# Nuclear Power Plant

FOURTH YEAR
ELECTROMECHANICAL ENGINEERING
DEPARTMENT

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2010

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# CHAPTER ONE
# INTRODUCTION

## 1.1 STRATEGY

- The strategic importance lies primarily in the fact that one large nuclear power plant saves more than 50,000 barrels of oil per day, such a power plant would pay for its capital cost in a few short years. For those countries that now rely on but do not have oil, or must reduce the importation of foreign oil.
- For those countries that are oil exporters, nuclear power represents an insurance against the day when oil is depleted.
- The unit costs per kilowatt-hour for nuclear energy are now comparable to or lower than the unit costs for coal in most parts of the world. Other advantages are the lack of environmental problems that are associated with coal or oil-fired power plants and the near absence of issues of mine safety, labor problems, and transportation bottle-necks.
- Natural gas is a good, relatively clean-burning fuel, but it has some availability problems in many countries and should, in any case, be conserved for small-scale industrial and domestic uses.
- Thus nuclear power is bound to become the social choice relative to other societal risks and overall health and safety risks. Other sources include hydroelectric generation, which is nearly fully developed with only a few sites left around the world with significant hydroelectric potential.
- Solar power, although useful in outer space and domestic space and water heating in some parts of the world, is not and will not become an economic primary source of electric power.
- The nuclear industry is facing many difficulties, particularly in the United States, primarily as a result of the negative impact of the issues of nuclear safety waste disposal, weapons proliferation, and economics on the public and government. The impact on the public is complicated by delays in licensing proceedings, court and ballot box challenges. These posed severe obstacles to electric utilities planning nuclear power plants, the result being scheduling problems, escalating and unpredictably costs, and economic risks even before a construction permit is issued. Utilities had a delay or cancel nuclear projects so that in the early 1980s there was a de fan moratorium on new nuclear plant commitments in the United States. It is, however, the opinion of many, including this author, that despite these difficulties the future of large electric-energy generation includes nuclear energy as a primary, if not the main,

source. The signs are already evident in many European and Asian countries such as France, the United Kingdom, Japan, and the U.S.S.R.

## 1.2 GENERAL HISTORY AND TRENDS

### 1.2.1 MAJOR EVENTS

- **1945:** "Nuclear energy emerged from scientific obscurity and military secrecy."
- **1945-55:** "An enthusiastic vision developed of a future in which nuclear power would provide a virtually unlimited solution for the world's energy needs."
- **1955-73:** The pros and cons of nuclear energy were debated; however, the optimists prevailed and nuclear energy grew to become an important source of electricity.
- **Pros:** Abundant, clean, and cheap energy. (We now know nuclear energy is not cheap.)
- **Cons:** Large amounts of radioactivity are produced in the nuclear reactor, mishaps cannot be totally ruled out, and nuclear energy cannot be divorced from nuclear weapons. (Also, the long-term storage of nuclear wastes is now a very important issue.)
- **1955-65:** Many reactors designed, built, and put into operation.
- **1965-73:** Most of the US reactors were ordered during this period.
- **1973-85:** Many US reactors canceled during this period.
- **1970-90:** Most US reactors licensed to operate during this period.
- **1990-present:** The number of nuclear reactors operating in the US and in the world leveled off, reaching a plateau. Few new reactors ordered and built.

Nuclear reactors started producing electricity in a significant way beginning about 1970 — just before the first international oil crisis in 1973. Thus, many countries saw nuclear energy as a means to reduce dependency on foreign oil. The US government saw nuclear energy as an important key to "energy independence." However, the 1973 oil crisis leads to "side effects," which adversely affected nuclear energy:

The oil crises reduced economic growth, thus, decreasing the demand for energy and electricity. These effects reduced the demand for new nuclear plants. By 1973, the cost of nuclear energy was no longer regarded as "cheap," as had been touted in the early days of nuclear energy development, and safety concerns were starting to have an impact on the public view of nuclear energy. Also, nuclear energy was regarded as "establishments," and there were many protests against the establishment and its programs. US nuclear energy capacity has been steady since the late 1980s. Currently, **about 22% of US electricity is generated from**

**nuclear energy**. However, **coal is "king," generating about 55% of US electricity**. **Hydro generates about 10% of US electricity**. The US generates more electricity from nuclear energy than any other nation. However, **France generates the greatest percentage of electricity from nuclear energy — about 75-80%**. France is followed by Sweden. In 1994, **Sweden generated about 50% of its electricity from nuclear energy**. Worldwide, for 1994, nuclear energy accounted for 6% of the primary energy consumption and 18% of the electricity generation. These numbers are just below the values for the US. 424 nuclear reactors operate worldwide, with a total capacity of 338GWe, spread over 30 countries. In all but a few countries, nuclear energy growth was brought to a stop or at least to a crawl in the late 1980s and the 1990s. A summary of the reasons is:

• Reduction in oil and gas prices, especially since the late 1980s.
• Reduced growth in energy, compared to the pre-1973 period.
• Rising cost of nuclear energy.
• Increasing fears about nuclear energy.
• Campaigns against nuclear energy.

Public interest in nuclear energy began about 1944, grew strongly until about 1974, reached its peak then, and by 1994 dropped to a low level. Is the age of nuclear energy over? Outside of a few countries, will more reactors be built? Has the verdict been given on nuclear energy?

### 1.2.2 TECHNICAL HISTORY AND DEVELOPMENTS

#### Developments Prior to and During WW-2

• 1896: discovery of radioactivity.
• 1911: discovery of the nuclear atom.
• 1911: Rutherford noted the enormous amount of energy associated with nuclear reactions compared to chemical reactions.
• 1932: discovery of neutron.
• 1938: discovery of nuclear fission.
• 1939: researchers recognized that enough neutrons were released during fission reactions to sustain a chain reaction (in a pile of uranium and graphite). A chain reaction requires the release of two neutrons (or more) for every neutron used to cause the reaction.
• 1942 (Dec. 2): demonstration of the first operating nuclear reactor (200 Watts).
• 1943 (Nov.): 1 mW reactor put into operation at Oak Ridge, Tennessee.
• 1944 (Sept.): 200 mW reactor put into operation at Hanford, Washington—for the production of plutonium. This reactor was built in only 15 months.

• 1944 (Sept.): nuclear reactor for electricity generation proposed, using water for both cooling and neutron moderation. Essentially, this is the birth of nuclear energy for civilian use.

**Developments after WW-2**

• 1946: AEC (Atomic Energy Commission) established to oversee both military and civilian nuclear energy.

• 1953: Putman report/book, a thoughtful analysis of the case for nuclear energy for electricity production.

• 1953: US Navy began tests of the PWR (pressurized water reactor).

• 1957: 60 mW reactor at Shippingport, PA began to generate electricity for commercial use. The plant was built by the AEC, though Navy leadership played a predominant role.

• 1953-60: exploratory period: 14 reactors built, of many different designs, all but 3 under 100 mW size.

• 1960-65: only 5 reactors built.

• 1965-73: main period of ordering of nuclear reactors in the US. Size was much larger than before, many reactors of 600 to 1200 mW size.

• 1974: “honeymoon” over-nuclear energy no longer highly valued by the public.

• 1973-78: fall off in orders, with no US orders after 1978.

• 1974-85: cancellation of orders, over half of orders were canceled, or construction never brought to completion. Most reactors ordered prior to 1970 were built and brought on line. Many reactors ordered after 1970 never came on line they were canceled.

• 1970-90: most of US’s reactors brought on line for commercial operation, indicating that most US reactors are 7 to 27 years old, or have 13 to 33 years of operation left, assuming a 40 year operating life.

• 1979: Three Mile Island accident. Reactor shut down.

• 1986: Chernobyl accident.

• Early 1990s: 7 nuclear reactors shut down, including 3 of early design and 4 of marginal performance. These shutdowns do not necessarily mean than a steady stream of reactors will be shut down before their nominal life of 40 years is reached.

• 1990s: Shoreham (Long Island) reactor shut down for good by public protest.

# CHAPTER TWO
# ENERGY GENERATION PROCESSES

## 2.1 INTRODUCTION

In 1803 John Dalton, attempting to explain the laws of chemical combination, propose his simple but incomplete atomic hypothesis. He postulated that all elements consist of indivisible minute particles of matter, atoms, that were different for different elements and preserved their identity in chemical reactions. In 1811 Amadeo Avo-gadro introduced the molecular theory based on the molecule, a particle of matter composed of a finite number of atoms. It is now known that the atoms are themselves composed of sub particles, common among atoms of all elements.

An atom consists of a relatively heavy, positively charged nucleus and a number of much lighter negatively charged electrons that exist in various orbits around the nucleus. The nucleus, in turn, consists of sub particles, called nucleons. Nucleons at primarily of two kinds: the neutrons, which are electrically neutral, and the proton: which are positively charged. The electric charge on the proton is equal in magnitude but opposite in sign to that on the electron. The atom as a whole is electrically neutral the number of protons equals the number of electrons in orbit. One atom may be transformed into another by losing or acquiring some of the above sub particles. Such reactions result in a change in mass Am and therefore release (or absorb) large quantities of energy *DE*, according to Einstein's law

$$\Delta E = \frac{1}{g_c} mc^2 \qquad 2.1$$

Where *c* is the speed of light in vacuum and $g_c$ is the familiar engineering conversion factor. Equation (2.1) applies to *all* processes, physical, chemical, or nuclear, in which energy is released or absorbed. Energy is, however, classified as *nuclear* if it is associated with changes in the atomic nucleus.

Figure 2.1 shows three atoms. Hydrogen has a nucleus composed of one proton, no neutrons, and one orbital electron. It is the only atom that has no neutrons. Deuterium has one proton and one neutron in its nucleus and one orbital electron. Helium contains two protons, two neutrons, and two electrons. The electrons exist in orbits, and each is quantitized as a lumped unit charge as shown. Most of the mass of the atom is in the nucleus. The masses of the three primary atomic sub particles are

Neutron mass $m_n$ = 1.008665 amu

Proton mass $m_P$ = 1.007277 amu

Electron mass $m_e$ = 0.0005486 amu.

