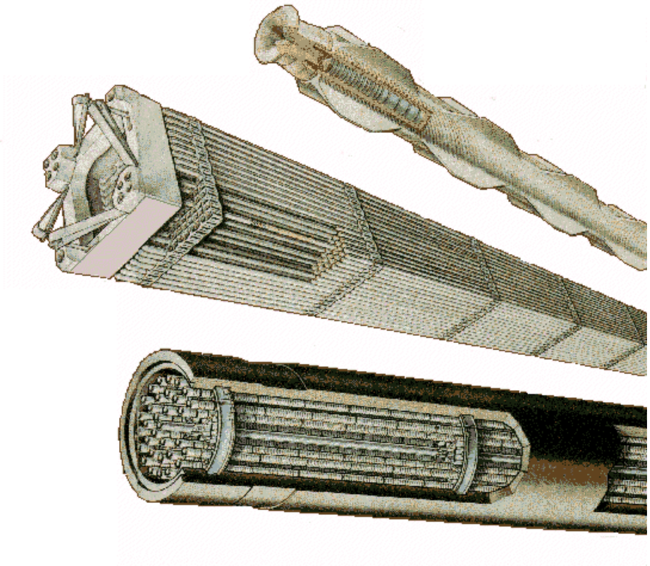
NBS-M018 /NBSLM03E Low Carbon Technologies and Solutions 2011

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



Nuclear Fuel Assemblies

Top: MAGNOX
Middle: PWR
Bottom AGR

Section 1: Nuclear Power – The basics
Section 2: Nuclear Reactors
Section 3: Nuclear Fuel Cycle
Section 4: Nuclear Fusion
Section 5: Introduction to Hazards of Radiation
Section 6: Early notes written relating to Fukushima Incident in March 2011

This handout is based on the handouts used in previous years when Nuclear Power issues were covered in more depth. This handout thus covers a fuller account of the topic over and above that covered explicitly in the lectures.

Note: The Handout was updated for NBS-LM03E to incorporate notes relating to the Fukushima Incident in Japan

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

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

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.**

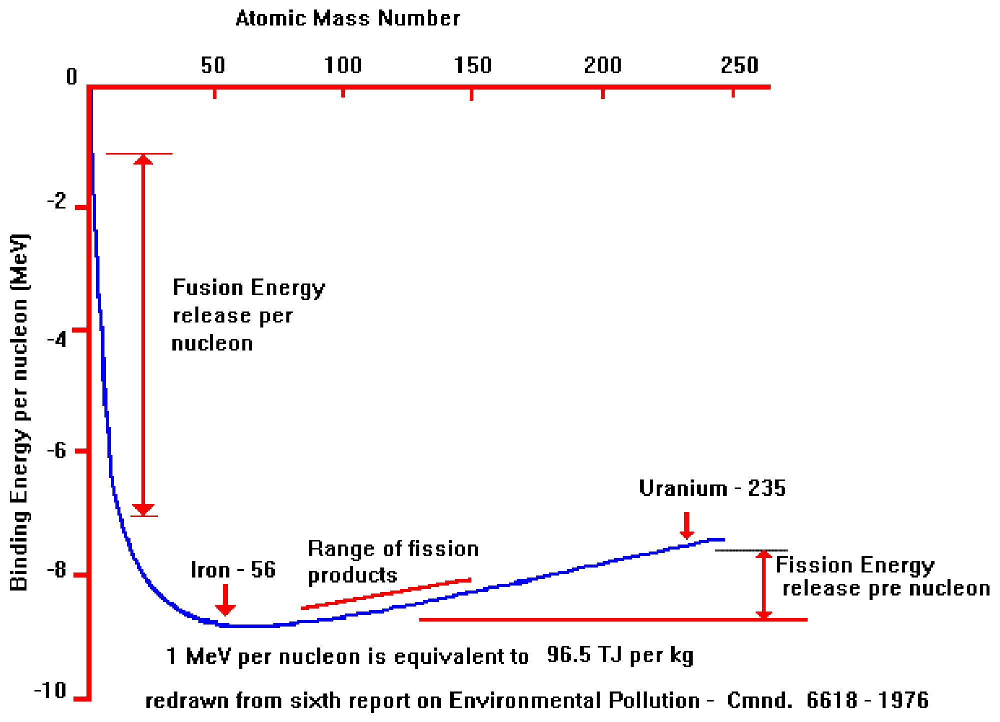


Fig. 1.1 Energy Binding Curve

- **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:-

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

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 CANNOT EXPLODE LIKE AN ATOMIC BOMB.

1.7 FERTILE MATERIALS

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

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

Uranium	**Uranium**	**Neptunium**	**Plutonium**
- 238	- 239	- 239	- 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^oC.

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. ELECTRICAL POWER OF REACTORS UNDER CONSTRUCTION, 31 DEC. 2009

Country	PWR		BWR		PHWR		LWGR/RBMK		FBR		TOTAL	
	No	MW(e)	No	MW(e)	No	MW(e)	No	MW(e)	No	MW(e)	No	MW(e)
ARGENTINA					1	692					1	692
BULGARIA	2	1906									2	1906
CHINA	20	19920									20	19920
FINLAND	1	1600									1	1600
FRANCE	1	1600									1	1600
INDIA	2	1834			2	404			1	470	5	2708
IRAN	1	915									1	915
JAPAN			1	1325							1	1325
KOREA	6	6520									6	6520
PAKISTAN	1	300									1	300
RUSSIA	7	5277					1	915	1	804	9	6996
SLOVAKIA	2	782									2	782
UKRAINE	2	1900									2	1900
USA	1	1165									1	1165
TOTAL	46	43719	3 (*)	3925	3	1096	1	915	2	1274	55	50929

(*) The totals include 2 unit s (2xBWR), 2600 MW in Taiwan, China.
During 2009, 11 reactors, 12154 MW started construction

Table derived from IAEA(2010) Nuclear Reactors around the World:

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**

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, 31 DEC. 2009

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	375															1	375
BELGIUM	7	5902																	7	5902
BRAZIL	2	1884																	2	1884
BULGARIA			4	1906															4	1906
CANADA													18	12569					18	12569
CHINA	9	7138											2	1300					11	8438
CZECH R.			6	3678															6	3678
FINLAND			2	976	2	1720													4	2696
FRANCE	58	63130															1	130	59	63260
GERMANY	11	14023			6	6457													17	20480
HUNGARY			4	1889															4	1889
INDIA					2	300							16	3687					18	3987
JAPAN	24	19286	30	27537															54	46823
KOREA	16	14983											4	2722					20	17705
MEXICO					2	1300													2	1300
NETHERLANDS	1	487																	1	487
PAKISTAN	1	300											1	125					2	425
ROMANIA													2	1300					2	1300
RUSSIA			15	10964											15	10219	1	560	31	21743
S.AFRICA	2	1800																	2	1800
SLOVAKIA			4	1762															4	1762
SLOVENIA	1	666																	1	666
SPAIN	6	5940			2	1510													8	7450
SWEDEN	3	2793			7	6243													10	9036
SWITZRLAND	3	1700			2	1538													5	3238
UK	1	1188							4	1414	14	7495							19	10097
UKRAINE			15	13197															15	13197
USA	69	66945			35	33802													104	100747
TOTAL	265	244661	92	83548	90	79168	4	5259	8	2284	14	8380	45	22638	15	10219	2	690	437	370705

During 2009, 2 reactors, 1068 MW were newly connected to the grid.

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

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

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

Annual Electrical Power Production for 2009

Total Power Production (including Nuclear)	Nuclear Power Production	% Nuclear generation
350700 GWh(e)	**62859.575 GWh(e)**	17.92%

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

Name	Type	Status	Location	Capacity (MWe) Net	Gross	Date 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
SIZETrawsWELL-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.

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The full website address is: **http://www.iaea.org/programmes/a2/**. It is possible to get operational experience of each reactor individually by clicking on the appropriate reactor in the online version of the document or alternatively searching in the full website database.

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 was still in operation at the end of 2011. Wylfa is the only other MAGNOX Station still operating

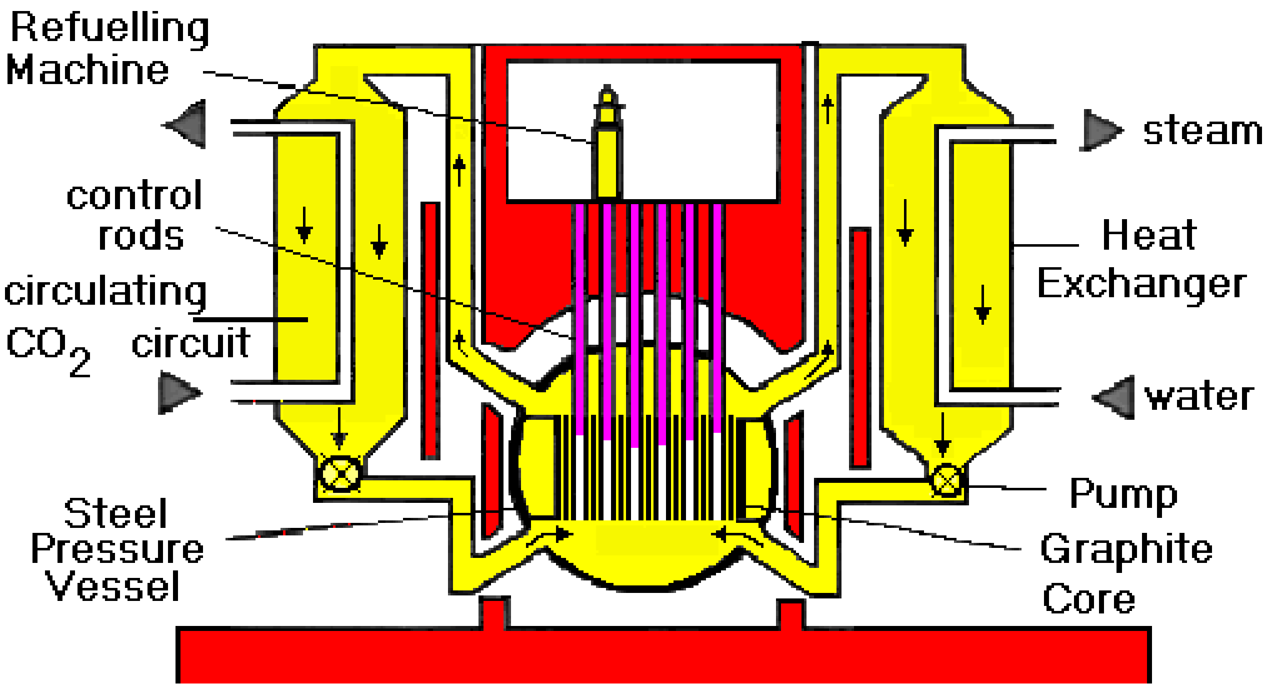

Fig. 2.1 Schematic section of an early Magnox Reactor. Later versions had a pressurised concrete vessel which also enclosed the boilers as with the AGRs. This reactor was developed in the UK and France. The 2 French reactors were closed in the late 1980s. There were originally 24 such reactors in operation 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.

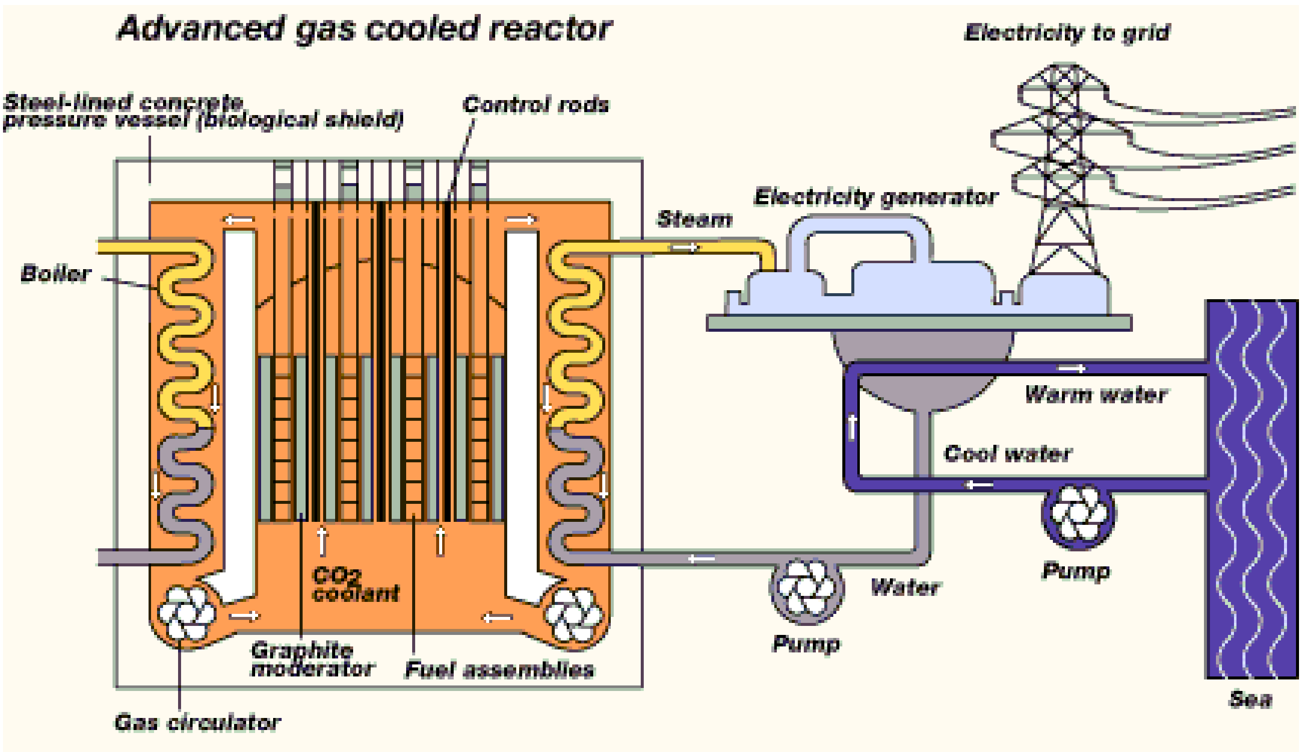

Fig. 2.2 Section of an Advanced Gas Cooled Reactor. This reactor was only developed in the UK. There are currently 14 such reactors in 7 stations in the UK.

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

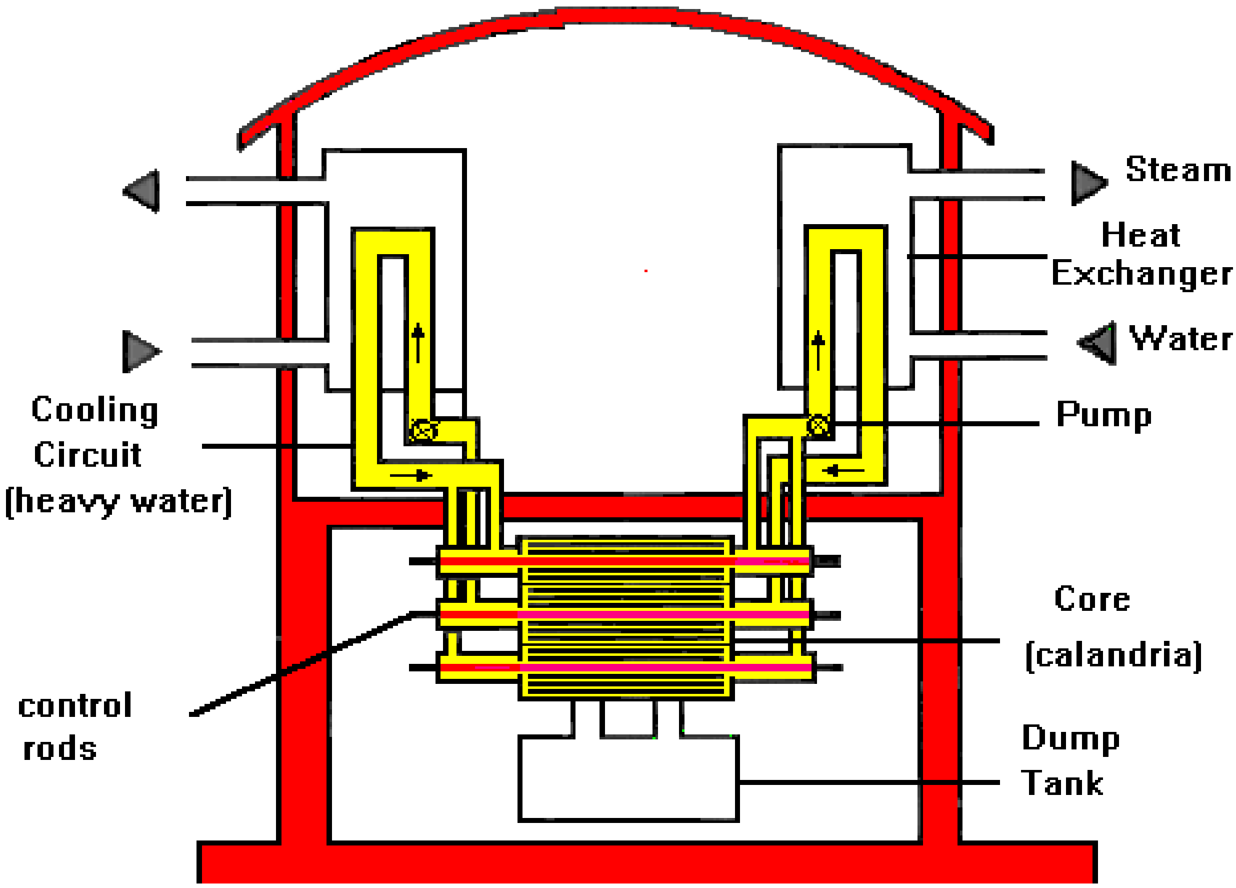

Fig. 2.3 A section of a CANDU reactor. This design was developed in Canada, and has the advantage that it is modular and can be built to any size. The British Steam Generating Heavy Water Reactor (SGHWR) was of similar design except the cooling circuit was ordinary water. The space surrounding the fuel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

