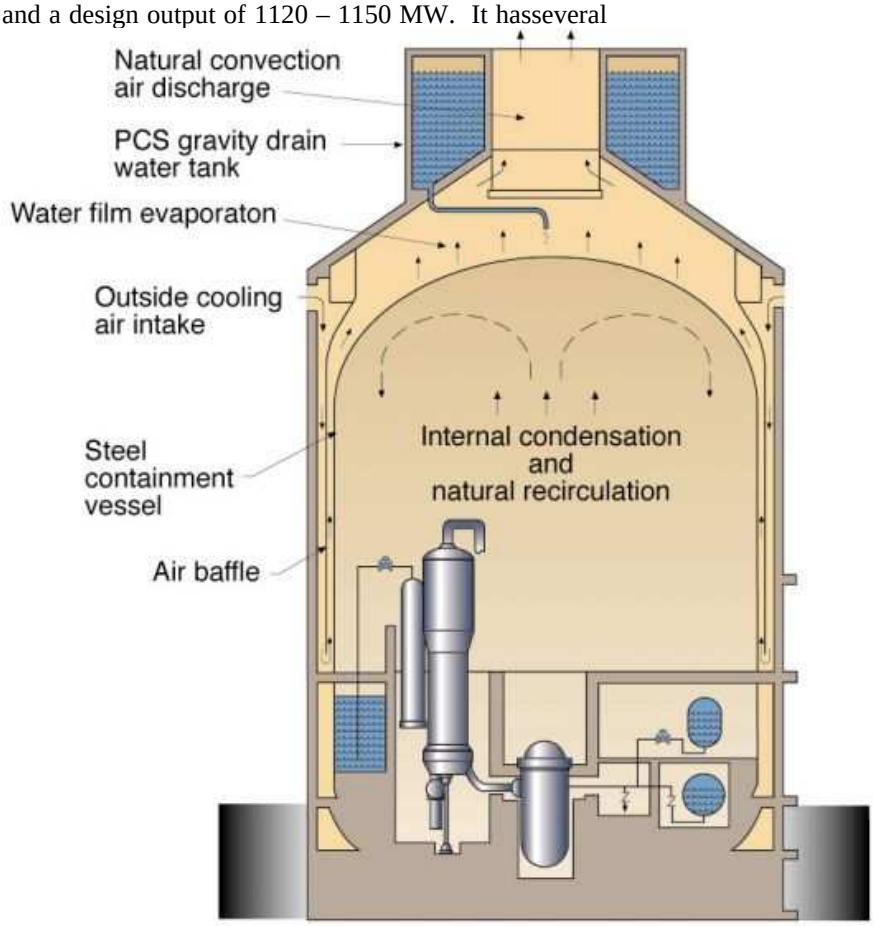


Fig. 6.8 Cross section of AP1000 Reactor and Containment Building showing passive cooling

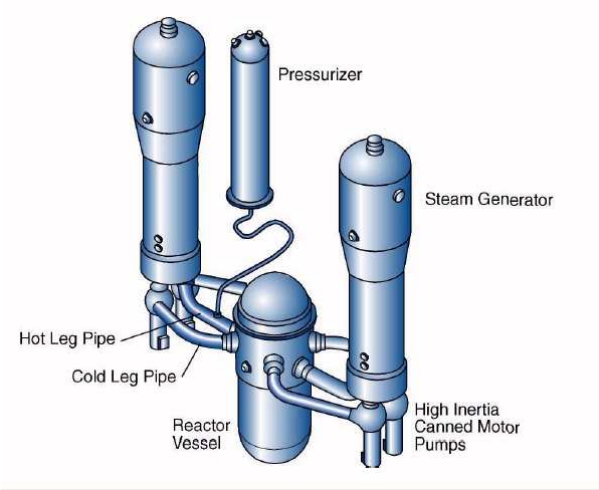


Fig. 6.9 Diagram showin two loops in AP1000 design. The EPR1300 has four separate steam generators. Both Reactors have just one Pressuriser.

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. 6.9) The efficiency is likely to be margingally higher than a normal PWR at around 33-35% 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

6.3.11 ACR1000 Advanced Candu Reactor

This reactor (Fig. 6.10) 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.

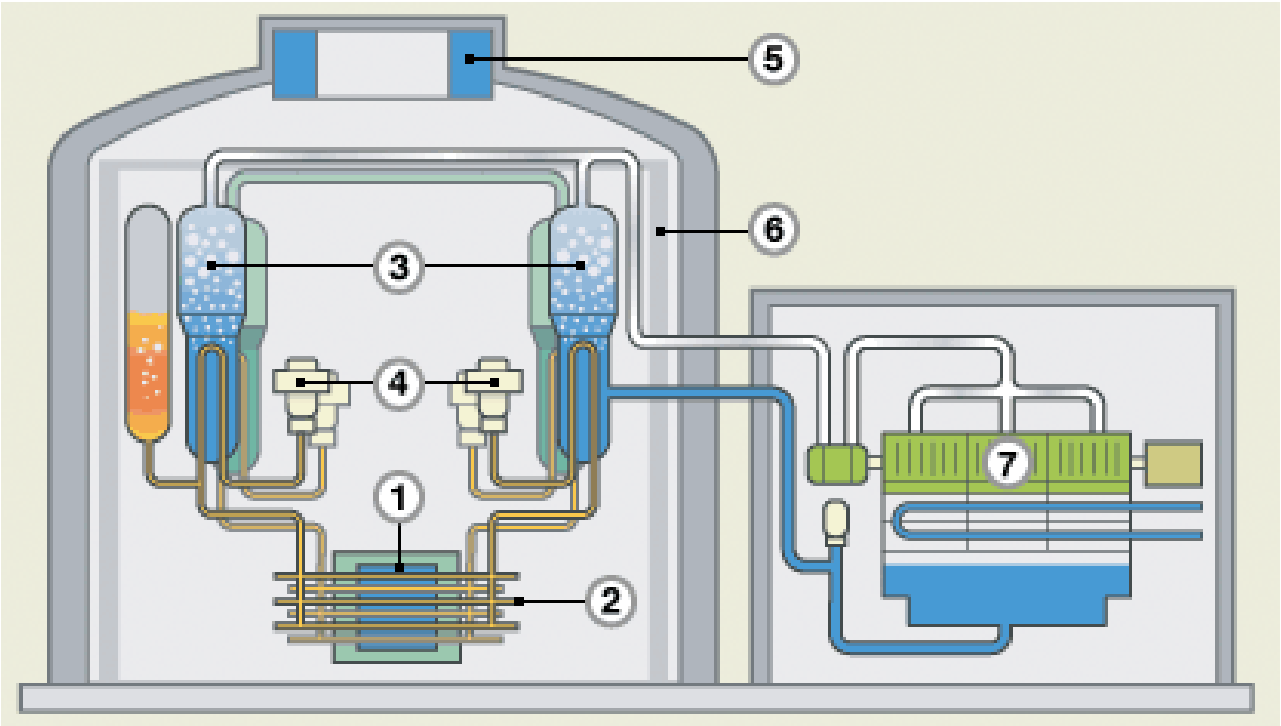


Fig. 6.10 Advanced Candu Reactor.

