CHAPTER 3

WORLD NEED OF NEW SOURCES OF ENERGY

"The Ancient Egyptians had good reasons to worship ATON the Sun"

It gives········· warmth to our bodies
········· potable water to quench our thirst
········· food anf vegetables to maintain our lives

"It is the oil crisis, caused by the 1973 Middle east oil embargo, that imposed our new thinking about the urgent need of renewable energies and our reconsideration of energy consumption in future"

A . THE ENERGY FUTURE

A.1. Energy use today and future options

Fossil fuels dominate the industrialized world's energy today, with smaller contributions from nuclear power, hydroelectric, and wood. Fig. 3.1 shows roughly the percentages of energy use in present times.

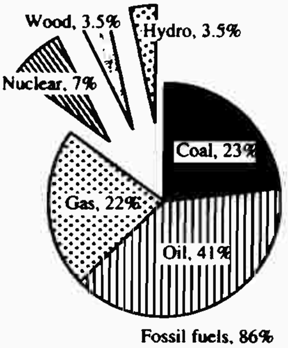


Fig. 3.1. Percentages of energy use at present.

About one third of the total energy resources goes into electricity generation. Hydroelectric and nuclear resources go entirely to electricity, and coal resources go mainly to electricity, while oil, natural gas, and wood go nearly entirely to non-electric uses. Less than 30% of the total energy used is exploited as useful energy, the rest disappear as waste thermal energy.

Energy resource depletion and environmental problems will probably drive the world away from using fossil fuels during the coming decades. But what will be our energy future? But what about the dramatic incidents of explosion of nuclear reactors, like what happened in Three miles island and in Chernobyl? Fusion reactors are much more promising since the reaction takes place non-explosively, but it is not easy to make such reactors now.

Renewable energy resources are widely-discussed as future options. An energy resource is renewable if it is continuously available, like sunlight. future renewable energy resources are the use of biomass and biological products including wood, waste paper, agriculture waste, even sugar crops and grains can be burned for thermal energy or transformed into liquid or gaseous fuels. Wind can generate electricity. The Sun can heat water or some other fluid that can be used for electric power generation as in solar ponds. Electricity can be generated directly using photovoltaic cells. All these options of energy are related directly or indirectly, to the Sun.. Geothermal energy of the Earth's hot water, steam, and hot rock, forms a renewable non-solar option for energy resource.

An option, which is not an energy resource, is increasing the efficiency of energy uses, such as home insulation, energy-efficient lighting, and energy-efficient automobiles and heat engines. Increased efficiency will reduce energy consumption without altering the services provided by that energy. Conservation of energy requires that we try to change our wastive way of living. For example, we can switch from automobiles to mass transportation, living in smaller homes, and building more compact communities. Many studies showed that energy consumption can be reduced dramatically by the increased efficiency alone, with no need for controversial changes in the amount or quality of the services we get from energy.

A.2. Problems arising from the use of fossil and nuclear energy

Different problems arise from the use of different kinds of energy sources. A serious problem that is nowadays critically considered is the global warming caused by the CO_2 gas left after oil and coal burning. Other problems show up, such as degradation of land, pollution, worker's health, accidents, waste disposal, etc. It is because of all such problems, energy analysts are looking very seriously at renewable resources and conservation. The seriousness of this problem could also be seen by considering the following table showing the years that remain until the total resource is gone, at the present annual rate.

Non-renewable energy resource	Years remaining to end
Coal	3600 years
Oil	25 years
Natural gas	69 years
Uranium	200 years

A.3. Geothermal energy

From thermodynamic point of view, a heat engine providing useful work could be operated between a source of high temperature and a sink of lower temperature. High underground temperatures of rocks or water form a source of thermal heat, which can be used to operate steam turbines for generating electricity. This renewable heat energy comes from the Earth's molten core. The easiest way to tap it is by drilling underground and directly getting natural hot water or steam. A model of a hot water geothermal power plant is schematically shown in Fig. 3.2. The water in the porous rock is heated by the Earth's hot core. The hot water escaping through a well, boils near the top providing steam which is to be used as driving force for electric generators. Geothermal hot water and steam are found in very few places allover the world. The hot dry rock lying several kilometers underground might be used to heat injected water from the Earth's surface, thus thermal energy could be extracted by circulating water. Usually two wells are dug, one to bring cold water down from the surface, and the other to bring hot water back to the surface. The underground rocks are fractured with pressurized water, and the water that passes through the fractures is heated. This particular form of geothermal energy would be useful in many parts of the world. However, the drilling and underground fracturing technology of the hot rocks is highly demanding and is as yet unproved.

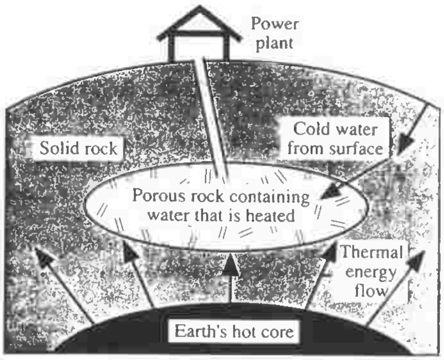


Fig. 3.2. Model of a hot water geothermal system.

A.4. The Sun as energy source

It is presently well-known that non-renewable energy sources are diminishing rapidly. Accordingly, it has become of vital importance to find other sources of energy. In this chapter we are going to discuss different kinds of energy in order to see how we can utilize them for the benefit of mankind.

The Sun is the primary energy source for almost all processes going on Earth, as shown in Fig. 3.3. Nearly all energy sources are derived from the Sun. Solar radiation contributes more than 99% to the energy balance of Earth. The Sun radiates energy equally in all directions, but only a small part reaches the Earth. This is measured by means of solar constant, K, defined as: **the radiant energy incident on unit area in unit time at the Earth's surface.** Its value on Earth, at noon, is about 1000 watts/square meter, and could be measured easily by the student in the laboratory. The entire population of the Earth make use only of (1/100,000) of the total power reaching us from the Sun, which is about 1.7×10^{11} KW.

Although the radiant power from the Sun is large yet it is very dilute. This diluteness comes from the variation of solar radiation from day to night and through seasons. In order to collect a sizeable

