NBSLM03E Low Carbon Technologies and Solutions (2010)

PART 1 of 3

Low Carbon Conversion and Nuclear Power

CHP Plant: Acknowledgement Gas Engineering Services Web Page

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

http://www2.env.uea.ac.uk/gmmc/energy/nbslm03e/nbslm03e.htm

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1. INTRODUCTION

Low carbon solutions to future energy supply and demand may be separated into several different categories:

- **Improving the overall energy efficiency in the production and distribution of energy.**
- **Using low carbon energy sources and conversion technologies.**
- **Using Nuclear Power**
- **Using Renewable Energy**
- **Improving end use conversion efficiency through**
  - **Improved appliance efficiency/technology**
  - **Improved insulation and related**
- **Enhancing Energy Management and analysis**
- **Awareness Raising**

Sstrategies for effective carbon reduction will involve one or more of these categories, but the most effective solutions will often be found by a combination of two or more categories, particularly in the area of energy management.

1. *Improving the overall energy efficiency in the production and distribution of energy.*

The overall efficiency in the production and distribution of energy relates to the Primary Energy Ratio (PER)_i.e. the amount of energy that is required to be extracted from the ground to produce 1 unit of energy delivered at the premises of end use. In the NBS-LM01E module it was shown that currently the PER for different fuels is as shown in the Table 1.1

Table 1.1 Primary Energy Ratios for different fuels in the UK 2008. Data derived from Digest of UK Energy Statistics 2009 – see section 10.5.4 of the handout for NBS-LM01E.

Fuel	Primary Energy Ratio
Coal	1.0227
Oil	1.1292
Gas	1.062
Electricity	2.911

These figures relate to the overheads in producing one unit of energy at the point of final end use, and will depend on the efficiency of extraction and distribution of the energy source.

2. *Using a low carbon fossil fuel source.*

Fuels like coal have a high carbon content and most of the energy is generated through the chemical combination of the Carbon with oxygen to form carbon dioxide.

Oil fuels have a generic formula of C_2H_n and in addition to carbon converting to CO_2 the hydrogen converts to H_2O and there is typically only 80 – 90% of the carbon emissions for an equivalent energy conversion.

Natural gas (methane) is CH_4 and the proportion of energy arising from the the conversion of hydrogen is much higher than oil and the carbon emissions will be lower at around 60% that of coal for an equivalent technology and efficiency. Gases like propane, butance (and LPG) have a higher proportion of carbon and thus these too will have a higher carbon emission per unit of energy compared to natural gas. Data relating to the carbon emissions of different gases may be found summarised in the ENV Data Book Table 11.12.1 which was updated in July 2009 and in more depth in the DEFRA/DECC publications updated October 2009) http://www.defra.gov.uk/environment/business/reporting/pdf/20090928-guidelines-ghg-conversion-factors.pdf

For direct combustions of typical fuels the carbon emissions per kWh as measured on a gross calorific value basis are shown in Table 1.2.

Table 1.2. Latest (2009) carbon emission factors for selected fuels (from DEFRA Website).:

Fuel	Emission factor gms/kWh (Gross CV)
Natural gas	183.58
LPG	214.19
Petrol	239.76
Diesel	250.12
Burning oil	245.55
Fuel Oil	265.30
Domestic Coal	295.82
Industrial Coal	307.94
Coal used for electricity generation	310.05

Note: these figures differ slightly from the values in the data book which refer to 2008.

These emission figures refer to the input energy NOT the output energy. Thus in a house with a gas condensing boiler with efficiency of 90%, the emission factor for useful energy produced can be obtained by dividing the 183.58 figures from the above tables by 0.9.

In the case of electricity generation, the emission factor for each unit of electricity generated may similarly be obtained if the efficiency of generation is known. Thus if the efficiency of coal fired generation is ~ 36%, then the meission factor for this type of generation would be 310.05/0.36 = 861.25 gms / kWh. If we take note of the Primary Energy Ratio from Table 1.1 and the typical loses of 8.5% in transmission, then the overall emission factor for electricity generated in a coal fired power plant (of efficiency 36%) as delivered to the point of end use will be 861.25 * 1.0227/ 0.915 = 962 gm/kWh.

If steam turbines rae used for generation the efficiencies will be around 36 – 38% irrespective of the fuel used and so for gas generation, the equivalent emission will be 570 gms/kWh. However, if combined cycle gas turbines (CCGT) are used with an efficiency of 50% then the overall emission factor will be 410 g/kWh.

3. *Using Nuclear Power*

Including all extraction fuel enrichment and fuel fabrication, the emissions associated with the generation of nuclear power are 5 – 10 gms depending on the reactor type. Even with transmission losses the emission factors is still very low.

4. *Using Renewable Energy*

In operation, most renewable energy sources will emit little CO_2. There is indeed an issue of embedded carbon in construction, but the embedded carbon factor per unit of electricity generated is very comparable between coal, nuclear nad renewables and is thus largely an irrelevant argument if the electricity has to be generated by one means or another. For hydro involving dams involving the creation of lakes as opposed ot run of river schemes, in addition to the embedded carbon in the dam/other infra structure, there is also the possibilitiy of green house gas emissions are the vegetation in the flooded area begins to rot.

For biomass there will be some emissions associated with harvesting and any fertilisers used. Furthermore, the carbon neutrality of biomass is only valid if the biomass is used sustainably. That is the amount sequestered by new growing biomass equals that emitted in energy generation. However, in a period of increasing biomass use there will be a consequential temporary increase in emissions. This last statement means that if we were to move rapidly to biomass use, carbon dioxide emissions would rise and then stabilise. In the short term there may be limited direct saving over using fossil fuels, although in the longer term there would be a saving. However, some evidence suggests that carbon dioxide saved earlier is to be be preferred to that saved later and if this is tru a rapid deployment of biomass should be avoided. Ideas for temporary sequestration such as using virgin wood in semi-durable products such as furniture and then ultimately consumed for energy after say 50 years need more consideration.

5. Improving end use conversion efficiency

There is scope for energy and carbon reduction by either:

- ***Improved appliance efficiency/technolog***
  Several opportunities occur hear including, the use of heat pumps localised combined heat and power, better control technoligies, improved appliance efficiency etc
  .
- ***Improved insulation and related method***
  Insulation levels in buildings can significantly reduce heat loss from buildings and consequently carbon emissions.

6. *Enhanced Energy Management and analysis*

Effective energy management is often overlooked and at UEA there have been several cases where savings in energy consumption of 50% have been achieved solely by effective energy management.

7. Awareness Raising

The user of energy in a building can enhance energy/carbon reduction if their awareness is raised and significant savings can be achieved.

The following sections of this and the other handouts for this module cover these separate aspects in more detail.

2. Low Carbon Energy CONVERSION Solutions

2.1 THE BASICS - Power Generation

The following is a summary of the introductory notes on Thermodynamics from NBS-LN01E. Whenever mechanical or electrical energy is generated using heat the efficiency is limited by the Carnot efficiency. This applies to all fossil fuel and nucleart power station. It alos applies to biomass and geothermal power stations. In conventional power stations, the fuel is burnt to raise steam which then turns a steam turbine and ultimately the generator.

Figure 2.1 schematically shows the situation in a typical power station.

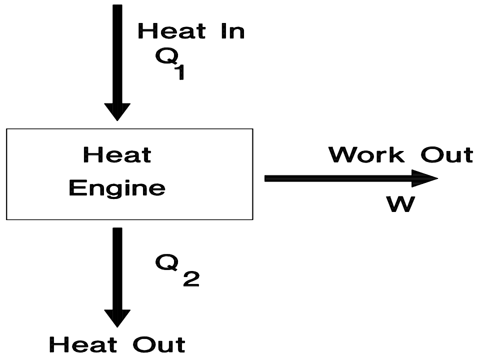


Fig. 2.1 A heat engine – see also Fig. 9.3 of NBS-LM01E

The Carnot Efficiency is given by:

$$\eta = \frac{Q_1 - Q_2}{Q_1} \qquad \text{…..2.1}$$

But the heat flows are proportional to Absolute Temperature and hence equation 2.1 is normally written as

$$\eta = \frac{T_1 - T_2}{T_1} \qquad \text{…………..2.2}$$

To improve the efficiency either T_1 must be increased or T_2 must be reduced. There is little scope for adjustment of T_2 as it represents near ambient temperature, but there are possibilities fro raising T_1. As T_2 is essentially comparable to the ambient temperature, power stations will have a lower efficiency in summer than in winter. The top temperature (T_1) is somewhat limited by the normal properties of steam to around 550 – 600°C and this limits the overall efficiency (see NBS-LM01E section 9 for an example).

It is possible to operate stations with super-critical steam – there are a few now operating in the world, and new generation coal will probably be of this type. This will increase the effective steam temperature to around 650 – 700°C and increase the overall power station efficiency (including all losses) from around 38% to around 42-43%.

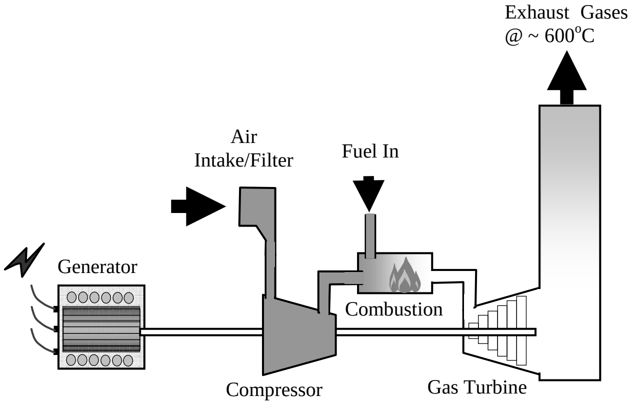


Fig. 2.2 Generation of electricity using a gas turbine.

Gas turbines (e.g. those used in aircraft, operate under much higher temperatures, but their exhaust temperatures are high, and so though they gain in efficiency by having high T_1 temperatures, they loose by having high T_2 temperatures. Figure 2.2 shows a schematic of paower generation using a gas turbine enegine

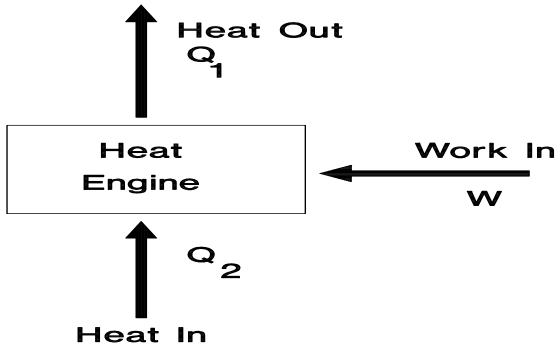
2.2 THE BASICS – Heat Pumps

Unlike power generation where there will always be low conversion efficiencies when we convert from Heat to Mechanical / Electircal Energy, a heat pump works as a reversed heat engine and in most cases efficiencies well in excess of 100% are possible and are typically 300 – 400+%.

Figure 2.3 shows a schematic of a heat pump (see also section 9.4 of NBS-LM01E).

In this case the efficiency or Coefficient of Performance as it is know is given by

$$\boldsymbol{COP = \frac{T_1}{T_1 - T_2}} \quad \ldots\ldots.2.3$$



Fi.g 2.3 A Reversed Heat Engine – heat pump – compare with Figure 2.1 and also section 9.4 of NBS-LM01E.

See section 5 for details of Heat Pumps.

3. COMBINED CYCLE GAS TURBINES

Conventional Fossil Fuel Power Stations (and also Nuclear stations) normally use steam as the working fluid irrespective of what the heat source is. Even though water has a very wide range of temperatures in which it is suitable for use as a working fluid, is plentiful, and non-toxic, problems do arise when pressures and temperatures are above the critical point. Although newer station may move into this supercritical region (see section 2). Consequently, these factors will limit the ultimate top temperature that can be achieved in steam stations, and this in turn will limit the maximum efficiency which can be achieved.

On the other hand, the temperatures normally found in such stations are well below the metallurgical limit, and there is potential for much improvement if a more suitable fluid could be found.

As indicated in section 2, open circuit Gas turbines (OCGT) are similar to those used in aircraft engines can exploit much higher input temperatures but have high exhgaust temperatures (e.g. those used in aircraft are inefficient typically having efficiencies of only 23%.

By using the waste heat from a gas turbine to raise steam in place of the normal boiler it is possible to greatly improve the efficiency, by utilising the high temperature performance of the Gas Turbine with the lower temperature performance of a traditional steam turbine. Typically efficiencies of 50% are now achievable, with the potential to improve this further over the next 20 years or so with improved gas turbine blade design. Indeed Great Yarmouth Power station can achieve 56% - the highest in the country. Such stations are known as combined cycle gas turbines (CCGT) and figured in the so-called dash for gas in the early 1990s.

In a typical Combined Cycle Gas Turbine Station (CCGT), there may be one, two or three gas turbines each with its own generator. The waste heat output from the gas turbines then raise steam for a single steam turbine. This is the configuration at some stations such as Deeside Power Station and are called ***multi-shaft machines.*** An alternative configuration has each gas turbine raising steam for a single Steam Turbine which is on a common shaft with a single generator. These are called ***single-shaft (or common shaft) machine***s (Figure 3.1)**.**

Advantages of CCGT's

The development of CCGT's only became possible with the relaxation of EC rules on the use of gas for electricity generation. In the UK this coincided with privatisation. In early 1991 there were no CCGT stations, currently there are nearly 25000 MW of capacity representing nearly 33% of our total generating capacity. This figure is likely to rise over the next decade to fill the gap left by the closure of our current nuclear stations and 50% of our coal fired stations. .

1) Until around 2004 gas was a cheap source of fuel and so has an inherent advantage over more costly coal. However, since that time we have been increasingly dependant on imports and subject to world prices in gas.

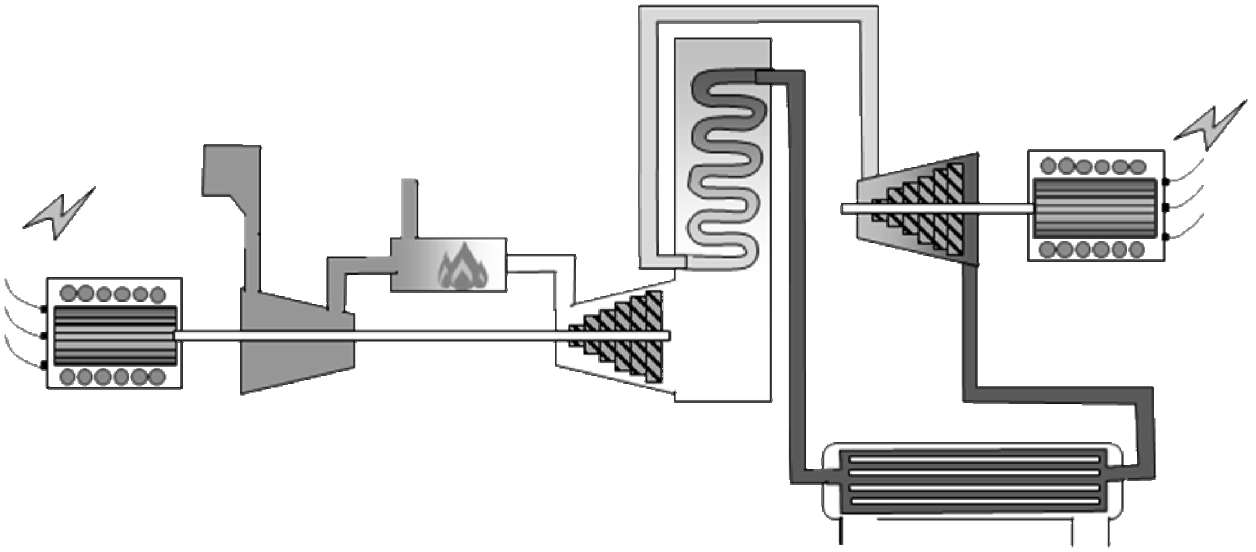


Figure 3.1. A multiple shaft CCGT – the Gas Turbine and Stean Turbine are on separate shafts each with its own generator. In some configurations there may be more than one gas turbine (each with a generator) and a single steam turbine. Compare this configuration with the single/common shaft configuration in Figure 3.2.

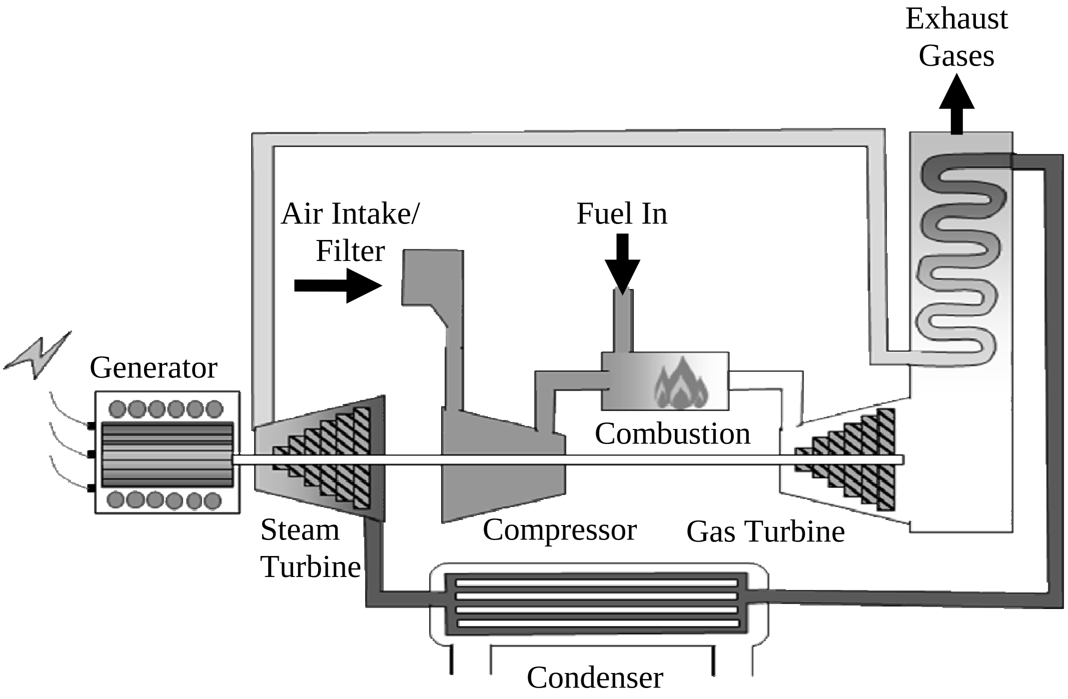


Figure 3.2. A single shaft CCGT – both Gas Turbine and Stean Turbine are on a common shaft which drives a single generator – compare this with the separate/multiple shaft configuration in Figure 3.1.

2) If gas were burnt in a conventional station to raise steam, then because of the chemistry of the fuel, only around 60% of emissions of CO_2 will take place. However, in the CCGT mode, the efficiency is much increased, and the emissions are much lower still - around 40% of that of coal for an equivalent output. Since 2005, electricity generating stations have had to have permits to emit carbon dioxide. In the first two phases of the EU Emission Trading System (EU-ETS), most permits were issued free although some had to be purchased at the market rate. Thus for the same electrical output only 40% of the permits were needed. Each station was given a basic allowance and had to purchase permits over an above this allowance. From 2012, all permits will have to be purchased. This will mean that 250% more permits will be needed for coal stations and this will make coal progressively more expensive.

3) There is minimal sulphur in gas, so SO_2 emissions are insignificant. Contrast this to coal where all operating coal stations post 2015 will require to be fitted with flue gas desulphurisation. However, because of the higher flame temperatures, NO_2 emission can be significantly higher unless the burners are designed correctly. Even then, much of the reduction comes from injecting steam into the flame, and unless the steam turbine is operating, emissions can be

quite high. This can be a particular problem on start up. Using multiple burners can often help.

4) As there is no coal handling plant, the station covers a much smaller area, and can be built much quicker.

5) The capital costs are also much cheaper, particularly as desulphurisation plants are not required.

6) The labour force is typically only 20 - 25% of that for a coal fired station, and hence the cost of generating electricity is reduced further

Disadvantages

1) Gas has a resource time which is less than coal. The UK was self sufficient in gas until 2004 and indeed was a net exporter. However since that time the UK has become increasing dependent on imported gas from Norway, Russia and the Middle East – see Fig. 3.3.

2) Some stations use to have an interuptible gas supply contract which means that they can be cut off at short notice. This nearly caused serious problems in 1996, when several stations were so affected (because of cold weather), just at the time of maximum electricity demand.

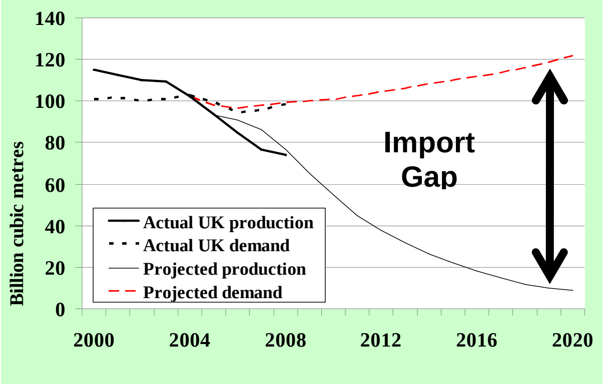
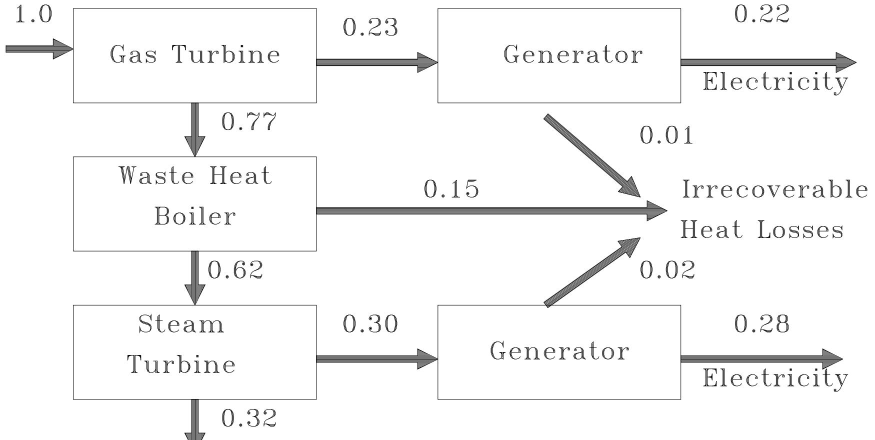


Figure 3.3 Gas Production and demand for UK showing increasing import gap.