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

6.3.12 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.

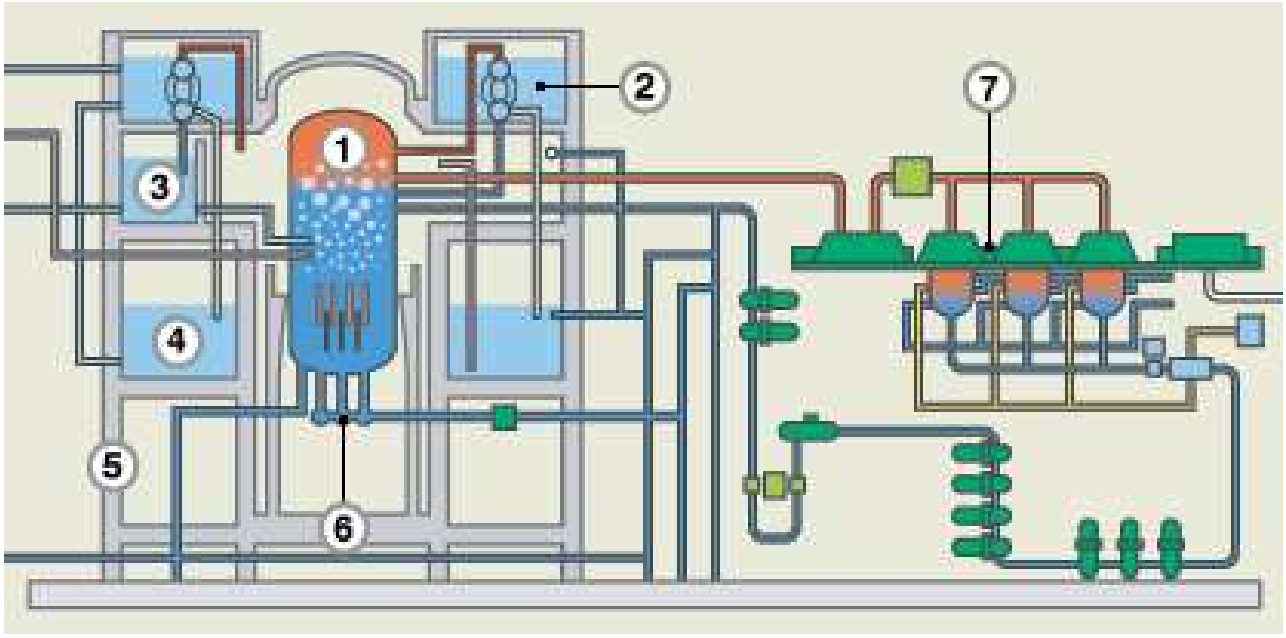


Fig. 6.11 Economic Simplified Boiling Water Reactor

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

6.3.13. Comment on Generation 3 in the context of the Nuclear White Paper, Jan 2008.

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 2009, the two remaining reactors types under consideration are the EPR 1300 and the AP1000, although there have been issues relating to both.

6.3.13 GENERATION 3+ REACTORS.

The most advanced design of 3+ Genertaion Reactor is the Pebble Bed Modulating Reactor. 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. 6.12, while the novel method of producing fuel elements is shown in Fig. 6.13.

FUEL TYPE - enriched URANIUM OXIDE
- 9% clad in specially created sand sized particles (see Fig. 6.13)
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