The abbreviation amu, for *atomic mass unit*, is a unit of mass approximately equal to 1.66 × $10^{-27}$ kg. These three particles are the primary building blocks of all atoms. Atoms differ in their mass because they contain varying numbers of them.

Atoms with nuclei that have the same number of protons have similar chemical and physical characteristics and differ mainly in their masses. They are called *isotopes*. For example, deuterium, frequently called *heavy hydrogen*, is an isotope of hydrogen. It exists as one part in about 6660 in naturally occurring hydrogen. When combined with oxygen, ordinary hydrogen and deuterium form *ordinary water* (or simply water) and *heavy water*, respectively.

The number of protons in the nucleus is called the *atomic number Z*. The total number of nucleons in the nucleus is called the mass *number A*.

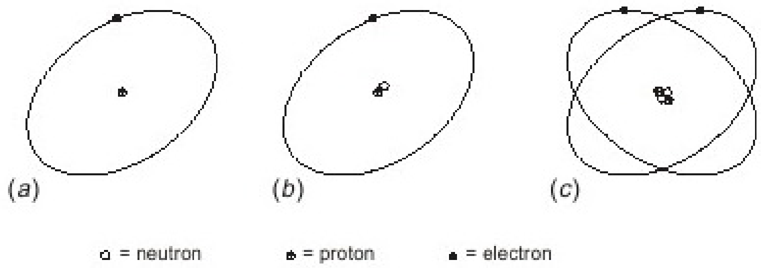



**Fig. 2.1**

As the mass of a neutron or a proton is nearly 1 amu, *A* is the integer nearest the mass of the nucleus which in turn is approximately equal to the atomic mass of the atom. Isotopes of the same element thus have the same atomic number but differ in mass number. Nucleus symbols are written conventionally as

$${}_{Z}X^{A}$$

Where X is the usual chemical symbol. Thus the hydrogen nucleus is ${}_{1}H^{1}$, deuterium is ${}_{1}H^{2}$ (and sometimes D), and ordinary helium is ${}_{2}He^{1}$. For particles containing no protons, the subscript indicates the magnitude and sign of the electric charge. The electron is – $e°$ (sometimes $e$ or β) and a neutron is ${}_{0}n^{1}$. Symbols are also often written in the form He-4, helium-4, etc.

Fig. 2.2 shows, schematically, the structure of $H^1$, $He^4$ and some heavier atoms and the distribution of their electrons in various orbits. Two other particles of importance are the positron and the neutrino. The

*positron* is a positively charged electron having the symbols $_{+1}e^0$, $e^+$ or β. The neutrino (little neutron) is a tiny electrically neutral particle that is difficult to observe experimentally. Initial evidence of its existence was based on theoretical considerations, nuclear reactions where *a*/3 particle of either kind is emitted or captured, the resulted energy (corresponding to the lost mass) was not all accounted for by the energy the emitted 13 particle and the recoiling nucleus. It was first suggested by Wolfgai Pauli in 1934 that the neutrino was simultaneously ejected in these reactions and it carried the balance of the energy, often larger than that carried by the β particle itself. The importance of neutrinos is that they carry some 5 percent of the total energy produced in fission. This energy is completely react lost because neutrinos do not rea and are not stopped by any practical structural material. The neutrino is given the symbol *u*.

There are many other atomic sub particles. An example is the *mesons*, unstable positive, negative, or neutral particles that have masses intermediate between an electron and a proton. They are exchanged between nucleons and are thought to account for the forces between them.

Electrons that orbit in the outermost shell of an atom are called *valence electron*. The outermost shell is called the *valence shell*. Thus, hydrogen has one valence electron and its K shell is the valence shell, etc. Chemical properties of an element are function of the number of valence electrons. The electrons play little or not part nuclear interactions.

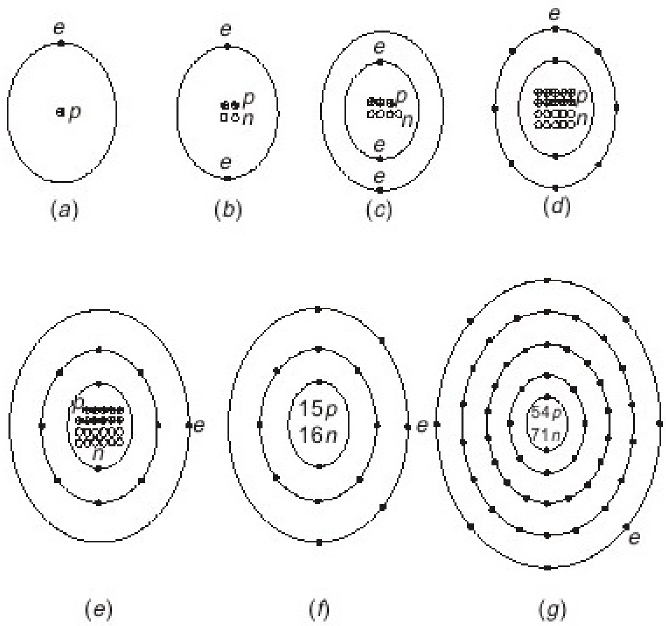



**Fig. 2.2**

## 2.2 SUMMARY OF NUCLEAR ENERGY CONCEPTS AND TERMS

### 2.2.1 Fission

Unstable (radioactive) elements spontaneously split (radioactive decay), emitting high energy particles. Collision of particles with other atomic nuclei can trigger further nuclear decompositions. A small amount of mass is converted into a large amount of energy, when atomic nuclei are split.

Einstein equation: $E = mc^2$, conversion of mass to energy.

$E$ = energy, $m$ = mass converted, $c$ = speed of light

2.2.2 Critical Mass

There is a threshold mass of a radioactive isotope at which the flux density of radioactive particles will sustain a chain reaction. If this reaction is uncontrolled the result is an atomic bomb explosion. If the radiation fluxes are controlled and limited, we call it a nuclear reactor, which can be the basis of an electric power plant.

| Types of Radiation | Atomic Weight | Charge |
|---|---|---|
| Alpha radiation (Helium nucleus) | 4 | +2 |
| Beta radiation (Electron) | ~0 | – 1 |
| Neutron | 1 | 0 |
| Gamma ray | ~0 | 0 |

2.2.3 Alpha Radiation

Alpha is quickly absorbed by matter because the particles have a large probability of collision with nuclei. Sources external to the human body cause radiation absorption within the thickness of the skin. Radiation from airborne particles in the lung is absorbed by surface membranes lining the lung. Alpha emitters ingested with food cause radiation absorption by the lining of the gut. The risk of genetic damage to adult organisms is very small because absorption takes place in surface cells.

2.2.4 Beta Particles

Beta particles penetrate to the deepest parts of the body and can cause genetic damage and disrupt the function of cells anywhere in the body. Building walls and earthwork provide substantial shielding.

2.2.5 Gamma Particles

Gamma has the greatest penetration due to their small cross-section. Gamma particles can pass through ordinary materials. Effective shielding requires blankets of lead. Gamma radiation is a danger to all cells in the body.

2.2.6 Uranium Fission

$$_{92}U^{235} + {_0}n^1 \rightarrow {_{92}}U^{236} \rightarrow \text{Fission Products}$$

$$_{92}U^{238} + {_0}n^1 \rightarrow {_{92}}U^{239} + \text{Gamma} \rightarrow \text{Fission Products}$$

$$_{92}U^{239} \rightarrow \underset{\text{Neptunium}}{{_{92}}NP^{239}} \rightarrow \underset{\text{Plutonium}}{{_{94}}PU^{239}}$$

After many steps, (and a long time) the ultimate product is non-radioactive Lead atoms. The neutrons, whose absorbtion is indicated above, come from splitting of later fission products in reactions not shown here. Note that U-235 fission in the presence of U-238 causes the conversion of part of the U-238 into Plutonium-239 which can be concentrated to make an H-Bomb. Intermediate isotopes of health significance include Cesium-137, Iodine-131, Strontium-90 and many others.

### 2.2.7 Half Life, T

Time for half the atomic nuclei to spontaneously split. The amount decays exponentially

$N = No \exp(-t/T)$

N = Amount of radioactive material,

No = Initial amount,

*t* = Elapsed time

## 2.3 ETHICAL PROBLEMS IN NUCLEAR POWER REGULATION

The Atomic Energy Commission (AEC), was formed to create a civilian nuclear energy industry, and had conflicting responsibilities:

- Promoting Nuclear Power
  - —funded research in plant design
  - —subsidized production of nuclear fuel
- Regulating Plant Safety
  - —defined safety procedures, poor enforcement
  - —inspecting, certifying plants
  - —certifying operators, poor training

As a result of these conflicting interests

- No Long Term Waste Dispotal Plan was Completed
  - —wastes are still accumulating in temporary storage
  - —radioactive waste? NIMBY
- Future Termination/Cleanup Costs are not Factored into Current Electric Rates
- Power Companies are Largely Self-Regulated
  - —avoid reporting radiation release or do not monitor releases.

—avoid safety regulations to save money.

## 2.4 CHEMICAL AND NUCLEAR EQUATIONS

Chemical reactions involve the combination or separation of whole atoms.

$$C + O_2 = CO_2$$

This reaction is accompanied by the release of about 4 electron volts eV. An *electron volt* is a unit of energy in common use in nuclear engineering. 1 eV = 1.6021 × $10^{-19}$ joules (J) = 4.44 × $10^{-26}$ kWh. 1 million electron volts (1 MeV) = $10^{+6}$ eV.