3) NO_2 emission can be a problem (see above)

4) The year on year performance of the Gas Turbine Stations appears to decline. Conventional Steam Stations seem to improve in their output with age, but, with few exceptions CCGT stations, are often down rated each year by 1 - 2%. per annum.



Total Electricity Generated = 0.50
Station uses = 6% = 0.03
Net available electricity = 0.47

Fig. 3.4 Energy Flow diagram in a CCGT with a separate shaft for the two turbines. Some multi-shaft CCGT's may have 2 or 3 gas turbines feeding a single steam turbine.

EXAMPLE:-

This example relates to a first generation multi shaft machine – see Figure 3.4 for the energy flows..

Gas turbine inlet and outlet temperatures are 950^{o}C (= 1223K) and 550^{o}C (= 823K) respectively.
Corresponding steam temperatures are 500^{o}C (= 773K) and 30^{o}C (= 303K) respectively.

also efficiency of waste heat boiler is 80%, and isentropic efficiency of gas turbine is 70% and that of steam turbine is 80% (all other efficiencies are as in previous example). What is overall efficiency of station?

FIRST the efficiency of gas turbine is

(1223-823)/1223 x 0.7 = 23%

i.e. 1 unit of fuel produces 0.23 units of work and this gives 0.23 x 0.95 = 0.22 units of electricity (0.01 units are lost) and 0.77 units into waste heat boiler.

The waste heat boiler then provides 0.77 x 0.8 = 0.62 units of energy to steam turbine, and 0.15 units are lost to the flue.

The overall efficiency of the steam turbine is

(773-303)/773 = 61%

so allowing for isentropic efficiency,

0.62 x 0.61 x 0.8 = 0.30 units of work are provided which in turn generates 0.95 * 0.3 = 0.28 units of electricity, while 0.02 units are lost from the generator.

Finally, 0.32 units are rejected to the condenser (i.e. the difference between the energy into the steam turbine and the work out from it).

So total electricity generated is 0.22 + 0.28 = 0.50 units. but 6% of electricity is used on station itself, so overall efficiency:-

= 0.50 x 0.94 = **47%**
=====

There has been a trend to single shaft machines in recent years as these tend to be a little more efficient, and there are also capital cost savings. However, in the multiple shaft scheme, the gas turbine can be used alone, and this allows greater flexibility – i.e. the gas turbine oculd be used for peak lopping as the stand alone gas turbines have been in the past. With greater renewable, this might be an important advantage in the future.

Equally, the New Electricity trading Arrangements (NETA) and subsequently BETTA(covered in the Regulation Module in the Autumn) reward those generators which are flexible and there may be a market for multiple shaft systems for peak lopping.

4. COMBINED HEAT AND POWER (CHP)

4.1 Introduction

Heat is rejected when we generate electricity

By First Law:-

$$W = Q_1 - Q_2$$

and efficiency = $\eta = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1}$

Now suppose that we could utilise all of Q_2, then we could redefine our efficiency as:-

$$\eta = \frac{W + Q_2}{Q_1} = \frac{Q_1 - Q_2 + Q_2}{Q_1} = 1$$

i.e. we would have 100% efficiency.

We cannot achieve this in reality as 10% is lost through combustion, there are generator losses, and station uses of electricity, but suppose we could use 80% of Q_2 the overall efficiency of energy conversion in the power station would rise substantially.

The temperature of exhaust steam at 30°C is too low for practical purposes, but if we raise temperature to say 80 - 90°C, then useful heat is available at the expenses of reduced electrical output.

QUESTION:

> How much heat is rejected by the main electricity generators e.g. PowerGen, British Energy on a typical winter's day?

Say Mean Temp is 5.5°C (mid January average)

Neutral Temperature (balance temperature for most houses is about 15.5°C) so we need 10°C of heating for each house.

Typical Mean Electrical Power output in winter is 40GW.

Overall average efficiency is about 35%, so heat rejected in cooling tower is around 60 GW (and a further 20 GW is lost elsewhere).

QUESTION:

> If all of this 60 GW (= 6 x 10^{10}W) were used, what proportion of our homes could be heated?

A typical heat loss rate for a house is 300 W°C^{-1} so with a 10°C temperature difference this is 3000 W

There are about 20 million households in Britain so percentage supplied from waste heat

$$= \frac{3000 \text{ x } 20 \text{ x } 10^6}{6 \text{ x } 10^{10}} \text{ x } 100 = 100\%!!!$$

i.e. all our homes could be heated without need for gas boilers or other forms of heating. Nor would anyone have to suffer from hypothermia. AND THAT IS EVEN WITH THE RELATIVELY POOR STANDARD OF INSULATION OF MOST OF OUR HOUSES.

- In a power station, for every unit of fuel entering approximately 0.10 - 0.15 units are lost to the stack, are used as electricity in the station itself or are generator losses which cannot be recovered.
- Of the remaining 80+% all the energy is potentially recoverable, but the emphasis until changes in the Electricity Act in the mid 1980's was on efficiency of electricity production.

Two cases (assume 80% of original energy available):-

Both have Inlet steam temperature @ 566°C e.g. DRAX etc.

exhaust temperature 30°C
exhaust temperature 100°C

Case 1: $\eta = \frac{536}{(566 + 273)} = 63.9\%$

Case 2: $$\eta = \frac{466}{(566+273)} = 55.5\%$$

Case 1: 0.8 * 0.639 * 0.75 = 0.38 units of electricity generated (0.75 is isentropic efficiency)
i.e. about 0.42 units of heat available at 30^{o}C
i.e. heat not that useful

Case 2: 0.8 * 0.555 * 0.75 = 0.33 units of electricity and 0.47 units of heat at ~ 100^{o}C
- heat at useful temperature

4.2 Types of CHP

1) back-pressure (BP) steam turbine
2) ITOC steam turbine (intermediate take off and condensing)
3) Open Circuit Gas turbine with WHB (Waste Heat Boiler)
4) CCGT with CHP - various combinations possible using WHB bypass with or without ITOC or BP steam turbines

- Some industries use multiple CHP systems
- A problem with all CHP is the matching of heat and electrical loads.
- For CHP there must always be a heat load.
- Can cause a problems if there is a major variation between summer and winter.

4.3 BACK-PRESSURE SYSTEMS.

A back pressure configuration for a steam turbine is shown in figure 4.1. Of note is the fact that ALL the steam is exhausted to the heat exchanger. In all cases the exhaust temperature will be higher than that for a normal steam turbine – e.g. 70 – 90^{o}C for a district heating scheme compared to ~30% for normal condensing operation. As a consequence and referring to equation 2.2, the efficiency of electricity generation will be noticeably LESS than normal operation, but as heat can be used usefully, the overall conversion efficiency will be higher.

- All of the steam is passed directly to a heat exchanger operating at about 100^{o}C for district heating purposes.
- There is no need for a condenser or cooling towers.

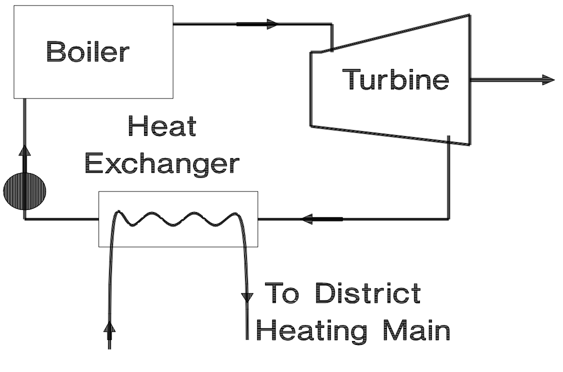


Fig. 4.1 Back Pressure Turbine

- However there must always be a heat load when electricity is to be generated. If this is only used for district heating there is a major problem when heat load is low in summer.
- Ideal for industry with large base heat load requirement.
- Schemes tend to design plant to deal with minimum heat load and use traditional boilers to meet peak demand. In domestic situations, the summer time demand for hot water is about 20% or less of total winter demand for heating and hot water. This approach for domestic CHP will only lead to small overall savings.
- Generally cheaper to install or convert than ITOC configuration.

4.4 ITOC TURBINES

Intermediate take off and condensing turbines retain the normal condensing operation of conventional turbines but also have a valve which can be set to divert a proportion of the heat directly to the condenser. A typical configuration is shown in Figure 4.2.

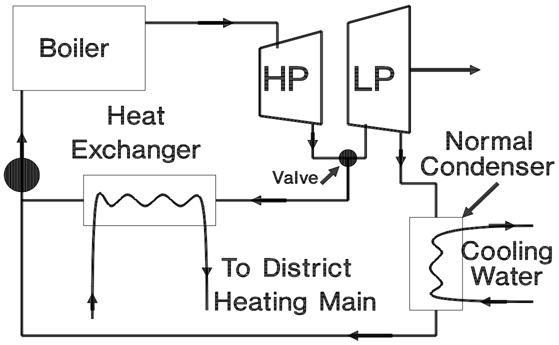


Fig. 4.2 ITOC Turbine Arrangement

- Disadvantage:- More complex hence more costly
- Can generate full amount of electricity in normal mode even when there is no heat load.

- Using temporary heat store (say 12 hour store), the heat output could be bypassed at times of peak electricity demand. Generator is already synchronised so additional electrical output could be brought on line in period of minutes.
- Can readily vary from 100% electrical to about 70% electrical and heat output equal to about 1.5 electrical.
- Below this amount of electrical output, heat output is also reduced because amount of steam in HP section of turbine has to be reduced.
- The additional flexibility provided by ITOC is never accounted. i.e. there is an external benefit in a reduced need for pumped storage capability.

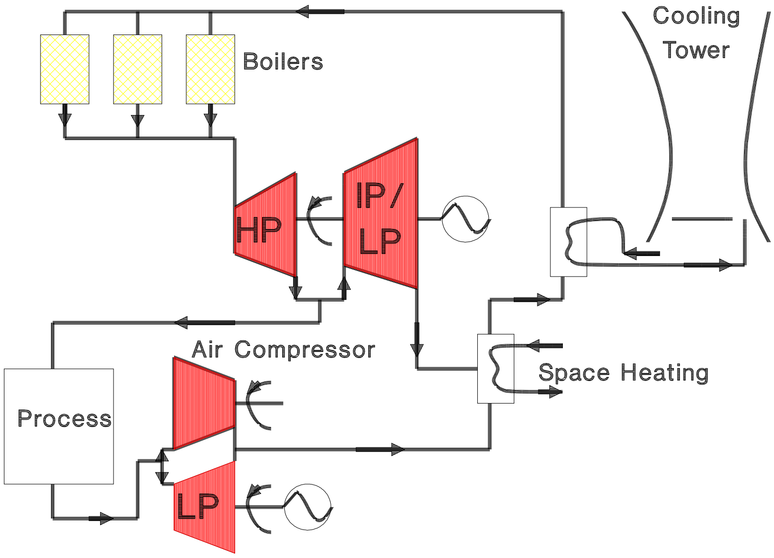


Fig. 4.3 Integrated CHP plant at former ICI Plant at Wallerscote

- An integrated CHP which was used at the ICI Wallerscote Soda Ash Plant until it closed in mid 1980's is shown in Figure 4.3
- Steam at high pressure and temperature - generated in boilers and passed through HP turbine so temperature was reduced to that required for process steam.
- 50-70% of steam was diverted for process steam (depending on demand), remainder passed through a two stage IP/LP turbine. The exhaust steam from the PROCESS was split, 50% went to drive air compressors; the remainder was used in a low pressure turbine to generate more electricity.
- Exhaust from both steam turbines heated water for space heating of offices - the remainder was rejected in cooling tower. ICI offered waste heat to Local Authority in late 1960's but Local Authority were not interested (or lacked capital) to install district Heating), so remainder was rejected in cooling tower.
- Plant was run with an eye to price of electricity.
  - Sometimes exporting - sometimes importing.

4.5 Small Scale CHP.

Unlike some countries, particularly Denmark and Russia, the UK does not have any city wide CHP schemes providing heating for domestic properties. On the other hand there are a number of small scale schems, some individual buildings and some complete sites e.g. UEA which are in operation. There are also tests under way on microchip plant.

All small scale schemes use either a diesel or gas engine as the prime mover. Heat is provided from three sources.

- The lubrication opil cooler
- Cooling water from the jacket (similar to the cooling of a car engine,
- Exhaust gases.

Some reciprocating CHP plant are as large as 30 MW, but usually much smaller – e.g. UEA has three 1 MW machines.

An advantage of a small scheme is that electricity generated is used locally and thus avoids the 8.2% (UK figure in 2006) oss from transmission and distribution losses normally associated with electricity supply. In some countries losses are much higher – e.g. in Libya and India the losses exceed 25%

4.6 A large scheme with Gas Turbine

- Until 2002, Norwich had a Main Gas Turbine (so-called JET) Station at Thorpe – which was on the left hand side of the railway just before the bridge across the River Wensum. There were two 55 MW open circuit gas turbines (OCGT) – see section 2. Figure 4.4 shows a schematic of the plant which was used for peak lopping during times of high demand.

Inlet temperature is	~ 1100°C
Exhaust Temperature is	~ 650°C
Isentropic Efficiency	~ 70%

Such a plant could be used as part of a CHP plant.

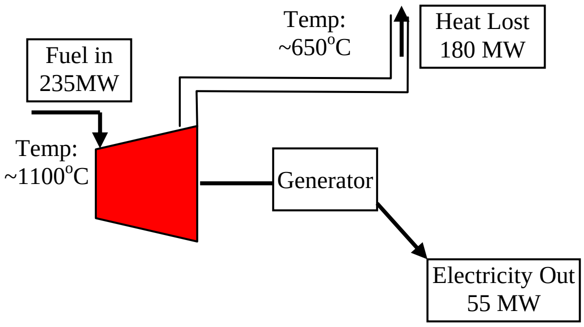


Fig. 4.4 Open Circuit Gas turbine used at Norwich JET Station where there were a x 55 MW units.

Overall efficiency of the gas turbine assuming :

$$= \eta_{isen} x \frac{T_1 - T_2}{T_1} . \eta_{generator} \quad = \mathbf{23\%}$$

$$= 0.75 . \frac{(1100-650)}{(1100+273)} .0.95 \quad = 23.4\%$$

assuming the isentoropic efficiency is 75%
and
the generator efficiency is 95%

The Fuel in = 55 / 0.234 = **235 MW**
Electricity out = **55 MW** for each unit
Heat rejected = 235 – 55 = **180 MW**

OCGT with Waste Heat Recovery

The most straightforward system to utilise the waster heat rleased in electricity generation from a gas turbine is shown in Figure 4.5 where an open circuit gas turbine is combined with a Waste Heat Recovery Boiler.

The Waste Heat boiler is designed to heat water from the heating main to about 100^{O}C, but since the exhaust temperature from Gas Turbine is about 650^{O}C, the efficiency will not exceed about 75% as used in this configuration,.

i.e. about 75% of the rejected heat can be useful used i.e. 0.75*180 = 135 MW. The overall efficiency in energy conversion is now:-

$$\eta = \frac{55+135}{235} = 80.8\%$$

- In this configuration, the WHB could be bypassed so that electricity generation was possible in normal OCGT mode. Alternatively any efficiency between 23% and 80% would be achievable by appropriate control of valves in exhaust stream.

NOTE: though the Power Station has now been demolished, it is the site of the proposed Norwich Powerhouse Project using biomass gasification and CHP.

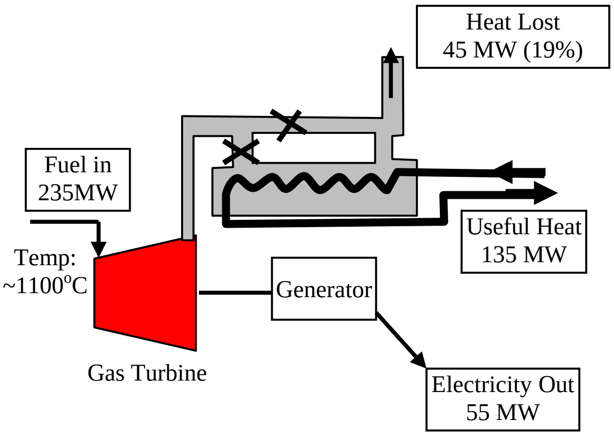


Fig. 4.5 OCGT with Waste Heat Recovery

4.7 COMBINED CYCLE GAS TURBINE with CHP

As well as OGCT configuration it is also possible to combine CHP with a Combined Cycle Gas turbine as shown in Figure 4.6

There are several options possible:-
a) with back-pressure steam turbine (as shown in Fig. 4.6)
b) with an ITOC steam turbine
c) as (a) but with parallel WHB for direct heating of hot water
d) as (b) but with parallel WHB for direct heating of hot water

Using the example shown in Figure 4.6:-

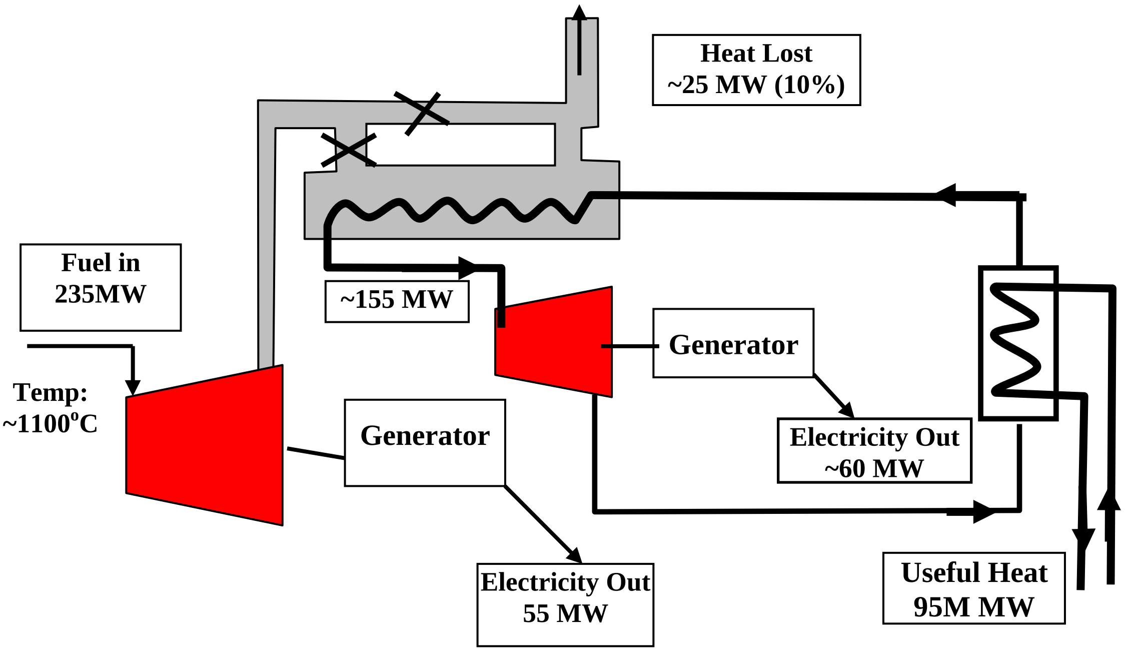


Fig. 4.6 Combined Cycle Gas Turbine with CHP

- The gas is exhausted from the Gas Turbine at ~ 650^{O}C, and passed through a steam generating boiler which raises steam to about 550^{O}C. About 10% of original energy is still lost to stack in this steam generator (i.e. approximately 25 MW). Hence there is about 155MW of supply to steam turbine.

- The exhaust temperature from steam turbine is 100^{O}C to give adequate heating for mains so efficiency of steam turbine is:-

- $$\eta = \frac{(550+273)-(100+273)}{(550+273)} \text{ X } 0.75 \text{ X } 0.95 = 39\%$$

i.e. 155 *0.39 MW of electricity are produced (=~60 MW) by the steam turbo-generator and 0.61*155 MW of heat are available for district heating (i.e. 95MW).

The overall useful energy converted will be 55+60 MW electrical + 95 MW. Heat giving a total of 210MW.

This gives an overall efficiency of:

210/235 = **89.3%**

- i.e. somewhat better than the simple case of a simple waste heat boiler as indicated in the previous example.

- The overall efficiency for such a configuration is usually in excess of 80 – 90% see section 4.11 for a more detailed worked example.

The overall benefits may be compared to the equivalent of not using CHP. In such a conventional scheme we would have to generate electricity 60+55MW =115MW of electricity by conventional means and and provide 95MW heat from say a condensing boiler.

It is convenient to examine the energy flows of an alternative system using a SANKEY Diagram (Fig. 4.7). We shall assume that electricity generation is via a coal fired power station with an overall efficiency of 37% and a further 3% transmission loss giving an overall delivered energy efficiency of 34%. Thus to provide 115 MW of electricity it would be necessary to consume 115/0.34 = 338MW coal. Further to provide 95MW of heat in a condensing boiler we would have to consumed 95/0.9 = 106MW gas giving an overall energy consumption of gas and coal of 444MW as opposed to 235MW in the example given. Thus the CCGT/CHP configuration would save 47%.

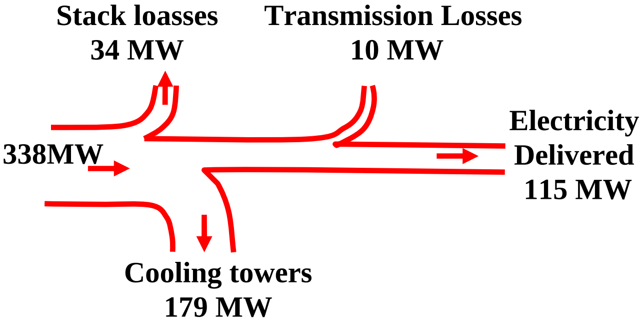


Fig. 4.7a Sankey Diagram for Electricity Generation

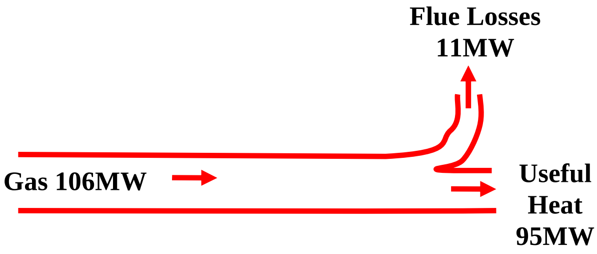


Fig. 4.7b Sankey Diagram for heat provision from a condensing gas boiler.