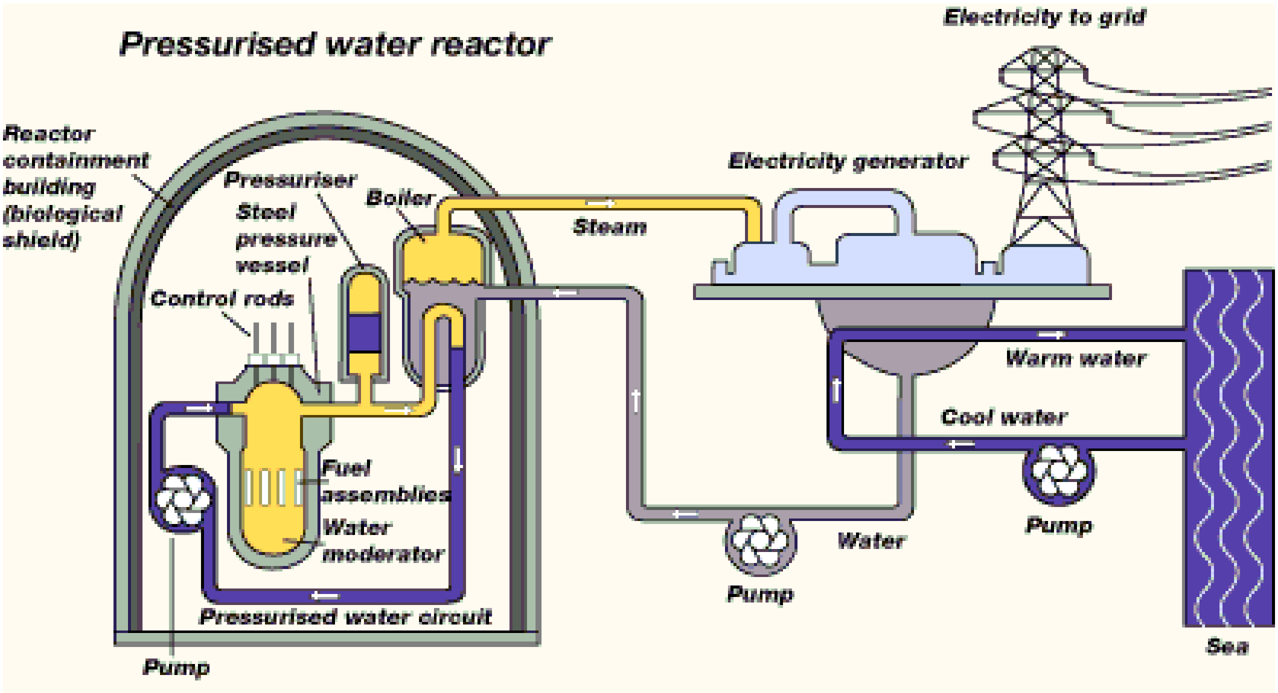

Fig. 2.4 A section of a PWR. This shows the safer design having the cold and hot legs entering the reactor vessel at the top. the reactor at Sizewell has a secondary dome outside the primary containment building. This is the only one in the world that has a double skin. One of the new designs being considered 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.

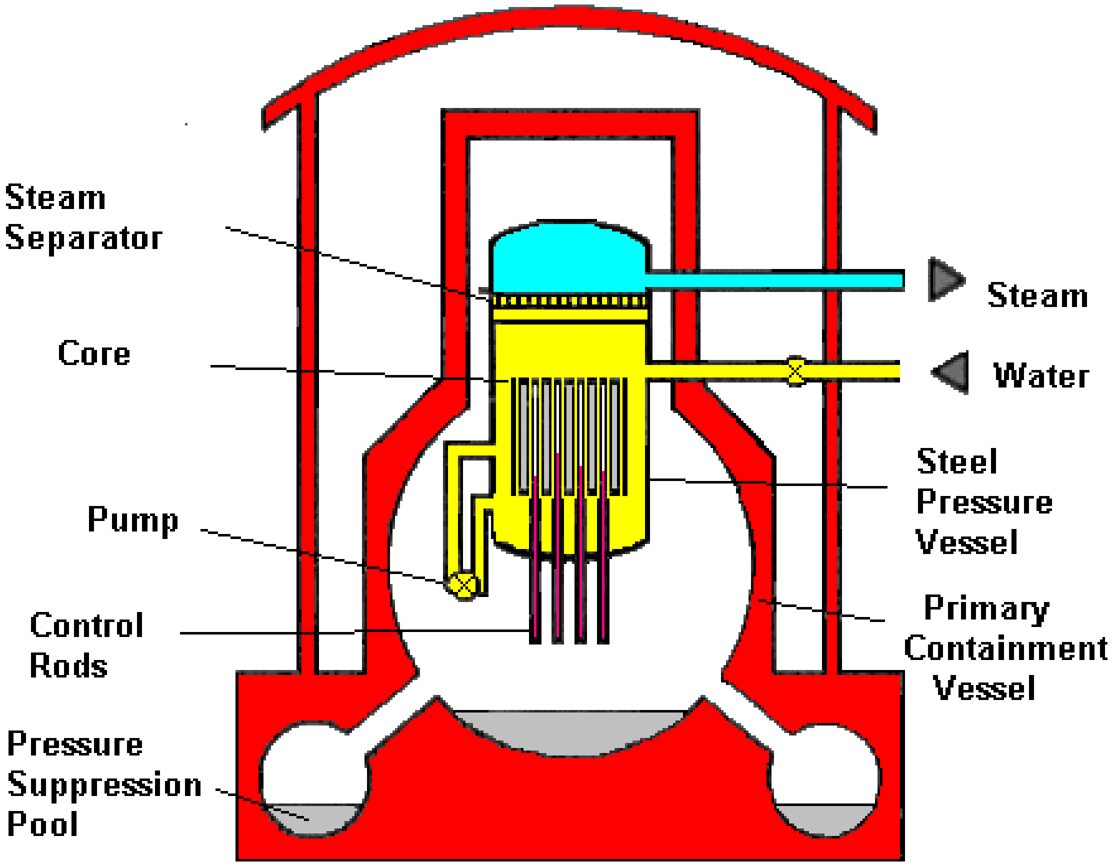

Fig. 2.5 A Boiling Water Reactor. Notice that the primary circuit steam is passed directly to the turbines.

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

NOTE: This section has been added since the lectures given to NBS-M018

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

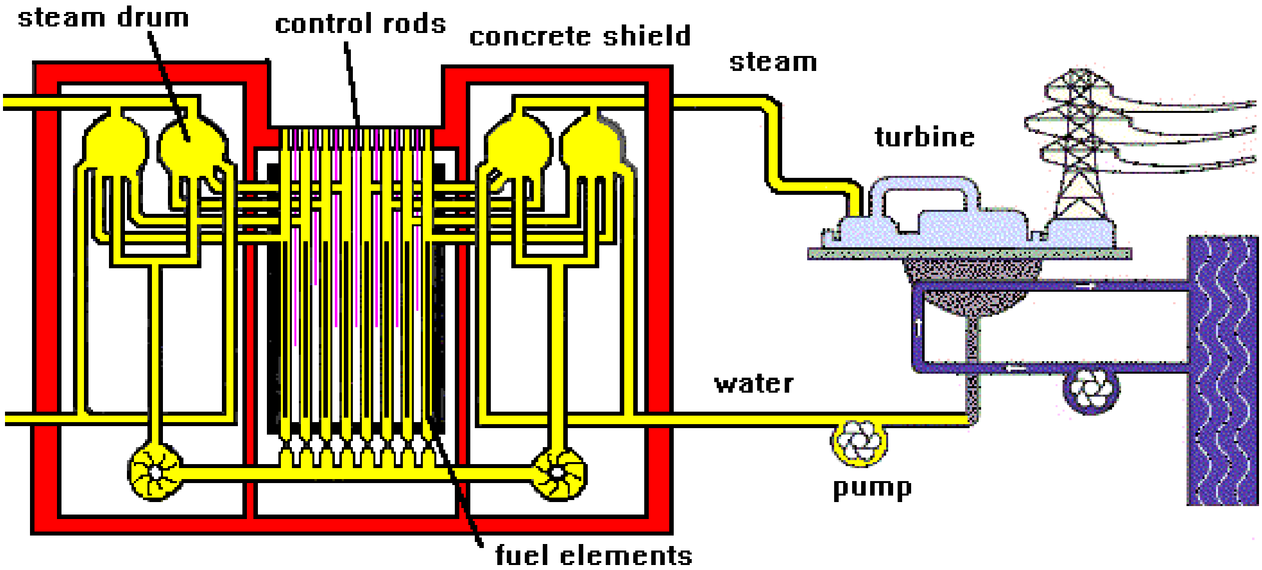

Fig. 2.6 The Russian Light Water - Graphite Moderated Reactor. This reactor was of the type involved in the Chernobyl incident in 1982.

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 with 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	2008 **	Still under full operation see below
Wylfa	2 x 490	1971-1	2010 **	

** http://webarchive.nationalarchives.gov.uk/+/http://www.berr.gov.uk/files/file49437.pdf

At **15:30 on 20th January 2011**, Oldbury Power Station was still operating at full power at a combined output of 435 MW (215 MW Unit 1, 220 MW Unit 2). At the same timeWylfa was exporting 483 MW from Unit 1 and 456 MW from Unit 2. Note at Wylfa there are two separate generating sets attached to both reactors. [data on output of any power station can be obtained 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	Date of revision
Dungeness B	1110	1965	1983	1985	2008	2018	Late 2005
Hartlepool	1210	1968	1983	1989	2014	2019	17/12/2010
Heysham 1	1150	1970	1983	1989	2014	2019	17/12/2010
Heysham 2	1250	1980	1988	1989	2023		
Hinkley Point B	1220	1967	1976	1976	2011	2016	2007
Hunterston B	1190	1967	1976	1976	2011	2016	2007
Torness	1250	1980	1988	1988	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

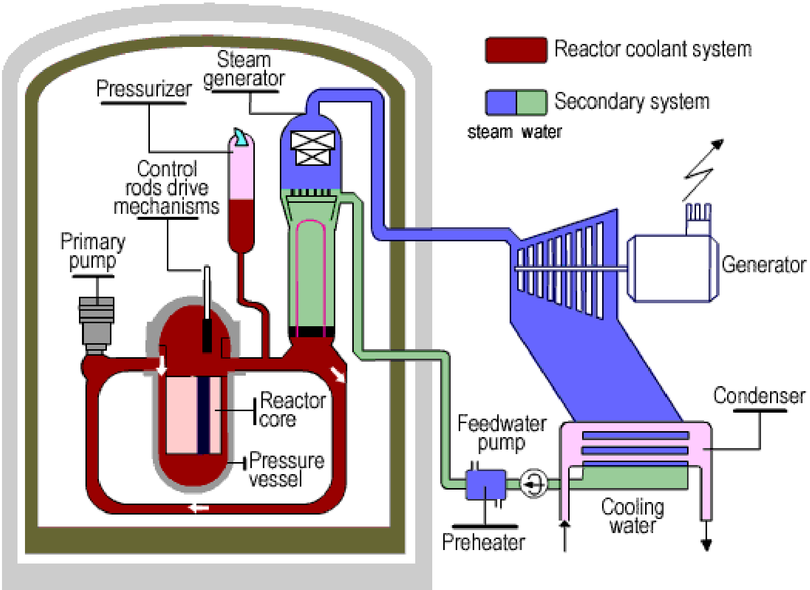


Fig.2.7 [From the AREVA WEB SITE]. This diagram is very similar to the PWR above.

2.3.10 European Pressurised Reactor

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 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. 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.

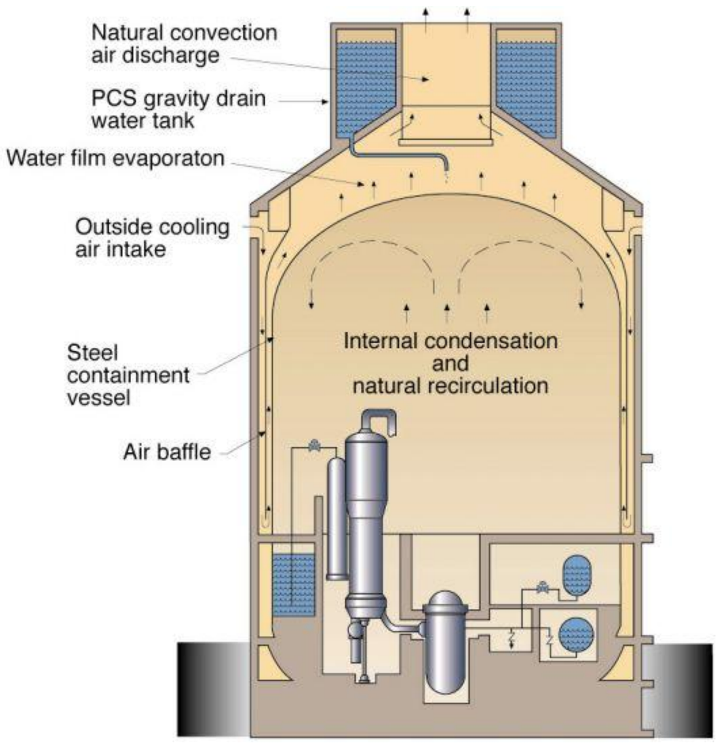


Fig. 2.8 Cross section of AP1000 Reactor and Containment Building showing passive cooling

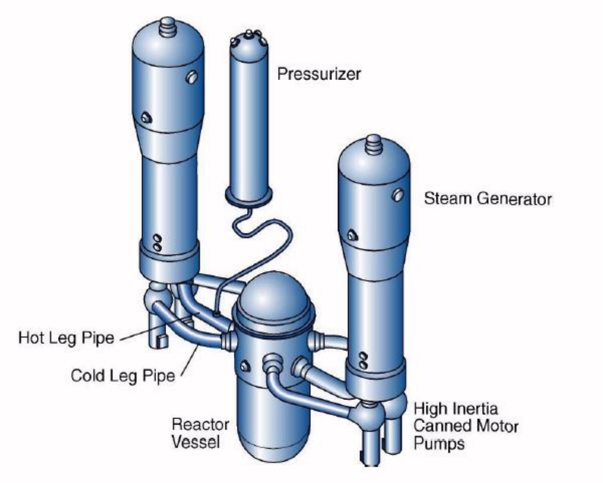


Fig. 2.9 Diagram showin two loops in AP1000 design. The EPR1300 has four separate steam generators. Both Reactors have just one Pressuriser.

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. It is likely that construction of nuclear stations other than those by EDF may be of the AP1000 desing. 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,

There is a good learning resource accessible by the WEBPAGE on the operation of the AP1000 and in particular its unique safety features. See the module WEB Page

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

and follow links to Nuclear WEBlinks or alternatively go straight to

http://www2.env.uea.ac.uk/energy/energy_links/nuclear.htm#Generation_3 – guided tour of AP1000

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.

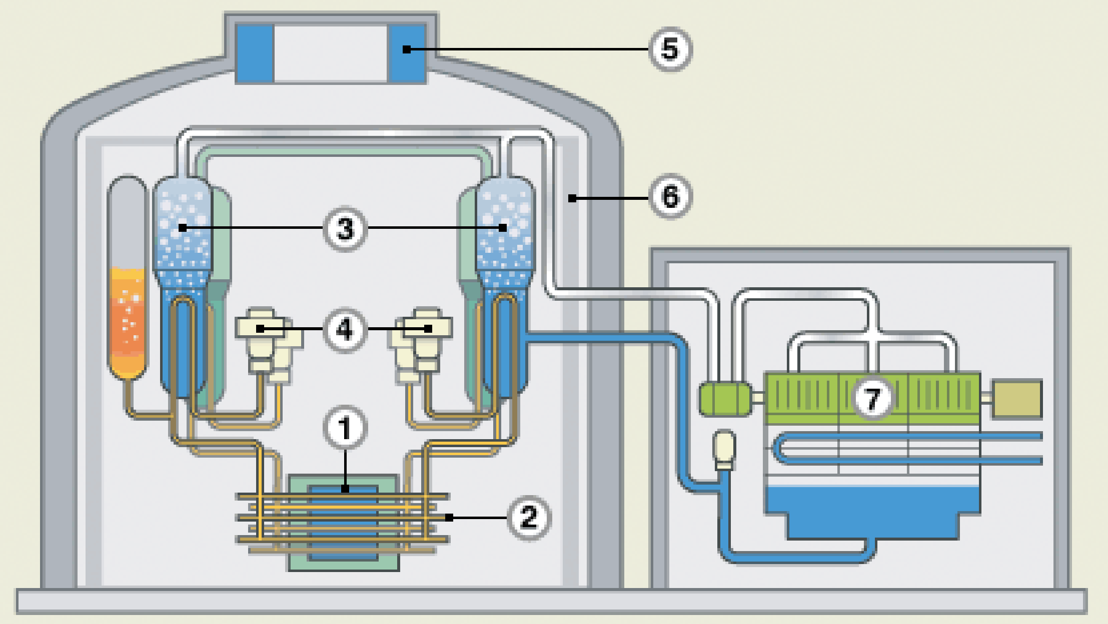


Fig. 2.10 Advanced Candu Reactor.