In chemical reactions, each atom participates as a whole and retains its identity. The molecules change. The only effect is a sharing or exchanging of valence electrons. The nuclei are unaffected. In chemical equations there are as many atoms of each participating element in the products (the right-hand side) as in the reactants (the left-hand side). Another example is one in which uranium dioxide ($UO_2$) is converted into uranium tetra fluoride ($UF_4$), called green salt, by heating it in an atmosphere of highly corrosive anhydrous (without water) hydrogen fluoride (HF), with water vapor ($H_2O$) appearing in the products

$$UO_2 + 4HF = 2H_2O + UF_4$$

Water vapor is driven off and UF, is used to prepare gaseous uranium hexafloride ($UF_6$), which is used in the separation of the $U^{235}$ and $U^{238}$ isotopes of uranium by the gaseous diffusion method. (Fluorine has only one isotope, $F^9$, and thus combi-nations of molecules of uranium and fluorine have molecular masses depending only on the uranium isotope.)

Both chemical and nuclear reactions are either *exothermic* or *endothermic*, that is, they either release or absorb energy. Because energy and mass are convertible, Eq. 2.1, chemical reactions involving energy do undergo a mass decrease in exothermic reactions and a mass increase in endothermic ones. However, the quantities of energy associated with a chemical reaction are very small compared with those of a nuclear reaction, and the mass that is lost or gained is minutely small. This is why we assume a preservation of mass in chemical reactions, undoubtedly an incorrect assumption but one that is sufficiently accurate for usual engineering calculations.

In nuclear reactions, the reactant nuclei do not show up in the products, instead we may find either isotopes of the reactants or other nuclei. In balancing nuclear equations it is necessary to see that the same, or equivalent, nucleons show up in the products as entered the reaction.

For example, if K, L, M, and N were chemical symbols, the corresponding nuclear equation might look like

$$_{Z1}K^{A1} + _{Z2}L^{A2} \rightarrow _{Z3}M^{A3} + _{Z4}N^{A4}$$

To balance the following relationship must be satisfied.

$$Z_1 + Z_2 = Z_3 + Z_4$$
$$A_1 + A_2 = A_3 + A_4$$

Sometimes the symbols y or v is added to the products to indicate the emission of electromagnetic radiation or a neutrino, respectively. They have no effect on equation balance because both have zero Z and A, but they often carry large portions of the resulting energy.

Although the mass numbers are preserved in a nuclear reaction, the masses of the isotopes on both sides of the equation do not balance. Exothermic or endothermic energy is obtained when there is a reduction or an increase in mass from reactants to products, respectively.

## 2.5 NUCLEAR FUSION AND FISSION

Nuclear reactions of importance in energy production are fusion, fission, and radioactivity. In fusion, two or more light nuclei fuse to form a heavier nucleus. In fission, a heavy nucleus is split into two or more lighter nuclei. In both, there is a decrease in mass resulting in exothermic energy.

The same as in force =1/g × mass × acceleration.

Table 2.1 Mass-energy Conversion factors

| Mass | MeV | J | kWh | mW day |
|---|---|---|---|---|
| amu | 931.478 | $1.4924 \times 10^{-10}$ | $4.1456 \times 10^{-17}$ | $9.9494 \times 10^{-13}$ |
| kg | $5.6094 \times 10^{29}$ | $8.9873 \times 10^{16}$ | $2.4965 \times 10^{10}$ | $5.9916 \times 10^{14}$ |

## 2.6 FUSION

Energy is produced in the sun and stars by continuous fusion reactions in which four nuclei of hydrogen fuse in a series of reactions involving other particles that continually appear and disappear in the course of the reactions, such as He, nitrogen, carbon, and other nuclei, but culminating in one nucleus of helium and two positrons resulting in a decrease in mass of about 0.0276 amu, corresponding to 25.7 MeV.

$$4\,_1H^1 = {}_2He^4 + 2\,_{+1}e^0$$

The heat produced in these reactions maintains temperatures of the order of several million degrees in their cores and serves to trigger and sustain succeeding reactions. On earth, although fission preceded fusion in both weapons and power generation. The basic fusion reaction was discovered first, in the 1920s, during research on particle accelerators. Artificially produced fusion may be accomplished when two light atom fuse into a larger one as there is a much greater probability of two particles colliding than of four. The 4-hydrogen reaction requires, on an average, billions of years for completion, whereas the deuterium-deuterium reaction requires a fraction of a second. To cause fusion, it is necessary to accelerate the positively charged nuclei to high kinetic energies, in order to overcome electrical repulsive forces, by raising their temperature to hundreds of millions of degrees resulting in a plasma. The plasma must be prevented from contacting the walls of the container, and must be confined for a period of time (of the order of a second) at a minimum density. Fusion reactions are called *thermonuclear* because very high temperatures are required to trigger and sustain them. Table 10.2 lists the possible fusion reactions and the energies produced by them.

Table 10.2

| Fusion reaction | | | Energy per reaction, MeV |
|---|---|---|---|
| Number | Reactants | Products | |
| 1 | D + D | T + $p$ | 4 |
| 2 | D + D | $He^3 + n$ | 3.2 |
| 3 | T + D | $He^4 + n$ | 17.6 |
| 4 | $He^3$ + D | $He^4 + p$ | 18.3 |

$n$, $p$, D, and T are the symbols for the neutron, proton, deuterium and tritium respectively.

Many problems have to be solved before an artificially made fusion reactor becomes a reality. The most important of these are the difficulty in generating and maintaining high temperatures and the instabilities in the medium (plasma), the conversion of fusion energy to electricity, and many other problems of an operational nature.

## 2.7 FISSION

Unlike fusion, which involves nuclei of similar electric charge and therefore requires high kinetic energies, fission can be caused by the neutron, which, being electrically neutral, can strike and fission the positively charged nucleus at high, moderate, or low speeds without being repulsed. Fission can be caused by other particles, but neutrons are the only practical ones that result in a sustained reaction because two or three neutrons are usually released for each one absorbed in fission. These keep

the reaction going. There are only a few fissionable isotopes $U^{235}$, $Pu^{239}$ and $U^{233}$ are fissionable by neutrons of all energies.

The immediate (prompt) products of a fission reaction, such as Xe° and $Sr^{y4}$ above, are called fission fragments. They, and their decay products, are called fission products. Fig. 2.4 shows fission product data for $U^{235}$ by thermal and fast neutrons and for $U^{233}$ and $Pu^{239}$ by thermal neutrons 1841. The products are represented by their mass numbers.

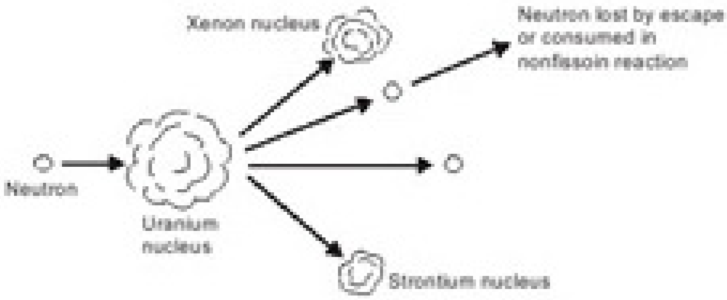



**Fig. 10.3**

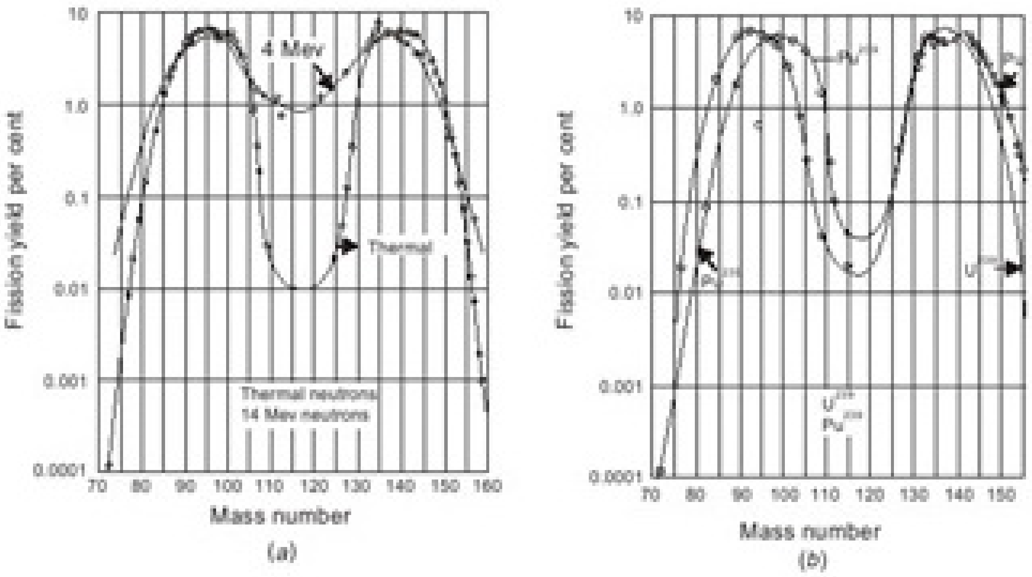



Fig. 2.4

## 2.8 ENERGY FROM FISSION AND FUEL BURN UP

There are many fission reactions that release different energy values. Another

$${}_{92}U^{235} + {}_{0}n^{1} \rightarrow {}_{56}Ba^{137} + {}_{36}Kr^{97} + 2\,{}_{0}n^{1} \qquad ...(1)$$

has the mass balance

$$235.0439 + 1.00867 \rightarrow 136.9061 + 96.9212 + 2 \times 1.00867$$

$$236.0526 \longrightarrow 235.8446$$

$$\Delta m = 235.8446 - 236.0526 = -0.2080 \text{ amu} \qquad \text{...(2)}$$

Thus $\Delta E = 931 \times -0.2080 = -193.6$ MeV $= -3.1 \times 10^{-11}$ J ...(3)

On the average the fission of a U235 nucleus yields about 193 MeV. The same figure roughly applies to $U^{233}$ and $Pu^{239}$. This amount of energy is prompt, *i.e.*, released at the time of fission. More energy, however, is produced because of (1), the slow decay of the fission fragments into fission products and (2) the non-fission capture of excess neutrons in reactions that produce energy, though much less than that of fission.