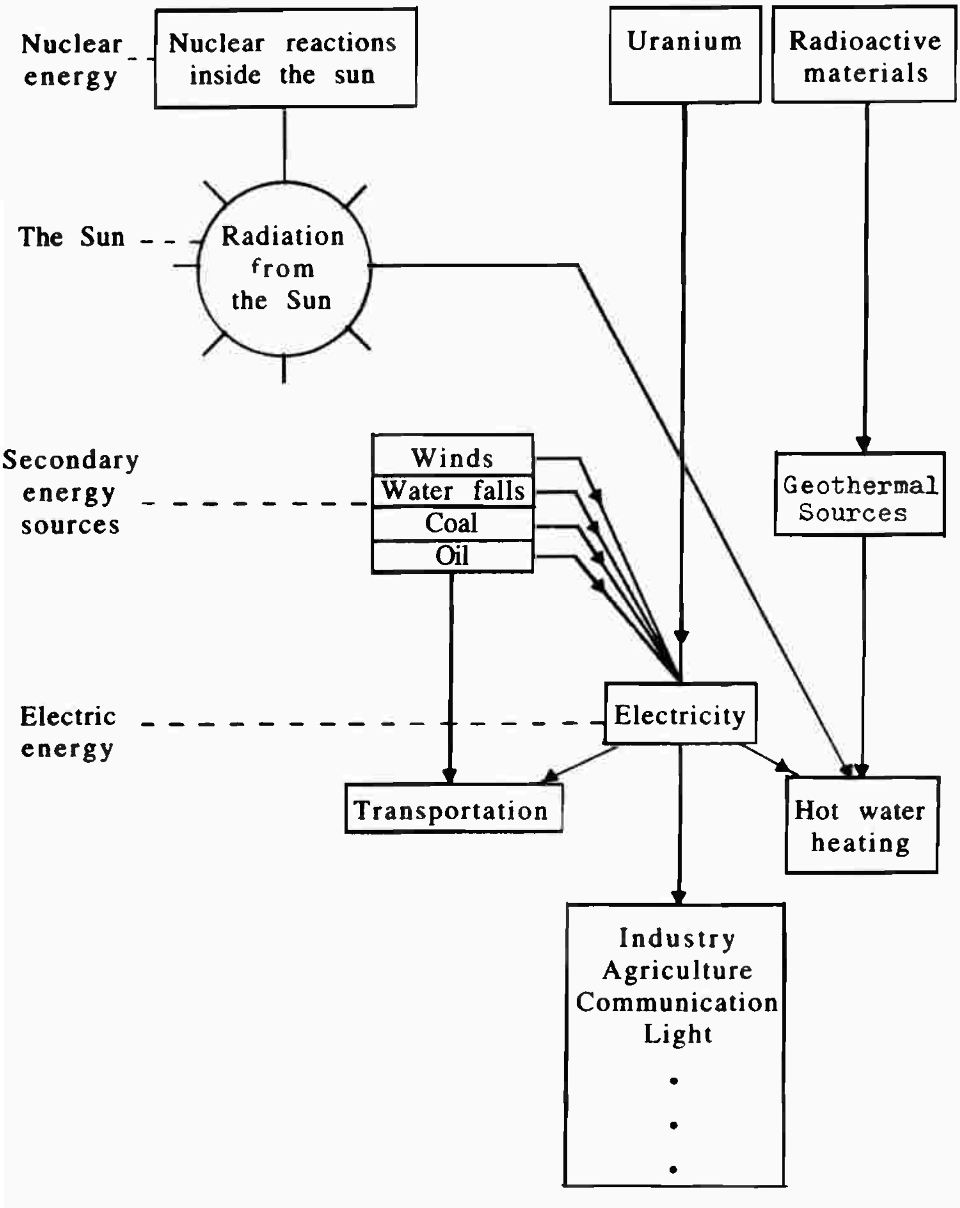


Fig. 3.3. The Sun is the primary energy source.

amount of solar energy one has to use large areas for long periods of time. It took about 600 million years to form the fossil fuels which are the result of photosynthesis in green plants, which are non-renewable energy sources. Renewable energy sources, such as wind and waterfalls, are generated by collection of solar power over the large area of the oceans.

A.5. Energy crisis in 1973

In the early seventies the price of oil rose steeply due to the war in the Middle East. The cost of electrical energy, and the running cost of transportation greatly increased. This activated, allover the world, the research connected with direct exploitation of radiant energy. The following methods of power generation from solar radiation were developed in recent years:

1. Indirect conversion into electrical energy via heat by solar central receivers and by solar ponds.
2. Direct conversion into electrical energy by solar cells.
3. Direct conversion into heat through a solar water heater schematically shown in Fig. 3.4. The solar panel receives the solar radiation and heats the fluid inside. The hot liquid goes to the heat exchanger in a storage tank where it cools down. It is then returned to the solar panel to repeat the cycle. The hot water is stored in an insulated tank for use in different purposes.

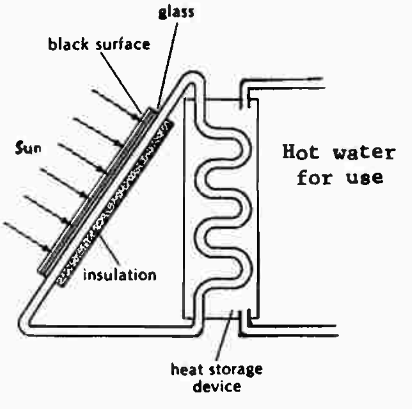


Fig. 3.4. Scheme of a solar water heater.

A.5. The solar furnace

Heat energy from the Sun could be concentrated by mirrors or lenses. The concentrated heat on a small spot could be used directly for cooking food, heating water or other materials. A large solar furnace is built in France at Odeillo, a view of which is given in Fig. 3.5. A large parabolic mirror is used to collect heat over a large area. Sixty three flat mirrors throw the sunlight at the parabolic mirror which concentrates about 600 kW of solar energy into a focal spot of cross dimension about 30 cm. Intense solar heat reaching a temperature of about 4000 °C is produced at the focal spot. This solar furnace was designed for research and not to generate power.

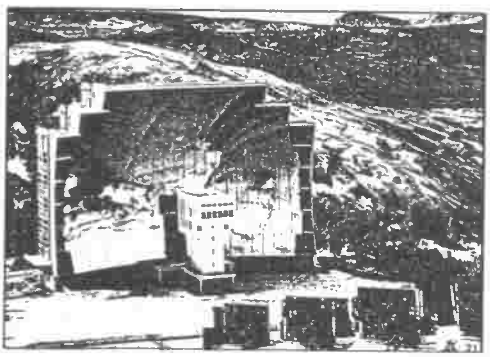


Fig. 3.5. The solar furnace at Odeillo, France.

However, a similar arrangement of mirrors could be used to collect solar heat for a power plant. The heat can be focused on a boiler that generated steam for a steam turbine.

A.6. Wind energy

Wind energy is the kinetic energy of air set into motion when the Sun warms the daylight side of Earth. Since very old times, it has driven sailing ships and turned windmills for grinding seeds and for pumping water. Today, it also generates electricity.

The atmosphere acts as a giant heat engine converting this heat into kinetic energy of motion of the air. The power of wind is rather dilute. In a wind of about 35 km/h, a vertical area of one square meter intercepts kinetic energy at the rate of 1.3 kW. Even if it is possible to extract all of this energy the generation of large amounts of power would require wind turbines. Fig. 3.6 shows an array of windmills presenting a very large frontal area to the wind. In regions where wind turbines are feasible, wind power is already financially competitive with coal for large-scale electric power generation.

Fig. 3.6. Wind generators, each one producing 100 kW of electricity (enough for about 100 house holds).

A.7. The solar pond

The solar pond is one way of exploiting solar energy. A solar pond is a saline lake in which the concentration of salt increases with depth. The Sun rays penetrate to the bottom of the lake and heat it. As a result of this the temperature at the bottom will be higher than that at the top by about 20-30 °C, because the high concentration of salt at the bottom increases the density of the solution there, so it is prevented from rising to the top even when heated, i.e. no convection currents occur. The temperature of the bottom layers might reach 90-100 °C. This phenomenon was elaborated near the dead sea where an artificial solar pond was constructed. Electrical power is generated with hot water forming the bottom layers of the pond as heat source, and the cold upper layers as reservoir. A heat engine could be operated between the two temperature levels, thus producing electrical energy, see Fig. 3.7.

