EFFECTS OF NUCLEAR RADIATION ON MEN AND MATERIALS

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PREFACE

All authorities agree that nuclear power for propulsion of military and civilian vehicles has become a reality.

The application of nuclear energy in mobile units has presented many unexpected and unheard of technological and biological problems. The design engineer is certain to be affected by many of these problems in the basic design of such vehicles.

The available information on the physicochemical and biophysical effects of radiation is widely scattered in handbooks and journals. Therefore, some basic principles and pertinent data have been accumulated here. Of course, this book does not attempt to replace any comprehensive literature. In fact, it is advisable for the design engineer to consult nuclear specialists for detailed information. Such specialists should be consulted in the embryonic stage of the development of the project. If the input of these specialists is given in an advanced stage of the project, the design engineer might find himself in the embarrassing position of having to make substantial and expensive changes in his design. Such changes could handicap the proficient utilization of the budget provided for the project.

I wish to take this opportunity to express my appreciation to the Martin Company for their assistance in the preparation of this book.

T. C. HELVEY

Orlando, Florida
September 1959

CONTENTS

Chapter 1

A FEW BASIC CONCEPTS

To make the contents of this book more meaningful and useful, certain basic concepts and definitions of nuclear physics should be described.

The available nuclear energy comes from the neutron-induced fission of heavy metal nuclei. The fragments of the fissioned atoms possess high kinetic energies. These fragments will penetrate metals and may influence their crystal structure lattice and alter the tensile strength or other characteristics of the metal. The range of these primary fragments is short, but they must be taken into consideration for structures in the immediate vicinity of the reactor core. In addition to these fission fragments, the reactor yields other radiating particles, mainly alpha particles, beta particles, gamma rays, and x-rays.

Alpha and beta particles come from a site of nuclear fission and will be of little significance to the design engineer, since they can be very easily absorbed even if they possess extremely high energies. On the other hand, neutrons, gamma rays, and x-rays are of serious concern to the design engineer. These particles have great penetrating power and have a potent influence on both men and materials.

The crew and the structure of nuclear-powered vehicles are exposed to natural and man-induced radiation. Both types are discussed in the following pages.

RADIATION

Radiation is the emission and propagation of radiant energy in the form of discrete units, called quanta. The term "radiation" should refer, by definition, only to the electromagnetic spectrum. It is, however, generally extended to include streams of subatomic particles. The nuclei of all atoms are in a dynamic state, and any change in this state will bring about some sort of radiation.

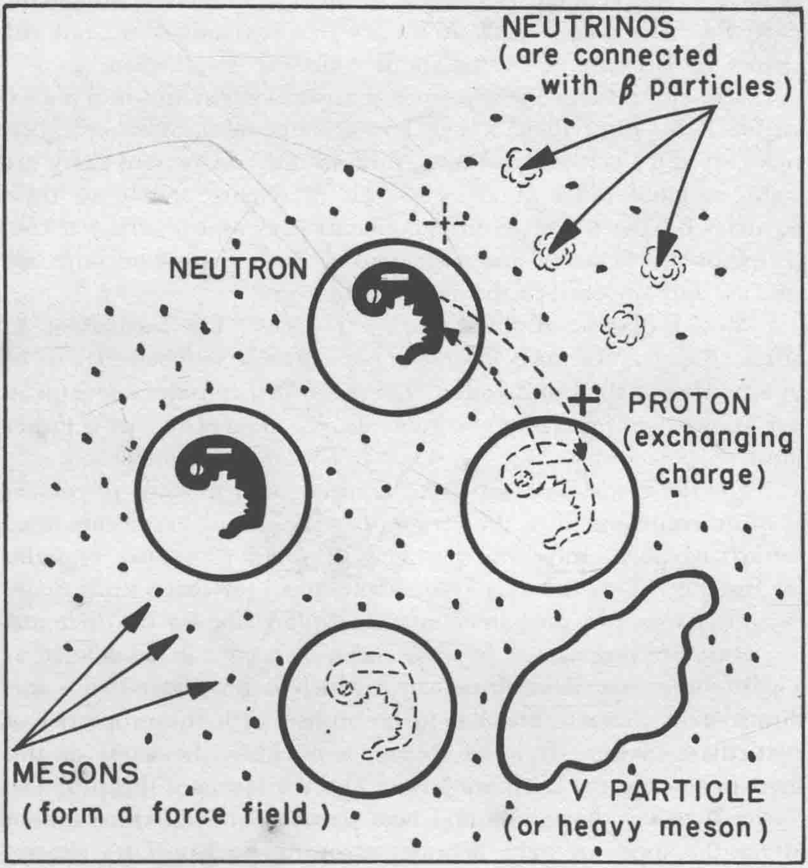
The electromagnetic spectrum consists of radio and heat waves, visible light, ultraviolet, x-rays, and gamma rays. Subatomic particles are the electrons, neutrons, protons, etc. At present there are eighteen more different types known to science. Some of these particles can be found in firm bond, such as alpha particles, consisting of two neutrons and two protons. Such compound units are emitted and absorbed in this particulate form.

