Safety and Environmental Aspects of Nuclear Reactors

12.1. The Biological Effects of Radiation

In recent years, increasing emphasis has been placed on the safety and environmental aspects of nuclear reactors. In some cases, public opposition has led to long delays in construction and even to the cancellation of projected power plants. While public concern has been expressed over a wide range of aspects of nuclear power, such as the possibility of proliferation of nuclear weapons arising from a move to a plutonium-based breeder reactor program, the principal source of controversy has centered around the potential effects of radiation exposure to the population either from normal operation of reactors or as a result of some postulated accident which could release radioactivity to the environment.

In order to appreciate the magnitude of the potential hazard associated with the release of radioactivity, it is first necessary to consider the effects on the human body of exposure to ionizing radiation. The present section will deal briefly with the biological consequences of radiation exposure and with the international radiation protection standards which have been adopted. Subsequent sections will deal with releases of radioactivity under normal operating and possible accident conditions, and with other environmental aspects of nuclear power stations.

The effects of radiation on living organisms arise from the damage caused to the molecules of their constituent cells by the passage of charged particles. The damage can be classified as somatic or genetic; somatic damage is damage which affects the individual exposed, while genetic damage involves the gametes, and can therefore affect future generations.

In order to understand the ways in which radiation affects the body, it is first necessary to look at the structure and function of the cell, which is the fundamental unit of life. A typical cell is illustrated in Fig. 12.1. Almost all cells consist of a central nucleus, surrounded by the nuclear envelope, which
divides it from the cytoplasm, which in turn is enclosed within the cell membrane, which forms the outer boundary of the cell. The cytoplasm, together with organelles such as the mitochondria, contained within it, is responsible for the metabolism of the cell, including the buildup of proteins and elimination of waste products. Within the cytoplasm is a complicated network of membranes, known as the endoplasmic reticulum, which forms a set of canals for transporting materials around the cell.

The nucleus is responsible for the direction of the metabolic activity of the cell. The key to this activity lies in the chromosomes, threadlike bodies containing a nucleic acid, deoxyribonucleic acid (DNA), and, more specifically, in the genes which are incorporated in the chromosomes. The great majority of human cells, the somatic cells, contain 23 pairs of chromosomes. The only exceptions are the gametes (sperm cells and ova), involved in reproduction, which contain only half this number. The combination of a sperm and ovum in the fertilization process produces a new cell (the zygote) with the required 23 pairs of chromosomes, which forms the basis for the new individual. Further development takes place by mitosis, or cell division, a process in which each chromosome duplicates itself prior to the cell splitting into two new cells, each of which emerges with an identical set of 23 chromosome pairs.

The reason that a relatively small amount of energy delivered to the body in the form of ionizing radiation can produce significant cell damage is that the energy transfer to the material takes place by a series of interactions with a few individual molecules, with relatively large amounts of energy being transferred in each interaction. When a charged particle, such as an \( \alpha \) or \( \beta \) particle, travels through matter, it interacts with the electrons of the atoms in the matter through an electrostatic interaction, causing the atoms to become excited or ionized. Many of the electrons produced by an initial ionization event are ejected with sufficient energy to produce further excitations or ionizations of the neighbouring atoms. The basic process is therefore one where the kinetic energy originally possessed by the incoming particle is gradually lost in producing excited and ionized atoms. The effect of exciting an atom, by the promotion of one of its electrons to a higher energy level, is to increase the chemical reactivity of the atom, while atoms which have been ionized are even more reactive.

While \( \alpha \) and \( \beta \) radiation produce direct excitation and ionization events as described above, a \( \gamma \) ray can only do so by first interacting with an atom of the material to produce a charged particle. There are three types of interaction which can take place. In photoelectric absorption, the \( \gamma \) ray transfers all of its energy to an orbital electron which is then ejected from the