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.

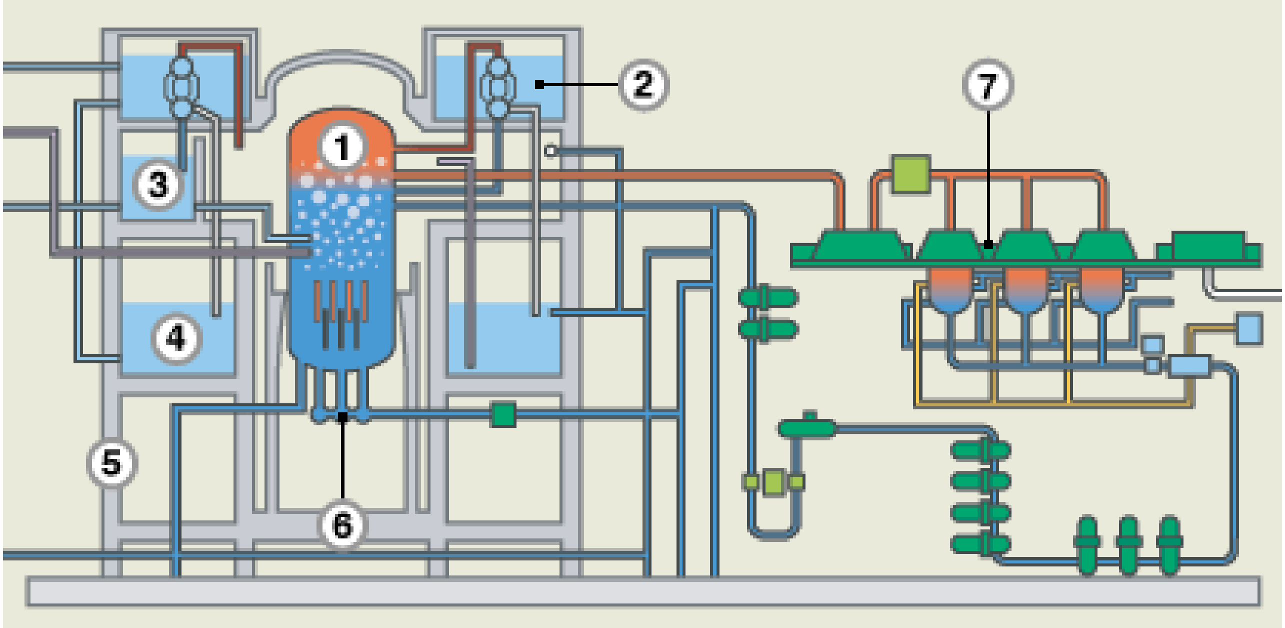


Fig. 2.11 Economic Simplified Boiling Water Reactor

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 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. 2.12, while the novel method of producing fuel elements is shown in Fig. 2.13.

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

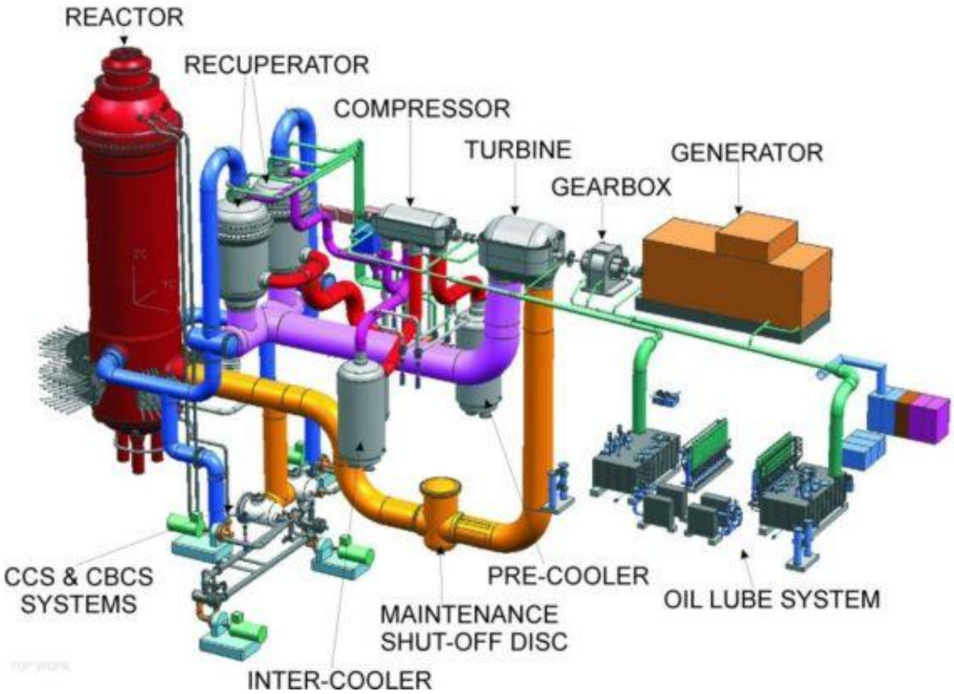


Fig. 2.12 Schematic Diagram of a Pebble Bed Modulating Reactor

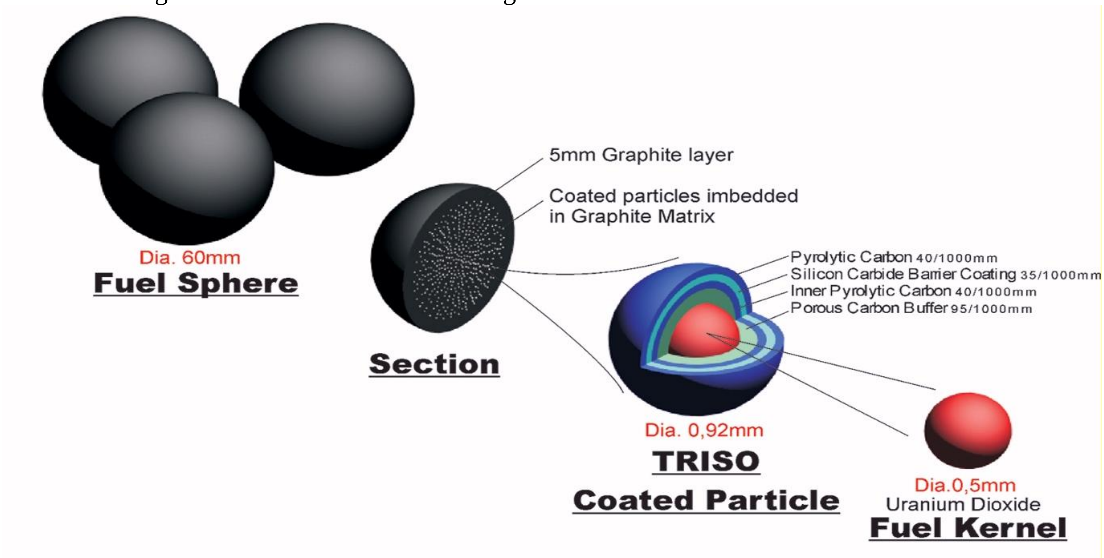


Fig. 2.13 Fuel pellets for a PBMR. The inner kernel is prepared by spraying uranyl nitrate to form small pellets 0.5mm in diameter. These are baked to produce Uranium Dioxide. Four layers are then deposited on the fuel particle: a) a porous graphite (which allows the fisiion products space to accumulate), 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 on the PMBR see: http://www.pbmr.com

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

2.3.16 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.

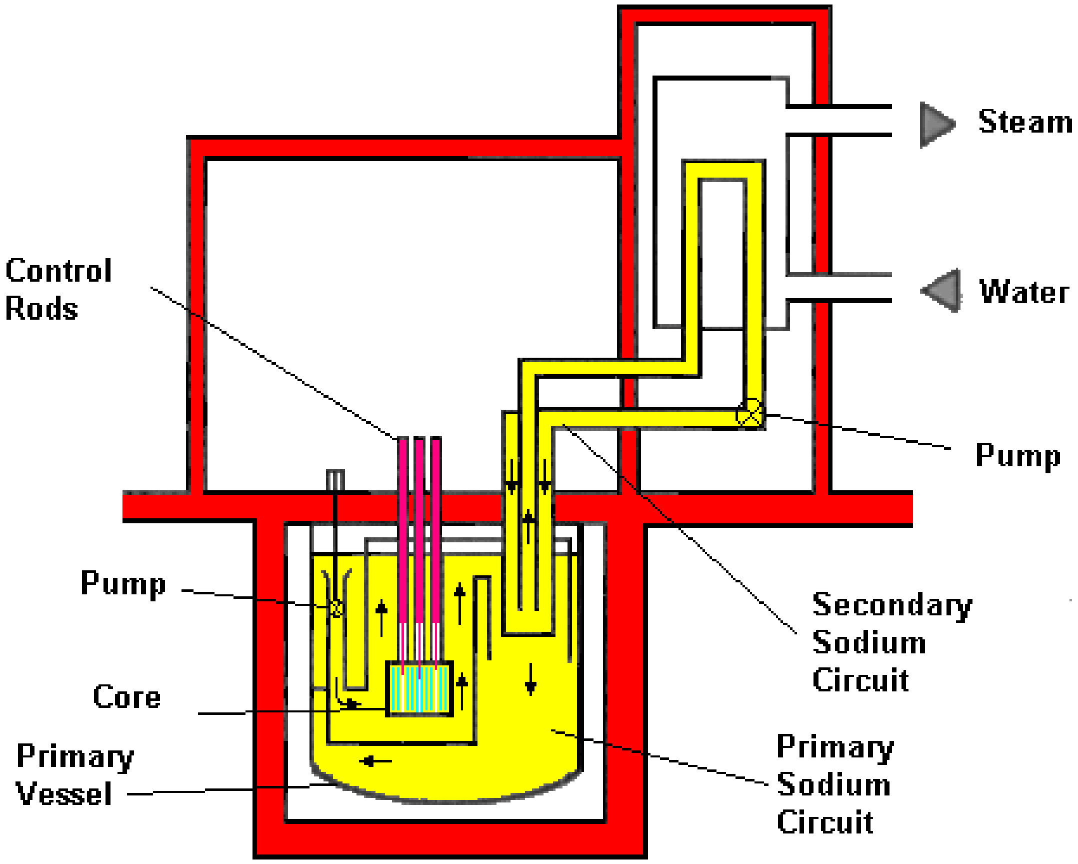


Fig. 2.14 A Fast Breeder Reactor. This type of reactor has depleted Uranium - 238 in a blanket around the fissile core material (of enriched U-235 or Plutonium). Fast neutrons can be captured by the fertile U - 238 to produce more Plutonium. Typically one kilogram of fissile Plutonium could produce as 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.

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.

2.3.17 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

2.3.18 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.

2.3.19 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 Gross	Electrical Net	Operator NSSS Supplier	Start of Construction	Grid Connection	Start Commercial Operation	Shutdown
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	Grid	Start Commercial	Shutdown

				Gross	Net		Constructio n	Connection	Operation	
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.

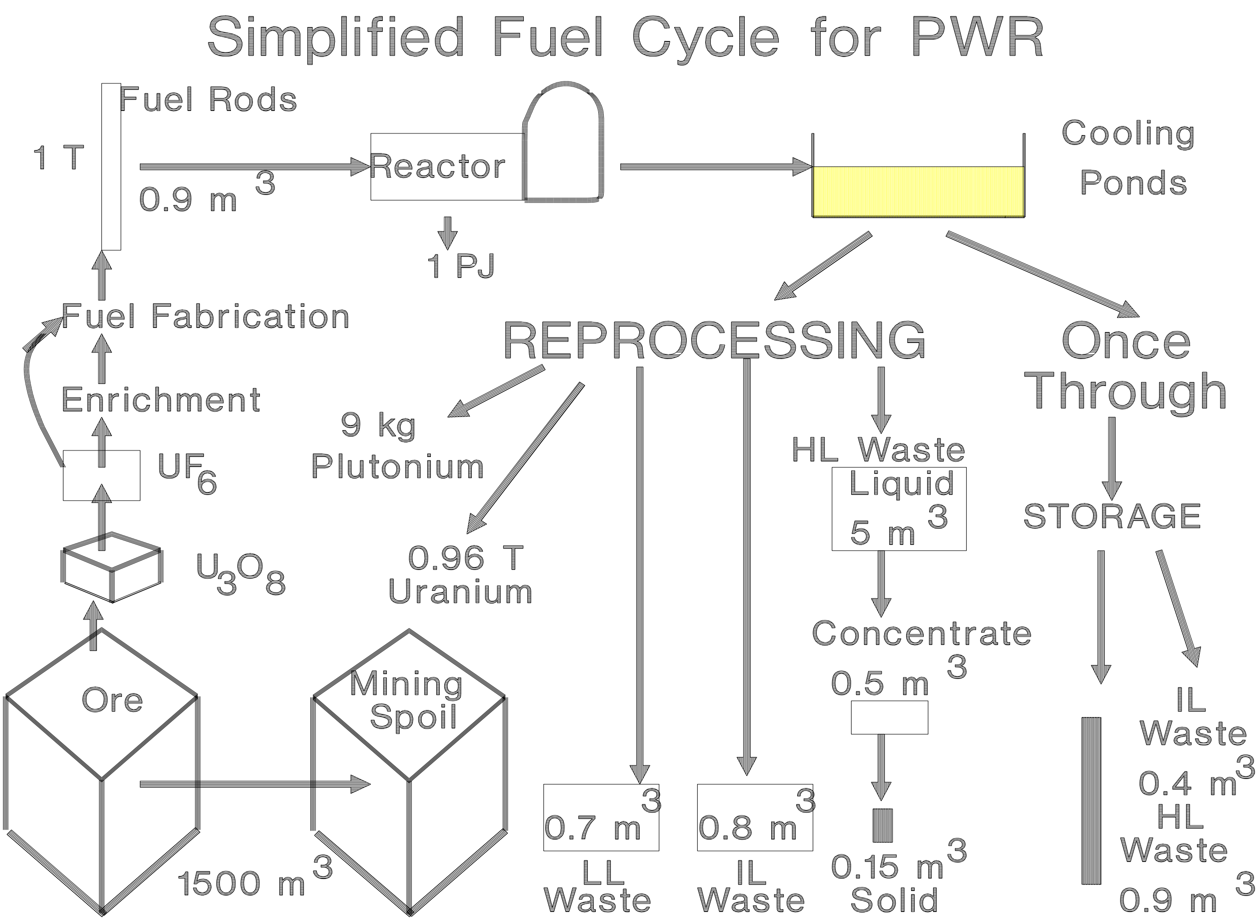


Fig. 3.1 Once through and Reprocessing Cycle for a PWR. The two cycles for an AGR are similar, although the quantities are slightly different. For the CANDU and MAGNOX reactors, no enrichment is needed at the front end.

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.

