Fig. 7.35 Typical nuclear power plant

There are three main types of thermal reactors: **gas cooled reactors**, **pressurised water reactors** and **boiling water reactors**. These are used in approximately 80% of the world's nuclear power stations.

Another type of reactor is a **fast reactor** or **breeder reactor**. This type of reactor uses high-speed or 'fast' neutrons to split the abundant U^{238} fuel atoms. The products of this fission are energy, and through a series of beta emissions, the breeding of more fissionable atoms. These fissionable atoms, in the form of Np and Pu act as a source of fuel:

$$n_0^1 \text{ (fast)} + U_{92}^{238} \rightarrow U_{92}^{239} \xrightarrow{\beta} Np_{93}^{239} \xrightarrow{\beta} Pu_{94}^{239}$$

Since fission occurs with fast neutrons, there is no moderator in a fast reactor.

The *advantages* of breeder reactors are as follows:

1. They use fast neutrons and therefore do not require a moderator.
2. They produce more fuel than they consume.

The *disadvantages* of breeder reactors are as follows:

1. They produce radioactive waste, e.g. Pu^{239}, that may be used to manufacture atomic bombs.

2. It is difficult to regulate the power produced in these reactors. The UK and France have commercial fast reactors.

Fusion power

Fusion power comes from the joining of light nuclei, such as deuterium, D_1^2, at a high temperature, ~ 10^8 °C. The reactants and products of nuclear fusion exist as a **plasma**. This is another state of matter other than solid, liquid or gas, in which matter consists of ions and electrons.

The *advantages* of fusion are as follows:

1. plenty of fuel; one type of fuel is D_1^2 in normal hydrogen or sea water;
2. no nuclear weapon material produced;
3. minimal radioactive waste.

The *difficulties* of fusion are as follows:

1. containing the plasma; one way to contain plasma is in a 'magnetic bottle' which is produced by large currents heating the plasma. The charged particles of the plasma follow a helical path down the magnetic bottle. However, kinks and pinches of the plasma occur and the plasma becomes unstable.
2. producing a sustained and controlled thermonuclear reaction because of plasma instability;
3. controlling the loss of energy from the plasma in the form of microwaves, X-rays, ultraviolet radiation and heat;
4. extracting heat energy in a useful form.

Uses for nuclear energy

Nuclear power plants and reactors are considered when there is a need in society for:

1. more electrical energy (due to a shortage of fossil fuels);
2. a mobile energy source, e.g. in submarines;
3. an energy source in remote areas, e.g. on the Moon or at the poles of the Earth;
4. radioisotopes for industry;
5. radioisotopes for research;
6. radioisotopes for medicine.

medicine.

Hazards associated with nuclear reactors

1. **Disposal of nuclear wastes.** Disposal of wastes, especially those fission products with a high level of activity, e.g. some isotopes of Sr and Cs, is a particular problem. The methods of disposal are:
   (a) dumping at sea;

(b) storing underground — this may be on the reactor site or in a remote geologically stable area, e.g. salt beds;

(c) building the waste into a stable synthetic rock or 'synroc'. This method, developed in Australia, has been found to be successful.

2. **Accidents in reactors.** An out-of-control reactor that melts is said to have undergone a 'meltdown'. The worst accident that can occur is the explosion of the core of a reactor, resulting in a radioactive cloud spreading over large areas of a continent. This happened in the USSR at Chernobyl on 25 April 1986. The radiation from such an explosion can cause death, radiation sickness and cancer. The wastes from an explosion can contaminate the water table, air, animals, plants and the ocean.

Social and environmental impact of nuclear energy

Primary energy consumption of developing and industrialised countries will have increased from about 100 million, million, million joules per year in 1960 to 600 in the year 2040.