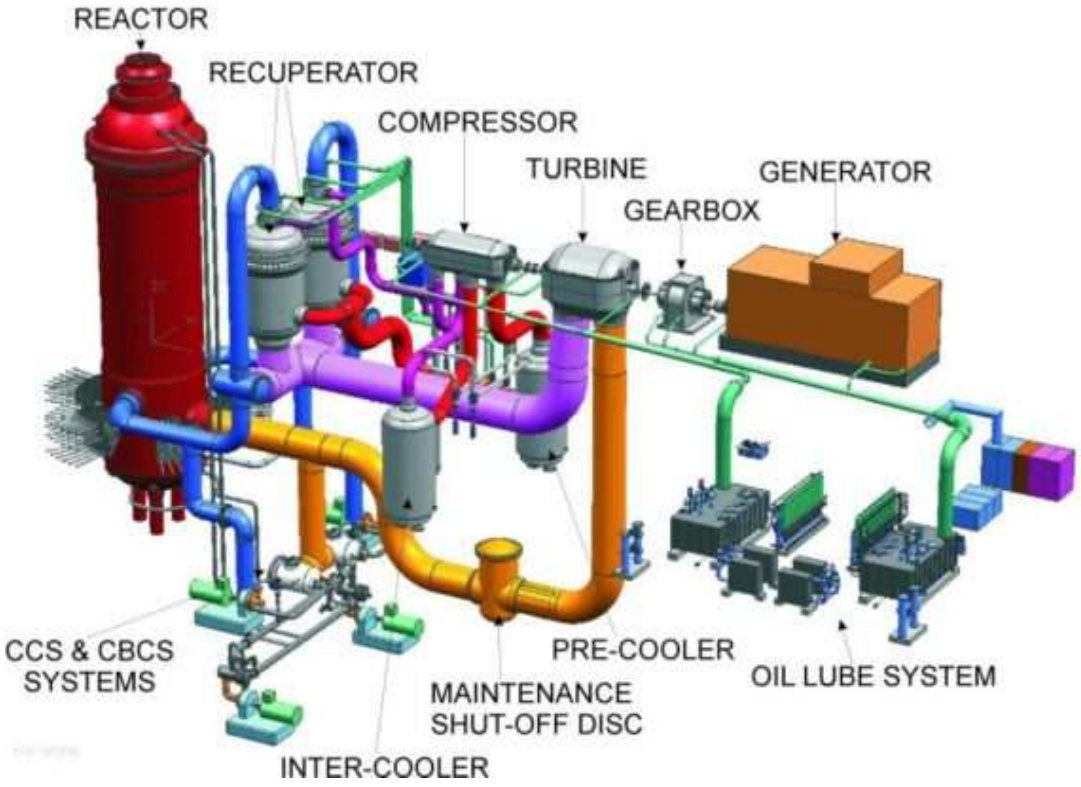


Fig. 6.12 Schematic Diagram of a Pebble Bed Modulating Reactor

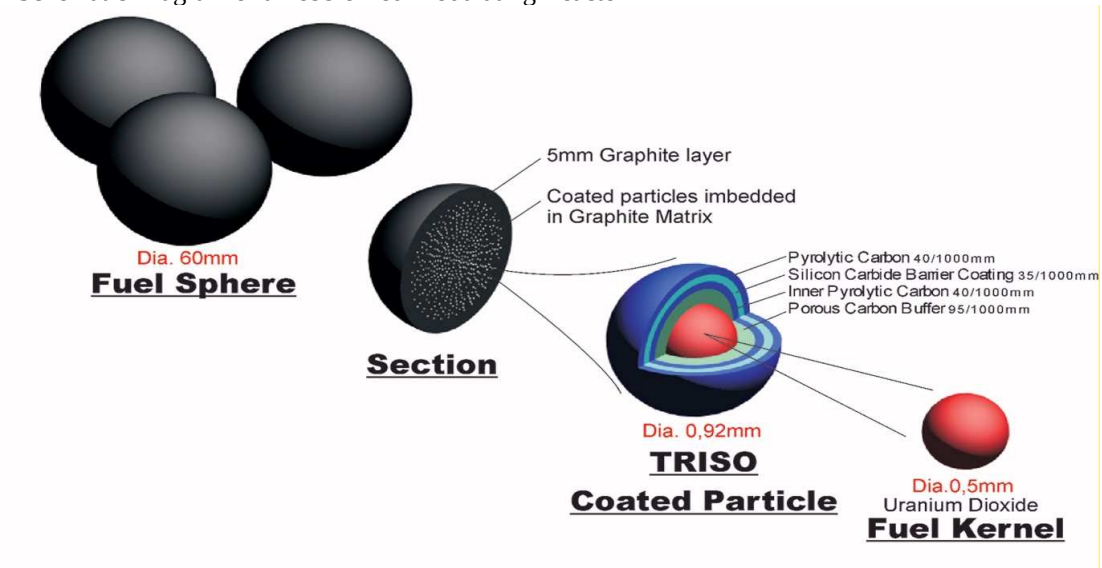


Fig. 6.13 Fuel pellets for a PBMR. The inner kernel is prepared by spraying uranyl nitrate to form small pellets 0.5mm in diameter. These are baked to produce Uranium Dioxide. Four layers are then deposited on the fuel particle: a) a porous graphite (which allows the fisiion products space to accumulate), b) a heat teated layer of pyrolitic dense carbon, a layer of silicon carbide, and finnaly 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 see: http://www.pbmr.com/download/FuelSystem.pdf

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

6.3.14 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.

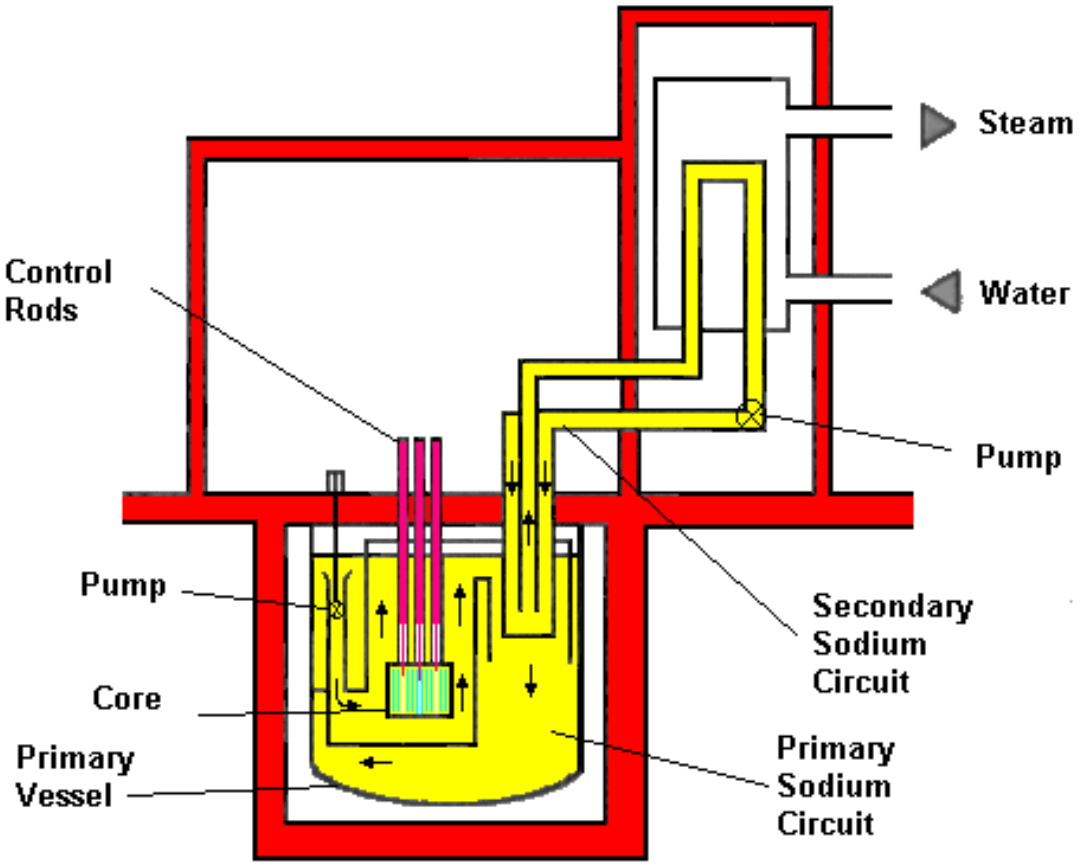


Fig. 6.14 A Fast Breeder Reactor. This type of reactor has depleted Uranium - 238 in a blanket around the fissile core material (of enriched U-235 or Plutonium). Fast neutrons can be captured by the fertile U - 238 to produce more Plutonium. Typically one kilogram of fissile Plutonium could produce as 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.

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.

6.3.15CONCLUDING 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. It is likely that the certification will start during 2008.

6.3.16 REPROCESSING IS ESSENTIAL FOR FAST BREEDER REACTORS.

- 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

6.3.17 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.

By 2004, four civil programme reactors had been closed and are being deomissioned - Berkeley and Trawsfynydd and Hunterston A in Scotland, and Bradwell with Hinkley Point A following shortly afterwards. At all of the above, the spent fuel has been removed and a start has been made on removing the non-reactor buildings from site. This is well advanced in the case of Berkeley.

In 2005, Calder Hall closed followed shortly by Chapel Cross. Then on 31st December 2006, Sizewell A, Dungeness A closed. In 2008, it is planned that Oldbury will close.