Most radiation originates in the nucleus. The nucleus of an atom (Fig. 1-1) is much more complex than it was believed to be by scientists of the last decades. There are still considerable gaps in our knowledge concerning the atom and the state of the art is rather fluid.

For those who are not quite familiar with modern physics, it is quite confusing that the terms "particles" and "rays" are used interchangeably. Rays and particles are both properties of light, for instance. This was very confusing even to physicists until quantum mechanics provided an acceptable explanation for the dilemma.

Rays are propagated in wave form. A wave can be defined as a periodic or aperiodic disturbance which is propagated in a medium. This characteristic has to be unified with the properties of particulate matter. It is, of course, not within the scope of this book to describe the fascinating story of the solution of this problem. Suffice it to say that alpha and beta particles and electrons cannot attain the speed of light because, according to Einstein's general theory of relativity, their mass would become infinitely large. On the other hand, electromagnetic radiation such as light, x-rays, and gamma rays, which are traveling at the speed of light, can be considered to be particles which do not possess a rest mass; that is, they are not existent at rest, but will be influenced by gravity.

Some subatomic particles, e.g., alpha particles, electrons, etc., carry electric charges; others, such as neutrons and gamma rays, are electrically neutral. It is significant that, when most of these par-



NUCLEUS

Fig. 1-1. The atomic nucleus.

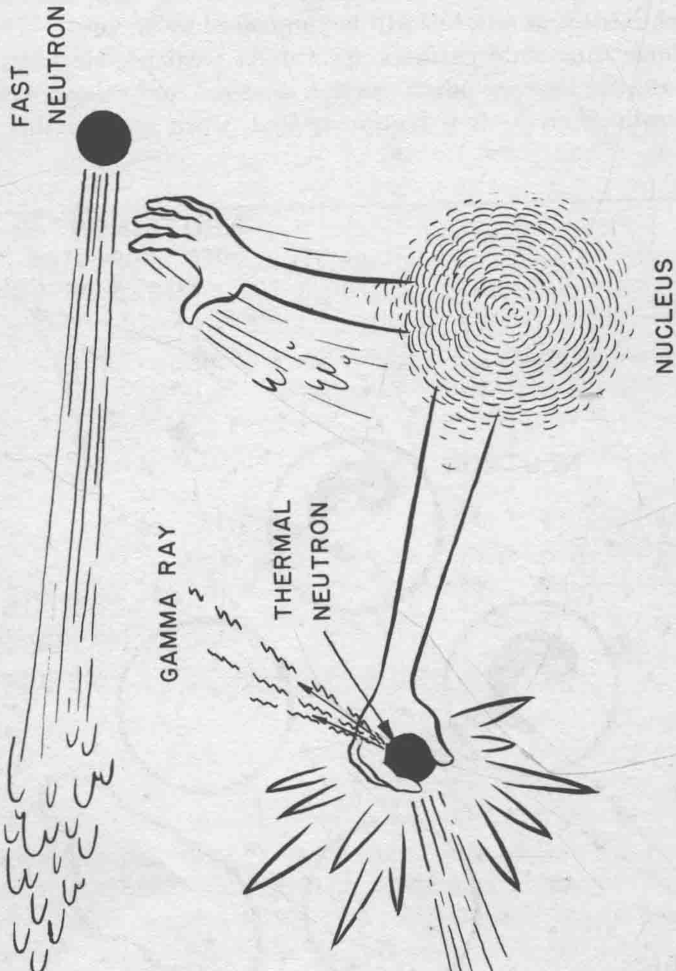


Fig. 1-2. The capture of neutrons by atomic nuclei.

ticles pass through matter, they give rise to ions – electrically charged atoms. Particles that are attached to an electric charge will transfer the charge to other atoms, and the noncharged particles will dislocate electrons from the orbits of electrically neutral atoms. Thus, the latter will become positively charged because the dislocated orbital electrons remove a negative charge.