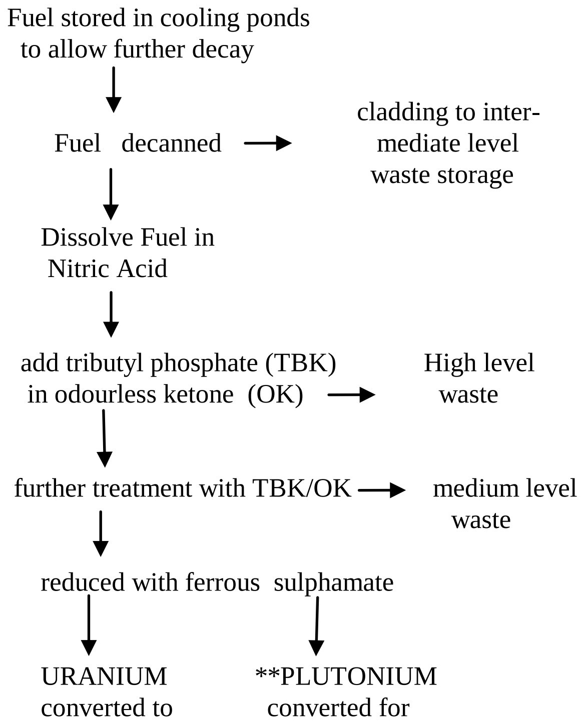
DISADVANTAGES:-

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



UO_3 and recycled	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

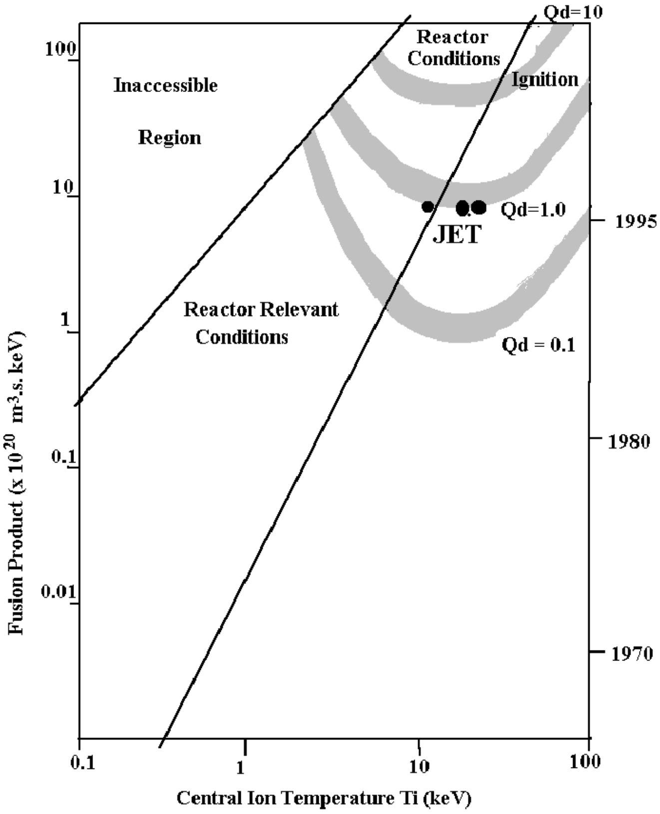
The triple product of the three above parameters is used as a measure to see how close to relevant reactor conditions, experiments currently achieve. This is illustrated in Fig. 4.1

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

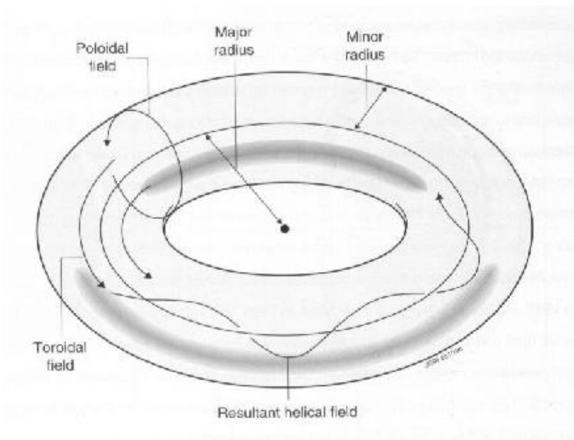
JET was not designed to go above about break even, and experiments are now looking at numerous aspects.

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



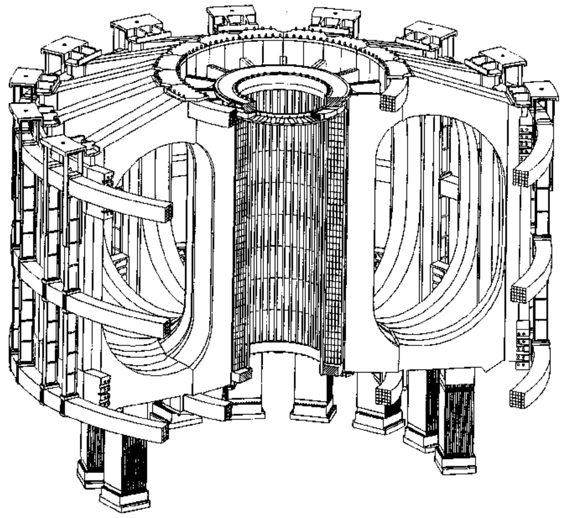
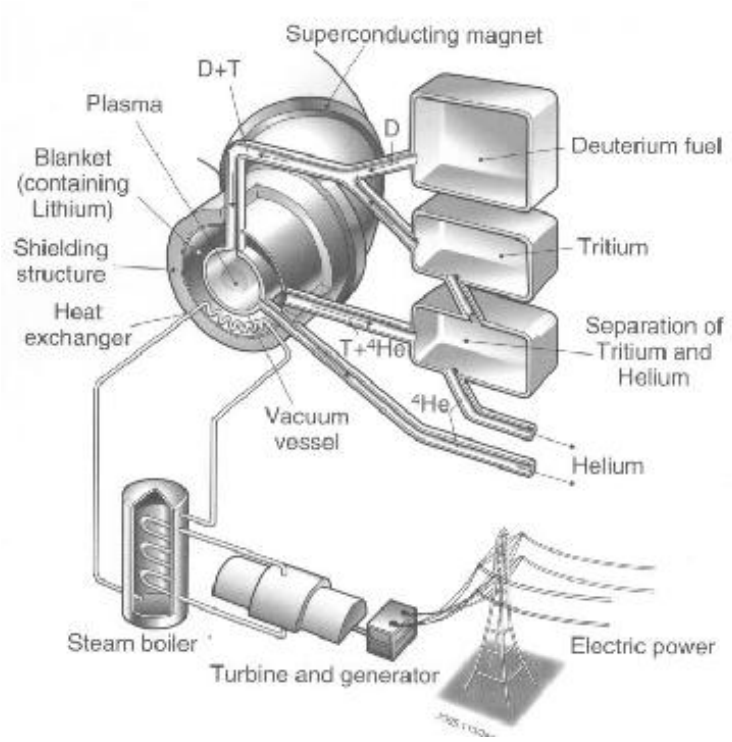


Fig. 4.3 Cross Section of the JET reactor - the Plasma chamber is "D" shaped

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



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

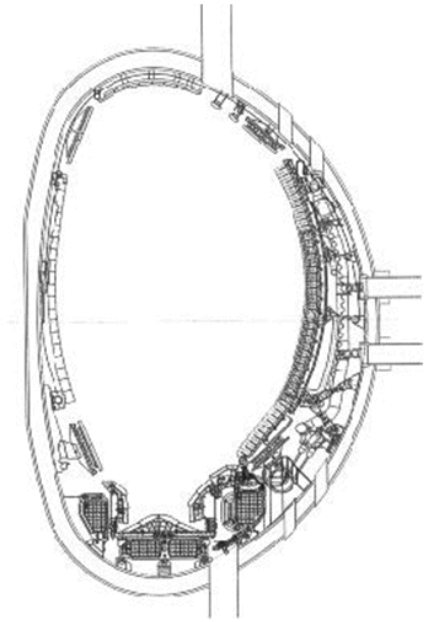


Fig. 4.5 the current shape of the "D" showing the divertor box at the base which is used to remove impurities.

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

5 NUCLEAR POWER - RADIATION AND MAN

5.1 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

5.2 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

5.3 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

5.4 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

5.5 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.

5.6 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

5.6 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

6. The Incidents at Fukushima following Earthquake of 11th March 2011

Introduction.

This section is based on notes written on a daily basis immediately following the earthquake on 11th March 2011. In the week that followed, information was scanty and there was quite some misinformation put out. I aimed to try to pull things together from different sources to explore what might have happened, and indeed much of my analysis did subsequently prove to be a fairly accurate assessment. I continued these report for 12 days, but which time further information became available. There is now a vast amount of objective data produced on a near daily basis. It is my intention that this section will be completely rewritten over next 2 – 3 months now that most information is now available. Nevertheless this does give a chronological development of the events. The original report which is accessible from the WEBSITE was split into 13 sections. The first 3 sections have been summarised already in additions to section 2.3.5 above. For consistency with the original document the section numbering is as follows – Section 6.4 below refers to section 4 for the original document, section 6.5 to section 5 and so on.

6.4. Nuclear Reactor Control and shut down phase 1

In many reactors the neutron absorbing control rods are held by electro-magnets and in the event of an incident (or power failure) will automatically fall by gravity. In the case of many BWRs and particularly the early ones, the control rods are driven up into the reactor and this will take typically around 5 – 7 seconds to complete. The attached table demonstrates that while some reactors continued throughout the quake, many shut down automatically as they were intended to do and this part of the phase was completed successfully.

You will remember from the lectures that it is quite difficult to sustain a nuclear reaction within the core and sufficient neutron density is required and also these must be of the slow moving neutron type for which moderators are needed. The purpose of the control rods is to absorb neutrons and thus shut down the reaction. Thus all the affected reactors shut down automatically as planned.

6.5. Aspects of the Incident – the early stages.

The second part of the incident is also something which I only covered briefly and that was the issue of radioactive decay. While it is clear that in all the 11 reactors which shut down automatically as soon as the earthquake hit, it is important to remember that this radioactive decay process still emits heat typically around 5 – 8% of the full output power during the first 24 hours falling to around 1% after a week and declining further thereafter. Thus it is critical that the cooling water circuits continue for several days to remove this residual heat.

In a MAGNOX reactor the heat output during operation is around 1 MW per cubic metre – which would be the equivalent of boiling a litre of water with a 1 kW element in the kettle. The analogy would continue that if the kettle switched off when the water boils the heat loss would be such that the kettle would loose heat and as long as the element remains covered, no problem would arise. However, imagine that the electricity does not turn off completely but still continues at say 10% (i.e. 100 W), this would be more than sufficient to keep the water boiling and if the water level was not continually topped up as the water boiled then the element would be exposed and fail. This is what effectively happens when a nuclear station is shut down so cooling is critical

In a boiling water reactor, the power density is nearly 100 times that of a MAGNOX reactor so in normal operation the heat generation is 100 times as will also be the decay heat generation, and at 10 kW (in the case of the kettle analogy) still generated after shutdown this potentially could cause the element to melt.

Notice this condition is much more critical in PWR and BWR plant compared to the British gas cooled reactors (MAGNOX and AGR).

In the case of FUKUSHIMA-DAIICHI-1, as with all similar situations which may occur with a turbine trip, pumps will automatically cut in to keep the cooling water circulating. However, with the simultaneous shutdown of 11 separate plant simultaneously and also a similar capacity of normal fossil fuel power stations, there was a substantial loss of power across Japan meaning there was insufficient power available to be drawn for cooling not only for this reactor but for all other 10 reactors which tripped simultaneously.

There are emergency procedures which then automatically cut in by drawing power (if necessary from batteries) until diesel or gas generators cut in to provide local emergency power. It would appear that such generators did indeed cut in and provided power for at least 20 minutes – some reports say 1 hour, but then some of these failed – either because they were knocked out by the tsunami, or the necessary distribution was so affected by the tsunami.

As it appears that the emergency core cooling failed as least in part if not in full, the temperature of the water/steam in the pressure vessel will rise and if this continues more water will convert to steam which occupies 1700 times the volume causing an increase in pressure in the circuit. Pressure vessels will be designed to withstand pressures at least 50% above normal operation and may be 100% or more above, so a small rise is of no consequence, but it this does continue to rise, then it is important that this pressure is released and it is probable, although this needs to be confirmed, that steam (remember this is radioactive because of the design of BWR) will be released into the containment building. This is planned in such an emergency and is not, by itself a serious consequence. In some BWR, there is a condensate suppression pool at the bottom as shown and this will tend to condense some of the steam now in the containment building.

Remember that in PWRs and BWRs small changes in volume accompanying changes in temperature can lead to significant changes in pressure – whereas in the gas cooled reactors the changes in pressure with changes in volume / temperature are less marked.

6.6. Reports of fires at power stations

In the early hours of the disaster there were reports of fires at power stations, but information was sketchy and it was not clear whether this referred to fires in the turbine hall as does happen in fossil fuelled power stations – e.g. a few years ago

Tilbury coal fired station was so affected. Within a turbo generator, hydrogen is used for cooling the generator as it is a particularly good conductor of heat. A hydrogen leak here could start a fire and/or an explosion. Whether this was the cause of the explosion is not known.

Hydrogen build up

If hot steam is released and it comes into contact with some hot surfaces, the steam can split into hydrogen and oxygen. This hydrogen could be the cause of an explosion as it was at the Three Mile Island incident where there was an explosion which, despite the core becoming uncovered was entirely contained within the containment building.

In most PWR and BWR nuclear power stations the containment building is dome shaped as this will withstand much higher pressures in the event of an explosion. Indeed Sizewell B has two independent domes. However, at Fukushima, the building appears to be cuboid, and it is not clear whether the containment building was within the building which failed and remained intact, and the actual building seen to fail being a shell covering the large space needed for cranes etc or whether it was the containment building itself which seems odd from its shape.

6.7. What then happened?

There indeed was an explosion as was seen from TV pictures, and this is likely to have been a hydrogen explosion. There is the possibility it could have been a structural collapse as a delayed effect of the earthquake – remember the twin towers in New York stood for some time after the terrorist attack in 2001 before they collapsed. However, the pictures as far as I could seen did suggest a small flame which would make hydrogen more likely. Once again this by itself – which ever is the case - is not overly serious and there were reports immediately afterwards that radiation levels were falling.

However, what is critical is the integrity of the pressure vessel. Later reports suggested that this was intact, and if this is so then the situation is likely to be recoverable, albeit with the reactor deemed a write off, but since it was almost at the end of its life (probably within next 12 months anyway) this would not have much of a financial impact.

If the pressure vessel integrity is compromised, and that is far from clear as I write at 18:25 on 12th March, then that is more serious, and there may be a melting of the fuel, but there can then be no nuclear explosion as the fuel is at far to low an enrichment and the moderator has been lost anyway. However. At 18:20 the World Health organisation said “the public health risk from Japan's radiation leak appears to be "probably quite low". This suggests that the vessel is still intact:

Care must be taken on how subsequent cooling is attempted as if water is used and it contacts with very hot fuel cladding (Zirconium), then more hydrogen could be produced leading to a further chemical explosion which might lead to a further leak of contamination.

Do remember that radiation is generally of little consequence, but contamination is something over which we should be concerned.

6.8. Consequence of Earthquake on UK energy

With 11 reactors in total tripped, it will take some time to bring them all back on line and Tokyo Electric Power Company TEPCO is planning to run its fossil fuel plant more than normal which will mean an increase demand for oil and gas (Japan has limited coal generation).

Already there are moves in the financial markets seeing oil prices likely to rise as demand rises at the same time as the Middle East problems. Russia has already been approached by Japan for more LNG shipments at a time when LNG shipment prices are also rising, and since the UK is increasing dependent on energy imports this could see significant price rises in wholesale electricity prices in the UK in the near future.

6.9. Update on 13th March 17:00

Consultation of various further information and including the IAEA Webpage over the last 18 hours allows an update.

6.9.1. Cause of Hydrogen Build up in Fukushima – Daiichi 1 reactor.

The most probable cause of this is not a hydrogen leak in the turbine hall which may have caused a fire in the turbine hall elsewhere, but as a result of the pressure venting from the reactor vessel. It would appear that the top of the fuel elements and or systems above in the reactor vessel came uncovered and this hot metal, particularly if it were the fuel cladding zirconium would have reacted to split the steam. This by itself is of little consequence.

However, the build up of hydrogen within the cuboid building was something that could ultimately result in an explosion as indeed happened. The alternative would have been to have regularly releasing the hydrogen and steam from the building minimising the build up.

When the explosion occurred – reports were of a massive or huge explosion, but I have rerun the video several times, and it can only be classed as small to moderated, and what appeared to be dramatic was the simultaneous steam release and the debris from the collapsing building. [Remember the very very large plumes of smoke and dust when the twin towers collapsed in 2001 – this was very very minor in comparison]. That it was a small explosion is confirmed by the higher detail images of Daiichi -1 available today showing the reinforcement steel intact and undistorted. Had the explosion been large then this steel would either have disappeared or been bent outwards, neither of which appear to be the case.

6.9.2. The integrity of the Pressure Vessel

The explosion clearly took place around the pressure vessel and the fact that the cuboid shell gave way probably helped to avoid damage to the pressure vessel itself. All evidence indicates that this is the case – e.g. the very short burst of radiation which then fell, and the very limited amount of contamination on the population.

The News reports are confusing in references to radiation and contamination. Radiation decays rapidly with distance and even a short distance away from the plant such as 1 km direct line of sight would be adequate to attenuate the level to safe level even in the most intense situation. One can walk away from radiation, and if one is irradiated such as when having an x-ray it stops immediately the source is switched off or the person moves out of the critical area. Contamination on the other hand is another matter, as dust particles which might be radioactive will continue to irradiate a person unless the contamination is removed. Thus stripping off clothing with contamination is all that is needed to protect a person from health effects ***unless*** the contaminated particle is either ingested or breathed into the lungs. It is for this reason that larger exclusion zones than required to limit impacts of radiation are set up.

6.9.3. Critical Unanswered Questions

The nuclear plants all shut down safely or continued operating normally immediately after the earthquake, despite the fact that in the BWR the control rods have to be driven up rather than falling gravity in most designs. The standby by generators appears to have started when the grid electricity supply failed as they should [although this still needs to be confirmed], and some reports suggest that they ran for 20 minutes – others for up to an hour before failure. However, was this failure to continue cooling:

1. a failure of the generators .
2. the generators being affected by the tsunami, bearing in mind the station is close to the coast,
3. a failure in the water supply as there are severe water shortages reported in the area.

Of these three, the first seems unlikely as there is now a second and possibly third plant at the Daiichi complex now suffering similar problems and it is improbable that all back-up generators (and there are typically at least 4) failing at all the plants.