The hot water of the pond could also be used for warming houses in winter.

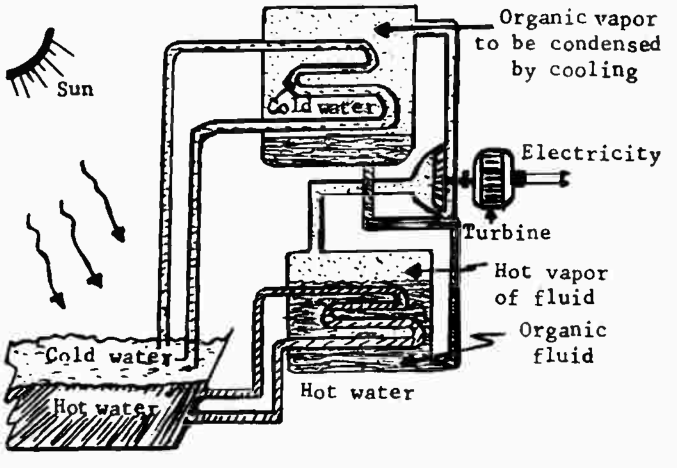


Fig. 3.7. A schematic diagram of a solar pond power station.

A.8. Solar energy converters (The solar cell)

Solar cells convert the energy of sunlight directly into electric energy. They are made of semiconducting materials that develop a voltage when sunlight strikes them, silicon is a typical example of such materials. A semiconductor behaves normally like an insulator: it is difficult to make their electrons flow. But if some energy from the Sun light is given, then these electrons can flow easily, as a conductor. Semiconductors form the basis of the solid-state revolution which is the basis of modern electronic technology. In addition to being a promising energy technology, photovoltaic cells are an instructive example of this electronic revolution.

In order to understand this vast field of solid-state electronics, one has to know something about bonding in solids and the energy bands created when the atoms are brought near together to form a solid.

A.8.1. Bonding in solids

Crystalline solids are formed of a large number of atoms arranged in a regular array, forming a periodic structure. The forces that hold these atoms together are of three types:

1. Coulomb forces due to attraction between positive and negative charges in neighboring atoms or ions. These forces are very strong, a familiar example of an ionically bonded molecule is sodium chloride, Na^+Cl^-, which forms common table salt. The sodium atom has one electron in the outermost orbit ($1s^22s^22p^63s^1$). If this electron is removed the Na^+ ion attains an electronic configuration similar to the nearest inert gas (neon) in the periodic table. On the other hand, chlorine atom has seven electrons in the outermost orbit ($1s^22s^22p^63s^23p^5$). Thus, if it receives an electron to complete an octet, the electronic configuration becomes that of argon (inert gas) which is more stable. NaCl is thus found in the ionic state with strong Coulomb forces binding the ions together. This strong binding is responsible for the high melting point of the salt.

2. A covalent bond is created between two atoms due to the sharing of electrons supplied by one or both atoms to form a molecule. It is known that atoms tend to loose or acquire electrons so as to attain a more stable configuration, namely, that of inert gases which have $2n^2$ electrons in their outermost shells. Many diatomic molecules owe their stability to covalent bonds. In the case of H_2 molecule, the two electrons are equally shared between the two nuclei thus forming a molecular orbital. Because of the Pauli exclusion principle, the two electrons in the ground state of the hydrogen molecule must have antiparallel spins. Another example of covalent bonding is the case of diamond which is formed of carbon atoms. Each atom shares an electron with each one of four nearest neighbors. Thus, each two neighboring atoms have two electrons shared together. Since a carbon atom has four electrons in the outer shell, $(1s^2 2s^2 2p^2)$, then this arrangement provides every atom with the 8 electrons needed for saturating the outer shell.

3. Van der Waals forces that bond molecular crystals are weak forces. The particles that constitute molecular crystals are all alike and electrically natural. Each particle carries positive and negative charges acting as an electric dipole. The net electrostatic force of attraction between the neighboring dipoles is only the difference between strong electrostatic attraction and electrostatic repulsion. The attraction is slightly stronger due to the fact that opposite charges are slightly nearer than similar ones for each two neighbors (see Fig. 3.8). Binding is here much weaker than in ionic crystals. Molecular crystals have low melting points because increasing the temperature and correspondingly thermal agitation, breaks down the regular structure and a liquid state is formed.

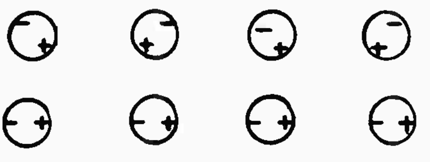


Fig. 3.8. Dipoles in molecular crystals.

A.8.2. The potential energy curve

We have seen that the bonding mechanisms in a molecule are primarily due to electrostatic forces between atoms (or ions). When two atoms are separated by an infinite distance, the force between them is zero, and so is the potential energy of the system. The potential energy of the system can be positive or negative, depending on the separation of the two atoms.

The total potential energy of the system can be approximated by the expression:

$$U = -(A/r^n) + (B/r^m)$$

where r is the interatomic separation, A and B are constants, n and m are integers ($m > n$). The first term refers to attractive forces and the second one to repulsive forces. Fig. 3.9 represents a sketch for the potential energy curve for two atoms forming a molecule. The potential energy for large separations is negative, corresponding to a net attractive force. At equilibrium separation the attractive and repulsive forces just balance, and the potential energy has its minimum value.

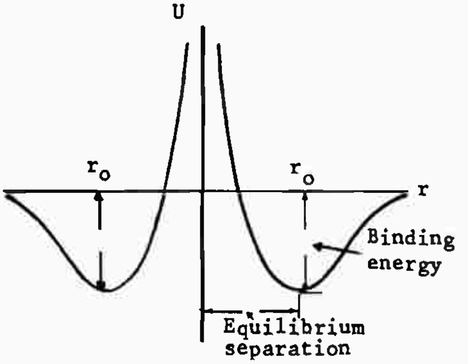


Fig. 3.9. The potential energy curve for a diatomic molecule.

A.8.3. The metallic solid and semiconductors

The valence electrons in a metallic solid are relatively free to move throughout the material. The metal structure can be visualized as a gas of electrons permeated by the positive ions. The binding mechanism in this case is the attractive force between the positive ions and the electron gas. The high electric conductivity of metals is produced by this free electron gas.

A semiconductor is a material with a resistivity between that of conductors and insulators. Silicon and germanium are typical examples of semiconductors. They are tetravalent, i.e. every atom has four electrons in their outermost shell. Each one of these valence electrons is shared with a surrounding atom in a tetrahedral arrangement forming covalent bonds. It is a characteristic feature of semiconductors that the addition of impurities to the material has a drastic effect on the resistivity. For instance, the silicon used in electronic devices is often "doped" with small amounts of arsenic or boron. The addition of just one part per million of arsenic will decrease the resistivity by a factor of 10^5. In order to understand how the doping of a semiconductor with a tiny amount of impurity causes a considerable increase in the number of charge carriers, and hence increase the conductivity, let us consider the microstructure of the doped semiconductor.