Chemical and physicochemical charges in inanimate and, especially, in living matter are brought about mainly by the ionizing effect of nuclear radiation. Neutrons, not carrying an electric charge, do not directly ionize chemical compounds. When fast neutrons are slowed down in matter of low specific gravity, such as water, hydrocarbons, air, boron, and aluminum, they become thermal neutrons. These neutrons have lost most of their kinetic energy except that which they retain from the ambient temperature, and thus they have the same speed as gas molecules in a motionless atmosphere. This speed is roughly 1 mile per second as compared with the many thousands of miles per second for fast neutrons.

When fast neutrons are slowed down and become thermal neutrons, they are easily captured by various nuclei. These nuclei then give off hard gamma rays, which have a highly penetrating and ionizing capacity (Fig. 1-2).

ELECTRON

The electron, a fundamental particle, was discovered by J. J. Thomson in 1897. It is one of the smaller particles known and has the smallest negative charge that can be isolated and measured at present. All negative electrical charges are exact multiples of this "unit of electric charge." A shortage of electrons is called "positive electricity" or "positive electric charge." An excess of electrons is called "negative electricity" or "negative electric charge."

Electric currents are produced by mass movements of electrons in electric conductors. The atomic weight of an electron is approximately 1/1840 of the mass of the hydrogen atom. Its mass, however, increases when in rapid motion. Therefore, beta particles, which are electrons emitted by radioactive atoms, and electrons in high-

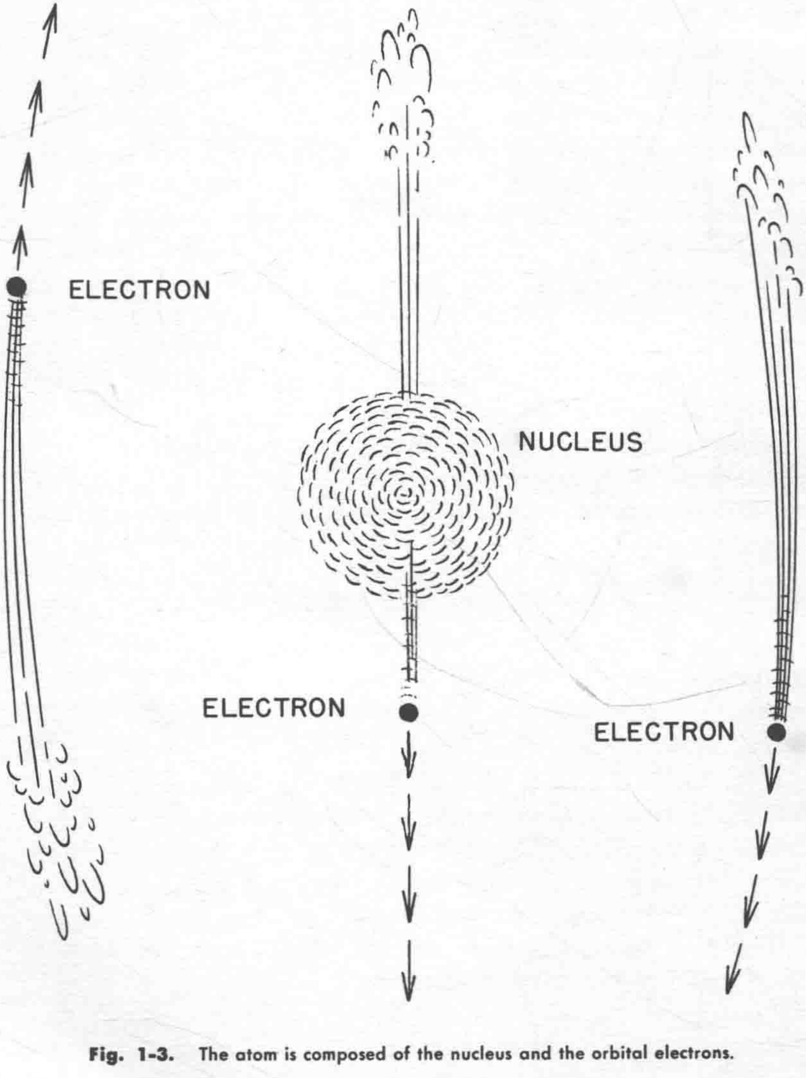


Fig. 1-3. The atom is composed of the nucleus and the orbital electrons.

voltage x-ray tubes have a mass several times their rest mass. Atoms are composed of a nucleus and a certain number of orbital electrons, circling in greatly elongated orbits (Fig. 1-3) and arranged in shells and subshells.