Since all the plants are parallel to the coast, then option (2) is possible, but why then contemplate using seawater as ordinary water would be far less corrosive of the plant. The strong likelihood is that (3) is the primary cause, although option (2) may also have figured as a partial cause.

6.9.4. Fukushima-Daiichi-1 present situation

All evidence points to the main pressure vessel being intact and cooling with sea water is now (16:00 13th March) is being pumped in to keep the core covered, In addition boron is added to this water as this is a neutron absorber assist further.

Using sea water is an odd solution as one would normally use ordinary water and the use of sea water does seem to reinforce the issue of option (3) being the primary cause of cooling failure. Using sea water, which is corrosive would make the plant unusable ever again

The Fukushima-Daiichi-1 plant is within 2 weeks of being 40 years old and was due to close shortly (within next 12 months or so) and so the decision to use sea water will have limited consequences on the future of the plant.

6.9.5 Other incidents. 17:00 March 31th

The situation is somewhat confused with different agencies, e.g. BBC, IAEA, Bloomberg Press etc, reporting different things. However, what does seem consistent is that at:

Fukushima-Daiichi-3

1. There appears to have been a similar loss of coolant at Fukushima-Daiichi-3 reactor close to the one previously causing concern. This is a larger reactor with a gross capacity of 784 MW and a net capacity of 760MW. Once again steam has been released from the pressure vessel and this probably may contain hydrogen again. With the experience of Reactor 1, the operators may try to release the build up of gas from the cuboid building to minimise the risk of an explosion, but this will almost certainly cause the release of some small amounts radioactivity and/or contamination.

   Remember that as BWR's and PWR's cannot replace defective fuel elements during operation, the primary cooling water circuit will almost certainly have contained some radioactivity/contamination before the incident started – unlike the situation in a MAGNOX, AGR, or CANDU reactor.
2. This reactor is 37 years old this year and the decision to use sea water as a last resort would only shorten its life bay a few years.
3. There are reports that this reactor is fuelled with mixed oxide fuel (MOX) which is a mixture of Uranium oxide (4-5% enrichment) with some plutonium which has been obtained either from reprocessing or from decommissioned nuclear weapons.
4. It is not clear what effect this mixed oxide fuel would have in a worst case scenario where the pressure vessel was ruptured. The primary source of contamination would be from the daughter products from the nuclear reactions, and the radiation issues arising from any plutonium would normally be relatively small compared to these. On the other hand there may be more significant chemical hazards.
5. There are reports of a possible faulty valve and or gauge, but the full significance of this cannot be assessed without more information.

Fukushima-Daiichi-2

1. This reactor is located between the number 1 and number 2 reactors and it is reported (16:00 on 13th March) that sea water is also being pumped into the core here which means that this reactor will never be used again.. This reactor appears to be identical with reactor 3 , but it is not clear whether MOX fuel is being used. This reactor will be 38 years old later this year.

Fukushima-Daiichi 4,5 and 6

These reactors were under going routine maintenance and refuelling at the time of the earthquake and are thus unaffected.

Fukushima –Daini 1,2,3 & 4

1. The situation at the site is confused with several corrections to statements being made. The latest information suggested that all four units 1 - 4 shut down automatically and that unit 3 is now in a safe cold shutdown state, whereas units 1,2, and 4 are still grid connected.
2. There are reports of a worker being killed and possibly some injured, but this appears to be associated with a normal industrial accident associated with the operation of a crane. One comment I saw suggested that that the operator fell

while mounting the crane at the time the earthquake hit and in which case is total unrelated to the operation of the power plant.

Onagawa 1, 2, & 3

1. There are reports of slightly increased radiation levels around one of these reactors, but IAEA state (13:35 on 13th March) that all reactors are under control. Onagawa No 3 reactor is only 10 years old this year

Clearly the overall situation is changing rapidly as more information is becoming available, but the above update was finished at 17:00 on 13th March. If there are any further developments a further update will be written.

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6.10. Updates: 15th March 2011

6.10.1 General coverage

The situation has indeed been very fast moving, and one must commend the Japanese authorities on the frequent updates in what must be a difficult situation. However, confusion still rains in the media, and there has been perhaps an over concentration on the nuclear issues when equally important issues have received little or no attention. I originally missed the images of the fires and explosions ranging out of control at the petro-chemical works/ oil refineries show on Friday evening. Apart from these initial pictures there has been limited reference.

The explosions and fires were clearly on a much larger scale than the nuclear explosions and quite probably there were workers killed or injured as the incident occurred during the working day. However, unlike the nuclear incident we are hearing next to no information. One BBC report did say that standing 2-3 miles away from one such plant that the smoke was acrid suggesting at least some toxic chemicals some may well have been carcinogenic. Is it that the fixation on the nuclear issues, serious as they may be, may be diverting attention away from a more serious issue to health? Remember one can readily detect radiation and radioactive contamination at very very low level, far more easily than concentration of chemicals which could be hazardous to health.

6.10.2 Update on impact on UK gas supplies

[See section 6.8 above].
According to Reuters, and as predicted wholesale LNG gas prices to the UK had risen 10% by 19:00 this evening [15th March] since the earthquake last Friday. This combined with the situation in the Middle East will see a further upward rise in retail prices as 25%+ of the UK gas supply now comes from LNG.

Update – Early May2011.

There are still several fossil fuel power stations in Japan which have not been recovered since the incident and also several nuclear stations in addition to Fukushima Daiichi which are not operating. Japan is currently purchasing much increased supplied of gas for next winter which are likely to see a noticeable upward pressure on gas and electricity prices in the UK towards the end of 2011. Forward contracts. This likely outcomae was confirmedaround 9th May when retail prices rises of 10 – 15% in the UK are expected.

10.3 Distorted Information in the media.

There will be an urgent review of plans for new nuclear plants, but a review of the safety issues on existing plant needs to be assessed. In many respects the Fukushima plants behaved very well to the earthquake despite their near 40 years of age, but it was the tsunami which I speculated might be the fundamental issue does seen to have been the main cause. I understand that the coastal units at Fukushima-Daiichi were designed to withstand a 6.5m tsunami, which as we now know was significantly overtopped at 9 – 10m – however, more about that later.

There are arguments against nuclear power which can be expounded and a reasoned and rational debate is required as we decide whether or not nuclear power should form part of a future electricity generating mix. However, many statements in last few days on blogs demonstrate a complete naiivity on the part of the writers. In some cases such articles are published in the media, and it is surprising that such comment are published without at least questioning the facts and reasoning behind the statements.

Thus on page 6 of the ***Opinion and Debate Section in the Independent Newspaper today (15th March),*** Terry Duncan writes:

> "I recall in my youth, more than 60 years ago, the hydro-power stations being built all over my native Highlands – they are still operating today.
>
> Why can this proved system of generating electricity not be used nationwide.?
>
> In some areas water to turn the turbines could be pumped and returned to the sea. Modern non corrosive materials could be used for the pumps and pipes making maintenance reasonably trouble free.
>
> Then we would have no fears of nuclear accidents, at dated plants, in a country which does experience earthquakes, although at present ,infrequent"

Terry Duncan demonstrates his ignorance, by

a) Not considering the accidents occurring in earthquakes from dam failures - e.g. the Malpasset Dam near Frejus burst in 1959 killing over 500 people immediately.

b) Where does he expect the power to come from to pump the water. We already have pumped storage schemes to provide a limited amount of storage capacity, but as everyone knows only around 80% of energy is recovered later in generation so it consumes far more energy than it comes.

   Where does Mr Duncan believe the power will come from? What is the point of pumping water around wasting energy unnecessarily when we should be saving it?.

There have been issues reported at three different complexes see section 9.5 above. The current situation (23:00 on 15th March) appears as

10.4 Situation at Onagawa and Fulushima-Daini

10.4.1 Onagawa 1, 2 & 3

All units at this site shut down correctly and went into automatic cooling and are now sufficiently cool that sufficient of the heat arising in the initial hours after shut down had dissipated (see section 5 for a description of the decay heat cooling requirements). It would appear that the decay heat has now fallen sufficiently so to be no longer an issue. Increased radiation levels were detected at this plant, but evidence now suggests that this is arose from the contamination cloud from Fukushima-Daiichi 1 explosion on Saturday morning. Radiation levels at the plant now appear to have fallen significantly..

10.4.2 Fukushima-Daini 1,2,3 & 4

It appears that these four reactors responded differently.

Reactor 3 went through the planned cooling phase as was sufficiently cool 34 hours after the incident.

The immediate first stage emergency core cooling systems failed on all three units causing temperatures within the core to rise with the possibility that a pressure release into the outer containment might have been necessary. However, back up secondary systems were brought into play at ***units 1 and 2*** with the reactors reaching cool condition at 01:24 and 03:52 on 14th March respectively. There had been some concern that water in the suppression pool in unit 1 had risen high, but that has now subsided.

Reactor 4 was still heating on the morning of 14th March and an exclusion zone of 10 km was placed around the plant. Subsequently at 15:42 cooling began and by the evening of 15th the reactor was now cool.

TEPCO and the Government did say (on 14th March) that as soon as the last reactor was cool the exclusion zone would be lifted. However, it is unlikely that this has been as Daini is south of Daiichi and the exclusion zone partly overlaps with the exclusion zone around the Fukushima Daiichi complex.

10.4.3 Fukushima Daiichi

This is the complex with the most serious incidents. There are 6 reactors: units 4, 5, and 6 were not operating at the time of the earthquake but were under refuelling and/or maintenance. All other reactors went through initial shutdown correctly as explained in section 5.

Daiichi Unit 4

A fire broke out in unit 4 cooling pond for spent fuel elements. This was not in the reactor building, but in the holding area where, as a result of the refuelling then under way may have included a significant inventory of the reactor fuel – some of which would be held in the pond before shipping for reprocessing or disposal. However, as noted later, the fire was NOT in the cooling pond.

This cooling pond is like a very deep swimming pool typically 10m or more in depth. The spent fuel is stored at the bottom and there is sufficient depth of water (5m or more) which acts as the biological screen for radiation so above the pool radiation levels are at a safe level. What is a worry was the report in the media of a fire in the pool which would suggest that some of the water had evaporated. That is odd as the volume of water is so large that it would take probably weeks to get to a really serious state. However, if that were to happen then this potentially could be much more serious than the incidents in 1, 2 and 3. If it became dry, then any burst fuel cans could release significant quantities of radio active nuclides. Some of these, Xenon etc have very short half lives and in matters of hours they have decayed to stable isotopes.

Iodine is more problematic as it has a half life of around 9 days, but by 90 days it will have decayed to 1/1000th of the original concentration, by 6 months to less than 1 millionth and in a year 1 trillionth. Supplying people in the immediate vicinity with non radioactive iodine minimises the take up of radioactive iodine in the thyroid gland, and can thus be managed. What is of more concern are releases of radioactive nucleides with half lives of a few years such as Strontium and Caesium an decay very little over the lifespan of a human.

Any radioactive nucleides with long half lives of hundreds or thousands of years are a little consequence radiologically as the radiation levels are low, often very low anyway. There is a myth that the most hazardous radioactive nucleides are those with long half lives. It is those with medium long half lives which we should be most concerned about. Those intense one with short half lives such as iodine can be managed.

The fire occurred ***NOT*** in the cooling pond but as a result of an oil leak in one of the circulating pumps for the cooling water.

For more information on the Daiichi cooling ponds see

http://resources.nei.org/documents/japan/Used_Fuel_Pools_Key_Facts.pdf

Daiichi 5 and 6

Like Daiichi 4, these reactors were not operating and were already shut down before the earthquake hit. There are reports of temperature rises in the cooling ponds for the spent rods, and this might imply a failure of the circulating pumps for the cooling ponds. Through radioactive decay, heat is still emitted from spent fuel for several months, albeit at increasingly lower rates as time progresses. The cooling pumps circulate the water in the cooling ponds in a closed loop through chillers to remove any heat.

It is not known whether in the Japanese cooling ponds the water is also circulated through clinoptilolite a material which absorbs any radioactive particles which might migrate to the cooling pond water from a burst fuel can.

Daiichi 1

A small explosion in the reactor building, but not the containment took place on the morning of the 12th March as noted in section 7. The fact that radiation levels around this reactor have fallen does support the diagnosis that the containment structure is largely intact. Sea water continues to be pumped in to maintain cooling although there are reports that the tops of some of the fuel elements may have been exposed. This would allow the zircaloy cladding of the fuel elements which is designed to retain the radioactive daughter products to become defective and release products. Equally, any steam in contact with hot zircaloy will partly split to hydrogen and oxygen which after pressure release to the outer containment building would bet he source of a potential hydrogen explosion as did happen and this would take any volatile radioactive daughter products away as indeed happened. Please read the commentary about the cooling ponds at Daiichi 4 to understand the consequences of such a release.

As long as such cooling continues the reactor should be brought to a stable condition. The core is almost certainly damaged, but the containment is still intact.

Information indicates that the reactor was due to close at the end of this month after 40 years of operation confirming my speculation in section , so the fact that sea water will have damage the core is of little consequence except that it will make the decommissioning more difficult.

The used of borated water (boric acid) is often mentioned. This is used in PWR and BWR's as a means of control as borated water strongly absorbs neutrons and will ensure that no further chain reactions take place.

Cooling of the core and containment vessel is continuing.

Daiichi – 3

An explosion similar to Daiichi 1 took place in the reactor 3 containment building at 11:01 local time yesterday (14th March). This was larger than that of unit 1 but once again the main containment of the core is largely intact although there may be some damage, and the sequence of events leading up to this was similar to that for unit 1. The was evidence of over-pressure within the containment structure but this fell.

There was a short surge in radiation to around 50 microSieverts per hour for a relatively short time falling quickly to 10 – 20 microSieverts per hour and in 90 minutes to 4 microSieverts per hour. 10 km distant at the Daini plant – no change in radiation was detected indication there was no contamination reaching the Daini site.
However, another source put the instantaneous radiation at 3000 microSieverts falling to around 200 microSieverts by 12:30. It is probable that this discrepancy comes from different locations of measurement and some may refer to other buildings on the site.

To put this in context the maximum does received by anyone at the Three Mile Island incident in 1979 according to Wikipaedia was 1000 microSieverts (1 milliSievert) with the average for people living within 16 km (80 microSieverts).

1 microSievert is the does one can expect from eating 10 bananas, whereas an Xray could subject the patient to up to 14000 microSieverts. In some places in the world the annual background radiation is as high as 50000 microSieverts per year.

Cooling of the core with seawater continues but it is not clear whether the containment is also being doused with sea water

Daiichi 2

This reactor had an explosion in the early hours of 15th March (JST). This seems to have been more serious and caused damage to the core suppression pool. However, the damage to the external building is less than for units 1 and 3. As with 1 and 3, core cooling with sea water continues.

6.10.5 General Comments

Clearly the situation is changing rapidly and apart from this documentation which I started on 12th March other website have appeared who clearly have more time than I do and the reader should also consult these following links. How long I shall continue to update the information does depend on the time I have which is getting more and more limited over next few days. In the meantime also consult the following articles in BraveNew Climate:

- Initial summary 13th March
- Update on 14th March
- further technical information
- Update on 15th March

UPDATES of 17th, 19th, 21st, and 23rd of March follow after the following table.

STATUS of NUCLEAR REACTORS in JAPAN following Earthquake on March 11th 2011.