A pentavalent atom like arsenic, contains five valence electrons. When arsenic atoms are added to the tetravalent silicon (Si) (which have four valence electrons), four valence electrons from arsenic atoms participate in the covalent bonds and one electron is left over, see Fig. 3.10. This extra electron is nearly free and might thus contribute in the conduction mechanism. The pentavalent atom donates an electron to the structure and hence is referred to as a donor atom. Semiconductors doped with donor atoms are called **n-type semiconductors,** because the majority charge carriers are electrons, whose charge is negative.

On the other hand, if the semiconductor is doped with trivalent atoms, such as indium, the three electrons of the indium atom form covalent bonds with the neighboring atoms, leaving an electron deficiency, or hole, in the fourth bond, see Fig. (3.10). Such impurity atoms are called acceptor atoms. A semiconductor doped with trivalent impurities is known as **p-type semiconductor**, because the charge carriers are positively charged holes.

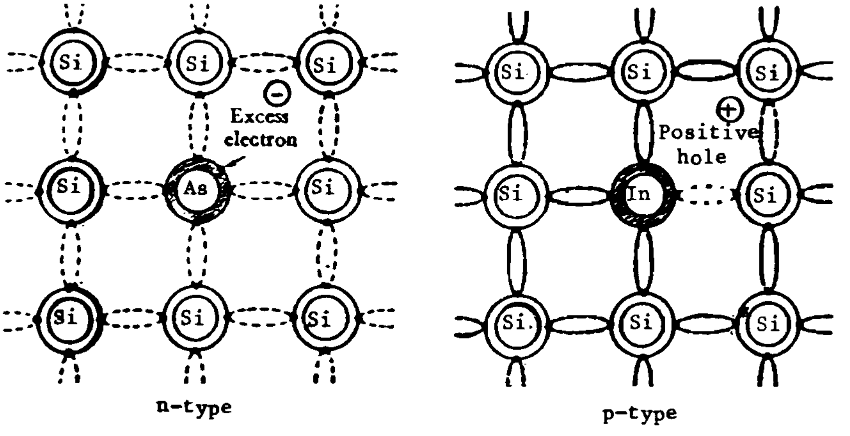


Fig. 3.10. n- and p- semiconductors.

A.8.4. The p-n-junction

By the aid of a special manufacturing process, p- and n-semiconductors can be melted so that a boundary or junction is formed between them. The completed p-n-junction consists of three distinct semiconducting regions as shown in Fig. 3.11, a p-type region, a depletion region, and an n-type region. The depletion region arises from the diffusion of the high concentration of electrons on one side to neutralize the high concentration of positive holes on the other side of the junction. The electrons which move to the p-semiconductor side recombine with the holes there. These holes therefore disappear, and an excess negative charge A appears on this side (see Fig. 3.11). In a similar way an excess positive charge B builds up in the n-semiconductor when holes diffuse across the junction. Together with the negative charge A on the p-side, an electromotive force (e.m.f.) or potential difference (p.d.) is produced which opposes the diffusion of charges across the junction. This is called **a barrier potential difference**. It has a magnitude of a few tenths of a volt.

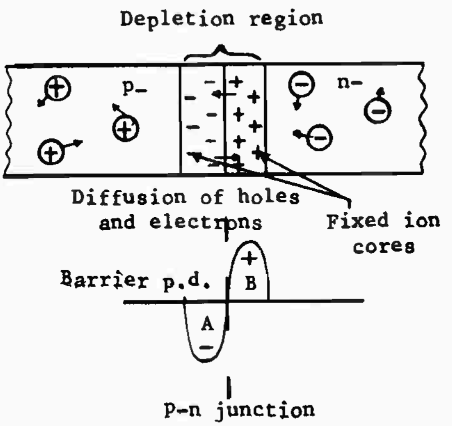


Fig. 3.11. p-n-junction and barrier p.d.

The built-in potential barrier across the junction prevents the further diffusion of holes and electrons across the junction and insures zero current through the junction when no external voltage is applied.

A notable feature of the p-n-junction is its ability to pass current in only one direction. It has a diode action and acts as a rectifier. If a positive external voltage is applied to the p-side of the junction, the overall barrier is decreased, resulting in a current that increases with the increase of the forward voltage, or bias. Reversing the bias, i.e. the positive voltage applied to the n-side of the junction, the potential barrier is increased, resulting in a very small reverse current that quickly saturates to a small value, I_0 (see Fig. 3.12).

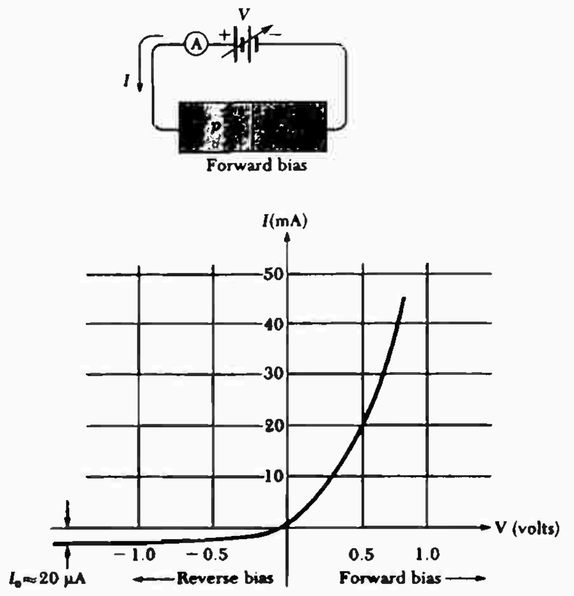


Fig. 3.12. The characteristic curve for a real diode.

A.8.5. The solar cell

Solar cells convert photon energy of the Sun directly to electric energy. A solar cell consists, as in Fig. 3.13, of a central core of n-type silicon surrounded by an outer layer of p-type silicon. The outer layer is very thin to allow the light of the Sun to penetrate it and reaches the boundary between the n-type silicon and the p-type silicon. Light photons thus pump electrons from the p-type to the n-type, across the p-n-junction.

The current of the solar cell is generated by the action of sunlight on the atoms within the depletion region of the p-n-junction where the electric field exists. When light photons strike one of these atoms it will ionize thus releasing an electron from the atom. Under the influence of the electric field at the p-n-junction, the electron accelerates toward the n-side of the junction and the hole toward the p-side. In the external circuit, the current will flow from the p-terminal to the n-terminal, see Fig. 3.13, i.e. the former acts as the positive pole of a battery and the latter as the negative pole.