The *total energy,* produced *per* fission reaction, therefore, is greater than the prompt energy and is about 200 MeV, a useful number to remember.

The complete fission of 1 g of $U^Z$ nuclei thus produces

$$\frac{\text{Avogadro's number}}{U^{235}} = 200\ MeV = \frac{0.60225 * 10^{24}}{235.0439} * 200$$

= 0.513 × 1024 MeV = 2.276 × 1024 kWh

= 8.190 × 1010 J = 0.948 MW-day.

Another convenient figure to remember is that a reactor burning 1 g of fissionable material generates nearly 1 MW-day of energy. This relates to fuel burnup. Maximum theoretical burnup would therefore be about a million MW-day/ton (metric) of fuel. This figure applies if the fuel were entirely composed of fissionable nuclei and all of them fission. Reactor fuel, however, contains other nonfissionable isotopes of uranium, plutonium, or thorium. Fuel is defined as all uranium, plutonium, and thorium isotopes. It does not include alloying or other chemical compounds or mixtures. The term fuel material is used to refer to fuel plus such other materials.

Even the fissionable isotopes cannot be all fissioned because of the accumulation of fission products that absorb neutrons and eventually stop the chain reaction. Because of this-and owing to metallurgical reasons such as the inability of the fuel material to operate at high temperatures or to retain gaseous fission products [such as Xe and Kr, in its structure except for limited periods of time-burnup values are much lower than this figure. They are, however, increased somewhat by the fissioning of some

fissionable nuclei, such as $Pu^{z3y}$, which are newly converted from fertile nuclei, such as $U^{238}$. Depending upon fuel type and *enrichment* (*mass* percent of fissionable fuel in all fuel), burnups may vary from about 1000 to 100,000 MW-day/ton and higher.

## 2.9 RADIOACTIVITY

Radioactivity is an important source of energy for small power devices and a source of radiation for use in research, industry, medicine, and a wide variety of applications, as well as an environmental concern.

Most of the naturally occurring isotopes are stable. Those that are not stable, *i.e.*, *radioactive*, are some isotopes of the heavy elements thallium (Z = 81), lead (Z = 82), and bismuth (Z = 83) and all the isotopes of the heavier elements beginning with polonium (Z = 84). A few lower-mass naturally occurring isotopes are radioactive, such as $K^{40}$, $Rb^{87}$ and $In^{115}$. In addition, several thousand artificially produced isotopes of all masses are radioactive. Natural and artificial radioactive isotopes, also called *radioisotopes*, have similar disintegration rate mechanisms. Fig. 2.5 shows a Z-N chart of the known isotopes.

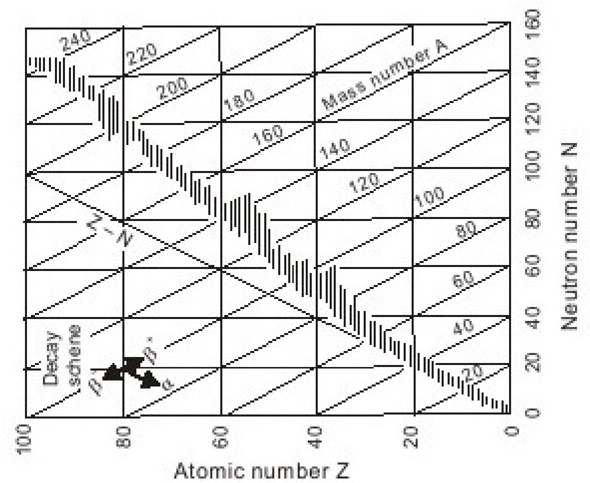



Fig. 2.5

*Radioactivity* means that a radioactive isotope continuously undergoes spontaneous (*i.e.*, without outside help) disintegration, usually with the emission of one or more smaller particles from the *parent* nucleus, changing it into another, or daughter, nucleus. The parent nucleus is said to decay into the *daughter* nucleus. The *daughter* may or may not be stable, and several successive decays may occur until a stable isotope is formed. An example of radioactivity is

$${}_{49}In^{115} = {}_{50}Sn^{115} + {}_{-1}e^{0}$$

Radioactivity is *always* accompanied by a *decrease* in mass and is thus always exothermic. The energy liberated shows up as kinetic energy of the emitted particles and as *y* radiation. The light particle is ejected at high speed, whereas the heavy one recoils at a much slower pace in an opposite direction.

Naturally occurring radio isotopes emit α, 3, or y particles or radiations. The artificial isotopes, in addition to the above, emit or undergo the following particles or reactions: positrons; orbital electron absorption, called K capture; and neutrons. In addition, neutrino emission accompanies β emission (of either sign).

**Alpha decay.** Alpha particles are helium nuclei, each consisting of two protons and two neutrons. They are commonly emitted by the heavier radioactive nuclei. An example is the decay of $Pu^{239}$ into fissionable $U^{235}$

$${}_{94}Pu^{239} = {}_{92}U^{235} + {}_{2}He^{4}$$

**Beta decay.** An example of β decay is

$${}_{82}Pb^{214} = {}_{83}Bi^{214} + {}_{-1}e^{0} + \nu$$

Where ν, the symbol for the neutrino, is often dropped from the equation. The penetrating power of β particles is small compared with that of *y*-rays but is larger than that of a particles. 6- and a-particle decay are usually accompanied by the emission of *y* radiation.

**Gamma radiation.** This is electromagnetic radiation of extremely short wavelength and very high frequency and therefore high energy. γ-rays and X-rays are physically similar but differ in their origin and energy: γ-rays from the nucleus, and X-rays from the atom because of orbital electrons changing orbits or energy levels. Gamma wave-lengths are, on an average, about one-tenth those of X-rays, although the energy ranges overlap somewhat. Gamma decay does not alter either the atomic or mass numbers.

# Chapter 3
# Design Requirements and Engineering Considerations

## 3.1 Introduction

This chapter is concerned with the thermal hydraulic design of the process systems that are required to transport heat energy away from the nuclear reactor source and transform this heat energy into useful work (generally electrical energy). The basic concept of the nuclear power plant is set by the overall objective, Do useful shaft work using a thermodynamic heat engine (a turbine) utilizing a heat source (a reactor) and a heat sink (a lake, sea, or the atmosphere).

This is conceptualized in figure 3.1. Figure 3.2 shows an overview of typical plant process systems. There are a number of inter-related systems, components and disciplines. These interact to form the design; limitations and characteristics of one affect the other. Consequently the process designer needs to have an appreciation of the characteristics and limitations of all the major pieces in order to carry out the detailed design of a particular system - i.e., in order to make intelligent choices. Design is, after all, the process of constraining the possible alternatives (in reaching a design objective) down to one choice. The overall goal is to provide an effective process within the context of the whole operation - this means the system must perform its process function safely and efficiently at a reasonable cost. The final arbitrators in resolving the conflicting demands of each subsystem are:

- low overall cost
- material limits (temperature, mechanical stress, erosion, corrosion, etc.)
- regulations
- past experience

- standardized design requirements
- quality assurance (QA)
- safety.

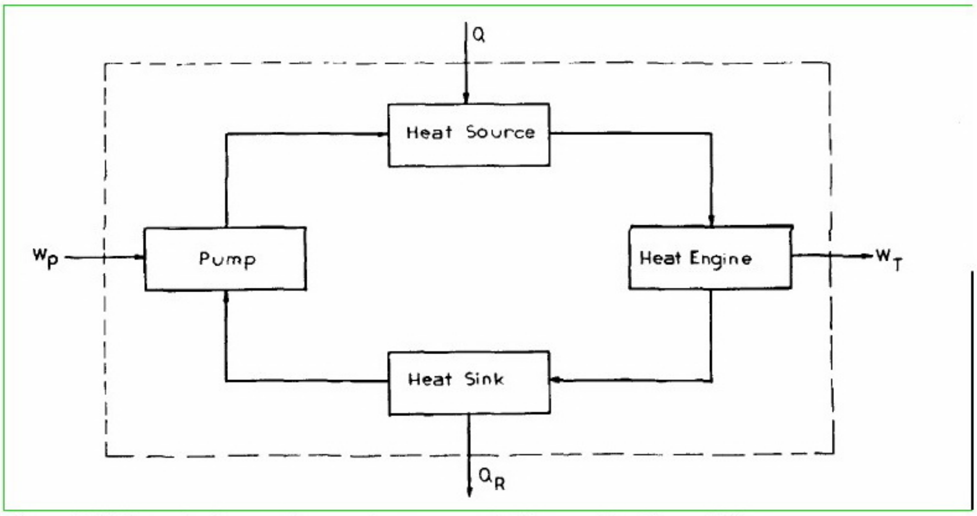



**Figure 1.1** Schematic diagram for a reactor power cycle [Source: Rust figure 2.7]

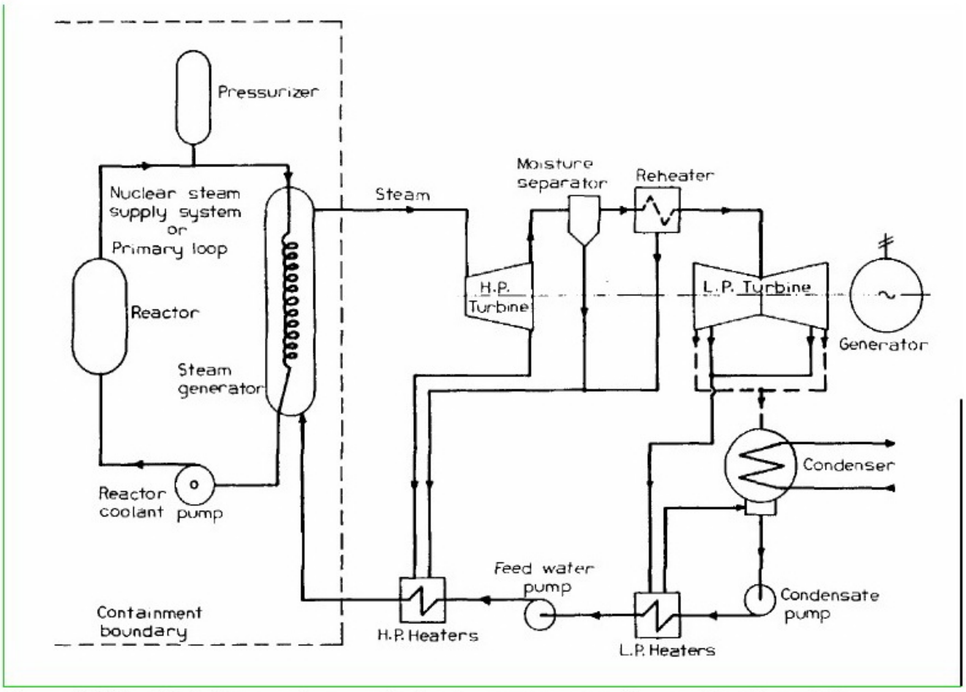



**Figure 1.2** Simplified diagram of a pressurized water reactor system [Source: Rust figure 1.1]

All presently developed nuclear power reactors act as sources of thermal energy, producing electricity through the conventional "heat engine" process. This is shown diagrammatically in Figure 3.3. In all current central generating station applications, steam is the final working fluid with more or less conventional steam turbines being employed to drive the electrical generators.