				Capacity (MWe)		Date	
Name	**Type**	**Status**	**Location**	**Net**	**Gross**	**Connected**	
FUKUSHIMA-DAIICHI-1	BWR	Operational	FUKUSHIMA-KEN	439	460	1970/11/17	Automatic Shutdown
FUKUSHIMA-DAIICHI-2	BWR	Operational	FUKUSHIMA-KEN	760	784	1973/12/24	Automatic Shutdown
FUKUSHIMA-DAIICHI-3	BWR	Operational	FUKUSHIMA-KEN	760	784	1974/10/26	Automatic Shutdown
FUKUSHIMA-DAIICHI-4	BWR	Operational	FUKUSHIMA-KEN	760	784	1978/02/24	Under Maintenance
FUKUSHIMA-DAIICHI-5	BWR	Operational	FUKUSHIMA-KEN	760	784	1977/09/22	Under Maintenance
FUKUSHIMA-DAIICHI-6	BWR	Operational	FUKUSHIMA-KEN	1067	1100	1979/05/04	Under Maintenance
FUKUSHIMA-DAINI-1	BWR	Operational	FUKUSHIMA-KEN	1067	1100	1981/07/31	Automatic Shutdown
FUKUSHIMA-DAINI-2	BWR	Operational	FUKUSHIMA-KEN	1067	1100	1983/06/23	Automatic Shutdown
FUKUSHIMA-DAINI-3	BWR	Operational	FUKUSHIMA-KEN	1067	1100	1984/12/14	Automatic Shutdown
FUKUSHIMA-DAINI-4	BWR	Operational	FUKUSHIMA-KEN	1067	1100	1986/12/17	Automatic Shutdown
HAMAOKA-1	BWR	Permanent Shutdown	SHIZUOKA-PREFECTURE	515	540	1974/08/13	
HAMAOKA-2	BWR	Permanent Shutdown	SHIZUOKA-PREFECTURE	806	840	1978/05/04	
HAMAOKA-3	BWR	Operational	SHIZUOKA-PREFECTURE	1056	1100	1987/01/20	Under maintenance
HAMAOKA-4	BWR	Operational	SHIZUOKA-PREFECTURE	1092	1137	1993/01/27	Continued operation
HAMAOKA-5	BWR	Operational	SHIZUOKA-PREFECTURE	1212	1267	2004/04/26	Continued operation
HIGASHI DORI 1 (TOHOKU)	BWR	Operational	Aomori Prefecture	1067	1100	2005/03/09	Under maintenance
JPDR	BWR	Permanent Shutdown	IBARAKI	12	13	1963/10/26	
KASHIWAZAKI KARIWA-1	BWR	Operational	NIIGATA-KEN	1067	1100	1985/02/13	Continued in operation
KASHIWAZAKI KARIWA-2	BWR	Operational	NIIGATA-KEN	1067	1100	1990/02/08	Not operating at time
KASHIWAZAKI KARIWA-3	BWR	Operational	NIIGATA-KEN	1067	1100	1992/12/08	Not operating at time
KASHIWAZAKI KARIWA-4	BWR	Operational	NIIGATA-KEN	1067	1100	1993/12/21	Not operating at time
KASHIWAZAKI KARIWA-5	BWR	Operational	NIIGATA-KEN	1067	1100	1989/09/12	Continued in operation
KASHIWAZAKI KARIWA-6	BWR	Operational	NIIGATA-KEN	1315	1356	1996/01/29	Continued in operation
KASHIWAZAKI KARIWA-7	BWR	Operational	NIIGATA-KEN	1315	1356	1996/12/17	Continued in operation
OHMA	BWR	Under Construction	AOMORI	1325	1383		
ONAGAWA-1	BWR	Operational	MIYAGI PREFECTURE	498	524	1983/11/18	Automatic Shutdown
ONAGAWA-2	BWR	Operational	MIYAGI PREFECTURE	796	825	1994/12/23	Automatic Shutdown
ONAGAWA-3	BWR	Operational	MIYAGI PREFECTURE	796	825	2001/05/30	Automatic Shutdown
SHIKA-1	BWR	Operational	ISHIKAWA-KEN	505	540	1993/01/12	Tripped on 1st March 2011 had not been restarted
SHIKA-2	BWR	Operational	ISHIKAWA-KEN	1108	1206	2005/07/04	Was shut down for routine maintenance a few hours before earthquake
SHIMANE-1	BWR	Operational	SHIMANE PREFECTURE	439	460	1973/12/02	Under maintenance
SHIMANE-2	BWR	Operational	SHIMANE PREFECTURE	789	820	1988/07/11	Continued in normal operation
SHIMANE-3	BWR	Under Construction	SHIMANE PREFECTURE	1325	1373	2011/12/15	

STATUS of NUCLEAR REACTORS in JAPAN following Earthquake on March 11th 2011.

				Capacity (MWe)		Date	
Name	**Type**	**Status**	**Location**	**Net**	**Gross**	**Connected**	
TOKAI-2	BWR	Operational	IBARAKI-KEN	1060	1100	1978/03/13	Automatic Shutdown
TSURUGA-1	BWR	Operational	FUKUI	340	357	1969/11/16	Under maintenance
MONJU	FBR	Long-term Shutdown	FUKUI	246	280	1995/08/29	[redacted]
TOKAI-1	GCR	Permanent Shutdown	IBARAKI-KEN	137	166	1965/11/10	
FUGEN ATR	HWLWR	Permanent Shutdown	FUKUI	148	165	1978/07/29	
GENKAI-1	PWR	Operational	SAGA PREFECTURE	529	559	1975/02/14	Continued in normal operation
GENKAI-2	PWR	Operational	SAGA PREFECTURE	529	559	1980/06/03	Under maintenance
GENKAI-3	PWR	Operational	SAGA PREFECTURE	1127	1180	1993/06/15	Under maintenance
GENKAI-4	PWR	Operational	SAGA PREFECTURE	1127	1180	1996/11/12	Continued in normal operation
IKATA-1	PWR	Operational	EHIME PREFECTURE	538	566	1977/02/17	Continued in normal operation
IKATA-2	PWR	Operational	EHIME PREFECTURE	538	566	1981/08/19	Continued in normal operation
IKATA-3	PWR	Operational	EHIME PREFECTURE	846	890	1994/03/29	Continued in normal operation
MIHAMA-1	PWR	Operational	FUKUI	320	340	1970/08/08	Under maintenance
MIHAMA-2	PWR	Operational	FUKUI	470	500	1972/04/21	Continued in normal operation
MIHAMA-3	PWR	Operational	FUKUI	780	826	1976/02/19	Continued in normal operation
OHI-1	PWR	Operational	FUKUI	1120	1175	1977/12/23	Started after maintenance a few hours before earthquake .Continued in normal operation
OHI-2	PWR	Operational	FUKUI	1120	1175	1978/10/11	Continued in normal operation
OHI-3	PWR	Operational	FUKUI	1127	1180	1991/06/07	Continued in normal operation
OHI-4	PWR	Operational	FUKUI	1127	1180	1992/06/19	Continued in normal operation
SENDAI-1	PWR	Operational	KAGOSHIMA PREFECTURE	846	890	1983/09/16	Continued in normal operation
SENDAI-2	PWR	Operational	KAGOSHIMA PREFECTURE	846	890	1985/04/05	Continued in normal operation
TAKAHAMA-1	PWR	Operational	FUKUI	780	826	1974/03/27	Under maintenance
TAKAHAMA-2	PWR	Operational	FUKUI	780	826	1975/01/17	Continued in normal operation
TAKAHAMA-3	PWR	Operational	FUKUI	830	870	1984/05/09	Continued in normal operation
TAKAHAMA-4	PWR	Operational	FUKUI	830	870	1984/11/01	Continued in normal operation
TOMARI-1	PWR	Operational	HOKKAIDO	550	579	1988/12/06	Continued In normal operation
TOMARI-2	PWR	Operational	HOKKAIDO	550	579	1990/08/27	Continued In normal operation
TOMARI-3	PWR	Operational	HOKKAIDO	866	912	2009/03/20	Continued In normal operation
TSURUGA-2	PWR	Operational	FUKUI	1108	1160	1986/06/19	Continued in normal operation

6.11. Update 10:00 (GMT), 19:00 (JST) on 17th March 2011

6.11. Background

This account should be read as a continuation of the accounts written previously on 12th, 13th and 15th March.

The situation continues to be changing. However, more sources of information are becoming available and the attempt here is to be as objective as possible by seeking several sources. However, in several cases information is still limited. Furthermore statements are being made which are likely to cause unnecessary concern and there is question as to the credibility of some statements in the media and concern may be directed in the wrong direction and be counter-productive.

JAIF provide regular (twice daily) summaries of the situation at all Fukushima reactors at both the Daiichi and Daini sites. The latest version of this at 17:00 (JST) on 17th March is attached at the end of this account.

6.11.1 Nuclear plants in Japan.

Of the 54 reactors in Japan, 40 were either under going maintenance (i.e. shut down) or continued in operation and were thus unaffected by the earthquake. Three further reactors were shut down for refuelling and are on the Fukushima Daiichi site – more about them later. All eleven remaining plant shut down automatically and went through core cooling as expected. The reactor at Tokai and the three at Onagawa and Reactor 3 at Fukshima Daini all achieved normal cool down within 2 days. The remaining reactors i.e. 1,2 & 4 at Fukushima Daini and all reactors at Fukushima Daiichi are covered in separate section below. The JAIF website provides 2 – 3 updates daily on technical state of all reactors including pressure measurements etc.

6.11.2 Situation at Fukushima_Daini

This site has four 1100 MW Reactors and is located a short distance down the coast from Fukushima Daiichi – the plant which has suffered significant damage

As mentioned on 15th, all four units at that site are in cold shut down. The normal shut down procedures activated after the earthquake with automatic shutdown. Unit 3 continued cooling as normal and achieved the full cool status after 34 hours. Some problems were experienced with the primary emergency cooling systems on units 1,2 and 4. Secondary systems were brought into play and by the end of 15th March, all reactors were in stable shutdown mode. There was evidence of increased radioactivity, but this may well be from contamination for the Daiichi site.

The latest information from JAIF classifies the incident at Daini 1,2 and 4 a level 3 on the scale 1 – 7. Note that this is a logarithmic scale, so the emergency level was 1/10000th of the incident at Chernobyl.

Table 11.1 Details of Fossil Fuel Power Stations still offline according to TEPCO New Release at 10:00 on 17th March

Station	Type	Units	Status following earthquake	Loss of generation
Hirono	Coal and Oil	1 & 2 600 MW oil 3 & 4 1000 MW oil 5 600 MW coal	Units 2 and 4 tripped following earthquake – still offline	1600MW
Hitachinaka	Bitumous Coal	1 x 1000 MW oil	Unit 1 shut down and is still offline	1000MW
Kashima	Oil	1,2,3 &4 600 MW oil 5 & 6 1000 MW oil	Units 2,3,5 &6 shut down and are still offline	3200MW
Ohi	Oil	1 & 2 1050 MW	Unit 2 shut down and is still offline	1000MW
Higashi-Ohgishima	LNG	1 & 2 1000 MW	Unit 1 shut down and is still offline	1000 MW
			Total	7800 MW

6.11.3 Thermal Fossil Fuel Power Stations

There is very limited data on other power stations, but clearly there is a significant power shortage in Japan. From the TEPCO Website, one of the main power generators the following information, the following information (Table 11.1) is available which with further research allows the extend of the current loss of generation to be assessed. Note: this does not include issues with power plant of other operators.
To put this in perspective the loss of generating capacity from the nuclear reactors which tripped was around 9000 MW which with the loss of power from fossil fuel generators gives around 16700MW . In the UK the current demand varies through the day but reaches around 45000 MW during the day at this time of year.

6.11.4 Impact on UK

There continues to be uncertainty on LN gas supplies to UK following the Japanese Earthquake. Bloomberg have indicated that at times the spot market for gas is up 20% on last week and 119% up on a year ago as supplies are diverted to Japan. The situation is more critical in that the pipe line from Libya to Italy is not operating and Germany has shut its oldest nuclear reactors following the earthquake. Bloomberg quoting Michael Hsueh, a London-based Deutsche Bank analyst said about the gas situation that ….“The U.K. market is most vulnerable, followed by Belgium, France and Spain,”

At the same time EU (Carbon Dioxide) emission trading permits have risen noticeably in last few days (albeit dropping back slightly this morning). Coal fired power station emit up to 2.5 times as much CO_2 as gas fired stations and thus require more permits to operate. The reasoning here is that if there a situation develops with gas supplies then generators are likely to switch to coal and pay the increased emission charges. In addition as the UK now imports up to 2/3rds of its coal, the price of coal is also likely to rise. All these effects will impact adversely on domestic UK electricity and gas prices.

Japan will undoubtedly see a surge in carbon dioxide emissions because of the substantial switch to fossil fuels. As I write, MPs in Hungary are debating whether to give 10Million tonnes of its credits to help Japan. It would be interesting to see if other countries follow suit as this would put further pressure on energy prices.

6.*11.5 The Situation at Fukushima Daiichi*

The key issues have moved from the reactors themselves to the associated spent fuel ponds which are located close to each reactor. In addition at Fukushima there is a seventh pond which is shared by all reactors. With this development it is important to understand a little about the function of the spent fuel ponds, and also the fuel assemblies etc. These aspects are covered in this section and subsections 6.11.5.1 and 6.11.5.2 before returning to the situation in the reactors themselves in section 6.11.5.3.

Units 4, 5, and 6 were ***not*** operating at the time of the earthquake, and the issues surrounding unit 4 therefore need some explanation as to what was happening. Units 4, 5 and 6 had been undergoing the biannual maintenance which also includes refuelling. Unlike the British design of MAGNOX reactor (a gas cooled reactor), the Canadian (CANDU heavy water reactor), and to a lesser extent the British Advanced Gas Cooled reactor, all of which can at least in part be refuelled on line, Pressurised Water Reactors (PWR) and the type at Daiichi (boiling Water) BWR have to be shut down completely.

In both PWR and BWR during refuelling which typically takes 2 – 3 months, all the fuel from the reactor are transferred to the spent fuel pond which as explained in section 10.4.3 is like a very deep swimming pool ~10m deep. The fuel is stored at the bottom and there is a minimum of 5m of water above the fuel to provide the biological shield.

After maintenance the reactor is refuelled, but many of the fuel rods will be returned to the reactor only those which have been in the reactor for around 4 – 5 years will be held in the spent fuel pond for up to 6 – 24 months before transfer to more permanent storage or reprocessing.

There appears a noticeable difference between the status in units 5 and 6 and unit 4. The former two were further through the refuelling cycle and there was less fuel in the spent fuel pond as it had been returned to the reactor, whereas in unit 4 it would appear that the full fuel inventory is in the pond.

As indicated in the previous report, section 10.4.3, the developing situation may be more critical if reports that the spent fuel pond in unit 4 is at a very high temperature, and some reports say that it is completely dry.

The reason why the water level in pond 4 has become low or possibly non existent is of particular concern. The pond in this design of BWR is placed near the top of the building to make it easier to transfer the fuel to and from the reactor. In most spent fuel ponds they are either at ground level or partially below ground. The volume of water is very large so that even if boiling too place it would take several days to evaporate the water during which time make up water could be provided. What is more likely is either:

1. Being at the top of the building the structural integrity of the pond became compromised during the earthquake leading to leaks.
2. As the water supplies were critical for dealing with reactors 1,2,3 the workforce may have withdrawn some water as an easy option before they decided to use sea water.
3. The explosion at the adjacent reactor 3 may have compromised the integrity of the structure as in (1) above.

Whatever the cause of the low water, radiation levels in the spent fuel pond hall would rise to potentially dangerous levels and impair the ability to restore the water levels by pumping water directly from the edge into the pond. This is quite probable as they are currently attempting to add water to the pond from helicopters (further from the radiation source therefore less hazardous) or from water cannon outside which would receive a significant amount of shielding from radiation from the building itself.

What happens if this spent fuel pond runs dry as at least one account has suggested. Firstly the fuel rods will start to heat up, but as they have been out of the reactor for some time, they would only be emitting a small proportion of what they had been. Nevertheless without cooling the fuel assembly would rise in temperature and would almost certainly rupture the fuel cladding and cause the release of radioactive particles as explained below.

6.11.5.1 Fuel assemblies for BWRs and PWRs

6.*11.5.2 Reports of a criticality*

Last evening (16th March) there were reports on the BBC Website of the possibility of a criticality happening. This is a most improbable likelihood. The fuel in a BWR is at most at 5% enrichment. In natural uranium, Uranium-235 which is the only active part of Uranium is present at only 0.7% with 99.3% being Uranium-238. Some reactors such as the British MAGNOX and the Canadian CANDU reactor use uranium in its natural enrichment, but most reactors require some enrichment.

However at that enrichment it is not possible for the material to sustain a chain reaction (i.e. go critical), as it requires neutrons to initiate the fission (splitting process). This fission will liberate 2 – 3 further neutrons which potentially could cause more fissions, however, these are readily lost outside the fuel or are moving too fast to create another fission,

In all nuclear reactors it is necessary to have a moderator to slow down the "fast" neutrons so that they can initiate a further fission reaction. The different reactor types use different moderators. Thus in the British MAGNOX and AGR designs, the moderator is graphite, in the Canadian CANDU it is heavy water, whereas in PWR and BWRs it is ordinary water. Thus unlike the British design, which has graphite as the moderator and carbon dioxide as the coolant gas, water is used in both BWR and PWRs as both a coolant ***and*** a moderator. If indeed there is a loss of water as there indeed is then the moderator will be lost in this design and this loss would stop any chain reaction from taking place. However, the fuel elements could still overheat as indicated in the previous section.

One might ask what happens in the cooling ponds – surely there is water present and could act as a moderator?. That is true, but the other requirement is for the fuel to be in a very tight geometry otherwise neutrons are lost and once again no chain reaction can take place. The fuel elements in the spent fuel cooling ponds are held in casks for ease of transport. These casks keep the fuel in a very low density thus preventing any chain reaction.

6.11.5.3 The situation in the reactors which were operating – i.e. 1, 2, and 3

At the time of writing it would appear that in all three reactors the water level in the pressure vessel is below what it should be an around half way up the fuel meaning that the top half will get very hot and the steam rising would react with the hot zirconium to produce hydrogen – the cause of the explosions.

The fuel integrity in all three reactors has been compromised, but the evidence indicates that the outer containment integrity in unit 1 is undamaged although damage is suspected in both units 2 and 3. Damage to the outer buildings – cuboids is severe in units 1, 3 and 4 (the latter because of issues with the spent fuel pond), but only slight in building 2.