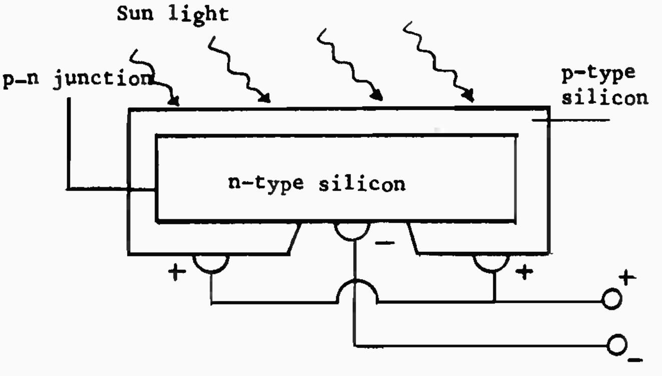


Fig. 3.13. Schematic diagram of a solar cell. The p-side acts as the positive pole of the solar battery.

The e.m.f. of a silicon solar cell is about 0.6 volts. However, the current that it delivers is rather small, e.g. a solar cell of surface area of 5 cm^2 will only deliver 0.1 ampere when exposed to full sunlight. Solar cells are not very efficient; only about 11% of the energy of sunlight gets converted to electric energy. Large panels are needed to produce appreciable amounts of electric power for human uses. Besides, for the need of electric energy at night, a battery system is required in order to store the energy for use after sunset.

B. NUCLEAR ENERGY

B.1. The energy of the nucleus

Radioactive decay is one way to get energy from the nucleus. Fission and fusion are two other ways to get energy. In a nuclear fission a single nucleus splits to form two smaller nuclei, the total mass of these two smaller atoms is less than the mass of the mother atom. The difference in mass transforms to energy according to Einstein's equation of energy-mass equivalence:

$$E = m c^2$$

c being the velocity of light.

In nuclear fission two nuclei combine (fuse) to form a single larger nucleus. Again the difference in masses appears as some kind of energy.

B.2. Constituents of the nucleus

A nucleus consists of protons and neutrons. A proton has an electric charge of +e, and a neutron is neutral, each has about the same mass. The nucleus of an atom of atomic number Z, is characterized by the mass number A, defined as the number of nucleons (protons and neutrons) in the nucleus, and the neutron number N, which is the number of neutrons in it.

$$A = Z + N$$

The term **isotopes** refer to nuclides with the same atomic number Z, but with different mass numbers A.

It is usual to represent nuclei with the symbolic way ^{A}X, where X represents the chemical symbol for the element. For example: Ordinary carbon is given by ^{12}C whose isotope is ^{14}C.

Some isotopes do not occur naturally but can be produced in the laboratory through nuclear reactions.

Nuclear masses can be determined with great precision with the help of the mass spectrometer. The proton mass is about 1836 times as that of the electron. It is usual to define, for atomic masses, the atomic mass unit (a.m.u.) in such a way that the mass of the isotope ^{12}C (carbon) is exactly 12 a.m.u. (1 a.m.u. = 1.66×10^{-27} kg).

Accordingly, the proton mass is 1.00727 a.m.u.; and the mass of the neutron is 1.00867 a.m.u.; and that of the electron is 0.000549 a.m.u. The energy equivalence of the a.m.u. is:

$$E_0 = m c^2 = 1.66 \times 10^{-27} \times (3 \times 10^8)^2 = 1.5 \times 10^{-10}\ J$$
$$= 9.38 \times 10^8\ eV = 938\ MeV$$

The rest energy of an electron could be calculated in the same way and is equal to 0.511 MeV.

B.3. Nuclear size

Experiments show that most nuclei are approximately spherical in shape. An expression which gives the approximate radius, r, of a nucleus of mass number A is:

$$r = r_0\ A^{1/3}$$

where $r_0 = 1.1 \times 10^{-15}$ m. The volume of a nucleus is thus:

$$V = (4/3)\,\pi\, r^3 = \left(\tfrac{4}{3}\pi\, r_0^3\right) A$$

Therefore, the nuclear volume is proportional to the number of nucleons, which means that the mass densities of all nuclei are nearly the same, about 3×10^{17} kg/m^3.

B.4. The nuclear force

The existence of the nucleus implies the existence of a force of interaction that binds the nucleons together within a small region of space. The gravitational force of attraction is far too weak to hold the positively charged nucleons against Coulomb repulsion. The nuclear force is much more complicated than gravitational or electromagnetic forces which could be represented by simple laws.

Nuclear forces can be separated into two fundamental types:

1. **The strong force** accounts for the nuclear properties. It is this force that binds protons and neutrons together to form an atomic nucleus. If the strong nuclear force did not dominate the nucleus, the repulsion between the protons would make the nucleus unstable, and the protons would fly apart.

2. **The weak force** acts between elementary particles and is responsible for some weak nuclear reactions. In radioactive decay, e.g. the nucleus spontaneously disintegrate into several fragments. The weak nuclear force causes a particular radioactive decay called beta decay. Besides, the weak nuclear force is important in controlling the rate of some nuclear reactions such as those occurring in the Sun.

Nuclear forces are very short-ranged. They operate at distances less than 10^{-14} m, but beyond this range the nuclear force is negligible.

B.5. Nuclear mass and binding energy

The total mass of a nucleus is always less than the sum of its individual nucleons. The energy equivalence of the mass difference is called **the binding energy** of the nucleus. Therefore, in order to separate a nucleus into protons and neutrons, energy must be provided to the system. The decrease in rest mass is accompanied by the release of energy from the system. The following example illustrates this point for the fusion reaction of hydrogen into helium. The Sun gets its energy via this reaction.

The helium nucleus has less energy than two hydrogen nuclei. When ^1H and ^2H fuse to form ^3He, the total mass of ^3He has less total energy and less rest mass.

Mass of ^1H = 1.6727×10^{-27} kg ;
Mass of ^2H = 3.3437×10^{-27} kg ;
Mass of ^3He = 5.0066×10^{-27} kg .

The first two masses add up to 5.0164×10^{-27} kg, which is 0.0098×10^{-27} kg more than the mass of the helium nucleus. Just as Einstein predicted, the mass becomes less when the system loses energy.

It is interesting to examine a plot of the binding energy per nucleon, E/A, as a function of mass number for various stable nuclei (see Fig. 3.14).

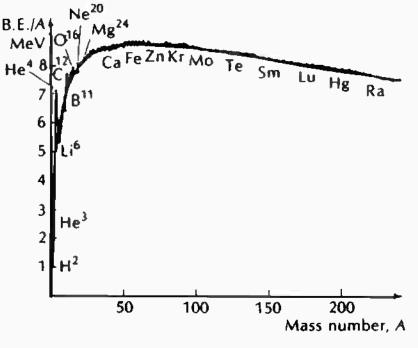


Fig. 3.14. A plot of binding energy per nucleon versus mass number of stable nuclei.

B.6. Nuclear fission

Neutrons are particles that carry no charge, and so they are not subject to Coulomb forces. They can wander through a material and cause nuclear reactions. A free neutron undergoes a beta decay with a lifetime of about 10 minutes, however, it is usually absorbed before it decays. The energy of fast neutrons is decreased by scattering effects by passing through matter, until its energy is of the order of thermal agitation energy, kT, then it gets absorbed by a nucleus. A neutron of this energy is called thermal neutron, and its absorption by a nucleus is called neutron capture. A neutron capture increases the mass number by one, and a gamma photon is emitted. The materials which highly scatter elastically fast neutrons thus reducing their energy are called **moderators**. Graphite and water are examples of moderators used in nuclear reactors.