Thus compared to the individual situations shown in the Sankey Diagrams.the CCGT/CHP configuration would save

(444-235)/444 = 47%

If the boiler had been a non-co0ndensing one then the gas input would have been 136MW and flue losses 41MW. In this case the total energy demand would now be 474MW and the saving through using CHP would be **50.4%.**

4.9 Developments in CHP

Unlike many other countries, the apporach in the UK in the last decade has been towards smaller scale CHP units based on a small community. Such schemes include

- Blocks of Flats e.g. Norwich Mile Cross [see http:/www.chpa.co.uk/norwich.pdf]
- Hostpitals
- Universities etc see http://www2.env.uea.ac.uk/gmmc/energy/env-m558/muen.2006.159.4.pdf

Such schemes are almost all based on diesel or gas engines as the prime mover.

The heat recovered comes from three separate sources
- lubrication oil cooling
- jacket cooling
- exhaust gas heat recovery

4.10 Two Worked examples

4.10.1 CHP with CCGT - a worked example

It is vital is that you understand exactly what is going on and it is helpful to make a flow diagram similar to Fig. 4.8) to ensure that you account for all the losses. Relevant data for the scheme are shown in Table 4.1.

There are 2 thermodynamic efficiencies to evaluate, one for the steam turbine, and the other for the gas turbine.

First work out efficiencies of two turbines using formula:-

$$\mathbf{efficiency} = \frac{\mathbf{T_1 - T_2}}{\mathbf{T_1}} * \mathbf{isentropic\ efficiency}$$

$$\text{gas turbine} \quad \frac{(1400)-(933)}{(1400)} * 0.75 = 0.25$$

$$\text{steam turbine} \quad \frac{(850)-(368)}{(850)} * 0.75 = 0.425$$

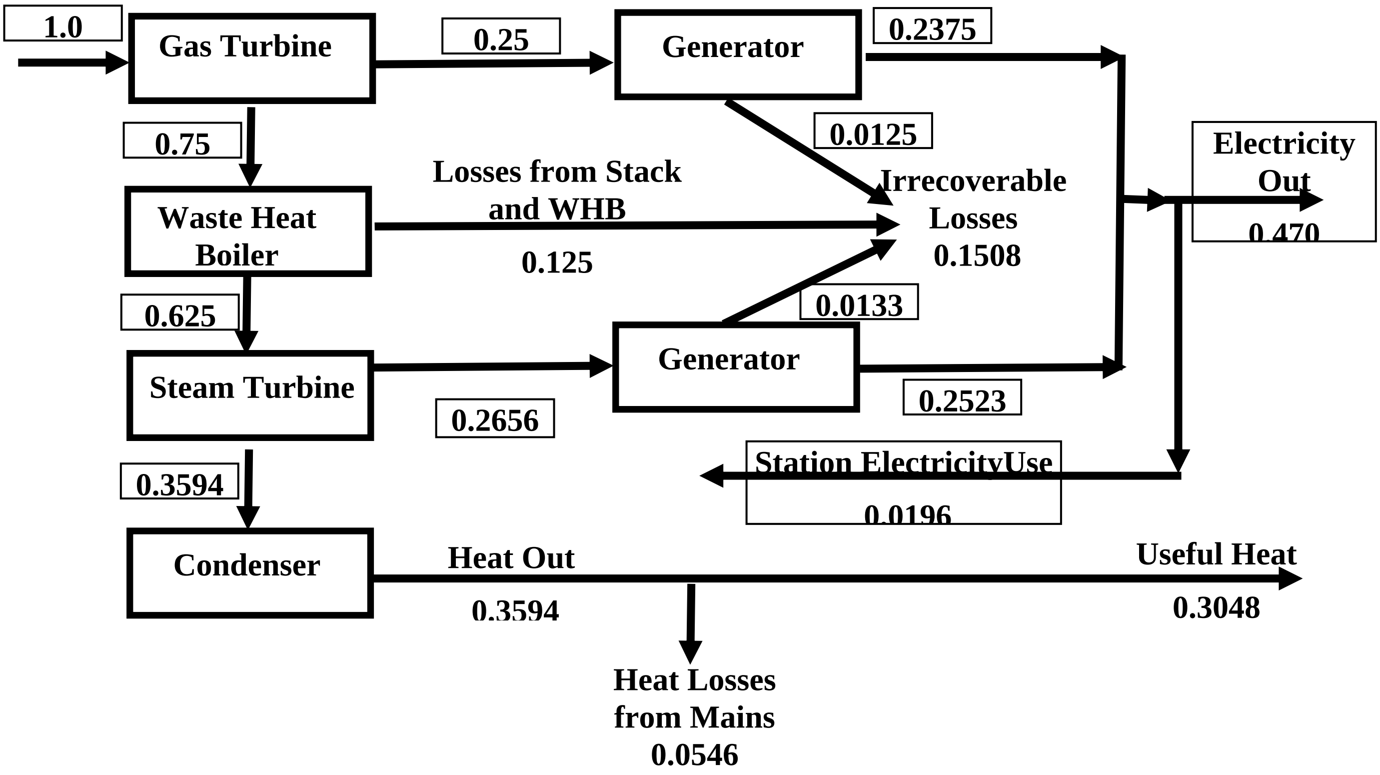


Fig. 4.8 Flow diagram for a CCGT Station with CHP

Table 4.1

	Temperature	Temperature (K)
Inlet temperature to gas turbine	1127 ^{O}C	1400
Exhaust temperature from gas turbine	660 ^{O}C	933
Inlet temperature to steam turbine	577 ^{O}C	850
Condenser temperature	95 ^{O}C	368
Combustion losses	7.0%	
Isentropic efficiency of both turbines	75.0%	
Generator efficiencies	95.0%	
Station use of electricity	4.0%	
Distribution losses on heating mains	15.2%	

- 1 unit of fuel in provides 0.25 units of mechnical power and 0.75 units to the Waste Heat Boiler. Of this latter, 0.125 units are lost through the chimney and radiation form the boiler with 0.625 units goin to the steam turbine.

- Of the 0.25 units of mechnical power to the generator, 0.2375 becomes electrical energy and the remaining 0.0125 are losses in the generator.

- Of the 0.75 untis to the WHB, 0.625 units eventually enters the steam, where 0.2656 become mechanical power and the remainder (i.e. 0.3594 units) are rejected to the CHP heat exchanger. Generator losses once again mean that the 0.2656 units reduce to 0.2523 units.

- Of the total of 0.4898 units of electricity, 4% is used in the station meaning 0.470 units are sent out

- There are 0.3599 units of heat available and so the total energy sent out from the station will be 0.3599+ 0.470 = 0.83 units. Thus the overall efficiency of the power station is 83.9%

- However, 15.2% of heat is lost through the distribution mains, and this the overall scheme efficiency will be 47 (from electricity) plus 0.848* 0.3594 = **77.5%**

4.10.2 A small scale CHP scheme

Sizing a CHP correctly depends on many factors.

- Heat Demand in Winter
- Heat Demand in Summer
- Electricity Demand in Winter
- Electricity Demand in Summer

There are WEB pages giving details of a scheme from Strathclyde

- Heat Profiles http://freespace.virgin.net/edward.guerra/Chp/uniheat.html
- Electricity Profiles http://freespace.virgin.net/edward.guerra/Chp/unielec.tml

It appears that these demands are rather less than at UEA but are probably similar. in shape

In sizing a CHP, a key aspect is the disposal of Waste Heat, and this may determine the optimum size of plant. It is possible to dump heat using fans as is done at UEA during the summer, but this uses energy, and there is clearly an optimum strategy to be adopted

The following is an approximate way to size a CHP scheme

The scheme involves six 1 MW CHP units to partly supply energy needs at an existing light industrial park currently heated by a district heating scheme fired by gas boilers with an efficiency of 80%..

Provision in the CHP units is made to dump surplus heat in summer up to a maximum of 2800 kW, however, when these are in operation they consume electricity at a rate given by 28.57% of heat rejected.

The following table shows the current Electricity Demand on a monthly basis

TABLE 4.2 Temperature and Electricity Demand

Month	Mean Temperature (^{o}C)	mean Electricity Demand (kW)
1	1.9	7800
2	4.5	7200
3	9	6800
4	12	6250
5	14	5800
6	16	5200
7	17	4800
8	16	4800
9	13	5200
10	11	6200
11	9	6800
12	4.1	7800

Estimate :

a) the proportions of the electricity and heat demand likely to be provided by the CHP units.

b) the overall proportional saving in primary energy from using the CHP units.

The overall primary energy ratios for gas and electricity are 1.06 and 2.90 respectively, while the neutral (balance) temperature is 15.5^{o}C. Hot water and process heat requirements are a steady thoughout year at 4 MW

For an approximate estimate it makes sense to assume that each month has an equal number of days = 30 days.

The best way to solve this is in tabular form shown below

In column 3 the heat required is worked out from the Temperature difference from the neutral temperature and the heat loss rate (1000 kW ^{o}C^{-1}) - remembering of course that when the actual temperature exceeds the balance temperature there is no requirement for space heating.

i.e. for month 1, the value = (15.5 - 1.9) * 1000 = 13600 kW

In colum 4 the base load heat of 4000 kW for hot water and process heat is added

Column 5 is a repeat of the data for the electricity demand, while **column 6** gives the heat available from the CHP untis. The heat output is 1.4 times that of electricity. If the total electricity demand exceed the generating capacity (i.e. 6000 kW, the the heat available from CHP will be 6000 x 1.4 = 8400 kW. If the electricity demand is less than 6000 then the heat available will be the actual electricity demand x 1.4. Thus for January - April and October - December, the CHP output will be constant at 8400 kW thermal (6000 kW electrical), but in the other months the available heat will be less.

In the summer months, the heat rejected is actually more than requried, and so **column [7]** is a revision of the heat supplied such that it equals the CHP output if the demand exceeds the CHP output i.e. during January – Mar and October to December but euqals the demand if the demand is less than the CHP output (i.e. the other months).

Table 4.3 First stage of analysis of performance of CHP plant

Month	Temp (^{o}C)	Space Heat Demand (kW)	Total Heat Demand (kW)	Electricity (kW)	CHP Heat available (kw)	Useful CHP Heat (kW)				
[1]	[2]	[3]	[4]	[5]	[6]	[7]				
Jan	1.9	13600	17600	7800	8400	8400				
Feb	4.5	11000	15000	7200	8400	8400				
Mar	9	6500	10500	6800	8400	8400				
April	12	3500	7500	6250	8400	7500				
May	14	1500	5500	5800	8120	5500				
June	16		4000	5200	7280	4000				
July	17		4000	4800	6720	4000				
Aug	16		4000	4800	6720	4000				
September	13	2500	6500	5200	7280	6500				
October	11	4500	8500	6200	8400	8400				
November	9	6500	10500	6800	8400	8400				
December	4.1	11400	15400	7800	8400	8400				

Column [8] is the supplementary heat requirement. Thus in the summer months no additional heat is required, but additional heat from the boilers is needed during the winter.

Whenever the CHP heat output is restricted (as it is in the summer months), then the electricity output will also be restricted and will be the heat output as determined by **column [7] divided by 1.4.** These values are shown in **column [9]**

Finally, the supplementary electricity required from the grid can be determined as **column [10] = column [5] - column [9]**

For simplicity in this example, it is assumed that all months have and equal number of days at 30 days or 720 hours. The totals are thus the annual energy requirements in each column (expressed in GWh).

Table 4.4 Final Stage of assessment of performance of CHP

Month	Temp.	Space Heat Demand (kW)	Total Heat Demand (kW)	Electricity (kW)	CHP Heat available (kw)	Useful CHP Heat (kW)	Supplementary Heat Needed (kW)	actual electricity that can be generated	Supplementary Electricity Needed
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8] = [4] – [7]	[9]	[10]
Jan	1.9	13600	17600	7800	8400	8400	9200	6000	1800
Feb	4.5	11000	15000	7200	8400	8400	6600	6000	1200
Mar	9	6500	10500	6800	8400	8400	2100	6000	800
April	12	3500	7500	6250	8400	7500		5357***	893
May	14	1500	5500	5800	8120	5500		3929***	1871
June	16	0	4000	5200	7280	4000		2857***	2343
July	17	0	4000	4800	6720	4000		2857***	1943
Aug	16	0	4000	4800	6720	4000		2857***	1943
September	13	2500	6500	5200	7280	6500		4643***	557
October	11	4500	8500	6200	8400	8400	100	6000	200
November	9	6500	10500	6800	8400	8400	2100	6000	800
December	4.1	11400	15400	7800	8400	8400	7000	6000	1800
			GWh	**GWh**	**GWh**	**GWh**	**GWh**	**GWh**	**GWh**
TOTALS			**78.48**	**53.75**	**68.34**	**58.97**	**19.51**	**42.12**	**11.63**

*** output restricted because of amount of heat to be rejected. - example assumes that heat dump is not used

Once the totals are available it is easy to compute the total Energy requirements both with and without CHP and to determine the effective saving in primary energy. The following data are assumed in the example:

Table 4.5 Efficiencies and Primary Energy Ratios.

Primary energy ratio: gas	1.06	efficiency boilers	85%
Primary Energy Ratio: electricity	2.90	overall CHP efficiency	81%

Table 4.6 Situation before installation of CHP

	Total demand	efficiency	PER	Primary Energy
	(GWh)			(GWh)
Heating – from column 4	78.48	0.85	1.06	97.87
Electricity from column 5	53.75	1	2.9	155.88
				253.74

Table 4.7 Situation after installation of CHP

	Total demand	efficiency	PER	Primary Energy
	(GWh)			(GWh)
CHP heating	58.97			
CHP electicity	42.12			
total CHP	101.09	0.81	1.06	132.29
supplementary heating	19.51	0.85	1.06	24.33
Supplementary electricity	11.63	1	2.9	33.73
				190.35

There is thus a saving in ***primary energy*** of 253.74 – 190.35 = **63.39 GWh or 25%**

Fig. 4.9 below illustrates the contribution of space and hot water heating provided by the CHP units while Fig. 12.10 shows the corresponding electricity demand, supply and import. Notice that the import of electricity is bimodal with a peak in both winter and summer. This is a reflection of the constraint in output imposed by the lack of a heat dump in the summer

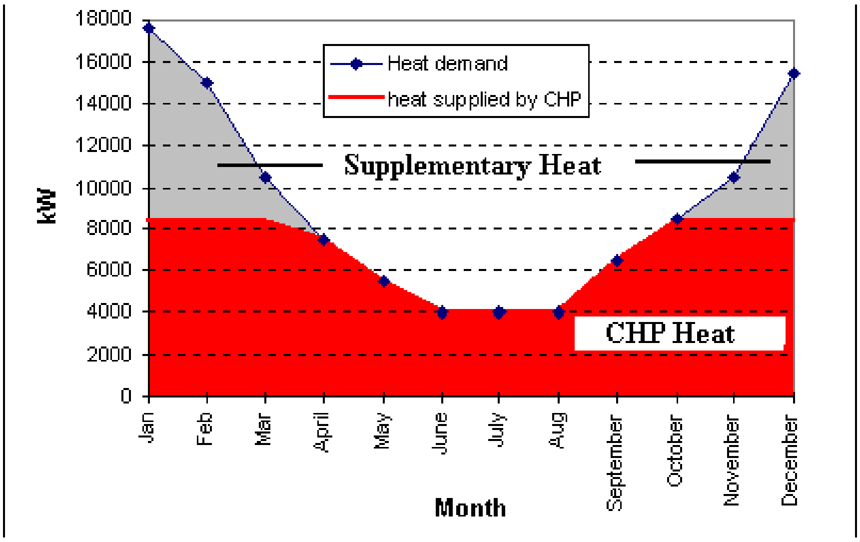


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Fig. 4.9 Heat Profile over the year – the supplementary heat would be provided by standard boilers.

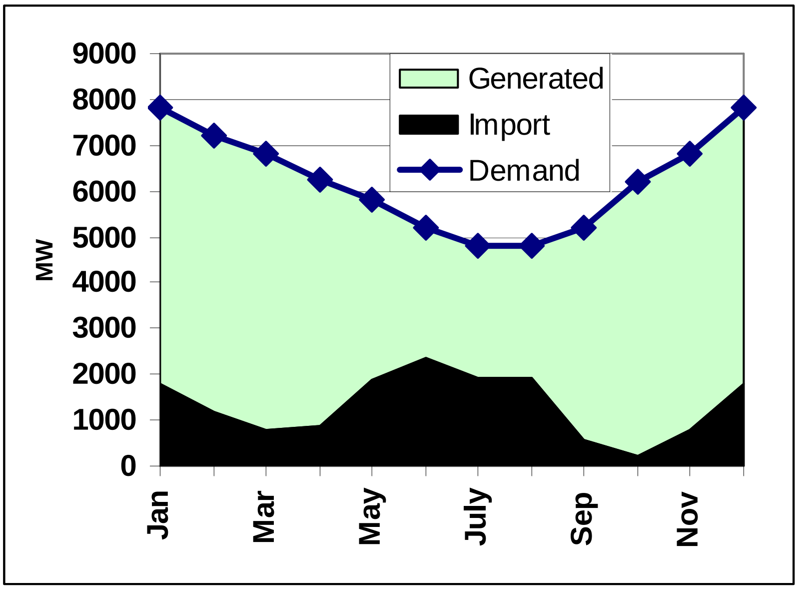

Fig. 4.10 Electricity Demand throughout the year – note the electricity imports (supplementary electricity) is highest when demand is lowest.

Most CHP units of the type indicated have provision for a heat dump of limited capacity, for instance there may be scope for up to about 2800 kW heat dump for a scheme of the scheme illustrated. However, whenever the fans for the heat dump are in operation, they consume not insignificant quantities of electricity. If we include this heat dump then all months except June can produce sufficient electricity for the demand, however, we may still have to import to cope with the demand for the fans.

In June, the basic heat demand is 4000 kW, and if the maximum heat dump is indeed 2800, then the maximum heat that can be rejected is 6800kW and is less than that required for the generation of 5200 kW of electricity, and so the electricity generation will still be constrained in this month.

The difference between using the local heat dump and hence boosting electicity generated on site or importing electricity in summer can often be quite small in primary energy terms (according to the electricity mix at present). What is clearly saved is the transmission losses, but CCGT's potentially could be more efficient overall.

Normally the heat dump fans can be used for short transients, but the decision on whether to generate the extra energy needed for the fans is usually based on economic reasons rather than environmental or resource reasons.

4.10.3 Effective carbon emission factor for electricity in an organisation where there is CHP.

Assuming the configuration and values estimated in the example in section 4.10.2, it is possible to estimate the effective carbon emission factor for all electricity used on site. The key information from Table 4.4 is summarised in Table 4.8

Table 4.8 Computation of overall effective carbon emission factor for electricity.

	Demand	Efficiency	Gross Demand	Carbon Emission Factor	Tonnes CO_2 emitted
CHP electricity	42.12	0.81	52.00	186	9672
CHP heat	58.97	0.81	72.80	186	
CHP electricity and heat	101.09	0.81	124.80	186	
supplementary heat	19.51	0.85	22.95	186	
supplementary Grid electricity	11.63	Not applicable	11.63	544	6327
Total for electricity			63.63		15999

The emission factor will clearly be loess than that of the Grid Electricity. 42.12 GWh of electricity is generated by the CHP plant and a further 11.63 GWh is imported from the grid giving a total of 63.63 GWh consumed. The efficiency of the CHP plant is 81% and assume this is agttributed to both heating and electricity, the CHP generated electricity would require 52.0GWh to gas to be consumed. The emission factor for gas is 0.186kg/kWh or 186 tonnes/GWh. The grid electricity carbon factor varies but is around 0.540 kg/kWh (540 tonnes/GWh). Thus the CHP electricity will be associated with 9672 tonnes of CO_2 – see line 1 of table 4.8 while the grid electricity will emit 6327 tonnes giving a total emission of 15999 tonnes. This means that the average emission factor is 15999/63.63 or 250.7 tonnes so the effective carbon emission factor for electricity used on site will be 0.2507 kg/kWh or 46.4% of normal grid electricity

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4.11 SUMMARY POINTS

- Moderate development of CHP in industry
- Almost no development of CHP on town-sized schemes in UK
- UK has largest number of small sized CHP units in Europe (e.g. for single building - hospital etc.).
- Most City wide schemes in Europe were developed in 50s and 60s - cheap fossil fuel deterred development in UK Some European countries have as much as 10-15% CHP on city wide schemes.
- Lack of co-ordinating energy body in UK (e.g. Local Authority) most significant drawback. Also competition from Gas and Electricity Utilities not healthy for spread of CHP
- Often argued that heat density in UK is too low - compared with higher proportion of flat dwellers in Europe but schemes in Europe with low housing densities have been included in networks.
- Argued that it is not cold enough in UK - Completely misses point, that this IMPROVES the economics as the load factor is higher because less extremes of temperature.
- Will require temporary disruption to streets, but a scheme for Norwich could provide employment for 200 people for 10 years.
- Until 2001, the UK saw substantial increase in smaller scale CHP schemes in last decade and was reputed to be a world leader in terms of deployment of this types of facility. However, the introduction of the NEW ELECTRICITY TRADING ARRANGEMENTS (NETA) on 27th March 2001 and the subsequent British Electricity Transmission and Trading \Arrangements (BETTA) on 1st April 2005 made such schemes less financially viable although in recent years there has been renewed interest including at the micro CHP level.
- There is scope for improving the performance by using adsoprtion chilling (see section 5.13), and this is planend at UEA

5. Heat Recovery Systems and Heat Pumps

5.1 Heat Recovery

There are many instances where heat can be recovered particularly in industrial applications, although there are also situations where this can be used effectively in newer domestic situations. Three good examples are Constable Terrace, Nelson Court, and the Elizabeth Fry Building and the Medical School and ZICER.