The thermal energy is generated within the nuclear fuel which resides within the nuclear reactor. This thermal energy is transferred from the fuel by a fluid medium called the reactor coolant. This fluid medium may be boiling water, in which case the steam may be used directly in the turbine (the reactor is then called a direct cycle reactor) or it may act as an intermediate heat transport medium, giving up its heat to raise steam in external heat exchangers called boilers or steam generators (the reactor is then called an indirect cycle reactor).

The various types of power reactors in use today differ regarding the nuclear fuel and the reactor coolants used and also in one further important regard, the type of medium used to slow down or moderate the high energy neutrons produced by the fission process.

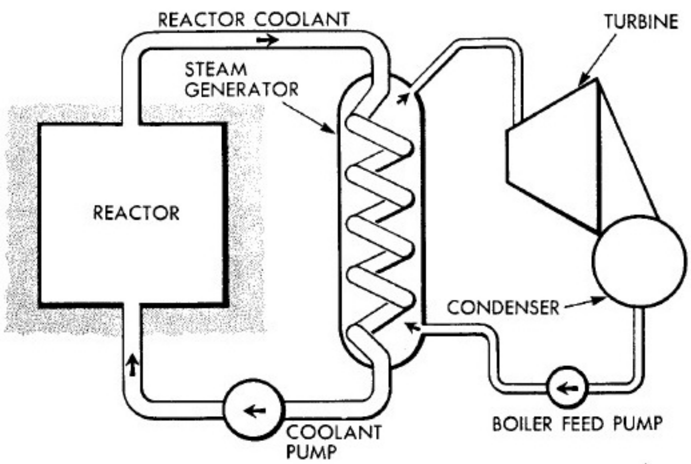



**Figure 3.3 Basic power reactor schematic arrangement**

## 3.2 Basic Neutron Cycle

Figure 3.4 depicts the basic neutron cycle wherein a slow neutron is absorbed by a fissile nucleus, causing fission and the emitting of 2 or 3 fast neutrons. The probability of these fast neutrons interacting with other fissile nuclei is low relative to the probability of fission with slow neutrons; hence, the fission neutrons must be slowed down or moderated. This is done by collision with the surrounding media. During the course of this interaction, some neutrons are lost by absorption that do not lead to fission (parasitic absorption).

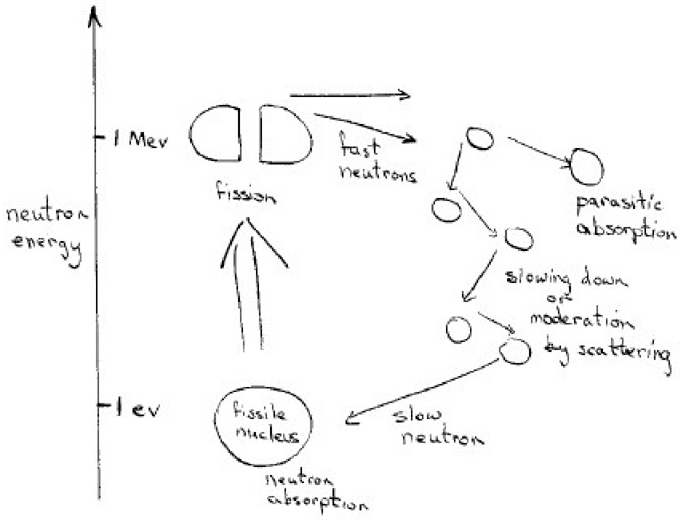
If one thermal (slow) neutron ultimately leads to at least one thermal neutron in the next generation, then a chain reaction is achieved. For this to be the case, the process must exhibit an "economy of neutrons". We need to:

- enhance the probability of neutron moderation
- reduce the probability of neutron absorption
- enhance the probability of fissioning.

This occurs subject to the following constraints:

- safety: the reaction needs to be controllable
- cost: overall cost should be minimized
- process: the reactor system must perform the desired function (ie, generate X MWe)

given the limitations such as heat sink capacity, etc




## 3.3 Possible Fuels

The probability of neutron capture leading to fission (called the fission cross section) is larger for slow neutrons than for fast neutrons. Hence, most practical reactors are "thermal" reactors, that is, they utilize the higher thermal reactors cross sections. Possible fuels include $^{233}U$ (a fissile material that can be formed from $^{232}Th$ by neutron bombardment) and $^{239}Pu$ (also fissile and produced from $^{238}U$ by neutron bombardment). With one notable exception, all other fissile fuels require a high energy neutron to fission and the cross section is low. The only naturally occurring fuel of significant quantities is $^{235}U$, hence most reactors use this fuel.

Naturally occurring uranium is composed of 0.7% $^{235}U$. The rest is $^{238}U$. This percentage is too low to sustain a chain reaction when combined with most practical moderators. Hence, to achieve criticality, either, the probability of fission must be enhanced or the moderator effectiveness must be enhanced. One group of reactor types (PWR, BWR, HTGR) enrich the fuel (a costly task) and use a cheap moderator (ordinary water or graphite). Alternatively, natural uranium (relatively

cheap) is used with an excellent but expensive moderator (heavy water). This is the CANDU approach. In a later section, we shall see why heavy water is such a good moderator. Enriching the fuel leads to a reactor system with a lower capital cost but higher operating cost than using natural uranium and heavy water. The overall cost over the life if the plant is about the same for either case. Fast fissions do occur with some of the U and can contribute up to 3% to the fission process. But more importantly, U is converted to Pu which subsequently fissions. In CANDU reactors and other reactors fuelled by natural uranium, roughly 50% of the power is generated through reactors with enriched fuel simply because there is relatively less $^{238}$U. This is less true for U present in the fuel.

Fast fissions do occure with $^{238}$U and can contribute up to 3% to the fission process. But more importantly, some of the 238U is converted to $^{239}$Pu which subsequently fissions. In CANDU reactors and other reactors filled by natural uranium, roughly 50% of the power is generated through 238U. This is less true with enriched fuel simply because there is relatively less $^{238}$U present in the fuel.

3.4 Heat Transfer Considerations

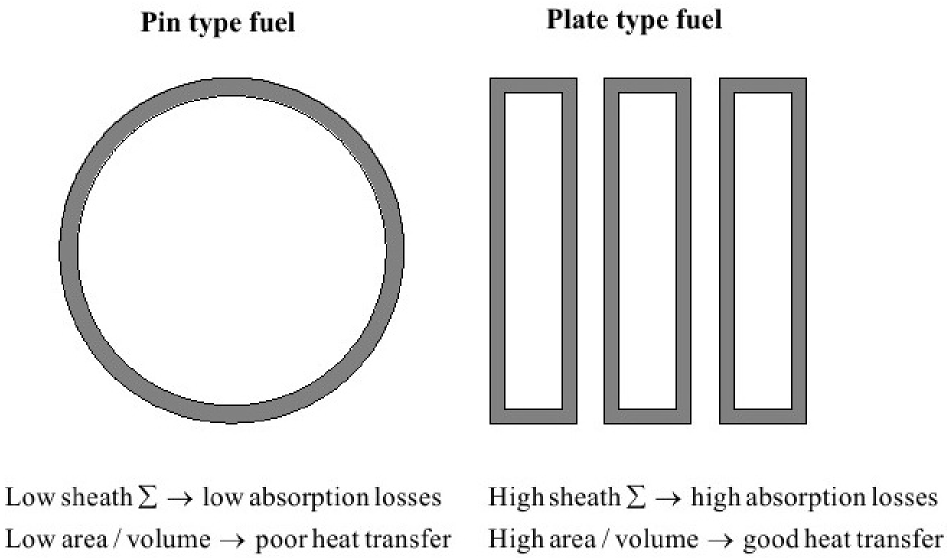



Figure 3 Tradeoff between heat transfer and neutron capture

In addition, to cope with internal pressure generated by fission product gases and swelling at high powers, the circular geometry is better. Tubes are also more economical to manufacture. Given that many geometries can be made to operate practically and safely, the choice boils down to one of cost.

## 3.5 Uranium Fuel Forms

In discussing fuel, coolants and moderators, you will note that neutron economy is repeatedly mentioned as an important parameter. This is true even for enriched uranium reactors because the amount of enrichment, and hence the cost of the fuel, is very sensitive to the neutron economy of the reactor. This is particularly so because the enriching of uranium is very costly since it involves an isotope separation process rather than a chemical separation process. No matter which process is chosen, it must utilize the very slight difference in physical properties between the U-238 and U-235 atoms; hence, the process is inherently costly.