Nuclear fission occurs when a heavy nucleus, such as uranium (^{235}U) splits into two smaller nuclei, known as **fission fragments**. The total rest mass of the fission fragments is less than the original mass of the mother nucleus. The mass difference appears as energy. Nuclear fission is done by slow neutrons that bombard uranium (^{235}U) following the reaction:

$$^{1}_{0}n + ^{235}_{92}U \longrightarrow ^{236}_{92}U \longrightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3\,(^{1}_{0}n)$$

The fission fragments are barium and krypton together with the release of three neutrons that have a great deal of kinetic energy following the fission event. In order to understand how fission occurs, we are going to treat the nucleons in a nucleus as if they were molecules in a drop of liquid. The nucleons interact with each other and undergo collisions with each other. This is analogous to the thermally activated motion of the molecules in a liquid, and that is why it is called **the liquid-drop model** of the nucleus.

According to the above liquid drop model, the fission of ^{235}U nucleus can be compared to what happens to a drop of water when excess energy is added to it. When enough energy is added to the drop, it will set into vibration. When the amplitude of vibration becomes large enough, the drop breaks up to fragments. The same happens in the uranium nucleus after capturing a slow neutron. At first a highly excited and distorted nucleus ^{236}U is formed. This nucleus then splits into two fragments, as shown in Fig. 3.15.

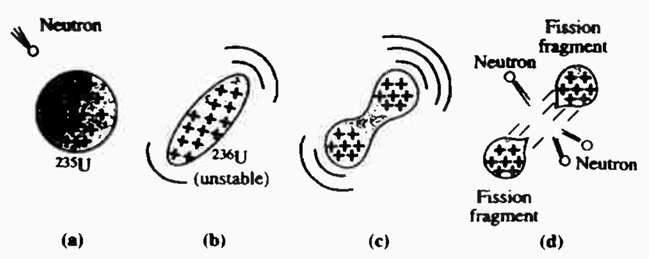


Fig. 3.15. Stages of the fission process of uranium $^{235}_{92}U$.

The released neutrons from the above fission can in turn trigger other uranium nuclei to undergo fission, with the possibility of chain reaction if the reacting uranium is greater than a critical size to maintain the reaction. A chain reaction is shown in Fig. 3.16.

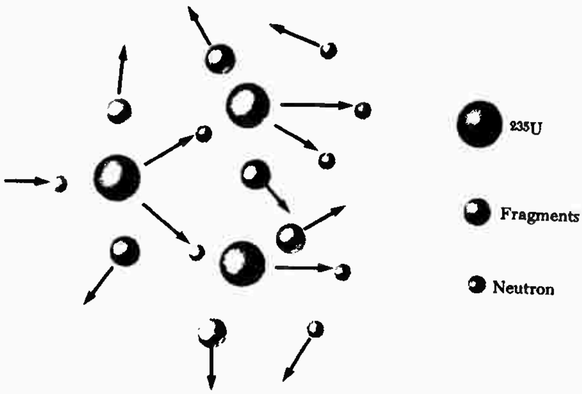


Fig. 3.16. A nuclear chain reaction.

A nuclear reactor is a system designed to maintain chain reaction in uranium fuel. Natural uranium (^{238}U) contains only a small proportion of ^{235}U, which does not exceed about 0.7% of the natural ore. Since ^{235}U is only fissionable, therefore, reactor fuels must be artificially enriched to contain a few percent of ^{235}U.

In order to maintain a chain reaction in a reactor, we must prevent neutrons from leaking out of the reactor core. If the fraction leaking out is too large, the reactor will not operate. Besides, not all neutrons are capable of being captured by the uranium nucleus. Only thermal neutrons participate in the chain reaction. Thus, a moderator, like graphite or water, is used to reduce the energy of neutrons and slow them down. The slowing down of neutrons by the moderator serves two purposes:

1. make them available for reaction with ^{235}U , and
2. decrease the chances of being captured by ^{238}U thus producing neptunium and plutonium.

To control the chain reaction in the reactor, and the power level, we have to introduce rods of material, such as cadmium, which are very efficient in absorbing neutrons and stop the reaction. By adjusting the number and position of these control rods in the reactor core, any power level within the design range of the reactor can be achieved.

Electric power plants operate using fission reactors in different places on Earth. The reactor core supplies heat to circulating water maintained at high pressure. Heat is transferred by means of a heat exchanger to a secondary loop containing water that is converted to steam which drives a turbine-generator system to produce electric power. Water in the secondary loop is isolated from the water going in the reactor core.

B.7. The critical mass and the fission bomb

A chain reaction will take place in a fissionable material if the number of neutrons released during the first incidents of fission multiplicate inside the material without much escaping from the surface of the mass and is lost. The multiplication factor is defined as the factor by which the number of neutrons increases between one step and the next along the fission chain. If no neutrons are lost from the fission chain, then the multiplication factor is simply equal to the average number of neutrons released per fission; but if some neutrons are absorbed or escaped without inducing a new fission, then the multiplication factor will be smaller. The mass whose multiplication factor is unity is said to be a critical mass, in which the chain reaction merely proceeds at a constant rate, as in a nuclear reactor.

In the case of a mass bigger than the critical mass, the chain reaction proceeds at an ever-increasing rate leading to an explosion, as in the nuclear bombs. For ^{235}U, the sphere of minimum size has a diameter of about 18 cm, and the corresponding minimum mass is about 53 kg. However, the critical mass could be diminished if the fissionable material is surrounded by a neutron reflector that prevents the escape of neutrons. In the nuclear bomb, a thick shell of beryllium makes a good neutron reflector.

B.8. The Hiroshima bomb

The bomb dropped on Hiroshima was of the fission type using ^{235}U as the fissionable material. It consisted of two pieces of ^{235}U such that the mass of each piece is sub-critical. When the two pieces, which were initially at a safe distance from one another, were suddenly brought close together, the bomb exploded. The device used for the assembly of the two pieces of uranium consisted of a gun which propeled one piece of uranium toward the other piece at high speed using an ordinary high chemical explosive. The Hiroshima bomb was 120 inch long and weighed 7000 pounds; it is shown schematically in Fig. 3.17.