6.12. Update at 23:00 (GMT) on 19th March 2011

6.12. Introduction

Developments have been somewhat less over the last few days. Issues are still serious at Fukushima Daiichi although as time goes by, there are signs of improvement. Elsewhere in Japan, in the power situation it appears from briefings from TEPCO (19th March) that the Ohi power station is now operational again, although 6800 MW of the TEPCO generating capacity is still shut down – see table 12.1

Table 6.12.1 Details of Fossil Fuel Power Stations still offline according to TEPCO at 09:00 (JST) on 19th March

Station	Type	Units	Status following earthquake	Loss of generation
Hirono	Coal and Oil	1 & 2 600 MW oil 3 & 4 1000 MW oil 5 600 MW coal	Units 2 and 4 tripped following earthquake – still offline	1600MW
Hitachinaka	Bitumous Coal	1 x 1000 MW oil	Unit 1 shut down and is still offline	1000MW
Kashima	Oil	1,2,3 &4 600 MW oil 5 & 6 1000 MW oil	Units 2,3,5 &6 shut down and are still offline	3200MW
Ohi	Oil	1 & 2 1050 MW	Would appear Ohi is now back up running	
Higashi-Ohgishima	LNG	1 & 2 1000 MW	Unit 1 shut down and is still offline	1000 MW
			Total	6850 MW

There are significant amounts of data now available relating to the Fukushima incident. However, a particularly good link is the video presentation prepared by NNK (the Japanese equivalent of the BBC). This has been translated and placed on Youtube and may be accessed by clicking on the image below. It is noteworthy that much of the analysis I did a week ago with limited data does indeed appear to have been largely correct. See next page for the link to YouTube film

In recent days there has been much objective data on the Internet and other objective assessments in addition to numerous misleading sets of information.

Some good objective sites with links to other information include the JAIF Website which may be access by clicking here. This gives data in a concise form and is updated two – three times a day. The TEPCO website also gives updates sometimes as frequently as hourly. This site also gives information on the general power situation in Japan.

6.12.1 Other information

The WNN website and IAEA Website also give assessments of the situation, but good accounts which I became aware of three days after I started writing are the blogs written by Barry Brookes and I have included some information from his information of 19th March below.

6.12.2 Level of Nuclear Emergency at Fukushima

Several days ago the Nuclear Level Emergency at Fukushima Daiichi was put at level 4. Today (19th) news reports said this has been raised to level 5. This does not necessarily mean that there has been a deterioration, but that probably a more accurate assessment has been possible. This would put it on the same level as Three Mile Island in 1979 and 100 times less than the situation in Chernobyl. However, the Level of severity does vary from reactor to reactor and this information is clearly indicated on the JAIF Website and summarised in Appendix 3 below. It appears that reactors 1, 2, and 3 are now categorised as Level 5 with unit 4 categorised as level 3. However, if the situation deteriorates in the spent fuel ponds in unit 4, this level will almost certainly be increased. Units 5 and 6 are not affected as an incident and thus have not as yet encountered an emergency level, although see the notes below.

As reported on 17th, the Daini plant remains at level 3 from units 1, 2, and 4 with unit 3 which shut down as expected incurring no emergency.

CTRL+Click on Image to access Youtube – it is around 7 – 8 minutes long

6.12.3 Situation at Fukushima Daiichi

6.12.3.1 Units 5 and 6

Neither reactor was in operation at the time of the earthquake as they were undergoing refuelling, and most of the fuel assemblies had bee returned to the reactor – see tale 12.2 and compare the fuel inventory of 5 and 6 with that of unit 4. However, as there was a lack of cooling in the spent fuel pond the temperature started rising slightly and reach around 65^{o}C by Thursday. There was the possibility that if the water level fell through evaporation then a situation similar to unit 4 might occur where if the fuel became exposed, hydrogen might build up and a further explosion might occur. Consequently the decision was taken to drill three 7 cm holes in the roof of each pond to provide vents to allow any hydrogen to escape. At the same time efforts were made to lay a new electricity cable to the site so that grid electricity could be used and provide a more reliable electricity source to ensure the circulating pumps and associated chillers could be restarted. This was achieved at unit 5 at around 05:00 on 19th and in the early evening in unit 6, and the evidence is that the temperature in the cooling ponds is now falling and hopefully should reach normal levels in a day or so.

Table 6.12.2 shows the situation with the fuel assemblies and as indicated on 17th, the fuel inventory in the ponds of both units is much less than that in unit 4.

Table 6.12.1 Fuel Assembly inventory in the Reactor and Spent Fuel Pond in each unit

Reactor Unit	Assemblies in Reactor Core	Assemblies in Spent Fuel Pond	Tons of Fuel in Spent Fuel Pond
1	400	292	50
2	548	587	100
3	548	514	90
4	0	1479	250
5	418	946	160
6	634	867	150

12.3.2 Units 1, 2, and 3

At the time of writing (22:00 on 19th) attempts are being made to connect the temporary grid supply to units 1 and 2 and some reports suggest that this has been achieved, but that checks are being done to get the pumps working in these units to allow more reliable pumping of water into the reactor and cooling ponds.

Unit 1, though seriously damaged does seem to be in a reasonably stable state, and things should improve when power is restored. There remains more concern still on units 2 and 3 as the containment structure is likely to be compromised, but the full extent of the damage is not yet known. Unit 3 is next to unit 4 and radiation levels in the vicinity of unit 4 may restrict the speed at which connection to the temporary cable can be achieved as workers will be more restricted in the time they can work on site to limit their radiation doses to safe level.

6.12.3.4 Unit 4

Despite being shut down, and the reactor not containing any fuel, this unit is perhaps of most concern relating to the spent fuel pond. The reactor itself is undamaged and may indeed have been open at the time of the earthquake. The problem is solely with the spent fuel pond where not only the spent fuel was being stored, but also the full inventory of the reactor during the refuelling operation.

The heat emission from all 1479 assemblies would have been much higher than that in ponds 5 and 6 and the lack of cooling and the suspected leak of the pond has allowed the fuel elements to be exposed. The temperature measurements in the pond ceased on 14th March when they apparently had reaching 84^{o}C and one must assume that the water actually boiled and evaporated.

The loss of water is particularly serious here as the fuel is kept in an open pond and the top 5m of water acts as a biological shield and as that appears not to be there, none of the workforce can enter the area. Water is being pumped from water cannon and unconfirmed reports suggest that 1200 tonnes of water have been pumped in. It must be assumed that at least 50% if not 80% of this has evaporated and that in effect only 250 – 600 tonnes has been effective. This represents only 25 – 60 cubic metres and with water up to 10 metres deep the pond would normally need probably art least 1000 cubic metres and probably much more depending on the size. Consequently it will be some time before sufficient water is in the pond to provide an adequate biological shield and also adequate cooling. Until this is achieved, the situation is serious, but as each hour goes by the situation will get better – remember the decay heat does reduce with time.

6.12.4 General Concluding Comments

I am unlikely to continue many more updates apart from occasionally. Further more, I have written things chronologically, and it would be appropriate to try to reorder what has been written into a more effective description, particularly now that many of the original uncertainties as to what happened have now, at least in part, been resolved.

SECTION 6.13 update as of 21st March 2011

6.13 Introduction and Summary

In the past 48 hours there has been much less development, however the following are key happenings:

1). A power cable has now been laid to the power plant so that it can now be grid connected.
2) Checks on the integrity of the electrical equipment are being made before switching over to using this equipment rather than the mobile fire trucks etc.
3) Stable cooling to cooling ponds 5 and 6 has been achieved with substantially lower temperatures in both ponds.
4) large quantities of water continue to be pumped into the cooling ponds.
5) White smoke/steam has been seen rising from reactor buildings and workforce have been temporarily withdrawn during these periods
6) Data of radiation levels on an hourly basis are now available in Tokyo and show a noticeable rise in the middle of today 21st March, However, these levels are still low. This information is reproduced in graphical form as Appendix 5
7) Radioactive iodine and caesium have been detected in food produced in exclusion zone and immediately outside, but radiation levels of radioactive iodine and caesium remain very low in Tokyo. These data are tabulated in Appendix 6.
8) All the Reactors at Fukushima Daiini, Onagawa, and Tokai Daini are now in a safe shutdown situations and have been so for last 4 days

6.13.1 Fukushima Cooling Ponds 5 & 6

Neither of these reactors or cooling ponds has experienced an explosion. Both reactors were in a shut down state and were being refuelled ta the time (see also section 11.5 and 12.3.1). However, the temperature was rising in these ponds and reached around 65 – 67°C very much above normal. There was a danger that continued evaporation could lead to a hydrogen build up and an explosion. Consequently three small holes were drilled in the roof of both cooling ponds to allow escape of the hydrogen. Over the last two days and with the aid of supplementary pumping, the temperature in both pools has been brought down to values in the range of 25 – 35 °C and are largely in a safe and manageable state, although when the grid electricity is fully connected this will bring the units back to normal.

6.13.2 Fukushima units 1 – 4

Water continues to be pumped from outside into the building at the rate of several tonnes per hour, although this is interrupted periodically if the crews have to be withdrawn when there is uncertainty over radiation levels. The levels at the plant as monitored are now regularly displayed on the internet. They are high and workers will only be allowed limited time close to the reactor buildings before they are relieved. The imperative is to get the electricity connected to the grid which has now been achieved. Subsequently checks are needed on the equipment and then hopefully full circulation with the inbuilt pumps can be resumed.

For the first time the temperature of the cooling pond 2 was displayed on the JAIF WEBSITE today (21st March 22:00 JST) as being 50°C. That measurement is now possible is an encouraging sign although the reading is still rather high.

The next few days will be important and if power is restored and the level of water in pond 4 can be increased to normal so as to provide an adequate biological shield the situation should become more manageable.

6.13.3 Radiation Levels in Tokyo

Hourly radiation data has been published on the internet since 15th march and a summary is shown in the graph below. Tokyo measure the radiation in microGrays / hr whereas most radiation is measured in micro Sieverts. For beta, gamma, radiation and X-rays the values are the same in both units. However, when alpha radiation is involved there is a weighting factor of 20. The effective weighting factor depends on the proportions of the different radiations, but might well be as high as a factor of 4.

The graph in Figure 13.1 shows the values in micrograys as actually measured. Noticeable is the rise in the last 24 hours to around 0.15 Grays per hour – if that level were to continue and the weighting factor is indeed 4, then the annual radiation dose if maintained at this elevated level would be equivalent to less than a single CT scan (approx 5800 microSieverts a year) and also equivalent to a person living in Aberdeen taking a few transatlantic flight a year.

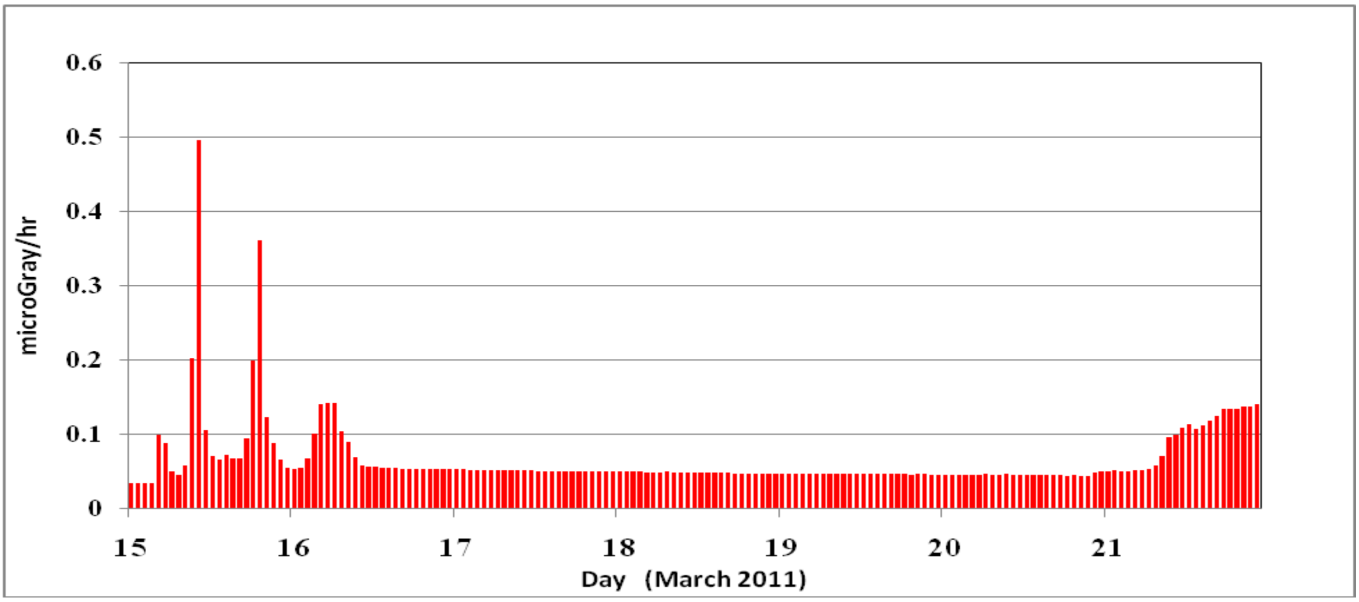

Figure 13.1 Hourly Radiation data measured at Shin-juku in Tokyo.

6.13.4 Radioactive Particles as measured in Tokyo

Since 15th March the presence of radioactive particles in the air in Tokyo has been measured as shown in Appendix 6.

Note the counting times do vary in the table, but the levels of Iodine 131, 132, and Caesium 134 and 137 are very low having an absolute maximum of 240 Bq/m^2. Remember radioactive potassium-40 naturally occurring within the human body is on a scale of around 4000 Bq (i.e. 4000 disintegrations per second) – Wikipaedia.

Appendices follow on the next pages

Appendix 1 First page of JAIF Assessment on 21st March at 22:00. This gives a traffic Light Appraisal of the different issues

Green – Low/No Issue
Yellow – Moderate Issues
Red - Severe/Serious Issues

Appendix 2 Radiation Data as measured at Shin-juku, Tokyo

Appendix 3 Measured concentrations of Iodine 131, 132 and Caesium 134, 137

APPENDIX 1: The following table is from JAIF at 22:00 on 21st March – consult JAIF WEBSITE for additional information.

Status of nuclear power plants in Fukushima as of 22:00 March 21 (Estimated by JAIF)

Power Station	Fukushima Dai-ichi Nuclear Power Station					
Unit	1	2	3	4	5	6
Electric / Thermal Power output (MW)	460 / 1380	784 / 2381	784 / 2381	784 / 2381	784 / 2381	1100 /3293
Type of Reactor	BWR-3	BWR-4	BWR-4	BWR-4	BWR-4	BWR-5
Operation Status at the earthquake occurred	In Service -> Shutdown	In Service -> Shutdown	In Service -> Shutdown	Outage	Outage	Outage
Core and Fuel Integrity	Damaged	Damaged	Damaged	No fuel rods	Not Damaged	Not Damaged
Reactor Pressure Vessel Integrity	Unknown	Unknown	Unknown	Not Damaged	Not Damaged	Not Damaged
Containment Vessel Integrity	Not Damaged	Damage Suspected	Might be "Not damaged"	Not Damaged	Not Damaged	Not Damaged
Core cooling requiring AC power	Not Functional	Not Functional	Not Functional	Not necessary	Not necessary (AC power available)	Not necessary (AC power Available)
Core cooling not requiring AC power	Not Functional	Not Functional	Not Functional	Not necessary	Not necessary	Not necessary
Building Integrity	Severely Damaged (Hydrogen Explosion)	Slightly Damaged	Severely Damaged (Hydrogen Explosion)	Severely Damaged (Hydrogen Explosion)	Open a vent hole on the rooftop for avoiding hydrogen explosion	
Water Level of the Rector Pressure Vessel	Fuel exposed partially or fully	Fuel exposed partially or fully	Fuel exposed partially or fully	Safe	Safe (in cold shutdown)	Safe (in cold shutdown)
Pressure of the Reactor Pressure Vessel	Stable	Unknown	Unknown	Safe	Safe	Safe
Containment Vessel Pressure	Stable	Stable	Decreasing after increase in Mar., 20th	Safe	Safe	Safe
Water injection to core (Accident Management)	Continuing (Seawater)	Continuing(Seawater)	Continuing(Seawater)	Not necessary	Not necessary	Not necessary
Water injection to Containment Vessel (AM)	Continuing(Seawater)	to be decided(Seawater)	Continuing(Seawater)	Not necessary	Not necessary	Not necessary
Containment venting (AM)	Temporally stopped	Temporally stopped	Temporally stopped	Not necessary	Not necessary	Not necessary
Fuel Integrity in the spent fuel pool	Water injection to be considered	Seawater Injection conducted in Mar. 20th	Water level low, Seawater spray continue and certain effect was confirmed	Water level low, Seawater spray continue Hydrogen from the pool exploded	Pool cooling capability was recovered	Pool cooling capability was recovered
Environmental effect	The West Gate: 269.5 μ Sv/h at 05:40, Mar. 20 North of Service Building: 2019.0 μ Sv/h at 15:00, Mar. 21 Radio nuclides were detected in milk produced in Fukushima prefecture and spinach from Ibaragi prefecture.					
Evacuation	20km from NPS ＊People who live between 20km to 30km from the Fukushima Dai-ichi NPS are to stay indoors.					
INES (estimated by NISA)	Level 5	Level 5	Level 5	Level 3	—	—
Remarks	Immediate threat is damage of the fuels in the fuel pool outside the containment vessel. The operation for spraying water to the pool is continuing at Uni-3 and 4 and certain effect has been confirmed based on the declining trend of radiation monitored. Seawater injection to the pool was conducted at Unit-2 on Mar. 20th. Work to recover AC power for Unit-1through 6 is in progress. External AC power has reached to the distribution switchboard for Unit-2. Integrity check of electric equipment of Unit-2 is going on, which must be done before energizing them. External AC power has replaced with the emergency diesel generator in Unit-5. Monitoring results of a few dairy and agricultural products such as milk in Fukushima and spinach in Ibaraki prefectures exceeded the national regulatory standard. Shipment of these products has been restricted for the time being.					