Often physical or biological constraints prevent a direct re-use of energy. Thus air in a building will become increasingly humid, and there will be a build up of carbon dioxide, not to mention smells. It is for health reasons that we need an adequate ventilation rate which in some buildings may have to be as high as 5 - 10 air-changes per hour. Since a significant part of heating a building is for heating the air, this can represent a substantive loss. On the other hand, if the stale air can be used to heat fresh incoming air without mixing with it, significant improvements in energy use can be achieved and high ventilation rates can still be maintained.

However, in most building relying on natural ventilation, it is not possible to recover heat in this way as the buildings are design for the air to seep out through the building itself, and

through gaps in windows as well as from intervention by occupants entering and leaving buildings and also opening windows.

5.2 Types of Heat Recovery

There are many heat recovery systems, and a few different examples will be selected as illustrative of the wide range of possibilities. The first represents the double fluid flow systems where stale fluid pass though a space while incoming fluid passes either in tubes within that space. in the surrounding space. There are two types - the shell and tube exchanger, such as used in a condenser in a power station or heat pump, or the parallel plate system which was used at the Southampton Geothermal station (and also on the roof of Constable Terrace and Nelson Court). The second type of heat recovery system involves the stale fluid passing through a space which it heats up for several minutes. After a present time, the stale air is diverted through a similar parallel space while the incoming fluid is heated from the residual heat previously heated by the outgoing fluid. After a similar interval of time, the system switches over again. Examples of this are the Pilkington Float Glass Works at Green Gates, seen on the 1997 Field Course), and the heat exchangers in the Elizabeth Fry Building, the Medical School and ZICER.

5.3 First Type of Heat Recovery System

This type include both Shell and tube (Fig. 5.1) and parallel plate heat exchangers (Fig. 5.2). The Shell and Tube heat exchangers should use contra-flowing fluids for optimum efficiency (Fig. 5.4).

In the typical shell and tube condenser, the cooling water in a power station passes through numerous small tubes within a large tube in which the exhaust steam from the turbine is condensed. In the alternative type, or parallel plate exchanger, the fluids flow at right angles to each other through rectangular channels. The thickness of the channels is small to optimise the heat transfer surface.

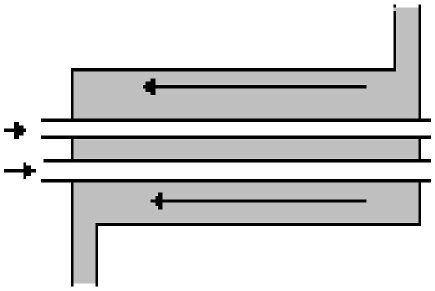


Fig. 5.1 A shell and tube Heat Exchanger

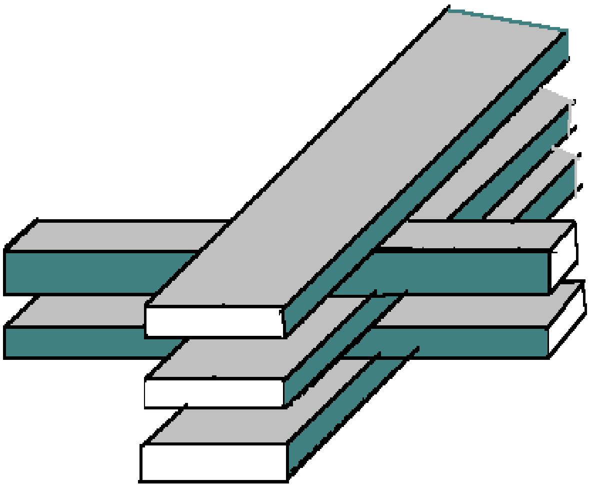


Fig. 5.2 A parallel plate heat exchanger.

Stale fluid flows through a series of rectangular ducts which are usually at right angles to rectangular ducts containing fresh fluid. Examples of this type of Heat Exchanger include Constable Terrace and Nelson Court, and the geothermal station at Southampton. In the latter, heat from the geothermal acquifer which is highly saline exchanges heat with the working fluid.

In the Shell and Tube type it is important to ensure that the fluids flow in a contra-flow manner. This is illustrated in Fig. 5.3 and 5.4. In Fig. 5.3, the fluids are shown flowing parallel to one another. The graph shows the temperature of the two fluids. The stale fluid has a relatively high temperature and this falls linearly through the exchanger. At the same time, the incoming fresh fluid start off cool and its temperature rises.

At the exit, the incoming fluid will always be slightly less in temperature than the final exhaust temperature of the exhaust fluid (the larger the contact area, the smaller will be this temperature difference). At very best the temperature of the incoming fluid will be the average temperature of the two incoming fluids.

The main reason for this is the large uncontrolled temperature gradient at the start, which from thermodynamics is inherently inefficient

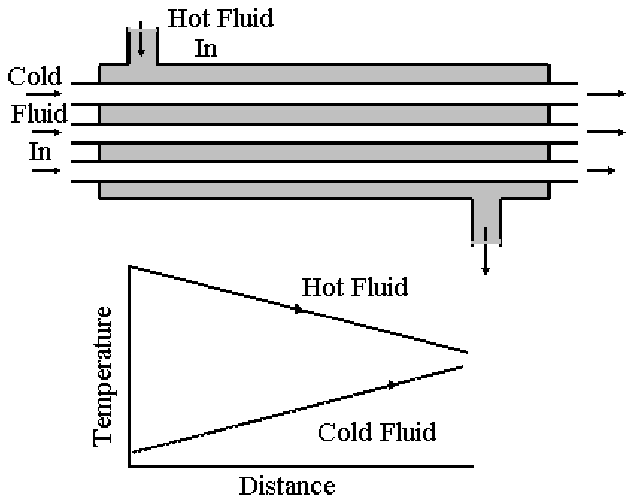


Fig. 5.3. A parallel flow Heat Exchanger. The cold Fluid can only be warmed at best to the mean of the two inlet temperatures.

If on the other hand the flow of one fluid is reversed (Fig. 5.4), then the temperature difference at all stages in the exchanger is small, and the efficiency of heat transfer is much greater. This the incoming fresh air is first heated by the last part of the exhausting stale air. While the leaving fresh air has the benefit of the full heat of the inlet stale air. Consequently, the fresh fluid can be heated to a high proportion of the original stale air temperature. Typically 80% or so of the stale air-temperature difference can be recovered. This is of importance in the waste heat boilers in combined cycle gas turbines. for instance.

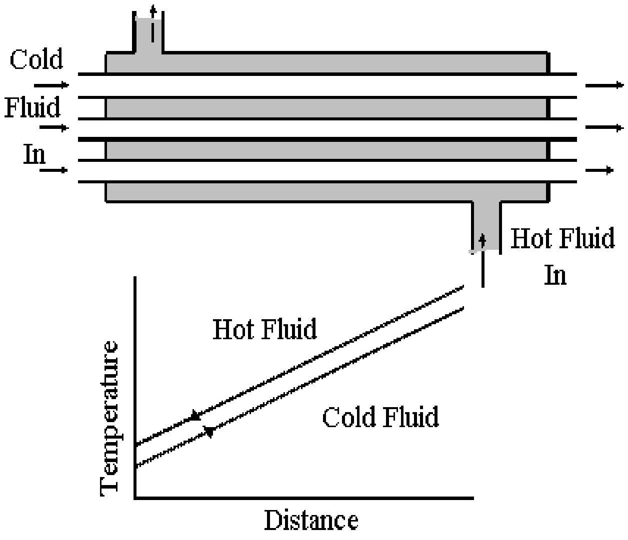


Fig. 5.4 Contra Flow Heat Exchanger - temperature of cold fluid rises almost as high as effluent hot fluid.

5.4 Regenerative Heat Exchangers

One problem with the first type of heat exchanger is that the contact surface area will be limited and will reduce heat flow unless exchangers are large.

At Pilkington Glass, large gas jets heat the molten glass to temperatures of around 1400^{O}C. The exhaust gases pass through ducts containing ceramic which heat up over a period of 20 minutes. At the end of this time. The gas jets on the opposite side fire and the waste heat now is rejected to a second chamber. Meanwhile the cold air for combustion is sucked in over the previously heated ceramic so that the incoming air is almost at the flame temperature thereby improving combustion. After 20 minutes the system is reversed again, and the cold air is now drawn in through the second chamber, while the first is heated again.

Such a Heat Exchanger is known as a Regenerative Heat Exchanger. A similar type of heat exchanger is used in the Low Energy Educational Buildings at the University of east Anglia e.g. the Elizabeth Fry Building, the School of Medicine, the ZICER Building and The Thomas Paine Study Centre. Figures 5.5 and 5.6 illustrate the operation of such a heat exchanger.

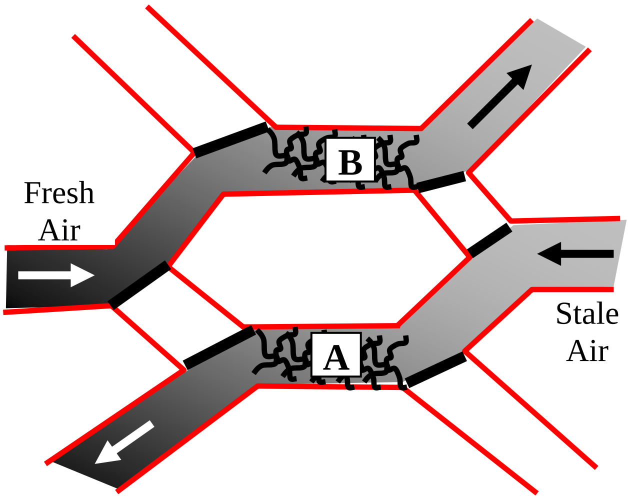


Fig. 5.5 Operation of the Regenerative Heat exchanger to recover energy from the exhaust air from a building – cycle 1

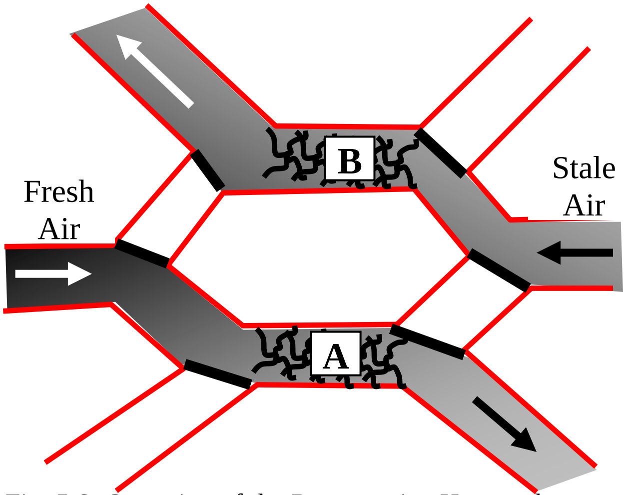


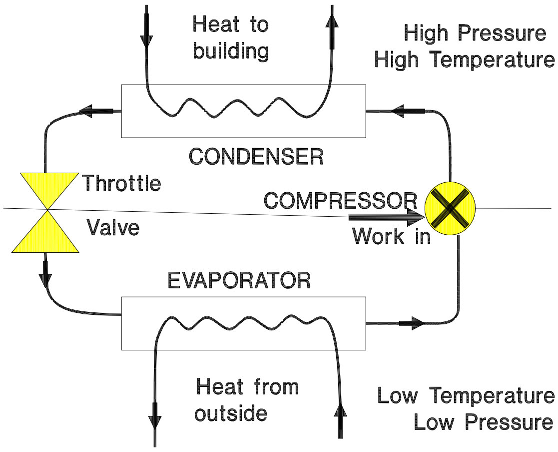
Fig. 5.6 Operation of the Regenerative Heat exchanger to recover energy from the exhaust air from a building – cycle 2

Stale air passes over heat exchanger A (Fig. 5.5) which contains material with a large surface area. This material heats up and cools down the exhaust air. At the same time cold fresh air passes over a similar exchanger B which was heated during a previous cycle. This air is warmed as it picks up heat from the exchanger before passing to the building. After 90 seconds flap valves redirect the air flow into the configuration shown in Fig.

5.6 where heat exchanger B is heated by the stale air and heat exchanger A heat the incoming cold air.

Such a heat exchanger can recover up to 85%+ of the energy in the stale air and as ventilation requirements in a well insulated building become significant (up to 80%), methods to recover stale waste heat ande yet allow ample fresh air are important.

15.5 Heat Pumps



A heat pump consists of four parts:-

1) an evaporator (operating under low pressure and temperature)
2) a compressor to raise the pressure of the working fluid
3) a condenser (operating under high pressure and temperature)
4) a throttle value to reduce the pressure from high to low.

Low temperature heat from an external source (e.g. air, ground, or water) is pumped through the evaporator (a contra-flow heat exchanger). In this, the refrigerant is under low pressure typically 0.1-1.0 bar, and enters as a liquid but soon boils as it passes through. On leaving the evaporator, the fluid is entirely a gas but still under low pressure. The heat transfer from to the refrigerant is essentially at constant temperature (as the fluid is boiling) and therefore efficient. For a heat pump for a house using the ground as the heat source the temperature will typically be around 0^{o}C.

The fluid is now compressed to typically one bar in a compressor (usually a reciprocating one for small devices or a rotary one for large devices). The outlet gas is now under high pressure (typically 3-7 bar) and at high temperature. For a domestic application, this high temperature will typically be around $50+^{o}$C (for hot water systems it is likely to be somewhat higher (around 65^{o}C), and for hot air systems, rather lower.

Heat is released from the refrigerant in the condenser which is once again a contra flow heat exchanger and transferred to the heat medium to heat the building. The refrigerant condenses back to a liquid at constant temperature.

Finally, the high pressure condensed liquid is expanded through a throttle valve to complete the cycle. This expansion is unrestricted, and an obvious inefficiency, but the amount of work that could be recovered here is small (as the volume change in a liquid is small on expansion) that technically and economically it would not be feasible to utilise this work. (Indeed it affect the overall practical COP very little).

If Q_1 is the heat rejected to the building,, Q_2 is the amount of heat extracted from the source, and W is the work input, then by the FIRST LAW:-

$$Q_1 = Q_2 + W$$

$$\text{i.e. COP} = \frac{Q_1}{W} = \frac{Q_1}{Q_1 - Q_2} = \frac{T_1}{T_1 - T_2}$$

If the heat pump has a heat source as the ground at 0^{o}C and supplies heat at 50^{o}C, then the Coefficient of Performance COP is given by:-

$$\text{COP} = \frac{(273 + 50)}{(273 + 50) - (273 + 0)} = 6.46$$

Note the temperature used in the equation must be in Kelvin

Thus, theoretically, for every one unit of energy we put in we get 6.46 units out. Practically, we can achieve about 50% of the theoretical COP, i.e. about 3.23 in this case

If we have an electrically driven heat pump, even allowing for the 3:1 inefficiency in generation, we can more than recover the "lost" energy in the power stations.

i.e. we need only 3 / 3.23 = 0.93 units of primary energy to supply 1 unit of useful energy as heat.

in the best alternative (using a condensing gas boiler), we would require:-

1 / 0.9 units = 1.11 units (i.e. a heat pump would save over 16% in delivered energy terms in this case (i.e. condensing cgas boiler), and considerably more with other types of heating

5.6 Types of Heat Pump

		Heat Source		
		air	**water**	**ground**
Heat Sink	**air**	**air to air**	**water to air**	**ground to air**
	water	**air to water**	**water to water**	**ground to water**
	solid	**air to solid**	**water to solid**	**ground to solid**

Examples:-

Air to air:-	**Refrigeration vehicles, many simple heat pumps, most air-conditioning plants.**
Air to water:-	**Proposed UEA scheme in 1981**
Air to solid	
Water to air	**Ditchingham Primary School**
Water to water	**Norwich Electricity Board Heat Pump during War; Royal Festival Hall. Southampton Geothermal Scheme. On an industrial scale heat recovery from water used to cool products in a distillery can be used to provide heat for the**

	distillery.
Water to solid	**Proposed Duke Street Refurbishment**
ground to air	
ground to water	**ENV demonstration scheme of 1980s – is also a possibility for existing houses with radiators although the COP can be low.**
ground to solid	**John Sumner's Bungalow (of 1950s) and a sensible option for new build properties**

Heat Sources:- Advantages/Disadvantages

	Advantages	**Disadvantages**
Air		Noise on external fans
	Readily Available	source temperature low when most heat needed: hence performance inferior at times of greatest need source temperature varies greatly:- hence cannot optimise design
Water	source temperature normally higher than air or ground in winter: hence improved COP	not readily available
	source temperature nearly constant: hence design can be optimised	
ground	reasonable availability	
	moderate source temperature - better than air, worse than water	capital cost is great if retro-fitted
	moderate variation in source temperature: some optimisation possible	

Supplied Heat:- Advantages/Disadvantages

	Advantages	**Disadvantages**
Air	• relatively low temperature: hence good COP • possibility of heat recovery using mechanical ventilation.	• can only be fitted into hot air systems: • cannot be used with most current Central Heating systems in UK.
Water	• more compact: can be incorporated with existing systems	• higher operating temperature: hence lower COP • Difficult to incorporate heat recovery
solid	• With underfloor heating generally temperature: hence good COP	• Cannot be fit underfloor heating retrospectively except with difficulty. .

- **Best combinations in energy terms is Water to Air or water to underfloor heating**
- **Worst combination in energy terms is Air to Water**

On current mix of electricity generation, 1MJ of useful energy from an electric heat pump will cause the emission of 41 gms CO_2 whereas a condensing boiler to produce same useful energy would emit 57 gms. For a non-condensing gas boiler the emission would be about 68 - 74 gms.

As recently as 1995, the CO_2 emission associated with heat pumps would have been approximately the same as a condensing gas boiler, because there were relatively few CCGT stations operating at the time.

5.7 General Points about Heat Pump Applications

- Heat Pumps are most efficient when the temperature difference between supplied heat and heat source are as small as possible.
- Ideal for heat recovery
- Many industrial applications (e.g. in brewing industry) where energy is required for distillation and cooling water is required for condensing product.
- In past processes were wasteful as cooling water ran to waste.
- By cooling the effluent to closer to ambient using a heat pump, much if not all energy required for distillation can be obtained. Savings of 50% in energy requirement have been achieved
- Other applications
  - swimming pools
  - ice/rink swimming pool complexes
  - domestic applications
  - improving performance of geothermal energy extraction at Southampton Geothermal Plant by reducing effluent temperature.

5.8 Example from a swimming pool.

The dominant use of energy in a swimming pool is to condition the Pool Hall air (Figure 5.5), and heat pumps can be particularly attractive as there is a need to control humidity in the pool hall to prevent corrosion of the structure and as a result there are often high air-exchange rates. The outgoing air is very moist and this provides and ideal opportunity for a heat pump as the exhaust air can be used as the heat source and high coefiiceints of perforamcne are possible. In addition the latent heat of the moisture in exhaust air will be a further benefit. A schematic of an arrangement in a swimming pool is shown in Figure 5.6.

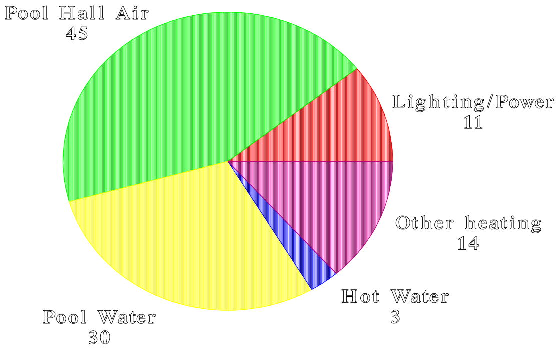


Figure 5.5 Energy use in a swimming pool

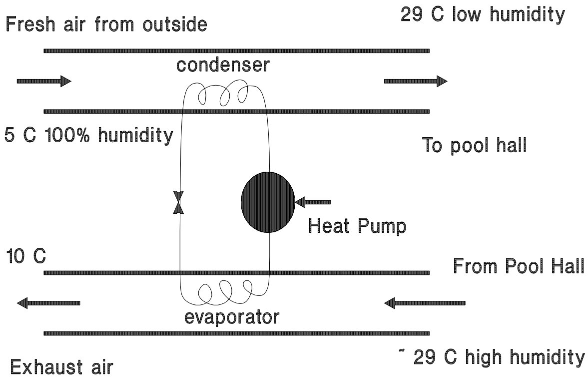


Figure 5.6 Schematic of heat pump use in a swimming pool

Typically the pool water temperature is around - 28°C while the pool air temperature is about 29°C

Humidity must be kept below about 50-60% to avoid corrosion to roof (Sir John Cass School - 1974).

Assume incoming air (winter) at 5°C and 100% relative humidity.

i.e. there are 7.5 gms water per kg of air.

Air at 29°C at 60% relative humidity has 15 gms of water per kg.

Evaporation depends on temperature difference between water and air (usually less than 1°C), the wetted area, and in this example would amount to:-

0.192 kg/hr/m^2 (derived from formula in ETSU document)

Hence ventilation rate V = 0.192 / (15 - 7.5) *1000

difference in water held at two temperatures.

= 0.0256 x 10^3 kg/hr/m^2

(this is about 30% below recommended level)

Energy required for air in pool hall

1) heat incoming air (5 --> 29°C)
2) heat moisture in incoming air (5 --> 29°C)
3) compensate for evaporation from pool (@ 28/29°C)

Total energy required by sq metre of pool

$$= (29 - 5) * (\underbrace{1.0}_{\text{sp ht air}} * 25.6 + \underbrace{4.1868}_{\text{sp ht water}} * 0.075 * 25.6)$$

$$+ \ 0.192 * 2.43 \times 10^6$$

$$= 807.3 + 466560 = 0.467 \ \text{MJ/hr/m}^2$$

For a condensing gas boiler, delivered energy required = 0.467/0.9 = 0.52MJ/hr/m^2, or 0.55 MJ of primary energy

If instead we exhaust at 10°C with 5 gm per kg of water, then energy recovered would be 21726 Joules of sensible heat and 542500 Joules of latent heat or 0.564 MJ in total.

We have more than sufficient to supply heating for pool and some left over for other purposes.