TABLE 3: LIST OF NUCLEAR POWER REACTORS which were GRID CONNECTED and which have now been decommissioned.

				Capacity (MW(e))			Construction	First	Grid	Commercial	Shut
Country	Code	Name	Type	Net	Gross	Operator	Start	Criticality	Connection	Operation	Down
ARMENIA	AM -18	ARMENIA-1	WWER	376	408	JSC	1973-1	1976-12	1976-12	1979-10	1989-2
BELGIUM	BE -1	BR-3	PWR	11	12	CENSCK	1957-11	1962-8	1962-10	1962-10	1987-6
BULGARIA	BG -1	KOZLODUY-1	WWER	408	440	KOZNPP	1970-4	1974-6	1974-7	1974-10	2002-12
	BG -2	KOZLODUY-2	WWER	408	440	KOZNPP	1970-4	1975-8	1975-8	1975-11	2002-12
CANADA	CA -8	BRUCE-1	PHWR	769	825	BRUCEPOW	1971-6	1976-12	1977-1	1977-9	1997-10
	CA -9	BRUCE-2	PHWR	769	825	BRUCEPOW	1970-12	1976-7	1976-9	1977-9	1995-10
	CA -2	DOUGLAS POINT	PHWR	206	218	OPG	1960-2	1966-11	1967-1	1968-9	1984-5
	CA -3	GENTILLY-1	HWLWR	250	266	HQ	1966-9	1970-11	1971-4	1972-5	1977-6
	CA -1	NPD	PHWR	22	25	OH	1958-1	1962-4	1962-6	1962-10	1987-8
	CA -5	PICKERING-2	PHWR	515	542	OPG	1966-9	1971-9	1971-10	1971-12	1997-12
	CA -6	PICKERING-3	PHWR	515	542	OPG	1967-12	1972-4	1972-5	1972-6	1997-12
FRANCE	FR -9	BUGEY-1	GCR	540	555	EDF	1965-12	1972-3	1972-4	1972-7	1994-5
	FR -2	CHINON-A1	GCR	70	80	EDF	1957-2	1962-9	1963-6	1964-2	1973-4
	FR -3	CHINON-A2	GCR	210	230	EDF	1959-8	1964-8	1965-2	1965-2	1985-6
	FR -4	CHINON-A3	GCR	480	480	EDF	1961-3	1966-3	1966-8	1966-8	1990-6
	FR -5	CHOOZ-A(ARDENNES)	PWR	310	320	SENA	1962-1	1966-10	1967-4	1967-4	1991-10
	FR -6	EL-4 (MONTS D'ARREE)	HWGCR	70	75	EDF	1962-7	1966-12	1967-7	1968-6	1985-7
	FR -1B	G-2 (MARCOULE)	GCR	38	43	COGEMA	1955-3	1958-7	1959-4	1959-4	1980-2
	FR -1	G-3 (MARCOULE)	GCR	38	43	COGEMA	1956-3	1959-6	1960-4	1960-4	1984-6
	FR -7	ST. LAURENT-A1	GCR	480	500	EDF	1963-10	1969-1	1969-3	1969-6	1990-4
	FR -8	ST. LAURENT-A2	GCR	515	530	EDF	1966-1	1971-7	1971-8	1971-11	1992-5
	FR -24	SUPER*-PHENIX	FBR	1200	1242	NERSA	1976-12	1985-9	1986-1	—	1998-12
GERMANY	DE -4	AVR JULICH (AVR)	HTGR	13	15	AVR	1961-8	1966-8	1967-12	1969-5	1988-12
	DE -502	GREIFSWALD-1(KGR 1)	WWER	408	440	EWN	1970-3	1973-12	1973-12	1974-7	1990-2
	DE -503	GREIFSWALD-2 (KGR 2)	WWER	408	440	EWN	1970-3	1974-12	1974-12	1975-4	1990-2
	DE -504	GREIFSWALD-3 (KGR 3)	WWER	408	440	EWN	1972-4	1977-10	1977-10	1978-5	1990-2
	DE -505	GREIFSWALD-4 (KGR 4)	WWER	408	440	EWN	1972-4	1979-7	1979-9	1979-11	1990-7
	DE -506	GREIFSWALD-5 (KGR 5)	WWER	408	440	EWN	1976-12	1989-3	1989-4	1989-11	1989-11
	DE -3	GUNDREMMINGEN-A	BWR	237	250	KGB	1962-12	1966-8	1966-12	1967-4	1977-1
	DE -7	HDR GROSSWELZHEIM	BWR	23	25	HDR	1965-1	1969-10	1969-10	1970-8	1971-4
	DE -8	KNK II	FBR	17	21	KBG	1974-9	1977-10	1978-4	1979-3	1991-8
	DE -6	LINGEN (KWL)	BWR	250	268	KWL	1964-10	1968-1	1968-7	1968-10	1979-1
	DE -22	MUELHEIM-KAERLICH (KMK)	PWR	1219	1302	RWE	1975-1	1986-3	1986-3	1987-8	1988-9
	DE -2	MZFR	PHWR	52	57	KBG	1961-12	1965-9	1966-3	1966-12	1984-5
	DE -11	NIEDERAICHBACH (KKN)	HWGCR	100	106	KKN	1966-6	1972-12	1973-1	1973-1	1974-7
	DE -5	OBRIGHEIM (KWO)	PWR	340	357	EnBW	1965-3	1968-9	1968-10	1969-3	2005-5
	DE -501	RHEINSBERG (KKR)	PWR	62	70	EWN	1960-1	1966-3	1966-5	1966-10	1990-6
	DE -10	STADE (KKS)	PWR	640	672	EON	1967-12	1972-1	1972-1	1972-5	2003-11
	DE -19	THTR-300	HTGR	296	308	HKG	1971-5	1983-9	1985-11	1987-6	1988-4