In all commercial power reactors, the fuel is used in solid form. Various

geometries are employed such as solid rods, plates, spheres, or annular rings. Solid round rods (see Figure 4) are used predominantly, primarily because of manufacturing costs. A basic parameter governing fuel design is the external surface area to volume ratio. Good heat transfer to the coolant medium is promoted by high values of this ratio whereas low fuel manufacturing costs and, generally, good neutron economy are promoted by low values of this ratio. This presents a "classical" problem in optimization during the reactor design process, as discussed previously.

In certain power reactors, the fuel material is in the form of uranium metal. Other forms are also used as listed in table 1. Before discussing the merits of the alternative forms, it is useful to consider the desirable properties of fuel material. These are listed in table 2.

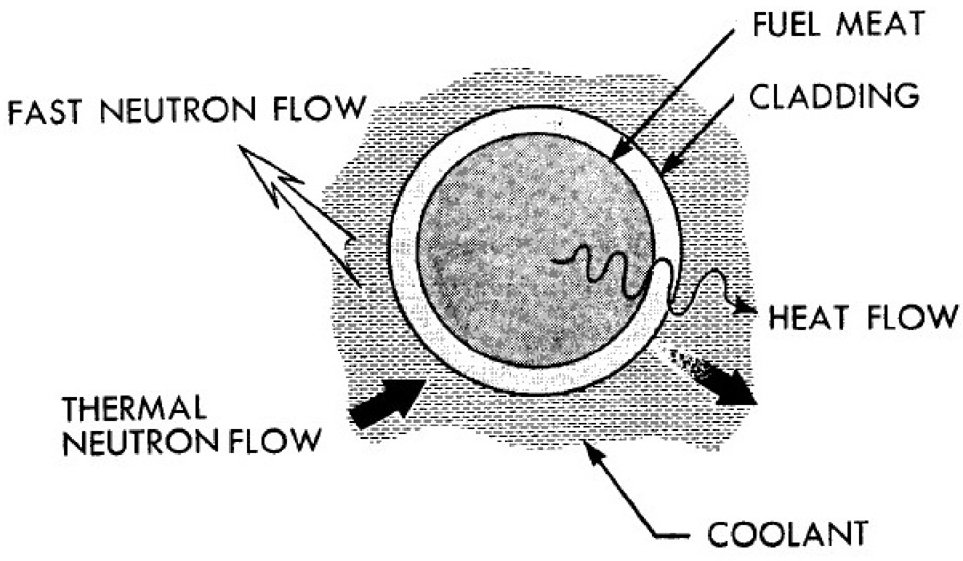



**Figure 4 Basic reactor fuel arrangement**

**Table 1 Forms of uranium in power reactor fuel**

1. URANIUM METAL
2. URANIUM/OTHER METAL. ALLOY
3. CERAMIC URANIUM DIOXIDE
4. URANIUM CARBIDE
5. URANIUM SILICIDE

**Table 2 Desirable fuel material properties**

1. LOW COST - CONSTITUENTS AND FABRICATION
2. GOOD NEUTRON ECONOMY
3. GOOD CORROSION RESISTANCE TO COOLANT
4. PHYSICAL STABILITY UNDER EFFECTS OF IRRADIATION, TEMPERATURE,
5. PRESSURE

Uranium metal is generally lowest in manufacturing cost and highest in neutron economy, the latter because of its high density and the absence of the other neutron absorbing elements. On the debit side of the ledger, it has poor corrosion resistance to most coolants which is of importance in the event of fuel cladding (to be discussed later) failures. Its geometric stability in reactor use is poor, primarily because of the swelling effects of fission products whose specific volume is, of course, greater than the parent uranium. Small quantities of alloying agents have been found useful but do not fully solve the problem.

The problem is aggravated by a metallurgical phase change at relatively moderate temperatures which causes further geometric distortion. This limits the operating power density achievable with the fuel.

Larger quantities of alloying agents such as zirconium can be used which effectively cure the geometric stability problem and the coolant corrosion problem. Unfortunately both the cost and neutron economy suffer. This fuel is used for certain specialized applications where the latter factors are not of overriding importance. Uranium - aluminum alloys are attractive for low power density, pressure and temperature situations such as research reactors.

Uranium dioxide is the form in which the uranium fuel is used in the vast majority of today's power reactors. It is somewhat more expensive to manufacture and less neutron economical than uranium metal because of its lower density but possesses excellent corrosion resistance to most

coolants and a high degree of geometric stability. Being a ceramic, it is capable of high operating temperatures.

Uranium carbide is attractive as a future fuel for certain types of reactors. It is relatively inexpensive to manufacture (comparable to $UO_2$) and has somewhat better neutron economy than $UO_2$ (because of its higher density, but not as good as uranium metal. It has good corrosion resistance to many coolants but unfortunately not to water. Its dimensional stability is good and it can operate at high temperatures. Uranium silicide is a more recent development having most of the advantages of uranium carbide and, in addition, adequate resistance to corrosion by water coolants.

The above properties of the various uranium fuel forms are summarized in the following table:

**Table 3 Uranium fuel form summary**

| U Fuel Form | Cost | Neutron Economy | Corrosion | Physical Stability |
|---|---|---|---|---|
| **U Metal** | Lowest (dense + no parasites) | OK | Poor | Poor (swells due to FP), limits power density |
| **U Alloy** | Higher | Lower | OK | OK |
| **$UO_2$** | Higher | Lower | Excellent | Excellent, high T possible |
| **UC** | Lower than $UO_2$ | $UO_2$<UC<U Metal | Good except against water | Good, high T possible |
| **US** | ~ UC | ~ UC | Good even with water | ~ UC |

### 3.7 Fuel Claddings

In the fission process, new isotopes of a wide variety of elements are produced. These are called fission products. Many of these remain radioactive for significant durations of time after they are generated and, hence, constitute a potential radiation hazard to plant operators and the public at large. It is therefore clearly desirable to keep these fission products "bottled up" within the fuel where they are generated. This is the primary function of the fuel cladding. This cladding takes the form of an impervious "skin" or "shell" which encloses the fuel material proper. Most cladding materials in current use are metals although ceramic-type materials have had limited use in certain applications. Table 3 lists the commonly used power reactor cladding materials. Before discussing the merits and demerits of each it is useful to consider the desirable properties of cladding materials. These are summarized in table 4.

**Table 4 Alternative fuel cladding materials**

1. ALUMINUM
2. MAGNESIUM (MAGNOX)
3. STAINLESSSTEEL
4. ZIRCONIUM
5. CERAMICS

**Table 5 Desirable cladding properties**

1. CORROSION RESISTANCE TO COOLANT
2. MECHAN ICAL DURABILITY
3. HIGH OPERATING TEMPERATURE CAPABILITY
4. GOOD NEUTRON ECONOMY
5. LOW COST - BASE MATERIAL & FABRICATION
6. IMPERMEABILITY TO FISSION PRODUCTS

Aluminum and its alloys possess many attractive properties such as low cost, easy fabrication, high ductility (important in preventing cladding failures), good neutron economy, and impermeability to fission products. Their major disadvantages for power reactor use are poor mechanical

properties at high temperatures and poor high temperature corrosion resistance with most coolants. Since the latter are temperature dependent, aluminum alloys are widely used in research reactor fuels where cladding operating temperatures are low but are not currently used in power reactors. Magnesium alloys are similar to aluminum alloys in most regards. An alloy called "Magnox" has, however, better high temperature properties and adequate corrosion resistance to permit its use in some $CO_2$ cooled power reactors.

Stainless steel is a very attractive material in all major regards except for its poor neutron economy. It has been and still is used in a number of enriched uranium reactors where its poor neutron economy is somewhat less important. Zirconium, in various low-alloy forms, is by far the most common cladding material in current use. Despite its relatively high base material cost, it combines to a large degree all of the other desirable cladding properties for use with most coolants. The use of ceramics and ceramic-type materials have potential for very high temperature applications. Their primary disadvantage is, of course, a lack of ductility which makes them liable to brittle fracture. The above properties of the various fuel cladding are summarized in the following table:

**Table 6 Fuel cladding summary**

| Cladding Type | Corrosion Resistance | Mechanical Durability | High T Capability | Neutron Economy | Cost | FP Containment |
|---|---|---|---|---|---|---|
| **Al** | Good except at high T | Low | Low | Good | Low | Good |
| **Mg** | ~Al, OK for CO2 | ~ Al | > Al | ~ Al | > Al | ~ Al |
| **Stainless Steel** | Good | Good | Good | Poor | Good | Good |
| **Zr** | OK | OK | OK | Excellent | High | Good |
| **Ceramic** | Good | Brittle | Excellent | OK | OK | OK |

### 3.8 Reactor Coolants

As discussed earlier, the purpose of the reactor coolant is to transport heat generated in the reactor fuel either to the turbine (direct cycle reactor) or to intermediate heat exchangers (indirect cycle reactor). The coolants may be liquids, two-phase liquid/vapour mixtures or gases. Table 5 lists the coolants commonly used in current power reactors. Table 6 lists the desirable properties of reactor coolants.