Normally, the temperature drop in a heat exchanger will be about 10°C (i.e. T_1 would be about 40°C and T_2 would be about 0°C), so

Carnot COP = (273 + 40) / 40 = 7.8

and a practical COP would be around 7.8 / 2 = 3.9

Now by first law $Q_1 = W + Q_2$ i.e. $Q_1 (1 - 1/3.9) = Q_2$

Now Q_2 = 0.564 MJ so heat supplied Q_1 = 0.759 MJ

and electrical work in to supply this is $Q_1/3.9$ = 0.195 MJ

Allowing for PER of about 3 for electricity this means that

3 * 0.195 MJ = 0.585 MJ of primary energy is needed.

on the other hand, to supply the 0.759 MJ by gas would require

0.759 / 0.9 * 1.06 (1.06 is the PER for gas)

Even for a condensing boiler = 0.894 MJ

the heat pump represents a saving of **34.5%**
=======

If, as is possible, the temperature/humidity of the exhaust could be reduced further, then savings would be greater.

Another Example

- Some swimming pools have installed gas driven heat pumps.

e.g. Farnborough Recreation Centre

- These have the same compressor as electric heat pumps but use a gas/diesel engine for motive power.
- They have the advantage that waste heat from the gas engine can also be used improving the saving in energy further.

In above example we need to supply 0.195 MJ of work. Typically a gas engine has an efficiency of around 30% and much of the wasted 70% (typically 60% of the input energy) can be recovered as additional heat.

To fully use the 0.564 MJ as reject heat we must have a coefficient of performance of 3.9 so to provide 0.195 units of mechanical work at 30% efficiency we need to supply

0.195 / 0.3 = 0.65 MJ of gas from which we get an additional 0.39 units of useful heat from the engine itself.

The total net heat obtained is thus 0.759 MJ from the heat pump and 0.39 from the engine = 1.149 MJ in total

Allowing for PER of gas then primary gas requirement in this case is now 1.06 * 0.65 = 0.689 MJ.

To provide the same quantity of heat by burning gas direct would require 1.149 / 0.9 * 1.06 MJ = 1.35 MJ

so the percentage saving in this case is (1.35 - 0.689)/1.35

= 48.9 %
========

5.9. Concluding Remarks on Heat Pumps

- For highest COP, temperature difference between source and sink must be as small as possible.
- Best source medium is water
- Best supply medium for domestic space heating is air as air is supplied at 35^{O}C in hot air systems to heat house. In hot water systems at least 65^{O}C is needed (otherwise radiators must be larger to give same output).
- Heat pumps are thus ideal with ducted systems and are even better when used with heat recovery (e.g. ducts from above cooking). As humidity normally rises indoors, significant gains can be obtained by removing latent heat from effluent air (see example on swimming pools where more heat is recovered from exhaust air than is needed to heat pool air).

  Heat recovery systems in ducted hot air schemes without a heat pump are possible, but much opportunity for energy saving is missed.
- Heat recovery from waste hot water is also possible (Nuffield College Oxford extracts heat from effluent sewage).
- Heat pumps are ideal in combination with low temperature heat from solar energy (can make effective use of solar energy which otherwise would be difficult to utilize).

Figures 5.7 and 5.8 show Sankey diagrams comparing the performances of electric and gas heat pumps

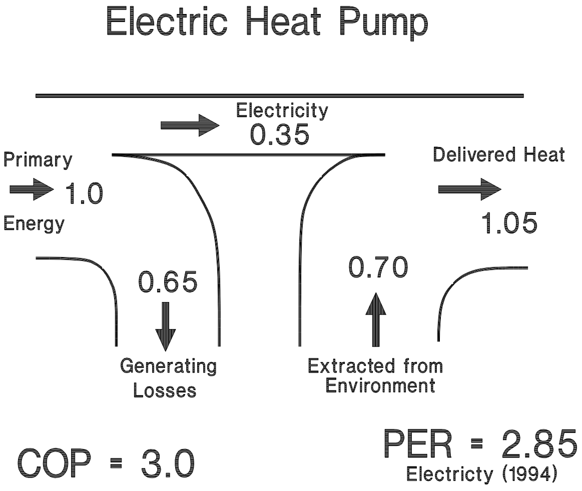


Figure 5.7 Sankey Diagram of energy flows in an electric heat pump

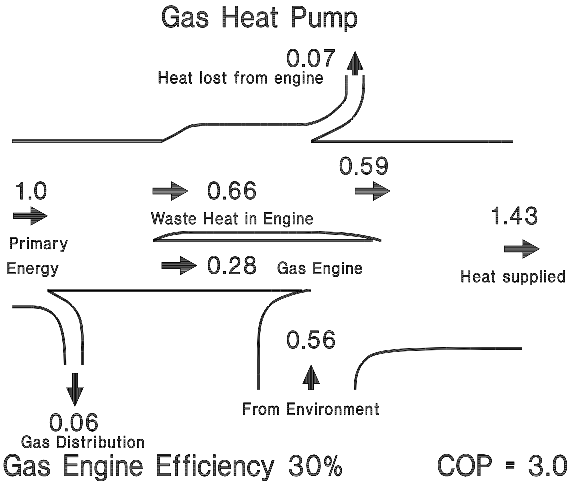


Figure 5.8 Sankey Diagram of energy flows in a gas heat pump

In 1979 (T.L. Winnington and N.K. Tovey, UEA) took out a patent on a heat pump which had an evaporator with multiple possible heat sources (Figure 5.9). Unlike previous attempts which used valves to control flow into different paths, the UEA patent passed the refrigerant through parallel paths simultaneously. Since the greatest heat pick up and vapour flow would automatically be through path of highest temperature, the heat pump would optimise automatically to best COP available.

In the example shown, three separate heat sources are show:-

1) waste hot water
2) solar heated hot water
3) exhaust air from building

Regrettably no money could be found to develop this idea although RenEnergy expressed interest in this idea in 2009.

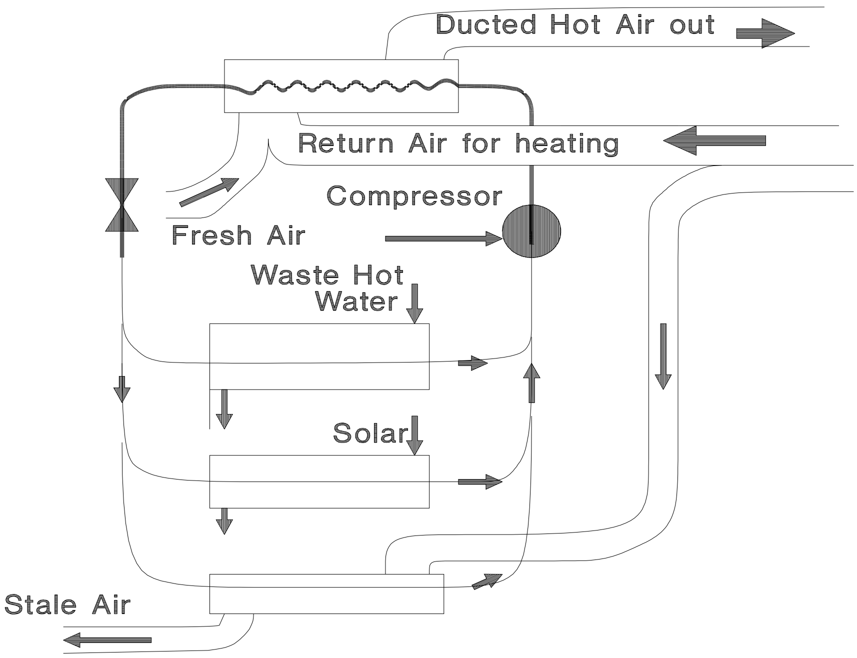


Figure 5.9 Winnington – Tovey idea for a heat pump

5.10 HEAT PUMPS - SUMMARY POINTS

- Principle of heat pumps has been known for over 100 years
- Heat Pumps as refrigerators have been used for 100 years.
- Several successful (or too successful!!) schemes have been installed.
- WHY not more widespread?
- Capital Cost - because most are one off - do not benefit from the advantages of mass production.
- Heat Pump should cost about same as a mini car engine, but for domestic market is 2 - 3 times higher.
- Trades Unions at Lucas in 1970's tried to lobby for development
- Opportunity missed with investment by Last Labour Government. Should have retooled production lines to make heat pumps rather than propping g up an ailing car industry. Would now have a huge export potential. As it is we now have to import most heat pumps.
- Negative reaction from Supply Industry for many years
- Cheap Price of Energy
- Lack of information
- In late 1980s – mid 1990s several mManufacturers no longer made heat pumps because of lack of demand.
- In recent years there has been an increased interest in heat pumps and the proposed Renewable Heat Initiative which the last Government planned to introduce in April 2011 (if it still makes the statues) is likely to significantly increase interest in heat pumps.

5.11 AIR CONDITIONING - (vapour compression)

Normal Air conditioners are nothing more than heat pumps, and we can analyse the performance in exactly the same way. One difference from heat pumps for houses is that in this case incidental gains add to the cooling requirement rather than reducing it as in the case of the heating mode. While air-conditioners are not common in British homes they are in extensive use elsewhere, and the following worked example is based on previous examination questions.

Normally, as with heat pumps the effective evaporator temperature is 10^{o}C or so below the required lower temperature while the condenser temperature is around 10^{o}C above the exhaust temperature.

A house has a heat loss rate of 250 W ^{o}C^{-1} and incidental gains amounting to 1250 W. The house is to be kept at a maximum of 25^{0}C while the mean external temperature is a shown in the following table. Estimate the total energy required when cooling is required.

Month	Mean External Temp
	(^{o}C)
January/December	14
February/November	18
March/October	20
April/September	23
May/August	30
June/July	35

Table 1 Mean external temperatures over the year

As with most heat pumps the isentropic efficiency will be around 50%, and for simplicity we shall assume that all months have 30 days (this simplifies our calculations!).

- First work out the free temperature rise = 1250 / 250 = 5 ^{o}C
- Thus add 5^{o} C to all external temperatures to determine neutral/balance temperature
- All months in which temperature is above 25 ^{o}C require cooling - i.e. April – September
- Now work out evaporator temperature = 273 + (25 - 10) = 288 K (remember degrees Kelvin!!!)

- Also in table below work out effective condenser temperature which will be 10^{o}C above external temperature, and also effective internal temperature - i.e. external temperature + free temperature rise

- Cooling requirement will then be Temp difference(external - internal) * 250 + 1250 (incidental gains) , but
- of course no cooling is required if temperature is at or below 25^{o}C. i.e. cooling requirement column is found by multiplying heat loss rate (250 W ^{o}C^{-1}) by effective internal temperature - 25.

- Work out carnot efficiency = $\frac{T_2}{T_1 - T_2}$

- Notice in this case we need the coefficient of performance in the cooling mode, not the heating mode and so T_2 appears on the top line rather than T_1

As with many questions it is much more efficient to do the calculations in tabular form as shown below.

Month	Mean External Temp (^{o}C)	Effective Internal Temp (^{o}C)	cooling required (kW)
January/December	14	19	No
February/November	18	23	cooling
March/October	20	25	required
April/September	23	28	750
May/August	30	35	2500
June/July	35	40	3750

Thermodynamic Efficiency Calculations

Month	Mean external temp (K)	Effective condenser temp (K)	Carnot efficiency	actual efficiency
April/ September	296	306	16.00	8.00
May/ August	303	313	11.52	5.76
June/July	308	318	9.60	4.80

Total energy required =

$$\sum \frac{\textbf{cooling requirement}}{\textbf{COP}} * \textbf{no of days * seconds in day}$$

=(750 / 8.00 + 2500 / 5.76 + 3750 / 4.80) * 30 * 2 * 86400

= 6.79 **GJ**

==

5.12 AIR CONDITIONING - (swamp box!)

Vapour compression air-conditioners are the traditional way to cool a building, but as they run on electricity they can be very energy demanding over the summer months. Thus in the USA, unlike the UK, the peak demand for electricity is always in the summer months.
In regions where the temperature is high, but the humidity is low, then there is a much more energy efficient method which typically uses only 25% of the energy required for a normal air-conditioner.

These so-called swamp boxes work by sucking incoming air through clothes which are kept moist by running water. The heat of the incoming air evaporates some of the water and the latent heat needed (which for water is considerable) cools the air sometimes as much as 20^{o}C. The only energy requirement is for the fan which is needed for air-conditioning anyway - albeit the fan power must be slightly larger as air is blown through the cloths.

In Arizona, these swamp boxes are common and work effectively from about April, when cooling is first required to mid/late June when the heat becomes higher and the humidity start to climb. From September to late October they are also ideal. In the months of July and August they may not always cope, but many houses only have this form of air-conditioning.

Several houses hove both a regular air-conditioner and a swamp box, using the former only for about 6 - 8 weeks a year.

It does seem somewhat surprising that no-one seems pt have combined the regular air-conditioner with the swamp box which would be more energy efficient in the hottest months than regular air-conditioning. In such a system, the swamp box section would be used for much of the year. In the hottest months, the normal air conditioner would exhaust into the swamp box which since this would keep the condenser temperature cooler than normal would mean that the combined system could be much more efficient than the regular air-conditioner by itself.

5.13 ADSORPTION HEAT PUMPS

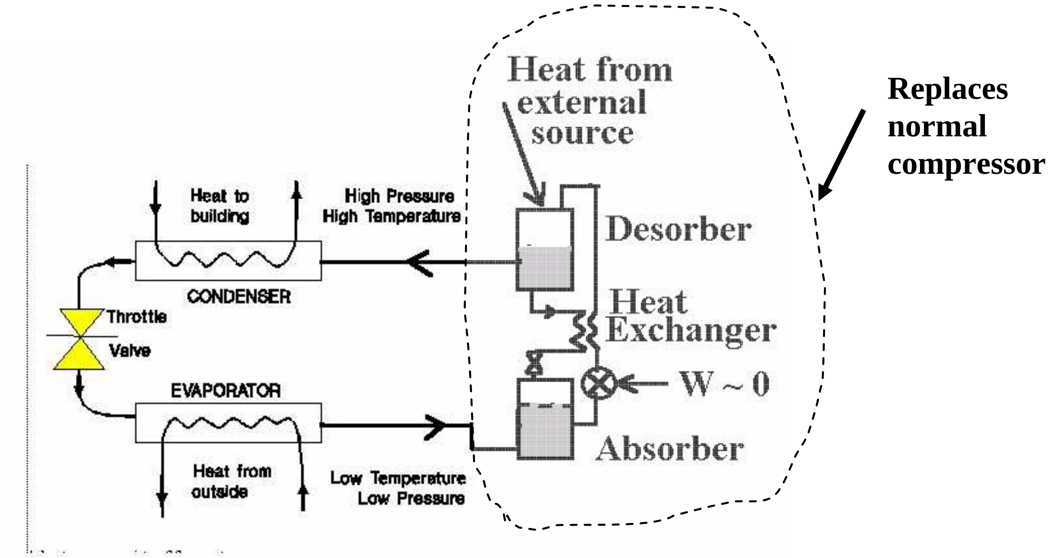
The majority of heat pumps work on the vapour compression principle as indicated above. However, it is possible to have a system which has much reduced power input (and in some cases zero mechnical power input) using the gas adsorption principle. (Figure 5.10). While technically, the COP of heat pumps/refreigeration units using the adsorption principle are significantly lower than mechanical compression devices, there are two main advantages:-

1. Fewer moving parts (none if no mechnical input is needed)
2. Low temperature waste heat from other sources (including low temperature solar heat) can be used to power the device.

The basic principle of the adsorption heat pump is that it works in exactly the same way as a vapour compression device as far as the evaporator, consdenser and throttle are concerned - the only difference is the compressor.

As in a varpour compression device, heat is absorbed at low temperature in the evaporator and then is passed to the absorber/desorper which replaces the compressor (see below). From the desorber, the fluid condenses in the condensor, before passing through the throttle valve as normal back to the evaporator.

The absorber works by noting that some gases are readily absorbed by another fluid at low temperature - e.g. ammonia in water (or lithium bromide solution), but at even moderately elevated temperatures, the aborption capability is greatly reduced and the original gas boils off. The absorber is kept cool and a concetrate fluid mixture forms. This is then passed through a compressor (in some cases no compressor is needed), and a very small anmount of work is needed to raise the pressure of the absorbed fluid (this is because a liquid is much less compressible than a gas). [Remember that the energy input is the force x distance moved so with only a very small change in volume, and hence work the pressure can be increased significantly].



Replaces normal compressor

Figure 5.10 An adsorption Heat Pump – this can be used for heating (e.g. Southampton Geothermal), or cooling – e.g. UEA scheme.

Heat is now supplied and the absorbed gas boils off (increasing the pressure further (thus in some cases one can dispense with the pump altogether) leaving a weak solution in the desorber which is returned to pick up more gas again in the absorber. To improve the efficiency, a heat excahnger is place between the two limbs of the absorber/desorber interchange. Coefficients of performance are usually in the range 1.2 - 1.6 for the heat pump mode and between 0.8 and 1.2 for the refrigeration mode.

Though theses performances are low, they do open opportunities for effective energy conservation. For instance, a limitation with CHP is the need to provide a heat load, and this can present a problem in summer. By using an absorption heat pump, waste heat arising during generation in summer can be used to chill water which can be used for air-conditioning or cooling purposes. Southampton Geothermal Scheme uses such an absorption chiller to provide chilled water in summer. An adsorption Chilkler was installed at UEA in May 2006.

6. NUCLEAR POWER – THE BASICS

6.1 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.**

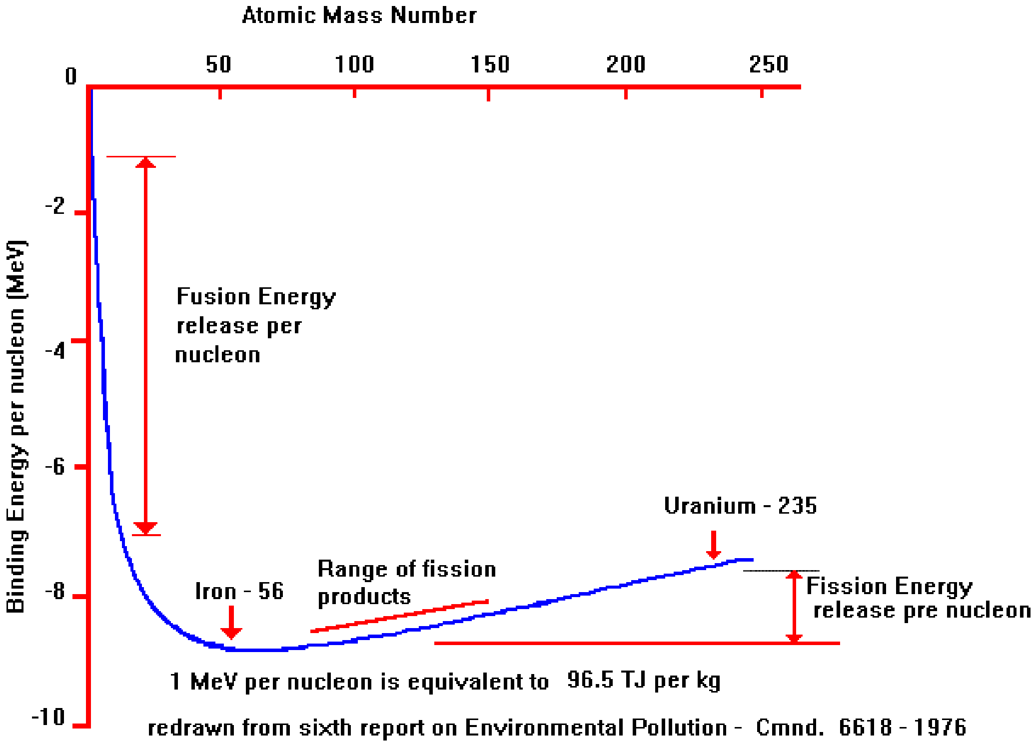


Fig. 6.1 Energy Binding Curve

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

6.2 NATURE OF RADIOACTIVITY - Radioactive emissions.

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

1) **ALPHA** particles - large particles consisting of **2 PROTONS and 2 NEUTRONS**
i.e. the nucleus of a **HELIUM atom.**
2) **BETA** particles which are **ELECTRONS**
3) **GAMMA - RAYS.** These arise when the kinetic energy of Alpha and Beta particles is lost passing through the electron clouds of other atoms. Some of this energy may be used to break chemical bonds while some is converted into **GAMMA -RAYS** which are

similar to **X -RAYS,** but are usually of a shorter wavelength.

4) **X - RAYS.** Alpha and Beta particles, and also gamma-rays may temporarily dislodge ELECTRONS from their normal orbits. As the electrons jump back they emit X-Rays which are characteristic of the element which has been excited.

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

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

URANIUM THORIUM PROTACTINIUM ACTINIUM

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

6.3 HALF LIFE.

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

$^{238}\mathbf{U}$	4.5 billion years
$^{235}\mathbf{U}$	0.7 billion years
$^{232}\mathbf{Th}$	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.

6.4 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 $^{235}\mathbf{U}$ device and the Nagasaki bomb being a $^{239}\mathbf{Pu}$ device.]

6.5 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.]

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).

I**T IS VERY DIFFICULT TO SUSTAIN A CHAIN REACTION, AND TO CREATE A BOMB, THE URANIUM - 235 MUST BE HIGHLY ENRICHED** > 93%, AND BE LARGER THAN A CRITICAL SIZE OTHERWISE NEUTRONS ARE LOST.

ATOMIC BOMBS ARE MADE BY USING A CONVENTIONAL EXPLOSIVE TO BRING TWO SUB-CRITICAL MASSES OF A FISSILE MATERIAL TOGETHER FOR SUFFICIENT TIME FOR A SUPER CRITICAL REACTION TO TAKE PLACE.

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

6.6 FERTILE MATERIALS

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

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

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.

7. NUCLEAR POWER - FISSION REACTORS

7.1 NORMAL FISSION REACTORS THUS CONSIST OF:-

i) a FISSILE component in the fuel

ii) a MODERATOR

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

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

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

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

In most reactors there are three fluid circuits:-

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

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

At the end of 2008 there were a total of 437 nuclear reactors world-wide in operation having a combined output of 371.6 GW. In most stations there are two or more reactors with the most being at Gravelines in france where there are six with a combined capacity or 5.7 GW. A further 44 reactors were then under construction with a combined output of 39 GW.

i.e. the total output of about 400 GW is about six times the total UK generating capacity.