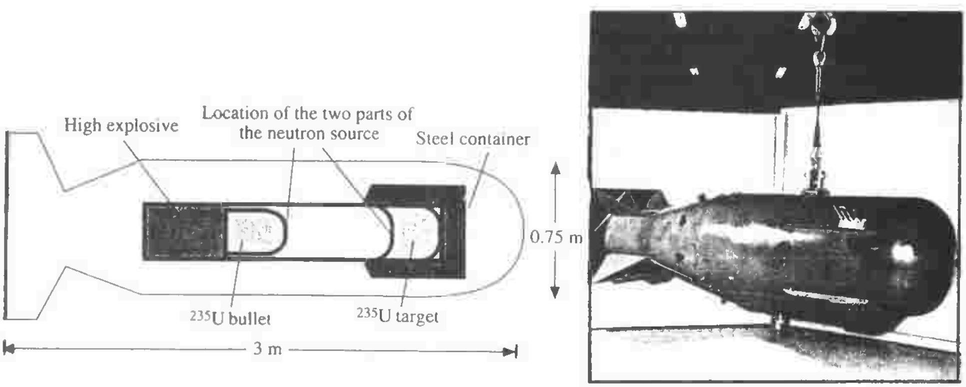
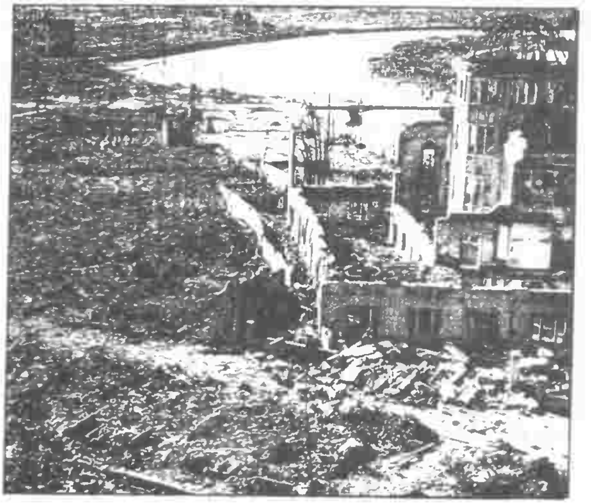


Fig. 3.17. The gun design of the Hiroshima bomb and the bomb dropped on Hiroshima.

The first nuclear weapon fell toward Hiroshima, its target, on August 6 (1945). Twelve kilotons of nuclear energy was released; 140,000 persons died immediately with an equal number wounded. An area of about 20 square kilometers was completely ruined as shown in Fig. 3.18. By the year 1950, more than 200,000 persons died forming about 50% of the city's population.

The mushroom cloud of the nuclear explosion.



Hiroshima, August 1945, after 12 kilotons of nuclear energy released.

Hiroshima, 1993, after being rebuilt. Note the ruins of the dome far behind the memorial statue. It was the only building left after the blast and is retained as such for remembrance.

Fig. 3.18

B.9. Fusion reaction and the energy from the Sun

When two light nuclei combine to form a heavier nucleus the process is called **nuclear fusion**. The difference in mass between the final fused nucleus and the combined rest masses of the original nuclei appears as released energy. Energy is created in our Sun by a fusion process of two hydrogen nuclei to form one helium atom through the following reactions:

$$ {}^{1}_{1}H + {}^{1}_{1}H \longrightarrow {}^{2}_{1}H + {}^{0}_{1}e + \text{nutrino } \upsilon $$

$$ {}^{1}_{1}H + {}^{2}_{1}H \longrightarrow {}^{3}_{2}He + \text{gamma photon } \gamma $$

$$ {}^{1}_{1}H + {}^{3}_{2}He \longrightarrow {}^{4}_{2}He + {}^{0}_{1}e + \text{nutrino } \upsilon $$

or

$$ {}^{3}_{2}He + {}^{3}_{2}H \longrightarrow {}^{4}_{2}He + {}^{1}_{1}H + {}^{1}_{1}H $$

The masses of the three reacting nuclei are:

mass of ${}^{1}_{1}H$ = 1.6727×10^{-27} kg

mass of ${}^{2}_{1}H$ = 3.3437×10^{-27} kg

mass of ${}^{3}_{2}He$ = 5.0066×10^{-27} kg

The sum of the first two masses is 0.0098×10^{-27} kg more than the mass of the helium nucleus. This mass difference is transformed to energy according to Einstein's relation ($E = mc^2$);

Energy released = $0.0098 \times 10^{-27} \times 9 \times 10^{16}$

= 8.815×10^{-13} Joules per one fusion

= 25 MeV

It could be seen that an enormous amount of energy is released by the fusion reaction. This suggested the possibility of using this energy for the benefit of mankind on Earth. But how could we make fusion reactions under control?

A major difficulty of making a fusion reaction is the fact that the Coulomb repulsion force between the two charged nuclei must be overcome before the strong force of the nucleus comes into play. The potential energy as a function of particle separation is schematically represented in Fig. 3.19.

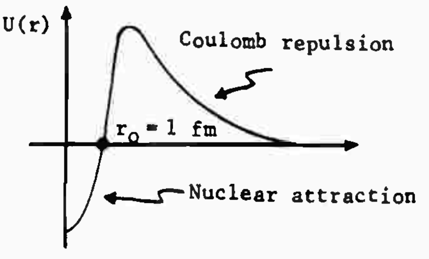


Fig. 3.19. The potential energy as a function of separation between two nuclei. The two nuclei require energy greater than the height of the barrier to undergo fusion.

B.10. Nuclear reactor, fuel, moderator, coolant

Uranium is made of two isotopes. One of them, ^{238}U has a half life comparable to the age of Earth (4.5 billion years). The other one ^{235}U has a half life much shorter (0.7 billion years), it makes only 0.7% of natural uranium.

When uranium is irradiated by slow neutrons, the released binding energy of the captured neutron is not enough to cover the activation energy for fission in 238 uranium, but it is enough to split the ^{235}U. In the fission of ^{235}U induced by one neutron, 2-3 neutrons are released, this makes the nuclear chain reaction possible.

The neutrons emitted in fission are fast. They slow down gradually by elastic collisions, if they are not captured. Unfortunately, ^{238}U captures the medium-energy neutrons without fission, so in the natural mix of uranium isotopes, the fission neutrons are absorbed by ^{238}U with good efficiency. Thus, the chain reaction in natural uranium is impossible.

The inhomogeneous nuclear reactor solved this problem. The uranium fuel rods are arranged as a lattice of rods, surrounded by materials in which the neutrons suffer elastic collisions. If the diameter of the uranium rods is smaller than the mean free path of neutrons, the neutrons produced in fission leaving the uranium rod, suffer collisions in the moderator, they slow down to the energies of thermal motion. Then, by random walk the thermal neutrons get back into a uranium rod. For slow neutrons the capture probability of ^{238}U is already low, but the fission probability of ^{235}U is high, thus they can produce further fissions, the chain reaction may run further.

The moderator material have to fulfill the following conditions:

1. They must be light nuclei, so that in elastic collisions they take over a considerable fraction of the kinetic energy of the neutron.
2. They must have low absorption probability for neutrons in the whole energy range.

Graphite and heavy water (D_2O) are good moderators. Common light water (H_2O) is a poor moderator because it absorb neutrons to form deutrons:

$$n + H \longrightarrow D$$

If, however, the uranium is enriched in ^{235}U a bit, the enriched uranium fuel plus light water moderator system may sustain a fission chain reaction in the reactor.

A great deal of effort is presently under way to develop controllable fusion reaction using deuterium, heavy water, as fuel. Thermonuclear reactors using water as fuel are considered ultimate energy sources because of the availability of its fuel, the water. An additional advantage of fusion reactors is that comparatively few radioactive by-products are formed. The end product, e.g. of the fusion of hydrogen nuclei is safe, it is non-radioactive helium. However, fusion of hydrogen nuclei requires extremely high pressures and densities of the reacting material that are not yet available. The fusion reaction that might be more promising is the use of deuterium and tritium, which are isotopes of hydrogen, in the future fusion reactor.