**Table 7 Alternatuve power reactor coolants**

1. $CO_2$ GAS
2. HELIUM
3. ORDINARY WATER
4. HEAVY WATER
5. ORGANIC FLUID
6. LIQUID METAL

**Table 8 Desirable features of reactor coolants**

1. HIGH HEAT CAPACITY
2. GOOD HEAT TRANSFER PROPERTIES
3. LOW NEUTRON ABSORPTION
4. LOW NEUTRON ACTIVATION
5. LOW OPERATING PRESSURE REQUIREMENT AT HIGH OPERATING TEMPERATURES
6. NON-CORROSIVE TO FUEL CLADDING AND COOLANT SYSTEM
7. LOW COST

Of the gases, two are in common use: $CO_2$ and helium. $CO_2$ has the advantages of low cost, low neutron activation (important in minimizing radiation fields from the coolant system), high allowable operating temperatures, good neutron economy and, for gases, relatively good heat transfer properties at moderate coolant pressures. At very high temperatures, it tends to be corrosive to neutron economical fuel cladding materials and also to the graphite moderator used in most gas-cooled reactors. Its chief drawback, as for all gases, is its poor heat transfer properties relative to liquids. As a result, coolant pumping power

requirements tend to be very high, particularly if high reactor power densities are to be achieved (desirable to minimize reactor capital costs). The other candidate gas, helium, possesses all of the good features of $CO_2$ and, in addition, is non- corrosive (if pure). Its chief disadvantages are higher costs, particularly operating costs, because helium is very "searching", leading to high system leakage rates unless extreme measures are taken to build and maintain a leak-proof system. This has, however, been successfully done in a number of cases. Of the candidate liquid coolants, ordinary water is by far the most commonly used. It is inexpensive, has excellent heat transfer properties, and is adequately non-corrosive to zirconium alloys used for fuel. and reactor structural components and ferritic or austenitic steel coolant system materials. Its disadvantages include only moderate neutron economy and its relatively high vapour pressure at coolant temperatures of interest. It is activated by neutrons in the reactor core but this activity dies away rapidly, permitting reasonable shutdown maintenance access to the coolant system. A further disadvantage is that water transports system corrosion products, permitting them to be activated in the reactor core. These activated corrosion products then create shutdown radiation fields in the coolant system. The water coolant may be used as a liquid in an indirect cycle system or may be permitted to boil, producing steam in a direct cycle system. Heavy water may also be used as a coolant. Its outstanding advantage is much better neutron economy relative to ordinary water. Its primary disadvantage is its high cost. Otherwise its properties are similar to ordinary water. Certain organic fluids (primarily hydrogenated polyphenyls) may also be used. They are moderate in cost, have a lower vapour pressure than water, are essentially non-corrosive, and are not significantly subject to neutron activation. Also they do not transport significant quantities of corrosion products which can become activated

in the reactor core. Their chief disadvantages include higher neutron absorption than heavy water (but lower than ordinary water), inflammability, and they suffer radio-chemical damage in the reactor core which leads to a requirement for extensive purification facilities and significant coolant make- up costs. On balance, however, they may well see wider application in the future. Certain liquid metals can be used as coolants. Of these, only sodium and a sodium/potassium eutectic called NaK have achieved significant use. Their advantages include excellent heat transfer properties and very low vapour pressures at high temperatures. Fuel cladding and coolant system materials require careful selection to avoid "corrosion". Their chief disadvantages include incomparability with water (the turbine working fluid), relatively high neutron absorption, a relatively high melting point (leading to coolant system trace heating requirements) and high coolant activation with sustained radiation fields after reactor shutdown. These disadvantages have effectively precluded the use of liquid metal coolants in commercial power reactors to date with one exception and this is the fast breeder reactor which will be discussed later. In this reactor, the neutrons are "used" at relatively high energy levels where the neutron absorption of the liquid metal is much less, overcoming one of the foregoing disadvantages. In addition, the economics of fast breeder reactors depend on very high core power densities where the excellent heat transfer capability of liquid metals becomes a major advantage. Furthermore, it is desirable in this type of reactor that the coolant not moderate the neutrons excessively. Liquid metals are superior to other liquids in this regard because they do not contain "light" atoms which are inherently effective moderators.

**Table 9 Coolant summary**

| Coolant Type | Cost | Neutron Economy | Corrosive | Heat Capacity | HT Coeff | Activation | Vapour Pressure | Other |
|---|---|---|---|---|---|---|---|---|
| **$CO_2$ Gas** | < He | Good | OK except at high T | Low | Low | Low | High | |
| **He** | Higher | Good | Good if pure | Low | Low | Low | High | Leaks |
| **$H_2O$** | Very low | Moderate | OK but transports corrosion products | High | Excellent | Yes but $T_{1/2}$ short | High | |
| **$D_2O$** | High | Excellent | Ok but transports corrosion products | High | Excellent | Like $H_2O$ but with tritium | High | |
| **Organic** | Moderate | $H_2O <$ organic $< D_2O$ | Excellent | High | Excellent | None | Low | *See note |
| **Liquid Metal (eg NaK)** | High | Not great | Must be careful to select materials | High | Excellent | High with long $T_{1/2}$ | Very low | **See note |

* Suffers radio-chemical damage

** Incompatible with water in the turbine. High Melting point, low cross section at high energy. Good for fast reactors and breeders.

### 3.9 Neutron Moderators

The most current power reactors are of the thermal type, i. e. , where the energy of the neutrons causing fission is in the thermal range. Since the neutrons produced by the fission process have very high energies, it is necessary that they be slowed down, or "thermalized". The medium employed for this is termed the moderator. It is deployed as a continuous medium surrounding the fuel "cells". The fuel cells form a geometric pattern, termed the reactor "lattice". The optimum spacing between these fuel cells is a function of several variables including the mass of fuel per cell, the mean free path of the neutrons in being thermalized, the degree to which the moderator wastefully absorbs neutrons, the cost of the moderating medium, etc. The best moderator is something that is the same size as a neutron, ie, the hydrogen atom, $H_1$. However, 2 hydrogen does absorb neutrons as well. The deuterium atom, $H_1$, at twice the mass of hydrogen, is almost as good a slowing down agent but, since it already has an extra neutron in the nucleus, it has a very low absorption cross section. So, overall, it deuterium is a far better moderator than hydrogen. By using deuterium in the form of heavy water, natural uranium can be used as a fuel. If ordinary water is used, the fuel must be enriched in A good moderator has a high scattering cross section, a low absorption cross section and slows down the neutron in the least number of collisions (high lethergy, ξ). Table 7 summarizes this. The "figure of merit" is defined as $\xi\Sigma_s / \Sigma_a$. Before discussing practical moderators, it is firstly useful to consider desirable properties of moderators. These are listed in table 8. Table 9 then lists the moderators currently used in commercial power reactors.

**Table 10 Slowing down parameters of typical moderators [Source: DUD76, table 8-1]**

**Table 10 Slowing down parameters of typical moderators [Source: DUD76, table 8-1]**

| Moderator | $A$ | $\alpha$ | $\xi$ | $\rho[g/cm^3]$ | Number of collisions from 2 MeV to 1 eV | $\xi\Sigma_s[cm^{-1}]$ | $\xi\Sigma_s/\Sigma_a$ |
|---|---|---|---|---|---|---|---|
| H | 1 | 0 | 1 | gas | 14 | — | — |
| D | 2 | .111 | .725 | gas | 20 | — | — |
| $H_2O$ | — | — | .920 | 1.0 | 16 | 1.35 | 71 |
| $D_2O$ | — | — | .509 | 1.1 | 29 | 0.176 | 5670 |
| He | 4 | .360 | .425 | gas | 43 | $1.6 \times 10^{-5}$ | 83 |
| Be | 9 | .640 | .209 | 1.85 | 69 | 0.158 | 143 |
| C | 12 | .716 | .158 | 1.60 | 91 | 0.060 | 192 |
| $^{238}U$ | 238 | .983 | .008 | 19.1 | 1730 | 0.003 | .0092 |

**Table 11 Desirable features of moderators**

1. HIGH MODERATING EFFICIENCY
2. LOW NEUTRON ABSORPTION
3. FREEDOM FROM DAMAGE - IRRADIATION, CORROSION
4. LOW COST - RAW MATERIAL, MANUFACTURE, INSTALLATION

**Table 12 Alternative power reactor moderators**

1. GRAPHITE
2. ORDINARY WATER
3. HEAVY WATER

Graphite has been widely used as a moderator for power reactors. The carbon atom is relatively "light", graphite is relatively inexpensive, and carbon is a relatively weak absorber of neutrons. Nevertheless, the carbon atom is sufficiently large, leading to relatively long neutron mean free paths for thermalization, that graphite moderated reactors tend to be large. Furthermore, the relatively large amount of graphite required leads to significant neutron wastage through absorption. Ordinary water is a much more efficient moderator in terms of the neutron mean free path for thermalization because of its hydrogen atoms. It is also very inexpensive. Unfortunately, however, hydrogen also has a significant "appetite" for absorbing thermal neutrons which hurts neutron economy. Heavy water is almost as good as ordinary water in terms of neutron mean free path since the deuterium atoms (which replace the hydrogen atoms in ordinary water) are relatively "light". Its outstanding advantage,

relative to ordinary water, is that it has a very small "appetite" for absorbing neutrons. Hence, it promotes a high level of neutron economy. Its major disadvantage is its high cost.

**Table 13 Moderator summary**

| Moderator Type | Cost | Neutron Economy | Moderator efficiency, $\frac{\xi\Sigma_s}{\Sigma_a}$ | Irradiation stability | Activation | Mean Free Path* |
|---|---|---|---|---|---|---|
| **Graphite** | OK | $H_2O$ < graphite < $D_2O$ | 192 | Excellent | Irrelevant | Long |
| **$H_2O$** | Very low | Moderate | 71 | Excellent | Good | Small |
| **$D_2O$** | High | Excellent | 5670 | Excellent | Good | Medium |

### 3.10 Moderating Arrangements

How do the fuel, the coolant, and the moderator "fit" together to form practical power reactors? The currently established alternatives are shown in Figure 5. If ordinary water is used as both coolant and moderator, it is practical to arrange the fuel "rods" in cluster assemblies as shown. The clusters about against each other. The space between the individual fuel rods is occupied by ordinary water which acts as both moderator and coolant. A relatively small volume of water is required because of the very short neutron mean free path with a hydrogen-based moderator. Hence, the fuel rods can be located relatively close to each other. This arrangement is used in both PWRs and BWRs. If graphite (a solid) is used as the moderator, it is possible to arrange the graphite and fuel into abutting composite assemblies. Coolant passages are arranged through the fuel rods (annular form) or through the graphite. The former approach is used in one Russian reactor type where the coolant is water and steam (for superheating). The latter is used in HTGCR's where the coolant is helium and the fuel is uranium carbide, permitting extremely high fuel operating temperatures. A third arrangement is where the fuel is in the form of assemblies completely separated from the moderator. This arrangement is used in heavy water moderated and most graphite moderated reactors. The choice between these alternatives is influenced by many factors, both of a neutron physics nature and a practical engineering nature, and is very dependent on the particular choice of fuel, coolant and moderator. Time does not permit a detailed discussion of all of these, although many of the factors have been touched on in a qualitative way in the preceding sections. Most of the rest, also in a qualitative way, will be touched on in the next section which deals with specific power reactor types.