7.2 REACTOR TYPES – summary

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

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

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

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

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

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

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

HTGR - HIGH TEMPERATURE GRAPHITE REACTOR - an experimental reactor. The original HTR in the UK started decommissioning in 1975, while West Germany (2), and the USA (1) have operational units. None are under construction. Variants of this design are under development as the PBMR (see section 6.3.10)

FBR - FAST BREEDER REACTOR - unlike all previous reactors, this reactor 'breeds' PLUTONIUM from FERTILE **^{238}U** to operate, and in so doing extends resource base of URANIUM over 50 times. Mostly experimental at moment.

TABLE 7.1. NUCLEAR POWER REACTORS IN OPERATION AND UNDER CONSTRUCTION, 31 DEC. 2008

	Reactors in Operation in 2008		Reactors under Long Term Shutdown		Reactors under Construction		Nuclear electricity supplied in 2008	
	No of units	Total MW(e)	No of units	Total MW(e)	No of units	Total MW(e)	TWh(e)	% total
ARGENTINA	2	935			1	692	6.85	6.18
ARMENIA	1	376					2.27	39.35
BELGIUM	7	5824					43.36	53.76
BRAZIL	2	1766					13.21	3.12
BULGARIA	2	1906			2	1906	14.74	32.92
CANADA	18	12577	4	2726			88.30	14.80
CHINA	11	8438			11	10220	65.32	2.15
CZECH REP.	6	3634					25.02	32.45
FINLAND	4	2696			1	1600	22.05	29.73
FRANCE	59	63260			1	1600	419.80	76.18
GERMANY	17	20470					140.89	28.82
HUNGARY	4	1859					13.87	37.15
INDIA	17	3782			6	2910	13.18	2.03
IRAN					1	915	NA	NA
JAPAN	55	47278	1	246	2	2191	241.25	24.93
KOREA	20	17647			5	5180	144.25	35.62
LITHUANIA	1	1185					9.14	72.89
MEXICO	2	1300					9.36	4.04
NETHERLANDS	1	482					3.93	3.80
PAKISTAN	2	425			1	300	1.74	1.91
ROMANIA	2	1300					10.33	17.54
RUSSIA	31	21743			8	5809	152.06	16.86
SLOVAKIA	4	1711					15.45	56.42
SLOVENIA	1	666					5.97	41.71
SOUTH AFRICA	2	1800					12.75	5.25
SPAIN	8	7450					56.45	18.27
SWEDEN	10	8996					61.34	42.04
SWITZERLAND	5	3220					26.27	39.22
UK	19	10097					48.21	13.45
UKRAINE	15	13107			2	1900	84.47	47.40
USA	104	100683			1	1165	806.68	19.66
Total	438	371562	5	2972	44	38988	2597.81	17.71

Note: The total includes the following data in Taiwan, China: — 6 units, 4949 MW(e) in operation; 2 units, 2600 MW(e) under construction; — 39.30 TW(e).h of nuclear electricity generation, representing 17.45% of the total electricity generated there; — 146 years 1 month of total operating experience.
Data from IAEA(2009) Nuclear Reactors around the World www-pub.iaea.org/mtcd/publications/pdf/rds2-29_web.pdf

Data obtained from Power Reactor Information System Website: http://www.iaea.or.at/programmes/a2/
If the online version of this handout is consulted then clicking on the Station Name will give details of the performance of the station over its lifetime (that includes stations which are now closed).

Table 7.2 Performance of SIZEWELL REACTORS

Reactor Name	**SIZEWELL – A1**	Date of Grid Connection:	21 Jan 1966
Reactor Type	**MAGNOX**	Date of Commercial Operation:	25 Mar 1966
Date of Construction Start:	01 Apr 1961	Lifetime Generation:	56776 GWh(e)
Date of First Criticality:	01 Jun 1965	Cumulative Load Factor:	71.76%

Year	Energy GWh(e)	Capacity (MWe)	Load Factor (%) Annual	Load Factor (%) Cumulative
1966	No annual data available			
1967				
1968				
1969				
1970	3630	652	63.56	32.31
1971	3868.6	490	90.13	48.29
1972	3265.4	490	75.87	54.28
1973	2910.3	420	79.32	58.19
1974	3116	420	84.92	61.8
1975	3424	420	93.32	65.55
1976	3403	420	91	68.3
1977	3324	420	90.59	70.44
1978	3372	420	91.9	72.32
1979	3310	420	90.21	73.76
1980	2792	420	76.09	73.93
1981	2131	420	56.98	72.74
1982	1889	420	51.48	71.36
1983	3151	420	85.88	72.24
1984	1845	420	50.28	70.98
1985	2688.81	420	73.28	71.11
1986	1990.53	420	54.25	70.24
1986	1990.53	420	54.25	70.24
1987	2759.96	420	73.8	70.42
1988	2672.56	420	72.84	70.53
1989	2595.04	420	70.73	70.54
1990	2691.72	420	73.36	70.66
1991	2746.36	420	74.85	70.83
1992	2266.78	420	60.61	70.42
1993	3023.42	420	82.4	70.88
1994	3375.74	420	92	71.64
1995	1555.761	210	84.57	71.88
1996	415.044	210	22.5	71
1997	1743.699	210	94.79	71.42
1998	1208.391	210	65.69	71.32
1999	1238.349	210	67.32	71.25
2000	949.402	210	51.47	70.93
2001	1783.292	210	96.94	71.35
2002	1335.484	210	72.6	71.37
2003	1834.658	210	99.73	71.81
2004	526.519	210	28.54	71.14
2005	1730.834	210	94.09	71.49
2006	1645.106	210	89.67	71.76

Capacity Data in above table refers to both Reactors A1 and A2 prior to 1995

Reactor Name	**SIZEWELL – A2**	Date of Grid Connection:	09 Apr 1966
Reactor Type	**MAGNOX**	Date of Commercial Operation:	15 Sep 1966
Date of Construction Start:	01 Apr 1961	Lifetime Generation:	53345 GWh(e)
Date of First Criticality:	01 Dec 1965	Cumulative Load Factor:	61.53%

SIZEWELL B

Reactor Name	**SIZEWELL – B**	Date of Grid Connection:	14 Feb 1995
Reactor Type	**PWR**	Date of Commercial Operation:	22 Sep 1995
Date of Construction Start:	18 Jul 1988	Lifetime Generation:	96043.695 GWh(e)
Date of First Criticality:	31 Jan 1995	Cumulative Load Factor:	86.57%

Year	Energy GWh(e)	Capacity (MWe)	Load Factor (%) Annual	Load Factor (%) Cumulative
1995	0	1188		
1996	8488.467	1188	81.34	81.34
1997	8469.807	1188	81.16	81.25
1998	10123.092	1188	97.01	86.5
1999	7959.009	1188	76.27	83.95
2000	8527.183	1188	81.71	83.5
2001	9197.957	1188	88.14	84.27
2002	9195.038	1188	88.36	84.86
2003	8854.185	1188	85.08	84.88
2004	9329.115	1188	89.4	85.39
2005	8696.25	1188	83.56	85.2
2006	8908.255	1188	85.17	85.24
2007	10264.305	1188	98.47	86.35
2008	9301.234	1188	89.13	86.57

Data for Tables on this page were derived from Power Reactor Information System Website: **http://www.iaea.or.at/programmes/a2/**

TABLE 7.3 REACTOR TYPES AND NET ELECTRICAL POWER, REACTORS CONNECTED TO THE GRID, 31 DEC. 2008

Data abstracted from Table 2 of Nuclear Power Reactors in the World http://www-pub.iaea.org/mtcd/publications/pdf/rds2-29_web.pdf

COUNTRY	PWR/WWER		BWR		GCR - Magnox		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)
ARGENTINA									2	935	2	935			2	935
ARMENIA	1	376													1	376
BELGIUM	7	5824													7	5824
BRAZIL	2	1766													2	1766
BULGARIA	2	1906													2	1906
CANADA									18	12577					18	12577
CHINA	9	7138							2	1300					11	8438
CZECH Republic	6	3634													6	3634
FINLAND	2	976	2	1720											4	2696
FRANCE	58	63130											1	130	59	63260
GERMANY	11	14013	6	6457											17	20470
HUNGARY	4	1859													4	1859
INDIA			2	300					15	3482					17	3782
JAPAN	23	18420	32	28858											55	47278
KOREA	16	14925							4	2722					20	17647
LITHUANIA											1	1185			1	1185
MEXICO			2	1300											2	1300
NETHERLANDS	1	482													1	482
PAKISTAN	1	300							1	125					2	425
ROMANIA									2	1300					2	1300
RUSSIA	15	10964									15	10219	1	560	31	21743
SLOVAKIA	4	1711													4	1711
SLOVENIA	1	666													1	666
SOUTH AFRICA	2	1800													2	1800
SPAIN	6	5940	2	1510											8	7450
SWEDEN	3	2787	7	6209											10	8996
SWITZERLAND	3	1700	2	1520											5	3220
UK	1	1188			4	1414	14	7495							19	10097
UKRAINE	15	13107													15	13107
USA	69	66739	35	33944											104	100683
TOTAL	264	243159	94	84959	18	8909			44	22441	16	11404	2	690	438	37156

A full list of all Nuclear Reactors in Each Country may be found at: http://www2.env.uea.ac.uk/gmmc/energy/env-2a36/nuclear_reactors_operating_around_world.xls

7.3 FISSION REACTORS

7.3.1 MAGNOX Reactors.

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

ADVANTAGES:-

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

DISADVANTAGES:-

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

On December 31st 2006, two further Magnox Reactors were closed after 40 years of service. Shortly there will only be two such reactors left in service at Oldbury and Wylfa. Operation of Oldbury has been extended to end of 2010 when Wylfa will also close.

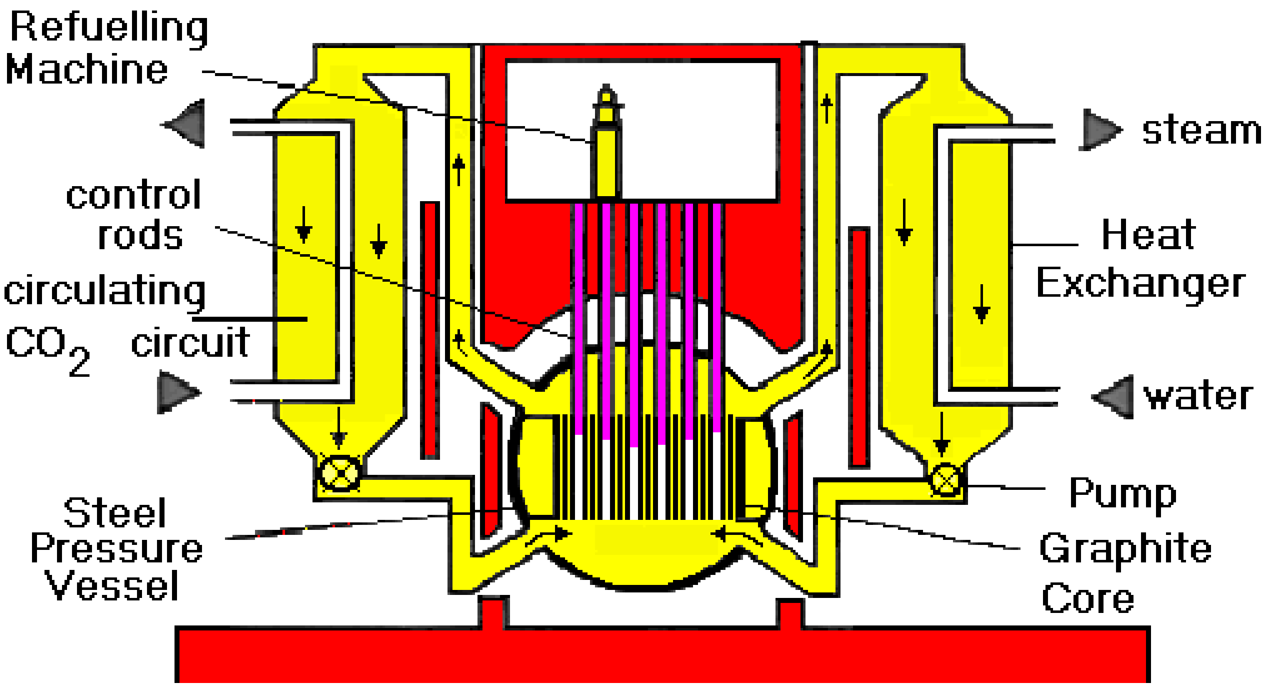


Fig. 7.1 Schematic section of an early Magnox Reactor. Later versions had a pressurised concrete vessel which also enclosed the boilers as with the AGRs. This reactor was developed in the UK and France. The 2 French reactors were closed in the late 1980s. There were originally 24 such reactors in operation 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.

7.3.2 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.

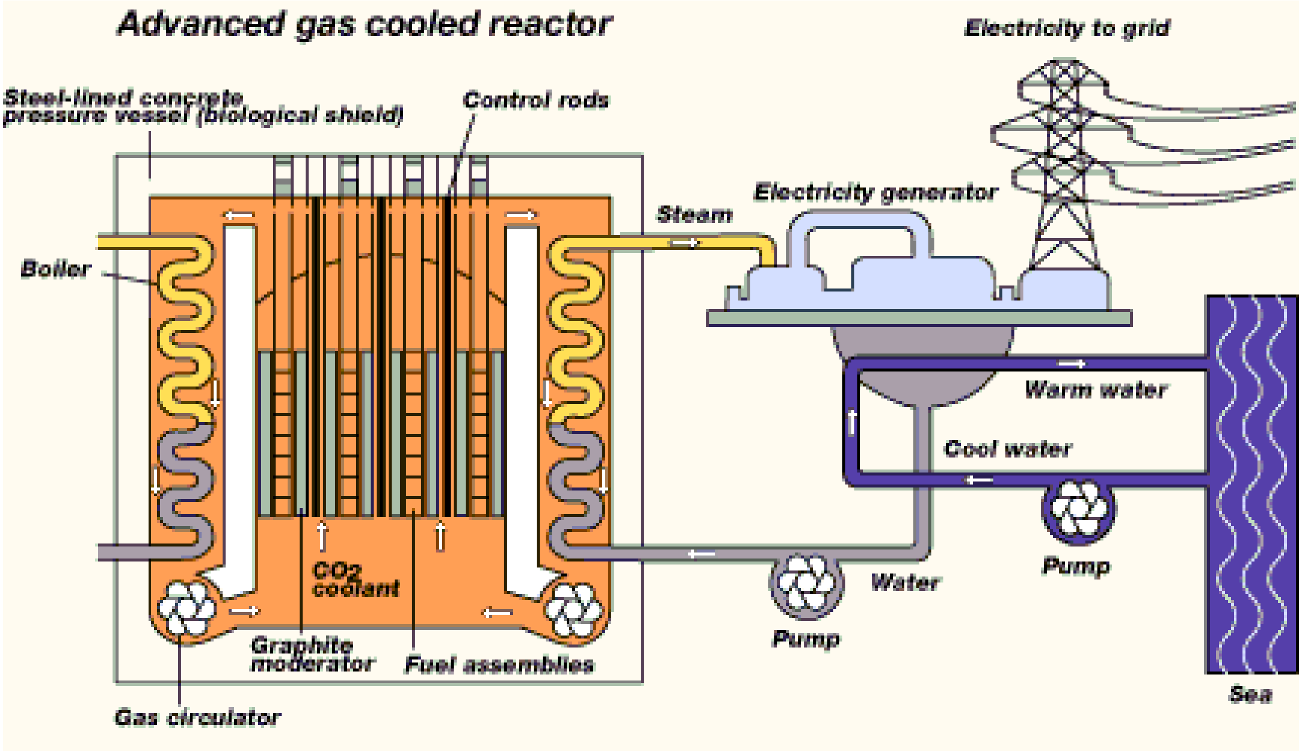


Fig. 7.2 Section of an Advanced Gas Cooled Reactor. This reactor was only developed in the UK. There are currently 14 such reactors in 7 stations in the UK.

7.3.3 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

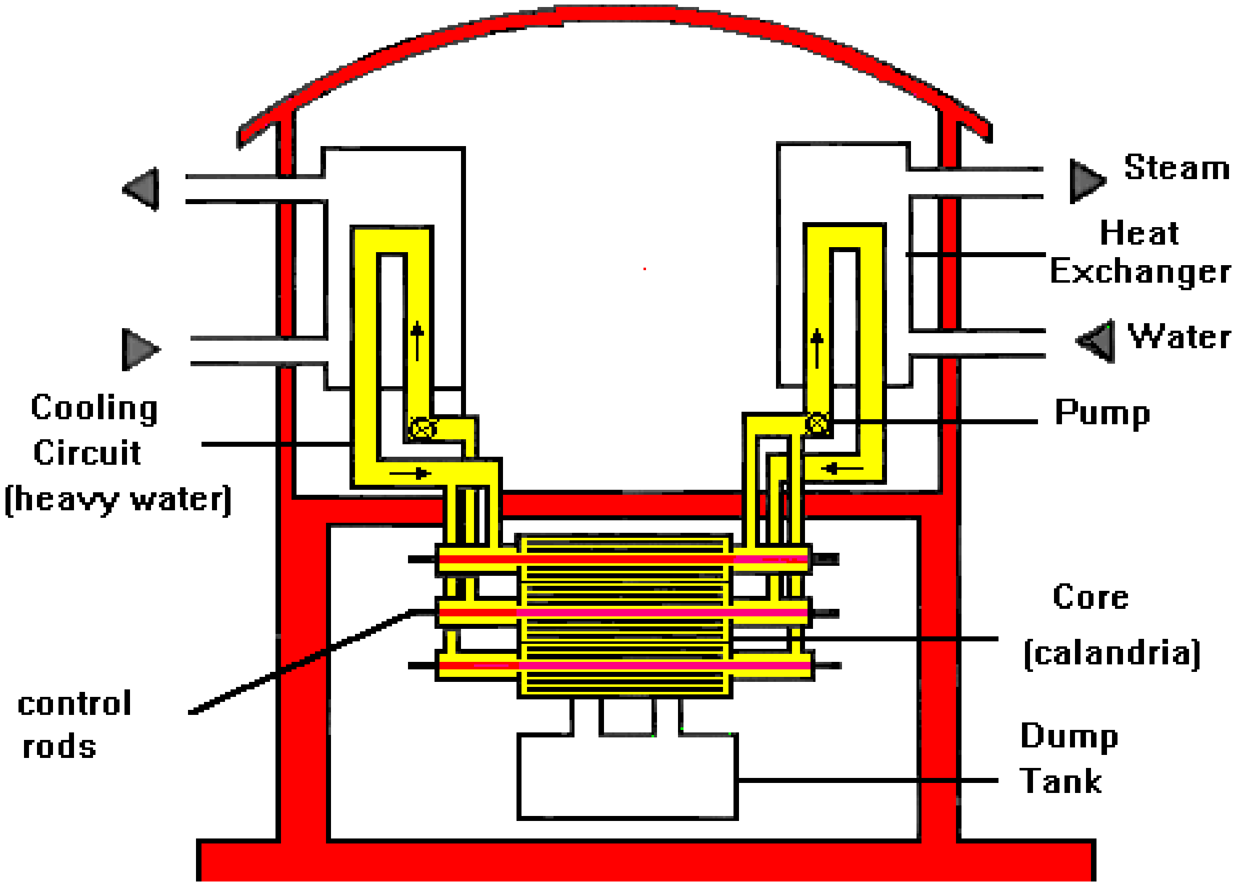


Fig. 7.3 A section of a CANDU reactor. This design was developed in Canada, and has the advantage that it is modular and can be built to any size. The British Steam Generating Heavy Water Reactor (SGHWR) was of similar design except the cooling circuit was ordinary water. The space surrounding the fuel elements in the calandria in a SGHWR was heavy water as in the CANDU design.

7.3.4 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.

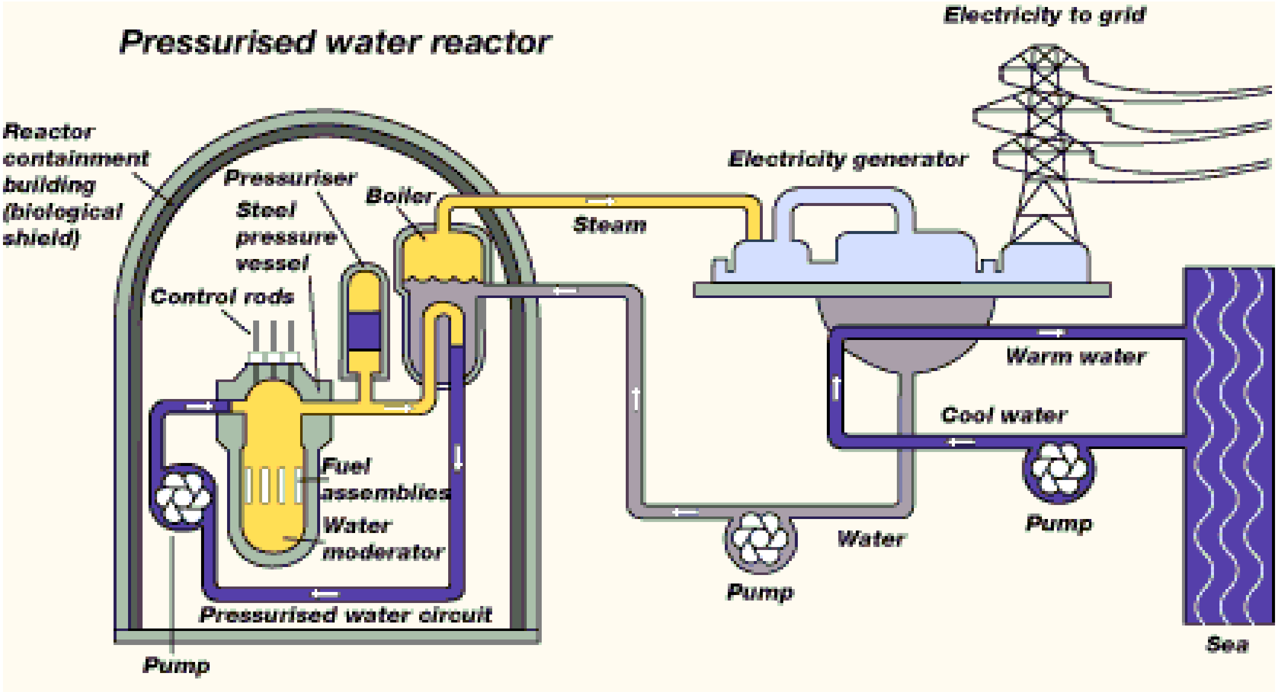


Fig. 7.4 A section of a PWR. This shows the safer design having the cold and hot legs entering the reactor vessel at the top. the reactor at Sizewell has a secondary dome outside the primary containment building. This is the only one in the world that has a double skin. One of the new designs being considered 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.