Power Station	Fukushima Dai-ni Nuclear Power Station			
Unit	1	2	3	4
Electric / Thermal Power output (MW)	1100 / 3293			
Type of Reactor	BWR-5	BWR-5	BWR-5	BWR-5
Operation Status at the earthquake occurred	In Service -> Automatic Shutdown			
Status	All the units are in cold shutdown.			
INES (estimated by NISA)	Level 3	Level 3	—	Level 3
Remarks	Unit-1, 2, 3 & 4, which were in full operation when the earthquake occurred, all shutdown automatically. External power supply was available after the quake. While injecting water into the reactor pressure vessel using make-up water system, TEPCO recovered the core cooling function and made the unit into cold shutdown state one by one. Latest Monitor Indication: 13.9 μ Sv/h at 15:00, Mar. 21 at NPS border Evacuation Area: 10km from NPS			

Power Station	Onagawa Nuclear Power Station		
Unit	1	2	3
Operation Status at the earthquake occurred	In Service -> Automatic Shutdown		
Status	All the units are in cold shutdown.		
Remarks	Safe		

Power Station	Tokai Dai-ni
Operation Status at the earthquake occurred	In Service -> Automatic Shutdown
Status	In cold shutdown.
Remarks	Safe

[Significance judged by JAIF]
- Low (green)
- High (yellow)
- Severe (Need immediate action) (red)

[Source]
Governmental Emergency Headquarters: News Release (-3/21 19:00), Press conference
NISA: News Release (-3/21 15:30), Press conference
TEPCO: Press Release (-3/21 15:00), Press Conference

[Abbreviations]
INES: International Nuclear Event Scale
NISA: Nuclear and Industrial Safety Agency
TEPCO: Tokyo Electric Power Company, Inc.

Appendix 2. Radiation Levels in Tokyo – see also Figure 6.13.1 (Units microGRays/hr)

	max	min	average	max	min	average	max	min	average	max	min	average
	15th March 2011			**17th March 2011**			**19th March 2011**			**21st March 2011**		
0:00 - 1:00	0.0367	0.0322	0.0345	0.0562	0.0503	0.053	0.0491	0.0436	0.0469	0.0529	0.0478	0.0505
1:00 - 2:00	0.0372	0.0329	0.0347	0.0557	0.0501	0.0526	0.0499	0.044	0.0469	0.0548	0.0475	0.0511
2:00 - 3:00	0.0373	0.0318	0.0345	0.0549	0.05	0.0524	0.0493	0.0449	0.0469	0.0522	0.047	0.0497
3:00 - 4:00	0.0384	0.0319	0.0347	0.0551	0.0499	0.0523	0.0503	0.0444	0.0475	0.0527	0.0474	0.0497
4:00 - 5:00	0.147	0.036	0.1	0.0555	0.049	0.0523	0.0498	0.0447	0.0472	0.0553	0.0485	0.0513
5:00 - 6:00	0.112	0.0562	0.0875	0.0544	0.0497	0.0521	0.0487	0.0438	0.0468	0.0548	0.0493	0.0519
6:00 – 7:00	0.0576	0.0438	0.0495	0.0549	0.0498	0.0519	0.0494	0.0444	0.0472	0.0591	0.0503	0.0537
7:00 – 8:00	0.0507	0.0412	0.0453	0.0539	0.0498	0.052	0.0499	0.0439	0.0475	0.0625	0.0539	0.0585
8:00 – 9:00	0.123	0.0403	0.0573	0.0551	0.0489	0.0516	0.0496	0.0447	0.0473	0.093	0.0588	0.0703
9:00-10:00	0.465	0.122	0.202	0.0538	0.0485	0.0515	0.05	0.0454	0.0476	0.101	0.091	0.0958
10:00-11:00	0.809	0.16	0.496	0.0544	0.0489	0.0514	0.0496	0.0445	0.0473	0.105	0.0944	0.1
11:00-12:00	0.151	0.0781	0.106	0.0532	0.0489	0.0511	0.0491	0.0447	0.047	0.12	0.101	0.109
12:00-13:00	0.0777	0.0663	0.0713	0.0533	0.0486	0.0508	0.0493	0.045	0.0469	0.12	0.106	0.113
13:00-14:00	0.0722	0.0624	0.0658	0.0545	0.0486	0.0507	0.0499	0.045	0.047	0.111	0.104	0.108
14:00-15:00	0.0752	0.0681	0.0716	0.0526	0.0488	0.0506	0.0487	0.0427	0.0465	0.116	0.106	0.112
15:00-16:00	0.0715	0.0646	0.0682	0.0526	0.0488	0.0503	0.0489	0.0433	0.0462	0.126	0.113	0.118
16:00-17:00	0.0749	0.0646	0.0682	0.0523	0.0478	0.0502	0.0493	0.0435	0.0461	0.131	0.12	0.125
17:00-18:00	0.157	0.0669	0.0941	0.0524	0.0475	0.0498	0.0499	0.0443	0.0462	0.139	0.128	0.134
18:00-19:00	0.32	0.113	0.2	0.052	0.0475	0.0501	0.0492	0.0433	0.0463	0.139	0.13	0.135
19:00-20:00	0.458	0.165	0.361	0.0537	0.0472	0.0499	0.0478	0.0445	0.046	0.137	0.131	0.134
20:00-21:00	0.168	0.0955	0.123	0.0523	0.0478	0.0498	0.0483	0.0433	0.0461	0.141	0.131	0.137
21:00-22:00	0.098	0.0761	0.0888	0.0525	0.0473	0.0497	0.0485	0.0443	0.0462	0.14	0.133	0.137
22:00-23:00	0.0763	0.0575	0.0657	0.0525	0.048	0.05	0.0491	0.0426	0.046	0.145	0.136	0.141
23:00-00:00	0.0599	0.053	0.0556	0.0523	0.046	0.0497	0.0488	0.0435	0.0459			
	16th March 2011			**18th March 2011**			**20th March 2011**					
0:00 - 1:00	0.0559	0.0514	0.0538	0.053	0.0474	0.05	0.0487	0.0433	0.046			
1:00 - 2:00	0.0607	0.0506	0.0547	0.052	0.0474	0.0498	0.0492	0.0441	0.0459			
2:00 - 3:00	0.0951	0.0589	0.0672	0.0523	0.0471	0.0493	0.0477	0.044	0.0459			
3:00 - 4:00	0.126	0.0845	0.101	0.0524	0.0464	0.0496	0.0485	0.0435	0.046			
4:00 - 5:00	0.151	0.124	0.141	0.0523	0.0464	0.0489	0.0481	0.0429	0.0457			
5:00 - 6:00	0.16	0.128	0.143	0.0515	0.0468	0.049	0.0485	0.0433	0.0459			
6:00 – 7:00	0.161	0.111	0.142	0.0508	0.0464	0.0489	0.0485	0.0443	0.0461			
7:00 – 8:00	0.11	0.0975	0.104	0.0513	0.0468	0.0493	0.0492	0.0439	0.0458			
8:00 – 9:00	0.103	0.0693	0.0891	0.0518	0.0465	0.0489	0.0489	0.0436	0.0458			
9:00-10:00	0.087	0.0555	0.0688	0.0506	0.0466	0.0486	0.0492	0.0441	0.0462			
10:00-11:00	0.0702	0.0546	0.0582	0.0509	0.0455	0.0483	0.0489	0.0433	0.0457			
11:00-12:00	0.0632	0.0537	0.0565	0.0515	0.0454	0.0485	0.0482	0.0438	0.0459			
12:00-13:00	0.0654	0.053	0.0562	0.0507	0.0466	0.0485	0.0475	0.0433	0.0453			
13:00-14:00	0.0569	0.0529	0.0547	0.0509	0.0464	0.0486	0.0488	0.0419	0.0451			
14:00-15:00	0.0569	0.0513	0.0541	0.0506	0.0457	0.0484	0.0472	0.0421	0.0448			
15:00-16:00	0.057	0.052	0.0542	0.0502	0.0457	0.0481	0.048	0.0423	0.0452			
16:00-17:00	0.0575	0.0517	0.0539	0.05	0.0461	0.0481	0.0472	0.0431	0.0453			
17:00-18:00	0.0572	0.0504	0.0534	0.0496	0.0452	0.0474	0.0484	0.0422	0.0448			
18:00-19:00	0.0562	0.0507	0.0532	0.0499	0.0456	0.0475	0.0473	0.0415	0.0444			
19:00-20:00	0.0565	0.0509	0.0533	0.0491	0.0447	0.0472	0.0468	0.0425	0.0445			
20:00-21:00	0.0555	0.0511	0.0532	0.0498	0.045	0.0473	0.047	0.0414	0.0443			
21:00-22:00	0.0569	0.0506	0.0532	0.0505	0.0445	0.0472	0.0464	0.0416	0.0443			
22:00-23:00	0.0558	0.0508	0.0532	0.0492	0.0443	0.047	0.0524	0.0405	0.0478			
23:00-00:00	0.0553	0.0499	0.0529	0.0492	0.045	0.0471	0.0515	0.0465	0.0494			

Data reconfigured from Shinjuku-ku – click below to access website and latest information it is updated hourly
http://ftp.jaist.ac.jp/pub/emergency/monitoring.tokyo-eiken.go.jp/monitoring/index-e.html

Appendix 3. Iodine 131, 132 and Caesium 134, 137 Bequerels per sqm

Sampling Time	ヨウ素131	ヨウ素132	セシウム134	セシウム137
	15th March			
0:00 -7:12	10.8	8.5	1.9	1.8
7:12- 8:23	3.4	1.2	0.2	0.2
8:23- 9:00	6.2	3.4	0.8	0.8
9:00-10:00	67	59	12	11
10:00-11:00	241	281	64	60
11:00-12:00	83	102	24	23
12:00-13:00	8.7	8.3	2.2	2.2
13:00-14:00	5.6	4.2	0.8	0.8
14:00-15:00	6.2	4.6	1	0.9
15:00-16:00	9.8	7.2	1.9	1.8
16:00-17:00	11	7.5	1.9	1.7
17:00-18:00	11	7.6	1.8	1.7
18:00-19:00	12	9.3	2.4	2.1
19:00-20:00	9.4	6.7	2	2
20:00-21:00	3.3	2.7	0.9	0.7
21:00-22:00	3.4	2.5	0.7	0.6
22:00-23:00	3.4	3	0.9	0.8
23:00-00:00	1.6	1.2	0.3	0.3
	16th March			
0:00 - 1:00	1.3	0.9	0.1	0.2
1:00 - 2:00	1.6	0.6	0.2	0.1
2:00 - 3:00	3.5	2.4	0.6	0.5
3:00 - 4:00	12	7.5	3.1	2.8
4:00 - 5:00	22	15	4.7	4.8
5:00 - 6:00	12	8.9	2.8	2.6
6:00 – 7:00	7.3	5.5	1.7	1.6
7:00 – 8:00	4.6	3.1	0.9	0.9
8:00 – 9:00	2.2	1.6	0.4	0.4
9:00-10:00	1	0.7	0.1	0.2
10:00-11:00	0.6	0.4	0.1	0.1
11:00-12:00	1.2	0.6	0.1	0.1
12:00-13:00	2.6	0.9	0.2	0.2
13:00-14:00	0.9	0.4	0.1	0.1
14:00-15:00	0.4	0.4	0.1	ND
15:00-16:00	0.3	0.3	0.1	ND
16:00-17:00	0.6	0.9	0.2	0.1
17:00-18:00	0.3	0.4	ND	ND
18:00-19:00	0.2	0.3	0.1	0.1
19:00-20:00	0.2	0.4	0.1	ND
20:00-21:00	0.1	0.3	ND	ND
21:00-22:00	0.2	0.4	0.1	ND
22:00-23:00	0.2	0.4	0.1	0.1
23:00-00:00	0.1	0.3	ND	ND

Sampling Time	ヨウ素131	ヨウ素132	セシウム134	セシウム137
	17th March			
0:00 - 1:00	0.1	0.3	ND	ND
1:00 - 2:00	0.2	0.2	ND	ND
2:00 - 3:00	0.1	0.2	ND	ND
3:00 - 4:00	0.1	0.3	ND	ND
4:00 - 5:00	0.1	0.2	ND	ND
5:00 - 6:00	0.1	0.3	ND	ND
6:00 – 7:00	0.1	0.3	ND	ND
7:00 – 8:00	0.1	0.3	0.1	ND
8:00 – 9:00	0.1	0.3	ND	ND
9:00-10:00	0.2	0.2	ND	ND
10:00-11:00	0.2	0.3	ND	ND
11:00-12:00	0.2	0.3	ND	ND
12:00-13:00	0.2	0.2	ND	ND
13:00-14:00	0.2	0.2	ND	ND
14:00-15:00	0.2	0.3	ND	ND
15:00-16:00	0.2	0.3	0.1	ND
16:00-17:00	0.1	0.2	ND	ND
17:00-18:00	0.1	0.2	ND	ND
18:00-19:00	0.1	0.2	ND	ND
19:00-20:00	0.1	0.2	ND	ND
20:00-21:00	0.1	0.2	ND	ND
21:00-22:00	0.1	0.2	ND	ND
22:00-23:00	0.1	0.2	ND	ND
23:00-01:00	0.1	0.1	ND	ND
	18th March			
1:00 - 3:00	0.1	0.1	ND	ND
3:00 - 5:00	0.1	0.1	ND	ND
5:00 - 6:00	0.1	0.2	ND	ND
6:00 – 7:00	0.1	0.2	ND	ND
7:00 – 8:00	0.1	0.2	ND	ND
8:00 – 9:00	0.2	0.4	ND	ND
9:00-10:00	0.1	0.2	ND	ND
10:00-11:00	0.1	0.1	ND	ND
11:00-12:00	0.1	0.2	0.1	ND
12:00-13:00	0.2	0.1	ND	ND
13:00-14:00	0.1	0.1	ND	ND
14:00-15:00	0.1	0.1	ND	ND
15:00-16:00	0.1	0.1	ND	ND
16:00-17:00	0.1	ND	ND	ND
17:00-18:00	0.1	0.1	ND	ND
18:00-19:00	0.1	0.1	ND	ND
19:00-20:00	0.1	ND	ND	ND
20:00-21:00	0.1	0.1	ND	ND
21:00-22:00	0.1	0.1	ND	ND
22:00-23:00	0.1	0.1	ND	ND
23:00-00:00	0.1.	0.1	ND	ND

Sampling Time	ヨウ素131	ヨウ素132	セシウム134	セシウム137
	19th March 2011			
0:00 - 1:00	0.1.	0.1.	ND	ND
1:00 - 2:00	0.1.	0.1.	ND	ND
2:00 - 3:00	0.1.	0.1.	ND	ND
3:00 - 4:00	0.1.	0.1.	ND	ND
4:00 - 5:00	0.1.	ND	ND	ND
5:00 - 6:00	0.1.	0.1.	ND	ND
6:00 – 7:00	0.2	0.1.	ND	ND
7:00 – 8:00	0.3	0.2	ND	ND
8:00 – 9:00	0.3	0.2	ND	ND
9:00-10:00	0.2	0.1	ND	ND
10:00-11:00	0.3	0.1	ND	ND
11:00-12:00	0.1	0.1	ND	ND
12:00-13:00	0.1	0.1	ND	ND
13:00-14:00	0.2	0.1	ND	ND
14:00-15:00	0.1	0.1	ND	ND
15:00-16:00	0.1	0.1	ND	ND
16:00-17:00	0.1	0.1	ND	ND
17:00-18:00	0.1	0.1	ND	ND
18:00-19:00	0.1	0.1	ND	ND
19:00-20:00	0.1	0.1	ND	ND
20:00-21:00	0.2	0.2	ND	ND
21:00-22:00	0.2	0.2	ND	ND
22:00-23:00	0.1	0.1	ND	ND
	20th March 2011			
0:00 - 08:00	0.1	ND	ND	ND
08:00-16:00	0.2	ND	ND	ND
16:00-24:00	1.3	0.3	0.5	0.6
	21st March 2011			
0:00- 3:00	4.4	1.1	2.2	2.2
3:00- 8:00	8.4	2.2	4.4	4.3
08:00-10:00	15.6	3.8	6.8	6.6
10:00-12:00	11.9	3.3	5.8	5.6
12:00-14:00	8.5	2.5	3.2	3.1
14:00-16:00	2.4	1.6	1.7	1.6
16:00-18:00	1.8	2.9	1	0.9
18:00-20:00	2.1	4.3	0.5	0.5
20:00-22:00	2	1.7	0.3	0.3
22:00-24:0510	0.9	0.3	0.1	0.1

N.D Not detected

Data reconfigured from Shinjuku-ku – click below to access website and latest information it is updated hourly
http://ftp.jaist.ac.jp/pub/emergency/monitoring.tokyo-eiken.go.jp/monitoring/index-e.html