				Capacity (MW(e))			Construction	First	Grid	Commercial	Shut
Country	Code	Name	Type	Net	Gross	Operator	Start	Criticality	Connection	Operation	Down
GERMANY	DE -1	VAK KAHL	BWR	15	16	VAK	1958-7	1960-11	1961-6	1962-2	1985-11
	DE -9	WUERGASSEN (KWW)	BWR	640	670	PE	1968-1	1971-10	1971-12	1975-11	1994-8
ITALY	IT -4	CAORSO	BWR	860	882	SOGIN	1970-1	1977-12	1978-5	1981-12	1990-7
	IT -3	ENRICO FERMI (TRINO)	PWR	260	270	SOGIN	1961-7	1964-6	1964-10	1965-1	1990-7
	IT -2	GARIGLIANO	BWR	150	160	SOGIN	1959-11	1963-6	1964-1	1964-6	1982-3
	IT -1	LATINA	GCR	153	160	SOGIN	1958-11	1962-12	1963-5	1964-1	1987-12
JAPAN	JP -20	FUGEN ATR	HWLWR	148	165	JAEA	1972-5	1978-3	1978-7	1979-3	2003-3
	JP -1	JPDR	BWR	13	13	JAERI	1960-12	1963-8	1963-10	1965-3	1976-3
	JP -2	TOKAI-1	GCR	159	166	JAPC	1961-3	1965-5	1965-11	1966-7	1998-3
KAZAKHSTAN.	KZ -10	BN-350	FBR	52	90	KATEII	1964-10	1972-11	1973-7	1973-7	1999-4
LITHUANIA	LT -46	IGNALINA-1	LWGR	1185	1300	INPP	1977-5	1983-10	1983-12	1984-5	2004-12
NETHERLANDS	NL -1	DODEWAARD	BWR	55	58	GKN(NL)	1965-5	1968-6	1968-10	1969-1	1997-3
RUSSIA	RU -1	APS-1 OBNINSK	LWGR	5	6	REA	1951-1	1954-5	1954-6	1954-6	2002-4
	RU -3	BELOYARSKY-1	LWGR	102	108	REA	1958-6	1963-9	1964-4	1964-4	1983-1
	RU -6	BELOYARSKY-2	LWGR	146	160	REA	1962-1	1967-10	1967-12	1969-12	1990-1
	RU -4	NOVOVORONEZH-1	WWER	197	210	REA	1957-7	1963-12	1964-9	1964-12	1988-2
	RU -8	NOVOVORONEZH-2	WWER	336	365	REA	1964-6	1969-12	1969-12	1970-4	1990-8
SLOVAKIA	SK -1	BOHUNICE A!	HWGCR	110	144	EBO	1958-8	1972-10	1972-12	1972-12	1977-1
SPAIN	ES -3	VANDELLOS-1	GCR	480	500	HIFRENSA	1968-6	1972-2	1972-5	1972-8	1990-7
SWEDEN	SE -1	AGESTA	PHWR	10	12	VAB	1957-12	1963-7	1964-5	1964-5	1974-6
	SE -6	BARSEBACK-1	BWR	600	615	BKAB	1971-2	1975-1	1975-5	1975-7	1999-11
	SE -8	BARSEBACK-2	BWR	600	615	BKAB	1973-1	1977-2	1977-3	1977-7	2005-5
UK	GB -3A	BERKELEY 1	GCR	138	166	BNFL	1957-1	1961-8	1962-6	1962-6	1989-3
	GB -3B	BERKELEY 2	GCR	138	166	BNFL	1957-1	1962-3	1962-6	1962-10	1988-10
	GB -4A	BRADWELL 1	GCR	123	146	BNFL	1957-1	1961-8	1962-7	1962-7	2002-3
	GB -4B	BRADWELL 2	GCR	123	146	BNFL	1957-1	1962-4	1962-7	1962-11	2002-3
	GB -1A	CALDER HALL 1	GCR	50	60	BNFL	1953-8	1956-5	1956-8	1956-10	2003-3
	GB -1B	CALDER HALL 2	GCR	50	60	BNFL	1953-8	1956-12	1957-2	1957-2	2003-3
	GB -1C	CALDER HALL 3	GCR	50	60	BNFL	1955-8	1958-3	1958-3	1958-5	2003-3
	GB -1D	CALDER HALL 4	GCR	50	60	BNFL	1955-8	1958-12	1959-4	1959-4	2003-3
	GB -2A	CHAPELCROSS 1	GCR	50	60	BNFL	1955-10	1958-11	1959-2	1959-3	2004-6
	GB -2B	CHAPELCROSS 2	GCR	50	60	BNFL	1955-10	1959-5	1959-7	1959-8	2004-6
	GB -2C	CHAPELCROSS 3	GCR	50	60	BNFL	1955-10	1959-8	1959-11	1959-12	2004-6
	GB -2D	CHAPELCROSS 4	GCR	50	60	BNFL	1955-10	1959-12	1960-1	1960-3	2004-6
	GB -14	DOUNREAY DFR	FBR	14	15	UKAEA	1955-3	1959-11	1962-10	1962-10	1977-3
	GB -15	DOUNREAY PFR	FBR	234	250	UKAEA	1966-1	1974-3	1975-1	1976-7	1994-3
	GB -7A	HINKLEY POINT A1	GCR	235	267	BNFL	1957-11	1964-5	1965-2	1965-3	2000-5
	GB -7B	HINKLEY POINT A2	GCR	235	267	BNFL	1957-11	1964-10	1965-3	1965-5	2000-5
	GB -6A	HUNTERSTON-A1	GCR	150	173	BNFL	1957-10	1963-8	1964-2	1964-2	1990-3
	GB -6B	HUNTERSTON-A2	GCR	150	173	BNFL	1957-10	1964-3	1964-6	1964-7	1989-12