7.3.5 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.

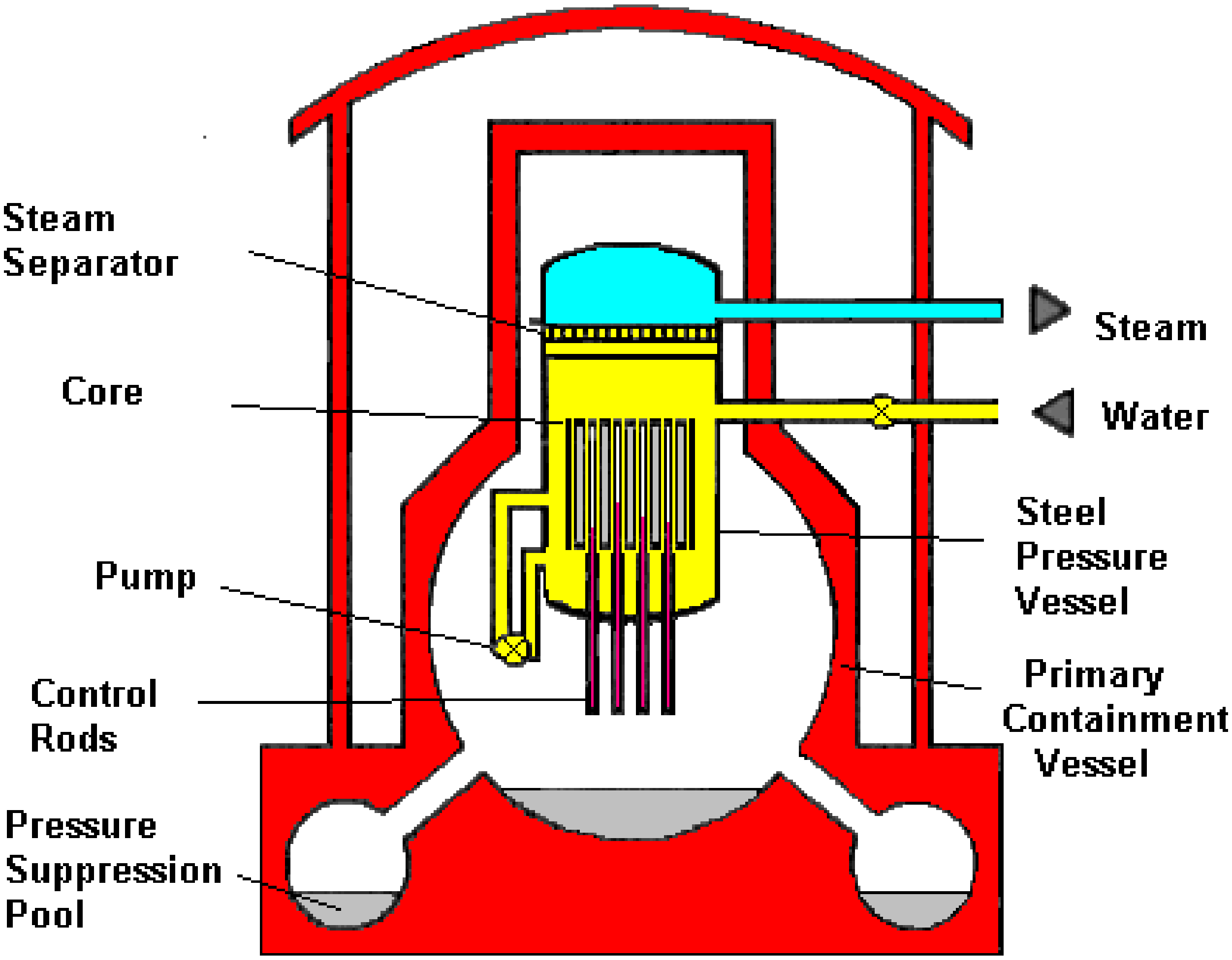


Fig. 7.5 A Boiling Water Reactor. Notice that the primary circuit steam is passed directly to the turbines.

7.3.6 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

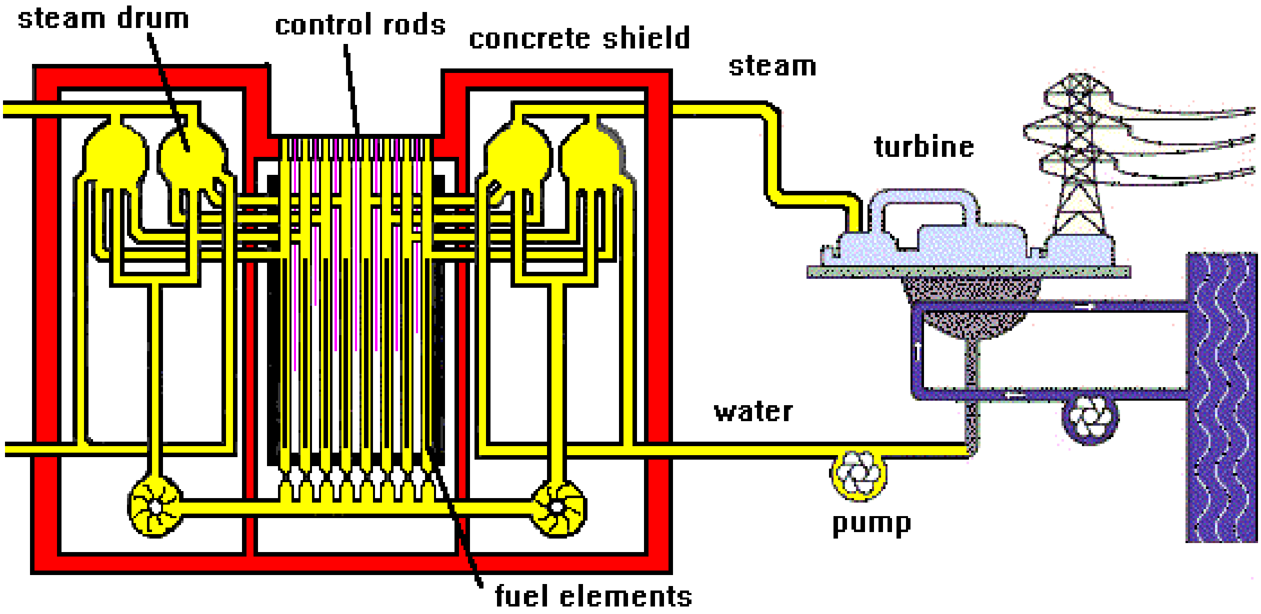


Fig. 7.6 The Russian Light Water - Graphite Moderated Reactor. This reactor was of the type involved in the Chernobyl incident in 1986.

7.3.7 Summary of key parameters for existing reactors.

Table 7.4 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 7.4 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

7.3.8 Third Generation Reactors

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

7.3.9 European Pressurised Reactor

Provisional Data

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

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

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

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

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

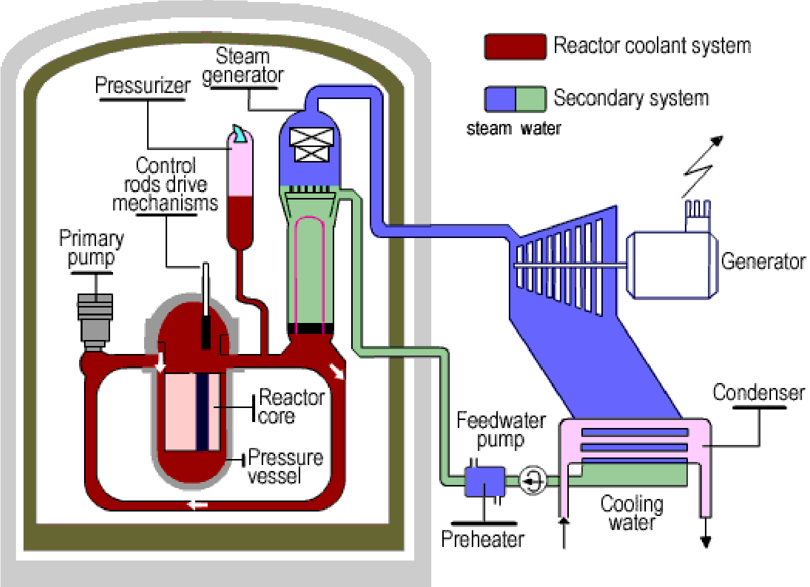


Fig.7.7 [From the AREVA WEB SITE]. This diagram is very similar to the PWR above.

7.3.10 AP1000 REACTOR

The AP1000 Reactor has been certified in USA and is a possible contender for a future Reactor in the UK. It develops the AP600 design but with bigger components and a design output of 1120 – 1150 MW. It hasseveral inherent advantages such as not requiring active provision of cooling (i.e. using gravity to spray water). This is achieved by having a large water tank on top of the containment building (Fig. 15.8).

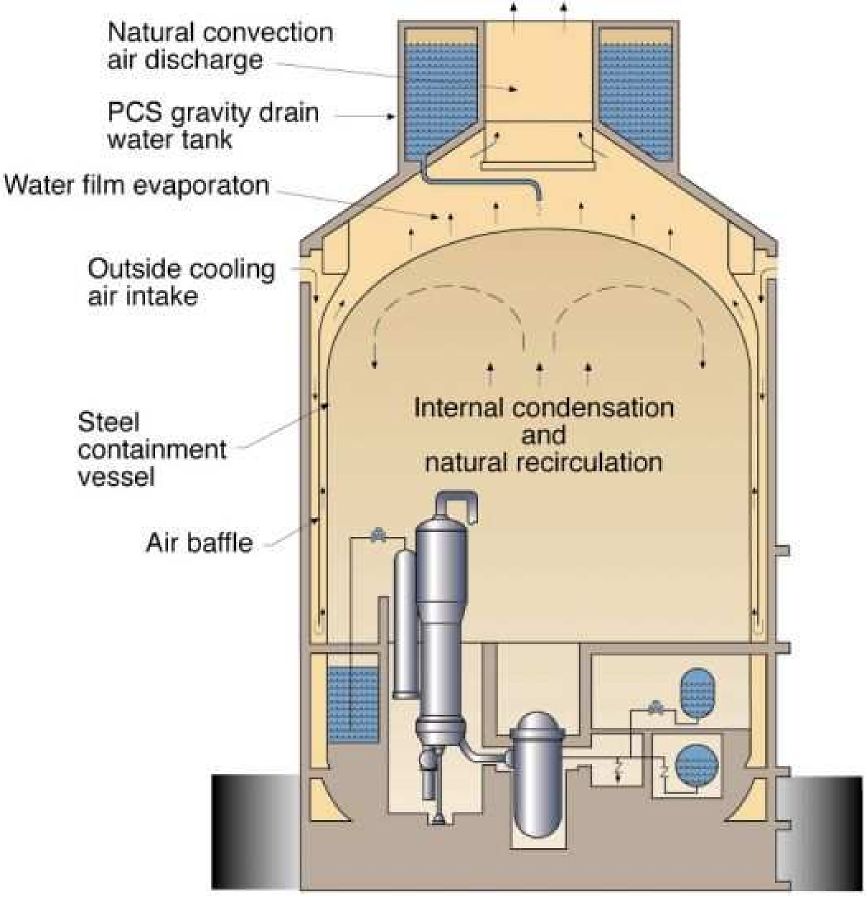


Fig. 7.8 Cross section of AP1000 Reactor and Containment Building showing passive cooling

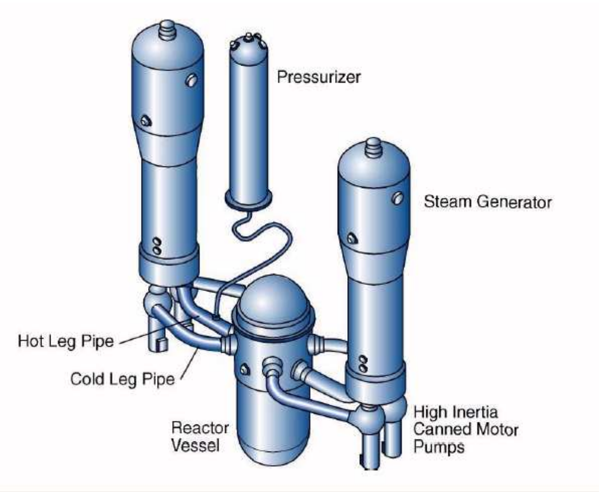


Fig. 7.9 Diagram showin two loops in AP1000 design. The EPR1300 has four separate steam generators. Both Reactors have just one Pressuriser.

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. 7.9) The efficiency is likely to be marginally higher than a normal PWR at around 33-35% which is less than that achieved by the AGRs. It is claimed that the safety of an AP1000 would be at least 100 times better than a comparable Reactor

7.3.11 ACR1000 Advanced Candu Reactor

This reactor (Fig. 7.10) is being developed in Canada as a development of the Candu concept, but although unlike the earlier models will almost certainly used slightly eenriched uranium oxide as the fuel rather than the unenriched oxide.

The Candu reactor can be built in a modular form and designs of 700 – 1200 MW are proposed. At present it has not received certification in USA, but forwarded pre-certification documents for certification in UK in May 2007.

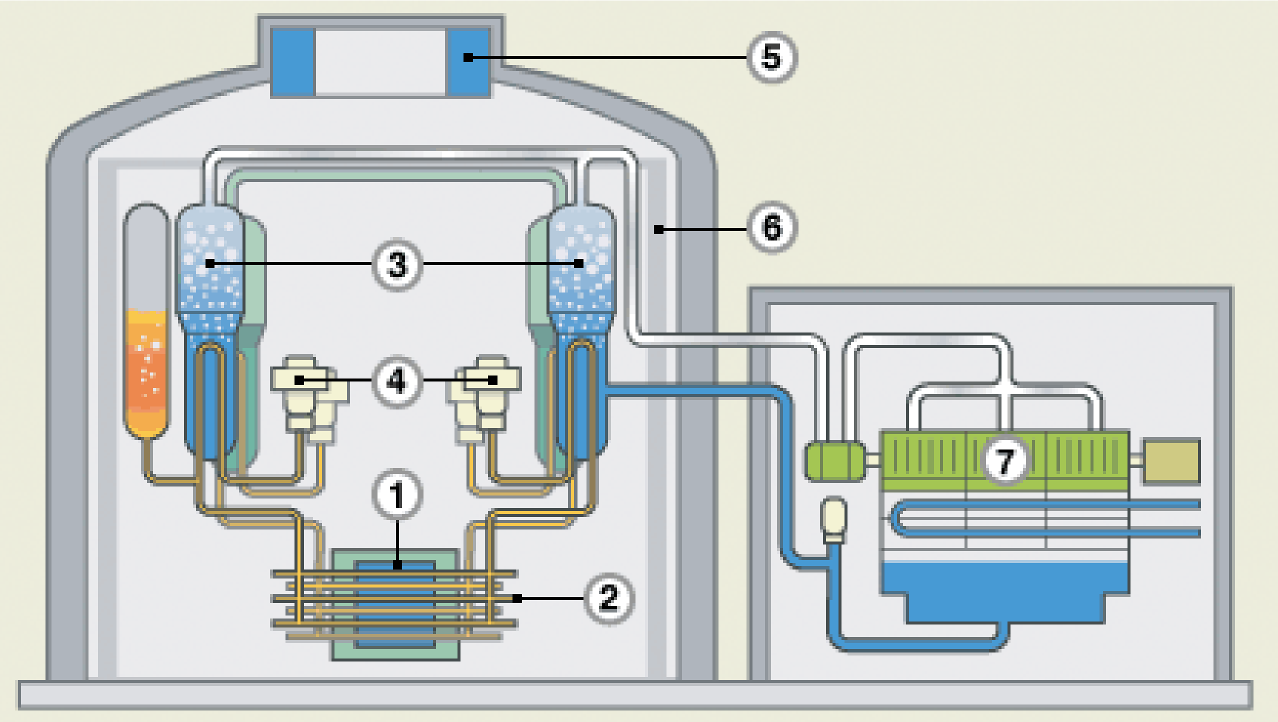


Fig. 7.10 Advanced Candu Reactor.

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

7.3.12 ESBWR: Economically Simple Boiling Water Reator

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

Like the APR1000 and ACR1000 it has a large passive cooling tank on the top of the reactors building. Fig. 15.11 shows a schematic of the design.

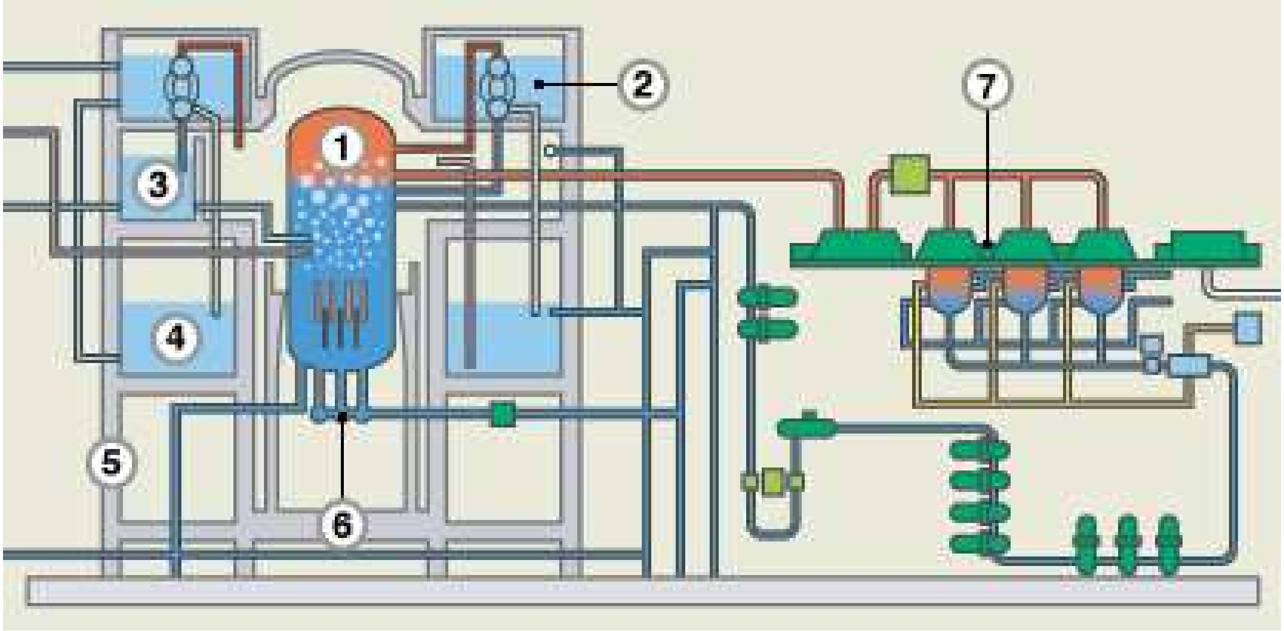


Fig. 7.11 Economic Simplified Boiling Water Reactor

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

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

All 4 desings listed above – i.e. the EPR1000, AP1000, ACR1000, and ESBWR submitted pre-certification documents for operation in the UK in May 2007. The Nuclear White Paper, indicates that it will 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.

7.3.14 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. 7.12, while the novel method of producing fuel elements is shown in Fig. 7.13.