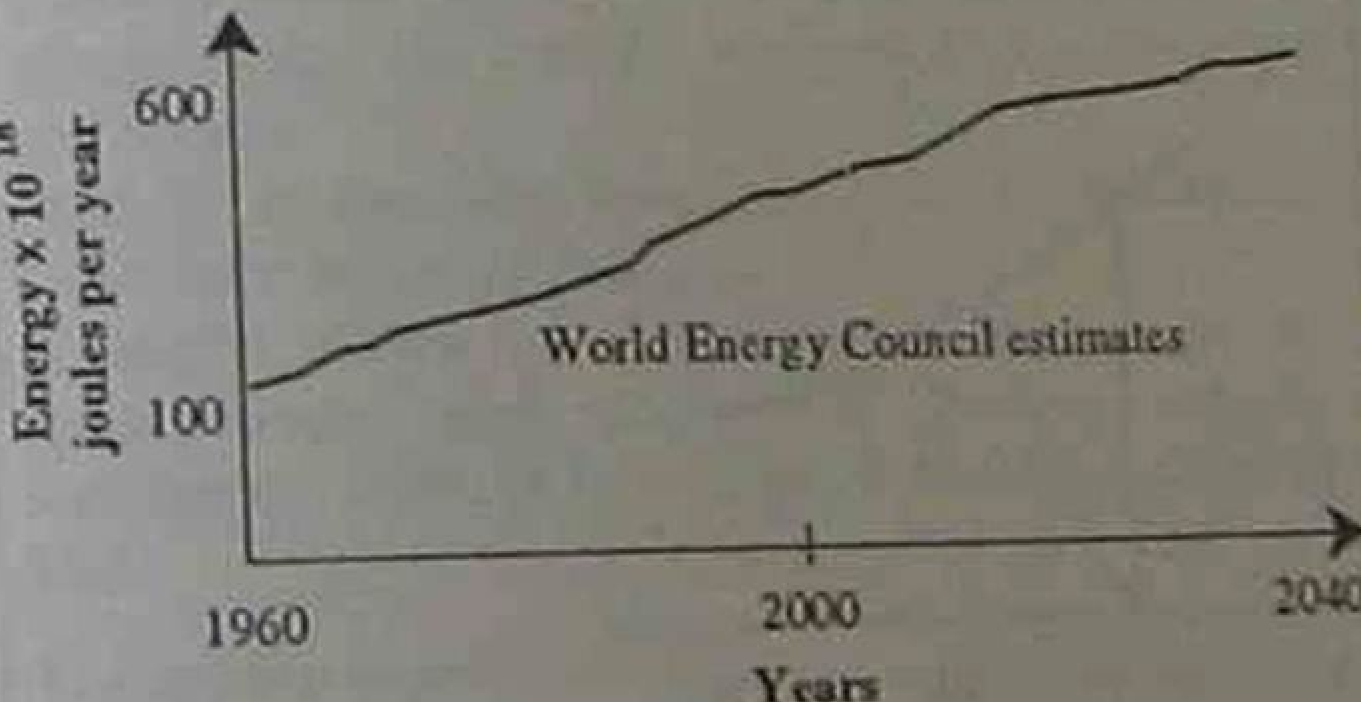

Fig. 7.36

Fig. 7.36

The world population is increasing rapidly and world energy demands are forecast to rise by 75% by the year 2020. All energy sources have their advantages and disadvantages. This demand could be met by the use of biomas (wood, plants and animal matter) and non-renewable fossil fuels (oil, coal and gas). These fuels are running out and burning them produces, first, the greenhouse gas carbon dioxide, which gives rise to global warming, melting of ice caps and the rise in sea levels, and, second, sulfur dioxide and nitrogen dioxide, the source of acid rain which contaminates the air we breathe, destroys plants, makes lakes and rivers lifeless and erodes buildings. Other energy sources are renewable solar power, wind power, tidal and wave power, hydropower, geothermal power and nuclear power, which do not produce carbon dioxide. In the UK about 20% of electricity needs are met from nuclear power. In Australia we have no commercial nuclear electricity and most of our electricity is generated by burning the fossil fuels coal, oil and gas. These fuels are in limited supply and could be saved and used as raw materials for transport, plastics, chemicals and pharmaceuticals.

chemicals and pharmaceuticals.

The operation of nuclear power plants for military, medical and industrial purposes and to produce nuclear electricity involves social and environmental risk to the community. The risk is twofold: disposal of radioactive waste which could contaminate the ecosystem and the possibility of a nuclear accident at a reactor resulting in radiation fallout and radiation sickness.

One tonne of uranium produces the same amount of electricity as 20 000 tonnes of coal. The use of uranium to produce electricity would leave more oil for transport, making petrochemical products, plastics and drugs, and coal to produce synthetic oil. In the UK it is estimated that nuclear power stations avoid the emission of 66 million tons of greenhouse gases every year. In France 75% of electricity is produced from nuclear energy, and carbon dioxide (CO_2) from power production was decreased by 80% in seven years. Should nuclear power, which produces neither greenhouse gases nor acid rain and is therefore described as a clean source of electricity, be considered as a future source of electrical energy in Australia?

Nuclear reactors are also used to produce radioactive isotopes or radioisotopes. The benefits from the use of radiation from radioisotopes are (i) in medicine to diagnose and treat cancer and sterilise equipment, (ii) in research to determine movement of ocean currents, underground water and termites in buildings and (iii) in the food industry to preserve food by killing insects, bacteria and fungi.

ADDITIONAL WORKED EXAMPLES

1. The nucleus of a radioactive nucleide, X, is represented by the symbol X_{92}^{234}. The atom undergoes an alpha decay to form atom Y, which in turn undergoes a beta decay to form atom Z. Atom Z emits a gamma ray. Write symbols with appropriate superscripts and subscripts to represent:

   (a) the atom Y;

   (b) the atom Z;

   (c) the atom Z in (b) after gamma emission.