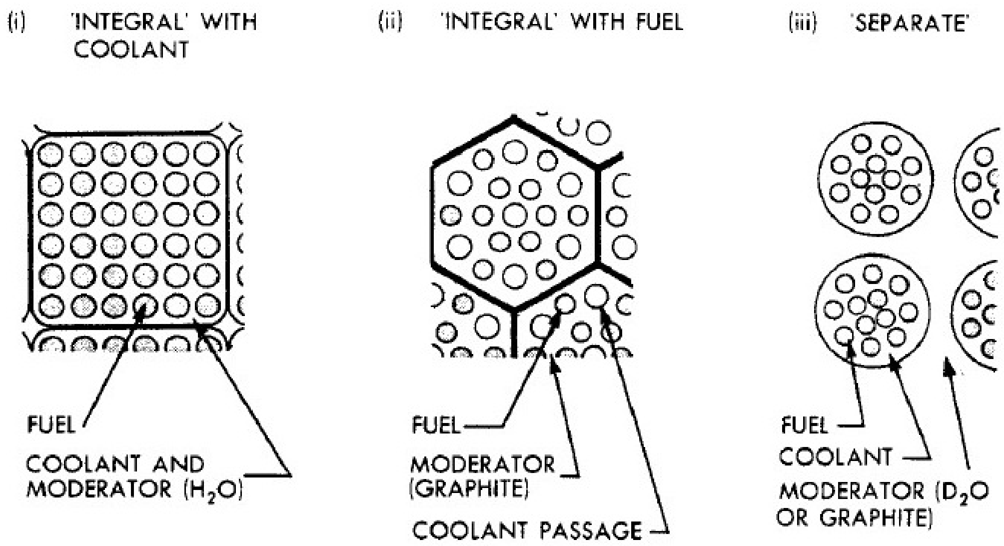



**Figure 5 Moderating arrangements**

### 3.11 HTS Design Requirments and Engineering Considerations

This section introduces the heat transport system and associated systems by a discussion of design requirements and engineering considerations which guide the design of systems to transfer fission heat to the coolant for the production of steam. The fissioning process results in heat generation in the nuclear fuel and surrounding media. This thermal energy can be utilized to produce electricity or process steam by the use of a heat transport medium, the coolant. Here we will discuss some of the thermalhydraulic features which characterize the CANDU system, but the story is similar for PWRs.

a)

The main objectives of the heat transport system are to provide heat transfer at high thermal efficiency and to allow the maximum amount of

b)

energy to be extracted from the fuel without surpassing safe limits. The

c) requirements for such a system can be summarized as follows:

Due to the decay heat produced by the fuel even when the reactor is shut-

d) down, continuous coolant flow must be provided. This leads to the requirement for pumps, pump flywheels, standby cooling,

e)

thermosyphoning, etc.

Costs should be minimized with due regard for the other requirements.

f)

This usually leads

g)

to trade offs between, for example, heavy water ($D_2O$) costs, pumping power costs,

h)

equipment and piping size and costs, layout and engineering constraints.

Layout should minimize man-rem exposure and maximize maintainability and accessibility within the constraints of other considerations. Provision must be made for pressure and inventory control of the heat transfer system. Excessively high pressure could damage the fluid boundaries (pipes, etc.). Low pressure could lead to high coolant voiding and possible fuel damage and to pump damage from

cavitation. Low inventory jeopardizes coolant circulation and pressure control. The system must be sufficiently reliable since downtime leads to high replacement energy costs, high man-rem exposure and repair costs. The design should provide high process efficiency. The system should exhibit ease of constructibility to reduce initial costs and time of construction, and to enhance maintainability. The system should meet and, preferably surpass all safety and licensing requirements. Various coolants can be used in the CANDU design to achieve the above objectives and requirements. Any nuclear station design employs a tradeoff in design features to best achieve the lowest cost power within the safety limits. The U.S. nuclear industry, for instance, because of the availability of enriched uranium from existing $UF_6$ diffusion plants, chose to use enriched uranium and $H_2O$ coolant in order to achieve the necessary neutron economy. From a neutron economy viewpoint, the medium surrounding the fuel, ie., the coolant and the moderator, must not absorb neutrons and must moderate the neutron energy by a minimum of collision interactions. $D_2O$ is by far the best moderator/coolant from this viewpoint. The cost, however, is high at approximately $300/kg in 1980 dollars. Using $H_2O$ as the coolant, as in the CANDU-BLW, Gentilly-1, gives poorer neutron economy than the CANDU-PHW and requires booster rods for startup until the positive void coefficient of reactivity adds a sufficient positive reactivity to maintain criticality. Because of this and because of reactivity control difficulties associated with the large void coefficient of reactivity, no new commercial CANDU-BLW's are planned. Organic coolant, Monsanto OS-84, requires slightly enriched fuel (1.2 to 2.4 wt%). This option was found feasible but, due to the success of the CANDU-PHW, no commercial OCR's are planned. Another nuclear consideration is that the coolant should have a low

induced radioactivity. Both $H_2O$ and $D_2O$ produce N-16 and 0-19 which emit γ's in the 6-7 MeV range. This leads to reduced accessibility and maintainability while on power. the short half life (<1 minute) allows shutdown accessibility. Tritium, H or T, has a 12 year half life and represents a major dose commitment for the station. Since tritium is a β emitter, the problem is one of leakage, leading to possible absorption/ingestion by humans. Organic coolant has very little induced reactivity and aids in ease of operations, accessibility, etc. The coolants should also be stable in a radiation environment. At the high system pressure of the heat transport systems of $H_2O$ and $D_2O$, radiolysis is not a problem. However, since hydrogen and deuterium have a tendency to diffuse through the pipework, the heat transport system becomes concentrated in oxygen and enhances corrosion. Supplying an excess of hydrogen or deuterium prevents this occurrence by driving the chemical equilibrium balance towards the associated state. Organic coolant is more susceptible to radiolysis and requires degassing and makeup. The choice of coolant also depends on other factors, such as pumping power, heat capacity, heat transfer coefficients, flowrates, pressure drop, boiling point, freezing point, corrosion, flammability, thermal stability, and cost. Water (both $D_2O$ and $H_2O$) is an attractive heat transport fluid since it offers a good balance of the above considerations. The specific heat, density and thermal conductivities are high compared to alternatives such as $N_2$, $CO_2$ and OS-84 (organic). Since pumping power is given by:

**Pumping power = pressure drop x volumetric flow rate,**

water requires less pumping power for a given heat removal. For the Bruce reactors (which generate about 750 MWe), approximately 24 MW's of pumping power are required for each reactor. Of this 24 MW, roughly 90% (or 21.5 MW) ends up in the primary heat transport system

as heat due to friction. At an overall station efficiency of 30%, the net unit load for pumping power is 24 - 21.5 MW (bearing and windage losses) plus 2l.5 x .7 = 15 MW (rejected energy) for a total of 18.5 MW. This represents over 2% of the electrical power generated. Since MW saved here by reducing pumping power is gained as electrical output, considerable emphasis is placed on lowering pumping power. Limiting flowrates for water depend on many factors such as temperature, the presence of boiling, water chemistry, geometry and flow regime. Fretting considerations have led to a 10 m/sec limit on fuel channel velocity in single phase water. Erosion/corrosion considerations have led to 4.3 to 6.1 m/s (14 to 20 ft/s) in the steam generator tubes and 16.8 m/s (55 ft/s) in heat transport piping. These limits may change as more is learned about the limiting phenomena. The fuel distribution in the coolant is such to maximize the surface to volume ratio of the fuel so that the highest heat transfer surface can be exposed to the coolant for maximum heat transfer without drying out the fuel surface. However, if carried to extremes the fuel volume in the core will be lower than optimum and parasitic neutron absorption due to the sheath will increase. Present designs employ 37 or 28 elements in a fuel bundle. The use of boiling in the coolant permits higher heat transfer due to the high heat transfer coefficient of post-nucleate boiling. Ideally, the coolant temperature should be as high as possible for maximum overall thermal efficiency. Thus a high boiling point, low vapour pressure liquid is desirable so that the heat transport system can be at the lowest possible pressure. This reduces the thickness of the pressure boundary and thus is important for reducing the parasitic burnup in the core. Organic coolant is far superior to water from this point of view. For the case of organic coolant, the secondary side $H_2O$ pressure is higher than the primary side OS-84 pressure. Thus boiler tube leaks will cause a water leak into the primary

coolant system. Freezing point concerns for $H_2O$ and $D_2O$ are minor. For OS-84 provision must be made to prevent freezing while shutdown and cold. Continuous coolant makeup reduces this problem. Corrosion of the heat transport system materials must be minimized because of possible deterioration, flow restrictions and contamination with active isotopes. The CANDU-PHW heat transport system has water coolant, low cobalt carbon steel piping, stainless steel end fittings, zircalloy pressure tubes and Monel or Incoly steam generator tubes. A pH of 10.2 to 10.8 is maintained by lithium hydroxide. Hydrogen gas is added to keep the dissolved oxygen content low to help minimize corrosion. The intent is to produce and maintain a continuous and adherent film of magnetite on all the carbon steel surfaces. Corrosion with organic coolant is a lesser problem, controlled by degassing, by using $N_2$ cover gas, and by a dechlorinator system. No flammability or thermal stability problems exist with water (except for the possible Zr-ater reaction producing $H_2$ during a LOCA giving the potential for $H_2$ explosion) but organic coolant is combustible, although it will not sustain combustion on its own. Organic coolant is also not as thermally stable as water. The current cost of $D_2O$ ($300/kg - 1995 dollars) is high, making it the more expensive coolant. This contributes to a high capital cost for the CANDU-PHW but a low operating cost due to the efficient use of natural U.