				Capacity (MW(e))			Construction	First	Grid	Commercial	Shut
Country	Code	Name	Type	Net	Gross	Operator	Start	Criticality	Connection	Operation	Down
UK	GB -8A	TRAWSFYNYDD 1	GCR	195	235	BNFL	1959-7	1964-9	1965-1	1965-3	1991-2
	GB -8B	TRAWSFYNYDD 2	GCR	195	235	BNFL	1959-7	1964-12	1965-2	1965-3	1991-2
	GB -5	WINDSCALE AGR	AGR	32	41	UKAEA	1958-11	1962-8	1963-2	1963-3	1981-4
	GB -12	WINFRITH SGHWR	SGHWR	92	100	UKAEA	1963-5	1967-9	1967-12	1968-1	1990-9
UKRAINE	UA -25	CHERNOBYL-1	LWGR	725	800	MTE	1970-3	1977-8	1977-9	1978-5	1996-11
	UA -26	CHERNOBYL-2	LWGR	925	1000	MTE	1973-2	1978-11	1978-12	1979-5	1991-10
	UA -42	CHERNOBYL-3	LWGR	925	1000	MTE	1976-3	1981-6	1981-12	1982-6	2000-12
	UA -43	CHERNOBYL-4	LWGR	925	1000	MTE	1979-4	1983-11	1983-12	1984-3	1986-4
USA	US -155	BIG ROCK POINT	BWR	67	71	CPC	1960-5	1962-9	1962-12	1963-3	1997-8
	US -4	BONUS	BWR	17	18	DOE	1960-1	1964-1	1964-8	—	1968-6
	US -144	CVTR	PHWR	17	19	CVPA	1960-1	1963-3	1963-12	—	1967-1
	US -10	DRESDEN-1	BWR	197	207	EXELON	1956-5	1959-10	1960-4	1960-7	1978-10
	US -1	ELK RIVER	BWR	22	24	RCPA	1959-1	1962-11	1963-8	1964-7	1968-2
	US -16	ENRICO FERMI - 1	FBR	61	65	DETED	1956-8	1963-8	1966-8	—	1972-11
	US -267	FORT ST. VRAIN	HTGR	330	342	PSCC	1968-9	1974-1	1976-12	1979-7	1989-8
	US -213	HADDAM NECK	PWR	560	587	CYAPC	1964-5	1967-7	1967-8	1968-1	1996-12
	US -133	HUMBOLDT BAY	BWR	63	65	PGE	1960-11	1963-2	1963-4	1963-8	1976-7
	US -3	INDIAN POINT-1	PWR	257	277	ENTERGY	1956-5	1962-8	1962-9	1962-10	1974-10
	US -409	LACROSSE	BWR	48	55	DPC	1963-3	1967-7	1968-4	1969-11	1987-4
	US -309	MAINE YANKEE	PWR	860	900	MYAPC	1968-10	1972-10	1972-11	1972-12	1997-8
	US -245	MILLSTONE-1	BWR	641	684	DOMIN	1966-5	1970-10	1970-11	1971-3	1998-7
	US -130	PATHFINDER	BWR	59	63	NUCMAN	1959-1	1964-1	1966-7	—	1967-10
	US -171	PEACH BOTTOM-1	HTGR	40	42	EXELON	1962-2	1966-3	1967-1	1967-6	1974-11
	US -312	RANCHO SECO-1	PWR	873	917	SMUD	1969-4	1974-9	1974-10	1975-4	1989-6
	US -206	SAN ONOFRE-1	PWR	436	456	SCE	1964-5	1967-6	1967-7	1968-1	1992-11
	US -322	SHOREHAM	BWR	820	849	LILCO	1972-11	—	—	—	1989-5
	US -320	THREE MILE ISLAND -2	PWR	880	959	GPU	1969-11	1978-3	1978-4	1978-12	1979-3
	US -344	TROJAN	PWR	1095	1155	PORTGE	1970-2	1975-12	1975-12	1976-5	1992-11
	US -29	YANKEE NPS	PWR	167	180	YAEC	1957-11	1960-8	1960-11	1961-7	1991-10
	US -295	ZION-1	PWR	1040	1085	EXELON	1968-12	1973-6	1973-6	1973-12	1998-1
	US -304	ZION-2	PWR	1040	1085	EXELON	1968-12	1973-12	1973-12	1974-9	1998-1

7. THE NUCLEAR FUEL CYCLE.

7.1 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.

7.2 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.

7.3 FRONT-END of NUCLEAR FUEL CYCLE (see Fig 7.1)

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.

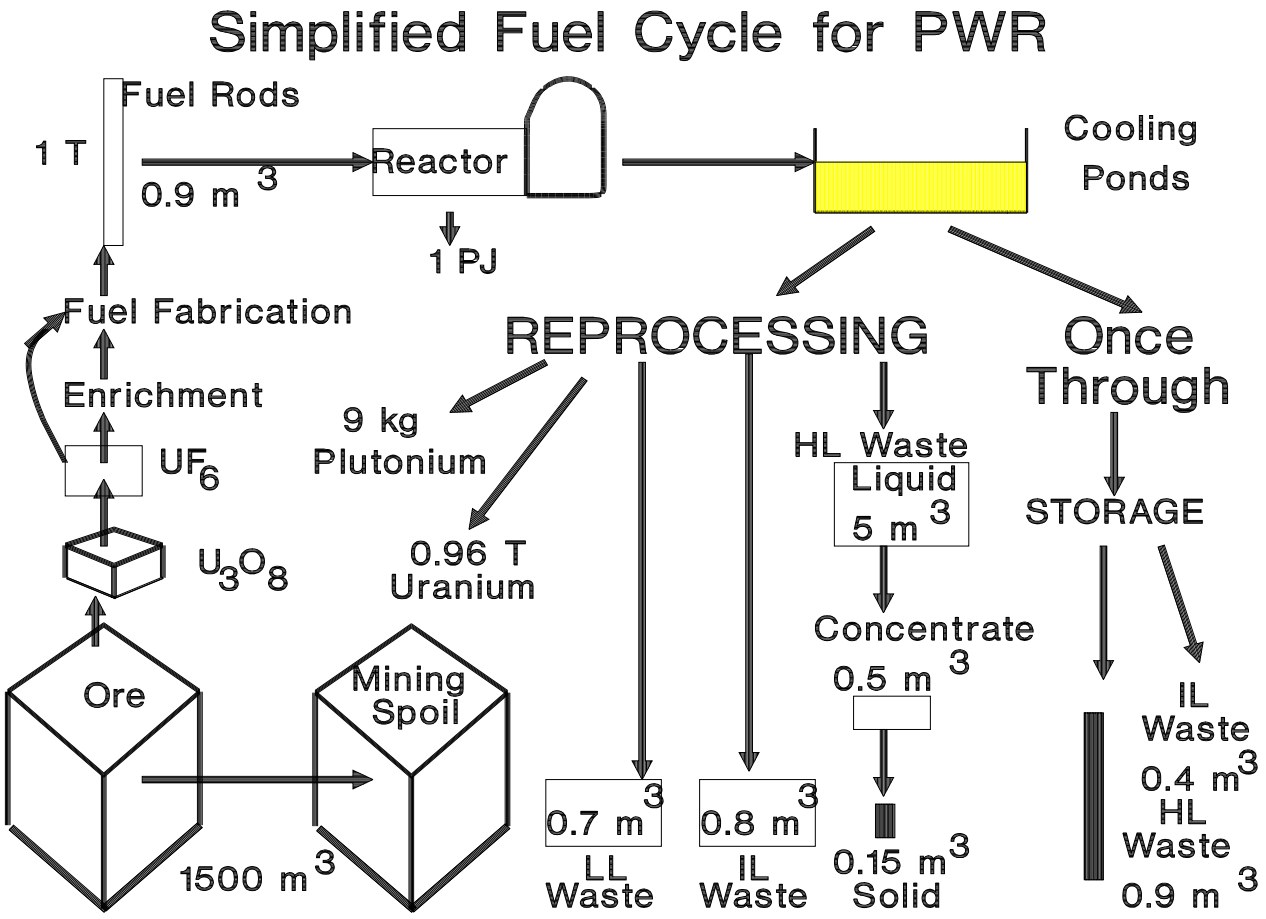


Fig. 7.1 Once through and Reprocessing Cycle for a PWR. The two cycles for an AGR are similar, although the quantities are slightly different. For the CANDU and MAGNOX reactors, no enrichment is needed at the front end.