   Justify your answers.

Answer

(a) Y^{230}_{40}. Alpha decay is the emission of a helium nucleus, He^4_2. To conserve mass during the decay, the superscript (mass number) decreases by 4; to conserve charge, the subscript (atomic number) decreases by 2.

(b) Z^{230}_{41}. Beta decay is the emission of an electron e^0_{-1}. To conserve mass, the mass number is unchanged; to conserve charge, the atomic number increases by 1.

(c) Z^{230}_{41}, with a lower energy nucleus than in (b), because γ decay involves the emission of a packet (photon) of energy from the nucleus.

2. The following data show the true activity of radon gas, which emits alpha particles, versus time:

Activity, *A* (Bq)	8030	5010	3280	2180	1270
Time, *t* (s)	0	30	60	90	120

(a) Draw a graph of activity (vertical axis) versus time.

(b) Graphically determine the time when the activity is:

(i) 5000 Bq;

(ii) 2500 Bq.

(c) Using your answer to (b), deduce the half-life, *T*, of Rn.

(d) With the aid of the Periodic Table of elements, write a balanced equation for the alpha decay of Rn^{220}.

Rn^{220}.

Answer

(a)

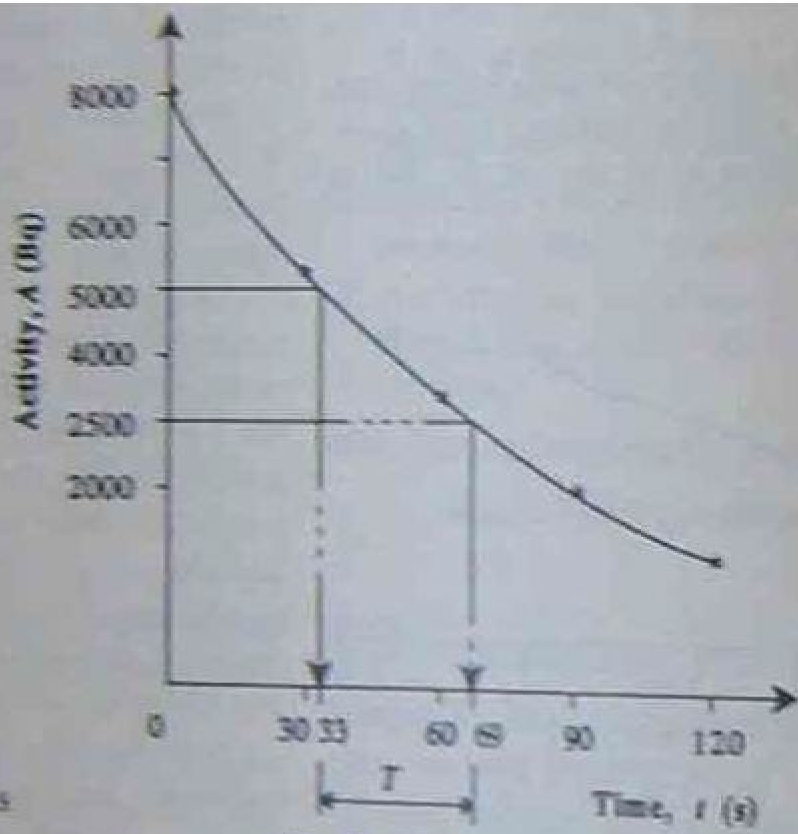

Fig. 7.37

(b) (i) ~33 s (ii) ~69 s

(c) $T = (69 - 33)\ s = 36\ s$

(d) $Rn^{220}_{86} = Po^{216}_{84} + He^{4}_{2}$

3. (a) A nucleus of cobalt undergoes a beta decay to form a nickel nucleus and an antineutrino as shown in the following equation:

(d) $Rn_{86} = Po_{84} + He_2^4$

Fig. 7.37

3. (a) A nucleus of cobalt undergoes a beta decay to form a nickel nucleus and an antineutrino as shown in the following equation:

$$Co_{27}^{60} \rightarrow Ni_Z^A + e_{-1}^0 + \text{antineutrino}$$

(i) State the mass number, A, and the atomic number, Z, of nickel.

(ii) The nickel nucleus undergoes gamma decay. Explain this process using an appropriate nuclear model.

(b) State *two* factors which give a measure of the nuclear stability of a large nucleus.

Answer

(a) (i) $A = 60$; $Z = 28$.

(ii) The nuclear shell model of the nucleus explains gamma decay as the rearrangement of nucleons to a lower energy state in the nucleus and the emission of a photon of gamma ray energy.