FUEL TYPE - enriched URANIUM OXIDE
- 9% clad in specially created sand sized particles (see Fig. 15.13)
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

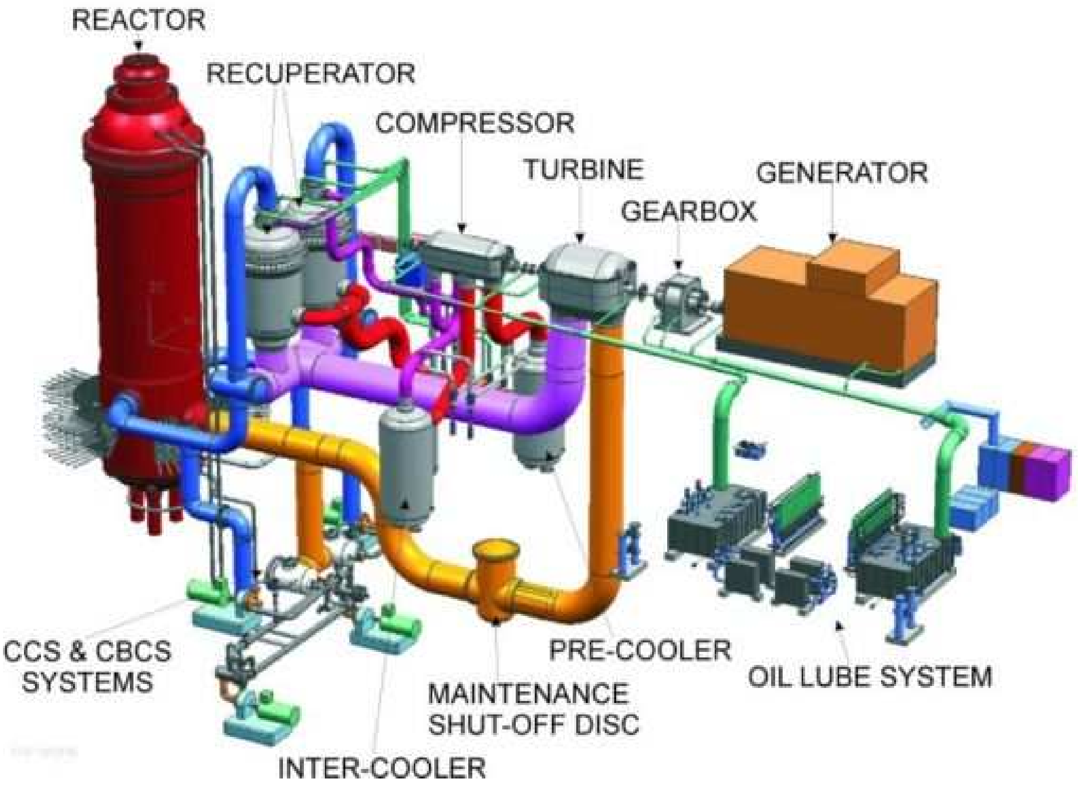


Fig. 7.12 Schematic Diagram of a Pebble Bed Modulating Reactor

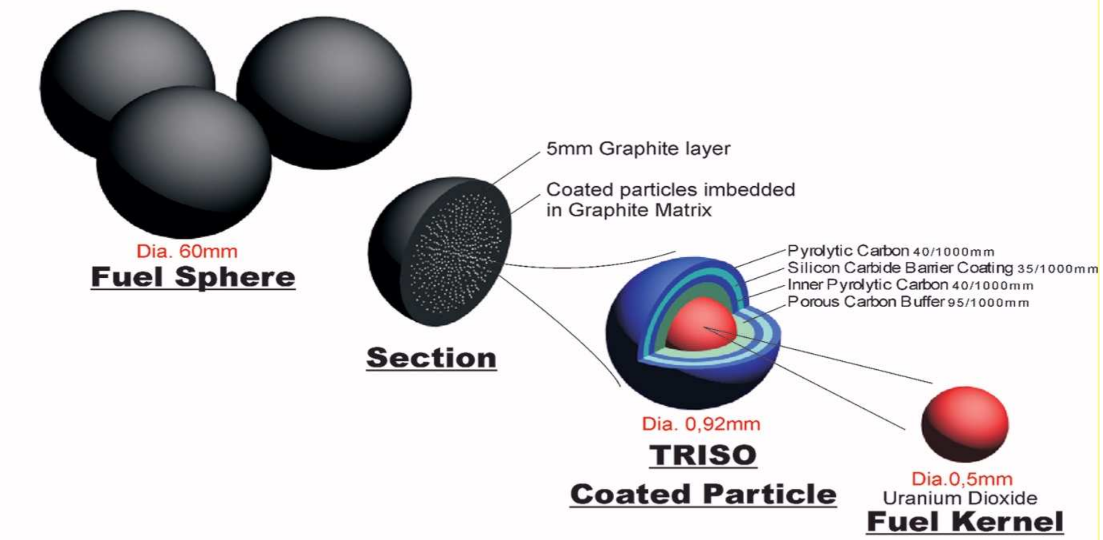


Fig. 7.13 Fuel pellets for a PBMR. The inner kernel is prepared by spraying uranyl nitrate to form small pellets 0.5mm in diameter. These are baked to produce Uranium Dioxide. Four layers are then deposited on the fuel particle: a) a porous graphite (which allows the fisiion products space to accumulate), b) a heat teated layer of pyrolitic dense carbon, a layer of silicon carbide, and finnaly another layer of pyrolitic carbon to form a particle around 0.9mm in diameter. Around 15000 of these particles are then packed together with graphite and finally coated with 5mm of graphite to form a pebble 60 mm in diameter. The reactor would have around 450 000 pebbles in total. For further information see: http://www.pbmr.com/download/FuelSystem.pdf

ADVANTAGES:-

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

DISADVANTAGES:-

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

7.3.15 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.

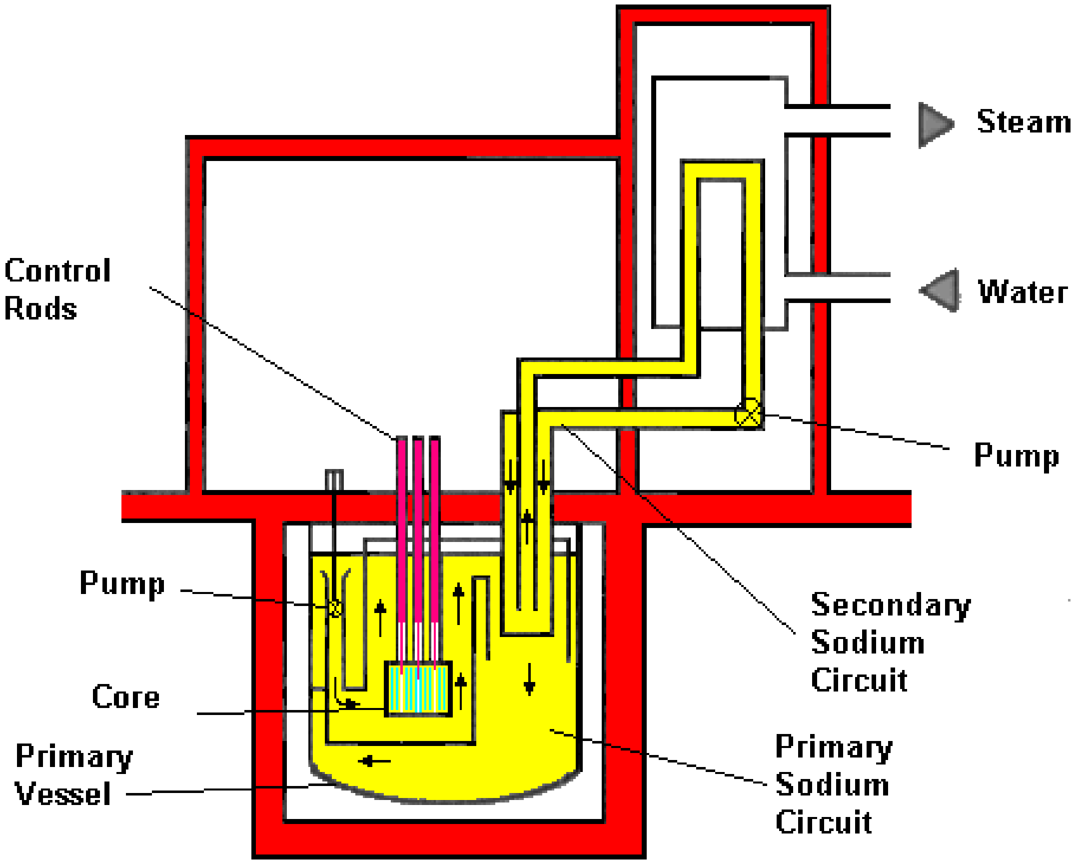


Fig. 7.14 A Fast Breeder Reactor. This type of reactor has depleted Uranium - 238 in a blanket around the fissile core material (of enriched U-235 or Plutonium). Fast neutrons can be captured by the fertile U - 238 to produce more Plutonium. Typically one kilogram of fissile Plutonium could produce as 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.

7.3.16 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. It is likely that the certification will start during 2008.

15.3.17 REPROCESSING IS ESSENTIAL FOR FAST BREEDER REACTORS.

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

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

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

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

15.3.18 NUCLEAR POWER -DECOMMISSIONING REACTORS

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

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

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

PHASE 1

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

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

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

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

Site will be returned to a greenfield site.

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

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

In 2005, Calder Hall closed followed shortly by Chapel Cross. Then on 31st December 2006, Sizewell A, Dungeness A closed. In 2008, it is planned that Oldbury will close with Wylfa following in 2010.

The AGRs are currently scheduled to be closed progressively between now and 2023 when at present only Sizewell B will be operating.

In the Energy White Paper in 2003, the UK Government indicated that Nuclear Power was not an option for the future, but that it would be kept under review. However, in the Nuclear Energy White Paper in January 2008, it was announced that there would be a new nuclear power station building programme.

It will not be until 2012 at the earliest that any construction would start and it is unlikely that any new nuclear facility will be operating much before 2020.

There may be the option of extending the life of some of the AGRs to allow time for new ones to come on stream. Indeed in mid January 2010, the German Government indicated that it was exploring was to extend the life of reactors in that country by up to ten years.

TABLE 7.5 LIST OF NUCLEAR POWER REACTORS which were GRID CONNECTED and which have now been decommissioned.

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

TABLE 7.5 LIST OF NUCLEAR POWER REACTORS which were GRID CONNECTED and which have now been decommissioned - continued.

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

TABLE 7.5 LIST OF NUCLEAR POWER REACTORS which were GRID CONNECTED and which have now been decommissioned - continued.

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

8. THE NUCLEAR FUEL CYCLE.

8.1 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.

8.2 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.

8.3 FRONT-END of NUCLEAR FUEL CYCLE (see Fig 8.1)

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

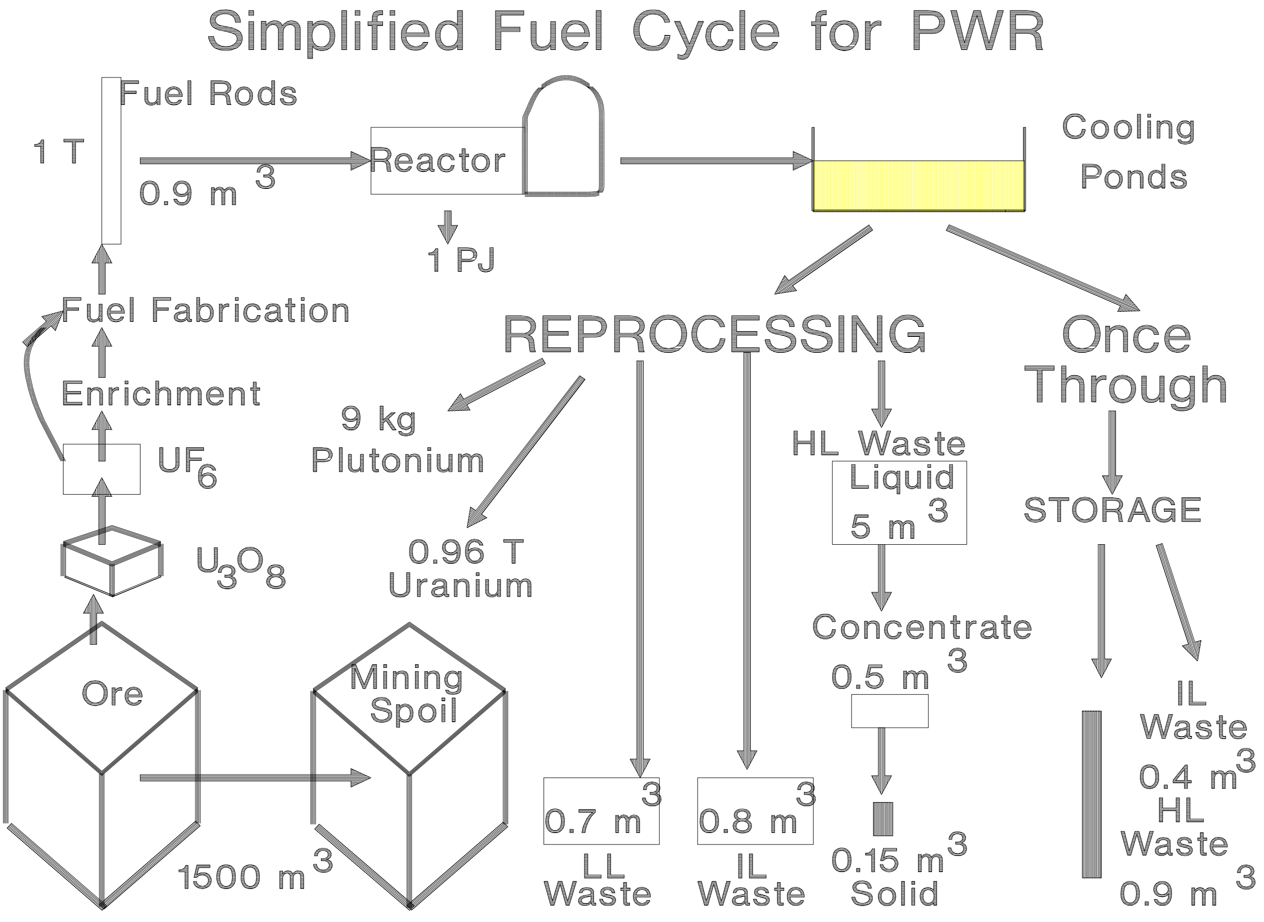


Fig. 8.1 Once through and Reprocessing Cycle for a PWR. The two cycles for an AGR are similar, although the quantities are slightly different. For the CANDU and MAGNOX reactors, no enrichment is needed at the front end.

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

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

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

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

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

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

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

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

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

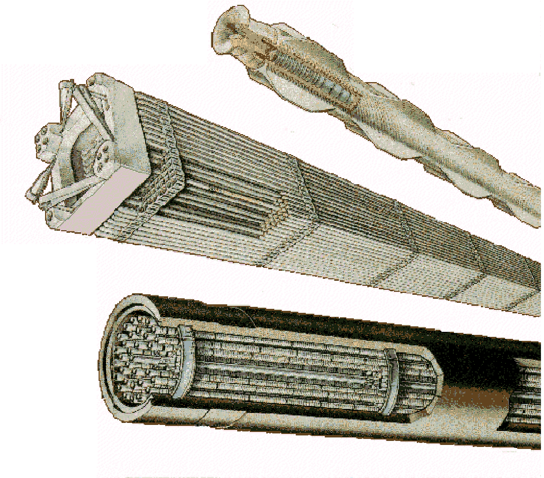


Fig. 8.2 Fuel Elements for different reactor types. Top: MAGNOX; middle: PWR; bottom AGR.

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.

8.4 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.

8.5 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.

8.6 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.

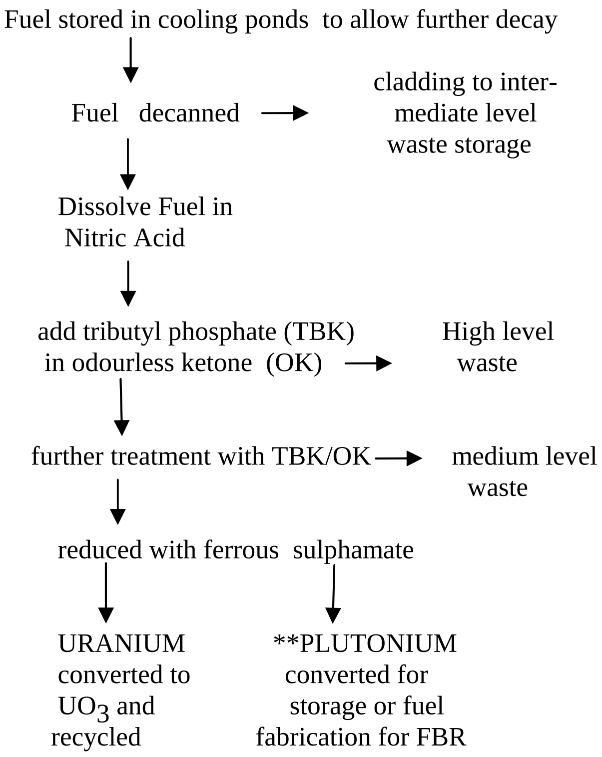
DISADVANTAGES:-

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').

8.7 REPROCESSING CYCLE - the chemistry



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

8.8 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!

9: Nuclear Fusion

9.1 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.

9.2 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.

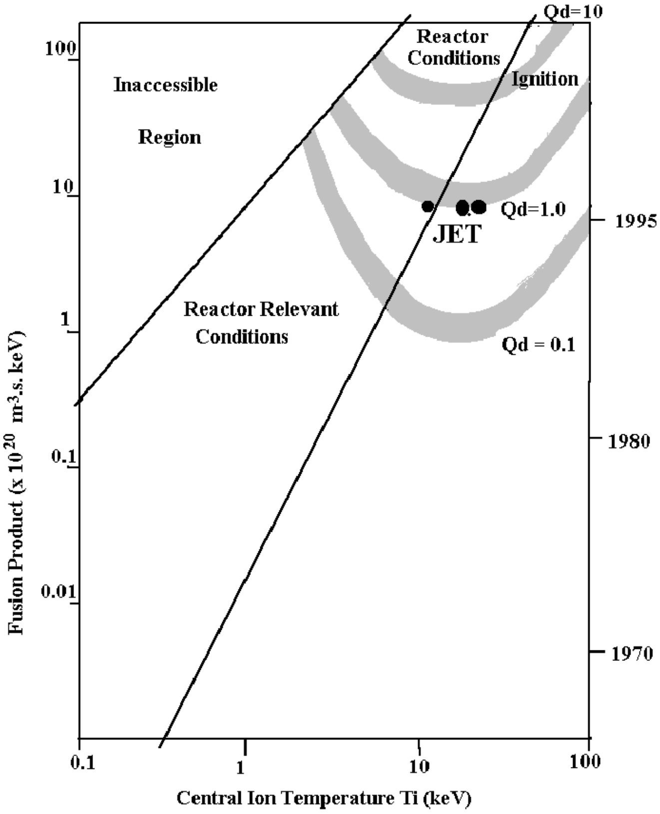
ii). The temperature must be high typically in excess of 100 million ^{o}C. The fusion reaction rate falls off dramatically such that at 10 million ^{o}C, the reaction rate is less than 1/20000th of that at 100 million ^{o}C.

iii). The confinement time of several seconds

iv).

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. 9.1

Fig. 9.1. Triple product plotted against Central Ion Temperature with a few selected data points from JET obtained during the 1990's



9.3 Progress towards fusion (based on triple product values)

Two terms are used here

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

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

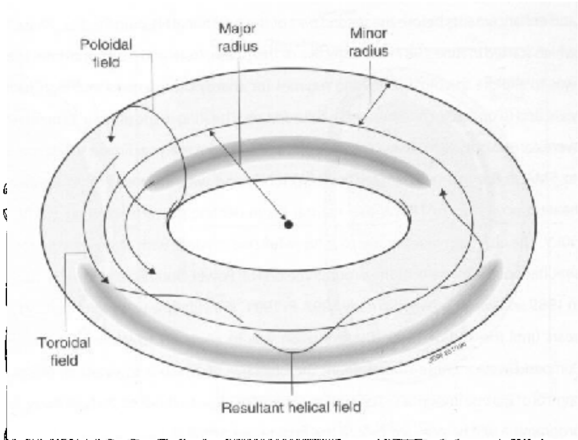
Date	Distance from Ignition
1970	25 000 times away
1980	700 times away
1983	100 times away
1988	20 times away
1989	10 times away
1991	Break even achieved and now about 6 times away from ignition

JET was not designed to go above about break even, and experiments are now looking at numerous aspects associated with the design of ITER - International Thermonuclear Experimental Reactor

Fig. 9.2 A simplified section of a fusion device showing the helical magnetic field

9.4 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 (Figure 9.2)



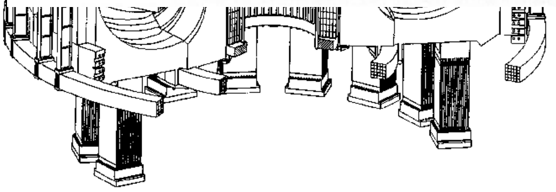


Fig. 9.3 Cross Section of the JET reactor - the Plasma chamber is "D" shaped.

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. 9.2, while the actual cross section of the JET reactor is shown in Fig. 9.3.

9.5 A full Reactor design for commercial operation

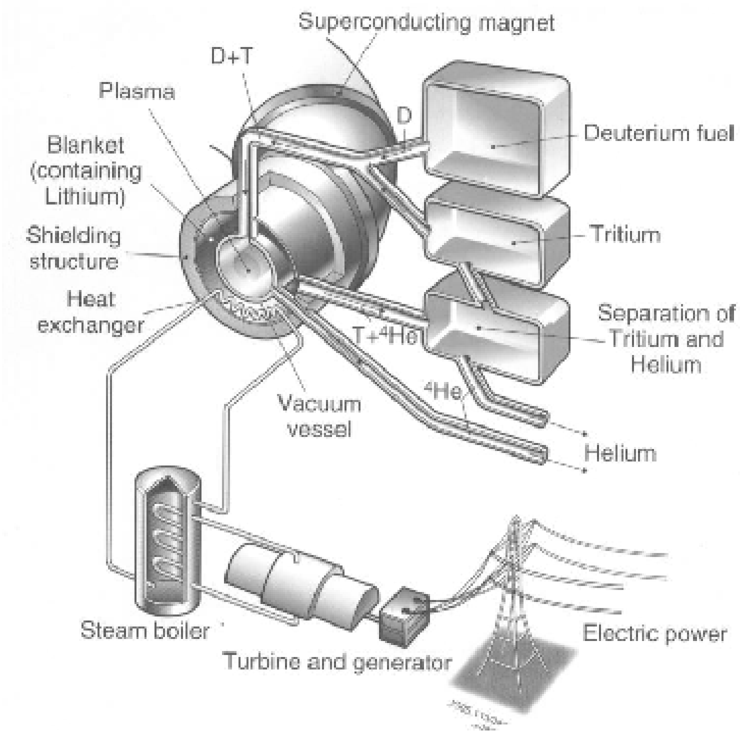
Fig .9.4 shows a schematic of how a commercial reactor might operate. The Deuterium and Tritium are fed into the reaction chamber and the waste product is Helium. Neutrons pass through to the Lithium blanket to generate Tritium and further Helium which are separated as shown. The heat from the reaction is cooled by a cooling circuit which in turn raises steam for generation of electricity in the normal way

Fig. 9.4 showing a schematic of a possible commercial fusion power reactor.

9.6 Why is it taking so long?

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

Current experiments in the late 1990's have tackled this problem by redesigning the "D" to incorporate divertors at the base. The magnetic field can be altered to cause the impurity ions to collect in the diverter area and hence be withdrawn from the system. The latest thoughts of the shape are shown in Fig. 9.5.



9.6 Safety

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

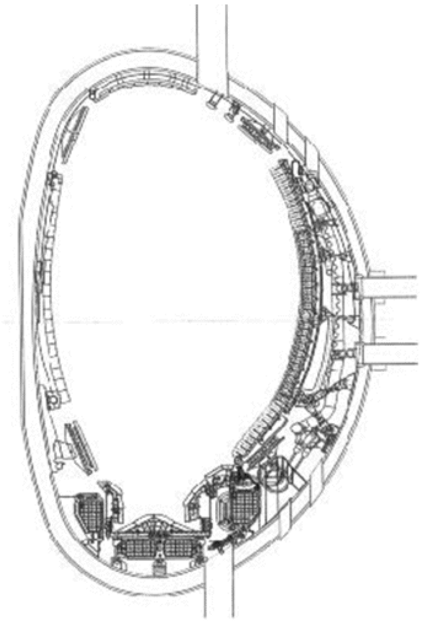


Fig. 9.5 the current shape of the "D" showing the divertor box at the base which is used to remove impurities.