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.

7.4 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.

7.5 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.

7.6 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.

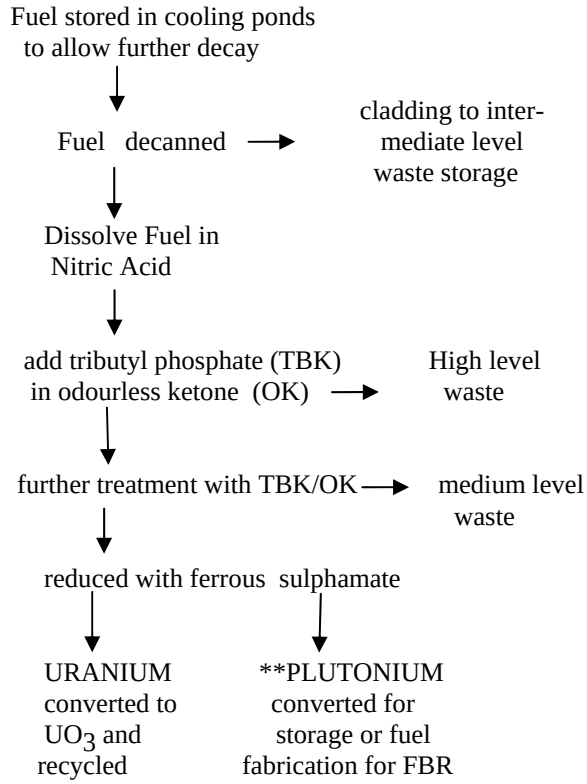
DISADVANTAGES:-

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').

7.7 REPROCESSING CYCLE - the chemistry



**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.

7.8 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!

8: Nuclear Fusion

8.1 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.

8.2 The Triple Product

To achieve fusion three critical parameters must be met

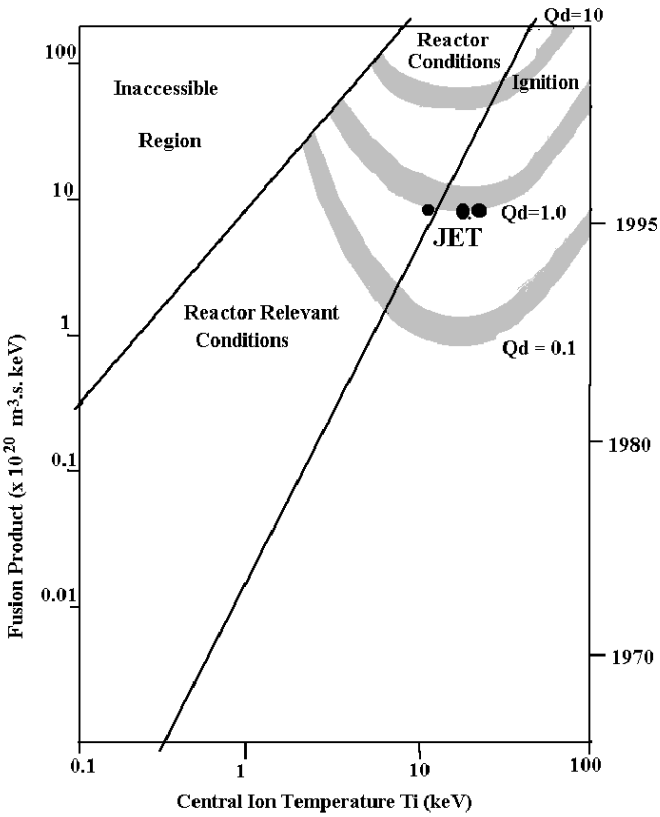
i). The deuterium - tritium gas must be as a plasma - i.e. at high temperature such that the electrons are stripped from their parent atoms rather than orbit them. In a plasma, deuterium and tritium become ions and it is the central ion density which is critical. If the pressure of the gas is too high, 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. 8.1

Fig. 8.1. Triple product plotted against Central Ion Temperature with a few selected data points from JET obtained during the 1990's



8.3 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.

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 associated with the design of ITER - International Thermonuclear Experimental Reactor

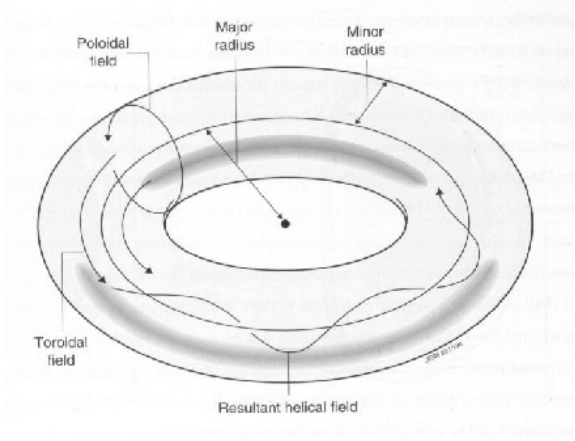


Fig. 8.2 A simplified section of a fusion device showing the helical magnetic field