(b) (i) The higher the binding energy per nucleon, the more stable the nucleus.

(ii) A high ratio (~1.6) of neutrons to protons in the nucleus means that the nuclear forces of attraction stabilise the nucleus against the repulsive coulombic forces within the nucleus.

Key facts and equations

- An *atom* is the smallest part of matter that can exist.
- An *element* is a substance composed of only one type of atom.
- The *nuclear atom* is composed of a nucleus of protons and neutrons, and electrons which orbit the nucleus.
- *Atomic mass* is the mass of an atom on a scale where the C atom has a mass of 12.000 00 atomic mass units (amu or u).
- A *nucleide* is a particular atom defined by its atomic number, *Z*, mass number, *A*, and the energy state of its nucleus.
- *Isotopes* are nucleides with the same atomic number, *Z*.
- The *history of the discovery of radioactivity*:

  1896—H. Becquerel discovered radioactivity of uranium salt.

  1898–1902—the Curies [illegible]

1898, 1902—the Curies discovered two radioactive elements, which they called polonium and radium, in the uranium ore, pitchblende.

1898—Rutherford identified alpha and beta radiation.

1900—Villard identified gamma radiation.

- For a summary of the *properties of nuclear radiation*, see Table 7.1.
- *Radioactive decay* is a random process. When unstable nuclei decay, the laws of conservation of charge, mass and energy, nucleons and momentum are obeyed.
- *Half-life* is the time taken for half the number of radioactive atoms to decay.
- A *decay series* is composed of a number of spontaneous and sequential decays usually terminating with the formation of a stable isotope of lead.

- The *nuclear atom*:
  1909—Rutherford conceived the idea of a nuclear atom.
  1913—Geiger and Marsden experimentally tested and verified Rutherford's model. Rutherford's model *could* explain alpha scatter by metal foil, but *could not* explain the line emission spectrum of hydrogen.
  1913—Bohr proposed an electron energy-level model of the atom which explained the hydrogen spectrum.

- *Nuclear forces* are repulsive and attractive charge-independent forces which are much stronger than coulombic forces. They have a short range up to about 3 fm.

- *Transmutation of elements* is the changing of an atom of an element into the atom of another element. This may be a natural process, as in radioactive decay, or it may be artificially induced, usually in accelerators where nuclei are bombarded with high-energy particles such as protons, alpha particles, deuterons etc.

- The neutron was postulated to exist by Ernest Rutherford, in 1920, to account for atomic mass measurements. Its existence was mathematically confirmed in 1932 by James Chadwick. From momentum and energy calculations, he explained the results of the α–n reaction which occurs when alpha particles impinge on Be nuclei, releasing neutrons which remove protons from paraffin wax.

- The *neutrino* is a nuclear particle postulated to exist by Pauli in 1933 in order to explain the beta particle energy spectrum formed during beta decay. The neutrino has no charge and no rest mass. Fermi explained beta decay as a neutron decaying to form a proton, a beta particle and an antineutrino; see the section on the neutrino above.

$$n^1 \rightarrow p^1 + e^0 + \bar{\nu}$$

- *Mass defect*, Δm, of an atom is the 'missing mass' when an atom is made from its constituent parts.

- *Binding energy*, BE, is the energy linked with the mass defect by the Einstein relation $BE = \Delta mc^2$. It is the energy released when an atom is formed, or the energy required to split an atom into its constituent parts. BE per nucleon is a measure of nuclear stability. For nuclides with $A > 20$, the average BE per nucleon is 8 MeV.

- Nuclides are stable when:

$$N = Z \text{ and } A < 20$$

or when: $$N > Z \text{ and } A > 20$$

Nuclei with excess neutrons undergo β^- decay to become stable. Nuclei with excess protons undergo β^+ decay to become stable. Large nuclei with excess protons tend to have small nuclear forces, so the coulombic forces make the atom unstable. All nuclei have about the same density.

- Nuclear models—the liquid drop model explains radioactive decay and fission; the shell model explains gamma decay.

- Accelerators are machines to accelerate particles (protons, deuterons, helium nuclei etc.) to smash atoms. From these events, we can gather information on nuclear structure, nuclear forces and fundamental particles.

Important features of an accelerator are:

—high accelerating voltages to give the particles high kinetic energy and a good chance of undergoing an effective nuclear collision;

—high ion beam current to help ensure lots of effective nuclear collisions.

- *Linear* accelerators. One type uses a large static voltage (Van de Graaff, 1931, and Cockcroft and Walton, 1932). Another type uses drift tubes and a long-period voltage (Sloan and Lawrence, 1931).
- *Orbital* accelerators produce a cyclic acceleration of particles. One type is the cyclotron (Lawrence and Livingstone, 1931), and another the betatron (Kerst, 1941).