B.11. Safety and waste disposal

One of the major dangers in a nuclear reactor is the possibility that the cooling system stops operation, and the reactor temperature increases to the point where the fuel elements would melt, and would melt the bottom of the reactor. Under such circumstances, tremendous amounts of heat generated could lead to a high-pressure steam explosion that would spread radioactive material throughout the area surrounding the power plant. Such incidents actually happened at Three Miles Island in U.S.A. and at Chernobyl in the late USSR.

Another problem in the use of nuclear energy as a source of energy, is the disposal of radioactive material when the reactor core is replaced. The waste materials contain highly radioactive isotopes which have long half life times. These isotopes must be stored over long periods of time in a way that there should be no chance of environmental contamination. Some nuclear Countries thought of drawing them in large vessels into the ocean, other Countries used to deceive poor developing Countries of the third world, by providing some money to allow such waste disposal be buried in their land. This problem has not yet been solved since all methods presently used to get rid of this nuclear waste disposal cause environmental contamination and produce radioactive pollution.

A third very important problem is the connection between nuclear power and nuclear weapons. The purchase of many Countries of nuclear material greatly increases the probability of having a nuclear war. A nuclear power industry could produce more than a million kilograms of plutonium per year. Only about ten kilograms are needed for a fission bomb. It could be seen that it will be very difficult to keep significant amounts of this plutonium from going into weapons.

B.12. Nuclear energy for electricity production

The splitting of the uranium atom and chain reaction which occurs in the nuclear reactor core generates a lot of heat. The water meant for cooling the reactor core circulates around the core to remove heat from the fuel. The removal of heat increases the temperature of water which may change directly into steam in the boiling water reactor design or remain in the liquid state under high pressure in the pressurized water reactor design. Steam generators transfer the heat from the core coolant loop to a second loop of water separate from the first. The water under lower pressure in the second loop, becoming steam, is used to drive turbines and generators to produce electricity (Fig. 3.20).

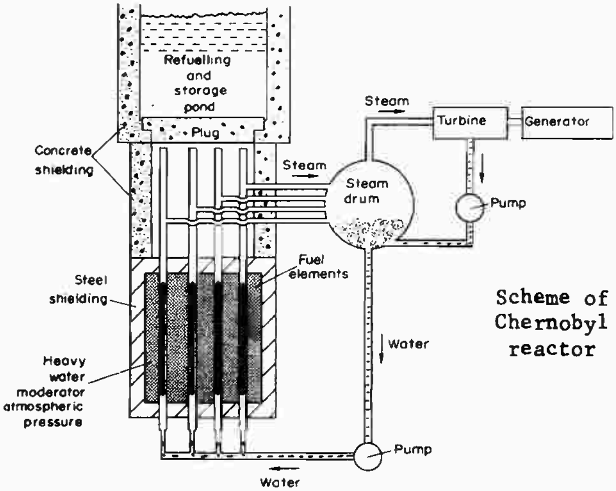


Fig. 3.20.

B.13. Accidents at Chernobyl and Three Miles Island

Errors, whether personal or from unknown reasons, happen always. A major and fatal error in the nuclear reactor business is to stop the coolant from flowing in the reactor core to remove the heat generated. This happened in the reactor of the three Miles Island and in the Chernobyl reactor. The core of the reactor partially melted at three Miles Island, whereas, it burst into two explosions at Chernobyl. The winds blowing over the area scattered the radiation everywhere. The escaped radioactive isotopes were those fission products, which diffused at fastest rate from the ruptured fuel rods into the burning graphite.

B.14. Fission products and their biological effects

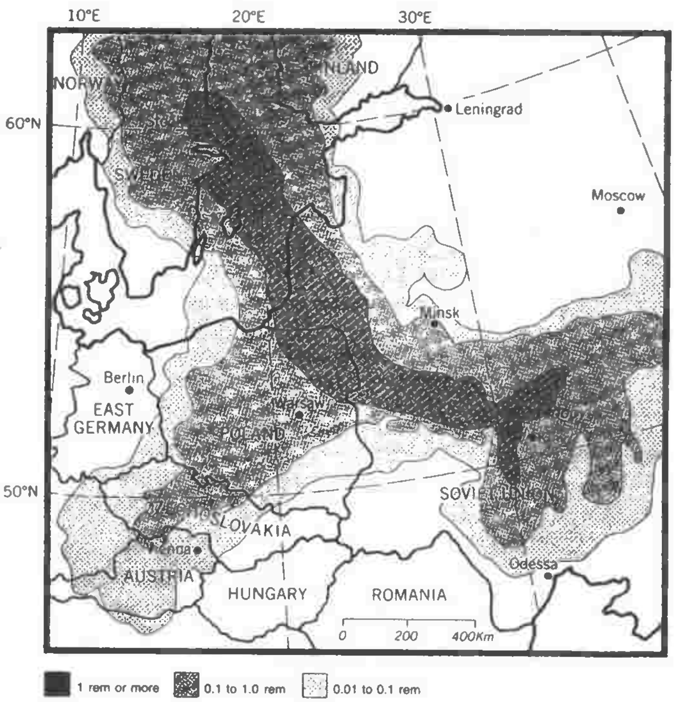
The most important fission products and radioactive isotopes are the biological active ones:

1. Iodine ^{131}I is used by animals and humans to be incorporated in the thyroid, its half life time (HLT) = 8 days.
2. Caesium ^{137}Cs (HLT = 27 years), and ^{134}Cs (HLT = 2 years) are mistaken to potassium and incorporated in the body everywhere.
3. Strontium ^{90}Sr (HLT = 28 years) is mistaken to calcium of the human body and is incorporated in the bones (made of $CaPO_3$), near to the bone-marrow where red blood cells are produced, thus causing leukemia.

The accident of Chernobyl lasted from 2nd April to 5th of May 1986. In May grass was growing fast and the short range contamination from ^{131}I was very dangerous. The grass incorporated ^{131}I from rainfall. The cattle was already grazing after the winter, they concentrated the iodine into the milk, to cover the increased iodine demand of the fast growing calves. But the same milk was consumed by the children, who accumulated the iodine (with the active ^{131}I included) into their growing thyroid. This effect would cause thyroid cancer in coming years. To protect the population from this contamination the milk produced from affected regions was destroyed, and by suppressing milk consumption of children. However, the danger of this short range contamination passed away due to the 8 days half life of this nucleus.

The long range contamination, being present now as biological hazard, is ^{137}Cs, which has dropped to the soil and stays there for 27 years and more, subjected to geological dilution. This may get to vegetables, strawberry, and also to the grazing animals. That is why many Countries until now put vegetable and meat trade, under strong control, particularly in Europe.

Chernobyl was more than an accident. It was a catastrophe. The released active ^{137}Cs nuclei will stay with us for decades. But nowadays we are aware of the benefits and hazards of nuclear power, positive and negative feedback, inherent instability and stability, risk and global responsibility. This could be taught to a wide sector of the youth population in order to learn from those mistakes and deal with the situation in the best way possible, reducing the potential consequences as much as possible.



The spread of radiation following the Chernobyl nuclear power plant accident. The three shaded regions represent three different levels of exposure to ^{131}I.