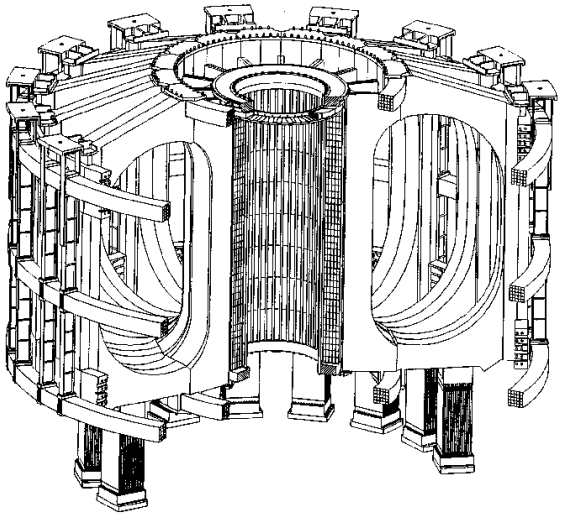


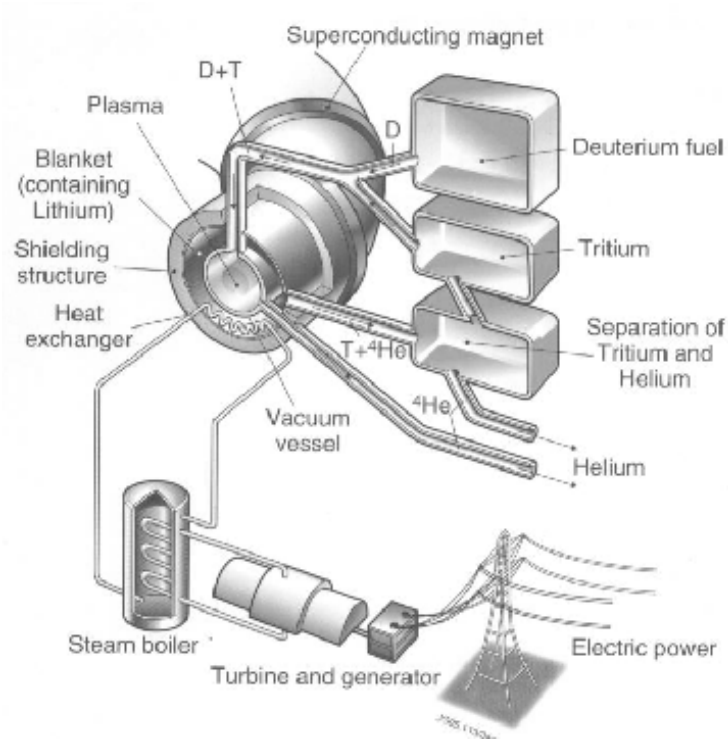
Fig. 8.3 Cross Section of the JET reactor - the Plasma

8.4. 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. 8.2, while the actual cross section of the JET reactor is shown in Fig. 8.3.

8.5 A full Reactor design for commercial operation

Fig .8.4 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.



chamber is "D" shaped.

Fig. 8.4 showing a schematic of a possible commercial fusion power reactor.

8.6 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 at the moment is 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.

Current experiments in the late 1990's 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. 8.5

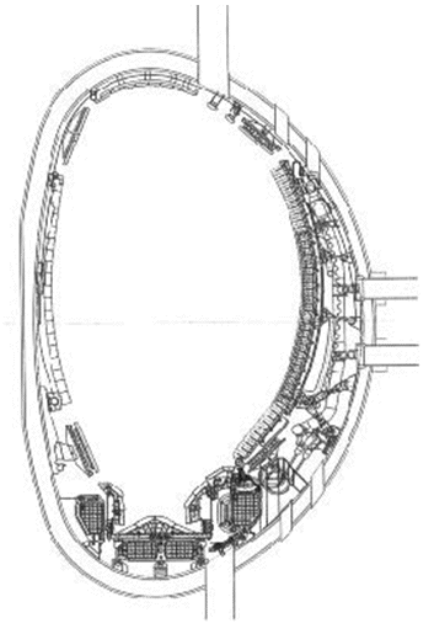


Fig. 8.5 the current shape of the "D" showing the divertor box at the base which is used to remove impurities.

8.6 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

9 NUCLEAR POWER - RADIATION AND MAN

9.1 QUANTITY OF RADIOACTIVITY - a measure of the number of atoms undergoing disintegration.

OLD UNIT:- CURIE (Ci) - number of disintegrations per second of 1g of radium.

NEW UNIT:-BEQUEREL (Bq) - one disintegration per second.

1 Ci = 3.7×10^{10} Bq

9.2 ABSORBED DOSE:-

OLD UNIT:- 1 rad = $0.01 Jkg^{-1}$ - thus absorbed dose is expressed in terms of energy per unit mass.

NEW UNIT:- 1 gray (Gy) = $1 Jkg^{-1}$

i.e. 1 Gy = 100 rad

9.3 RELATIVE BIOLOGICAL EFFECTIVENESS (R.B.E):-

Takes account of fact that different radiations have different effects on living tissue. Thus absorbed dose as measured above in GRAY is modified as follows:-

	WEIGHTING FACTOR
X-rays, beta & gamma rays	1.0
Neutrons & protons	10.0
Alpha particles (helium nucleus)	20.0

NEW UNIT:- Sievert (Sv)

OLD UNIT:- rem (Rad Equivalent Man)

1 Sv = 100 rem

9.4 NUCLEAR RADIATION (annual doses):-

- includes allowance for inhaled radon of 0.8 mSv.

RECOMMENDED MAXIMUM DOSE TO GENERAL PUBLIC

- 5 mSv in any one year or 0.1 Sv averaged over 1 lifetime.

RECOMMENDED MAXIMUM DOSE TO MONITORED WORKERS

- 50 mSv. in any one year

Location	mSv
NATURAL RADIATION	
UK average	1.9
London	1.6
Aberdeen	2.5
USA average	1.8
Colorado	3.3
India (Kerala)	8.0 - 80.0
Sri Lanka	30.0-70.0
Brazil - Minas Gerais	17.0-120.0
Rio de Janerio	5.5 - 12.5
MAN MADE	
diagnostic X-Ray	0.45
radiotherapy	0.05
Atmospheric Weapon Tests	0.01
Miscellaneous	
TV + air travel	0.008
Nuclear Power Stations	0.0003
Reporcessing	0.0025
Coal Fired Power stations	
radioactive emissions in ash/stack	0.001 - 0.002

9.5 ACTUAL DOSES RECEIVED BY CRITICAL GROUP OF GENERAL PUBLIC (as % of DOSE LIMIT i.e. 5 mSv) as a result of nuclear installations.

Sellafield - fishermen/lava bread eaters -	30% **
Trawsfynydd - eaters of locally caught fish	8%
Other Power Stations	<0.3%
Fuel fabrication/ Harwell/ Dounreay	<1.0%

NOTE: * Discharges from Sellafield were significantly reduced following commissioning of SIXEP in 1986.

** Even for Sellafield this is less than the background level, and would be achieved by 3 medical x-rays or by moving to Colorado.

9.6 ACTUAL DOSES RECEIVED BY POWER STATION WORKERS

- number of workers in each group - These data are for early 1990s

	< 5 mSv	5 - 15 mSv	15 - 50 mSv
Berkeley	152	276	17
Bradwell	503	82	6
Hinkley Point A & B	1135	139	1
Trawsfynydd	404	130	13
Dungeness	786	2	0
Sizewell	472	10	0
Oldbury	512	18	5
Wylfa	677	15	0
TOTAL	4641	672	42

9.6 PROBABILITY OF DEATH FOR AN INDIVIDUAL IN UK PER YEAR

ACTIVITY	RISK
Smoking 10 cigarettes a day	1 in 400
All Accidents	1 in 2000
Traffic Accidents	1 in 8000
Leukaemia from natural causes	1 in 20000
Industrial Work	1 in 30000
Drowning	1 in 30000
Poisoning	1 in 100000
Natural Disasters	1 in 500000
Struck by Lightning	1 in 2000000
Risk	
> 1 in 1000	considered unacceptable
1 in 10000 to 1 in 100000	warrants money being spent to eliminate or reduce effects
< 1 in 100000	considered as an individual risk and warning may be sufficient - e.g. floods, landslides etc.
< 1 in 1000000	generally considered acceptable