Two of these electrons can have a maximum probability for being in the nucleus, a place theoretically excluded from all places where electrons can be. This apparent impossibility may be explained by assuming that the electron can be expressed as a wave and has a wavelength larger than the diameter of the nucleus, and thus may bypass the nucleus. The number of the extranuclear orbital electrons equals the number of protons in the nucleus, i.e., the atomic number of the element. Disturbances of the electron close to the nucleus produce x-ray quanta, and the disturbances of the outer electronic structure produce the optical spectra. Changes in the outermost shells are involved in the molecular structure and are responsible for chemical reactions.

PROTON

The proton is recognized as one of the fundamental nuclear particles. It was discovered by Rutherford in 1920 and is identified as the nucleus of the common hydrogen isotope symbolized by ${}_1H^1$. This symbol means that hydrogen has a mass number of 1 and an atomic number of 1. The mass of a proton is about 1840 times the mass of an electron and slightly less than the mass of a neutron. Protons are positively charged, and the numerical value of the positive charge of each proton is equal to the charge of an electron. The major massive parts of the nucleus of an atom are considered to be protons and neutrons (collectively called nucleons). The number of the protons in the nucleus equals the atomic number of the isotope, and the combined total of all the nucleons is called the mass number.

NEUTRON

The neutron is another of the fundamental nuclear particles. It was discovered by Chadwick in 1932. The mass of the neutron is slightly greater than that of the proton. It has no electric charge.

Based on Heisenberg's theory, if neutrons and protons are in close proximity, as in an atomic nucleus, the electric charge may be oscillating between them, so it is not possible to state specifically which nucleon is a proton and which is a neutron at a given time (Fig. 1-1). Being electrically neutral, neutrons penetrate most solid bodies rather freely. They produce very few ionizations in air or in other gaseous media. A fast neutron will produce not more than 1 ion pair per 100 inches of its path in air. When an electron is dislodged from a molecule, it carries a negative charge and leaves the molecule positively charged. The positively charged molecule and the electron are called an ion pair.

Neutrons are important and very useful agents for the production of nuclear reactions, fissions, and fission chain reactions. Since neutrons are electrically neutral, they are not repelled by the positively charged protons in the atomic nuclei, and therefore they make much better "projectiles" for nuclear bombardment than do the positively charged alpha particles, protons, and deuterons. Free neutrons may be captured by atomic nuclei, and the resulting nuclear reaction usually produces the nucleus of a different element or isotope. The capture probability of neutrons by an atomic nucleus depends on the so-called "capture cross section" of the nucleus and the speed of the neutron. There is a minimum speed to which neutrons can be slowed by colliding with atoms. In this state, they are called thermal neutrons and will be absorbed with great probability by atoms (Fig. 1-2). Free neutrons can be produced in many ways. The most convenient method is the bombardment of certain atomic nuclei with protons, deuterons, or alpha particles. Free neutrons are also byproducts of nuclear fission and of dissociation, i.e., nuclear disintegrations caused by gamma rays, which are then called photoneutrons.

ALPHA PARTICLE

This particle often arises from decaying natural radioactive elements. It was discovered by Rutherford in 1904 and is identified as the nucleus of a helium atom that has lost its two planetary electrons and is therefore positively charged. Each alpha particle consists of two protons and two neutrons and has a positive electric charge which is numerically double the electronic charge. Alpha particles which are ejected by disintegrating radioactive substances vary in their velocity, range, energy, and number, according to the emitting substance, and are characteristic of the latter. All alpha particles emitted by a homogeneous radioactive substance – one that does not contain more than one element – have the same range and speed. Their velocities lie between 1.4 and 2.0×10^9 cm per sec, and their energies range up to 10.5 Mev (million electron volts), depending on the emitting substance. They are limited in penetration to about 8.6 cm in air and a sheet of paper will stop them. They will cause dense ionization in the air along their path: a single alpha particle can produce 20,000 to 40,000 ion pairs. The energy and range of alpha particles vary with the decay constant of the substances by which they are emitted. The decay constant is the rate of disintegration of a radioactive element.

BETA PARTICLE

The beta particle is a negatively charged particle, i.e., an electron ejected at high velocity from the nucleus of the atom when one of its neutrons changes into a proton (Fig. 1-4). Some of the isotopes are typical beta emitters. The beta particle is not an orbital electron, although it has the same mass and charge. It is hurled from the nucleus at the instant of its formation. The energy, velocity, and range of beta particles vary widely; the same homogeneous radioactive element emits beta particles of different energies, velocities,

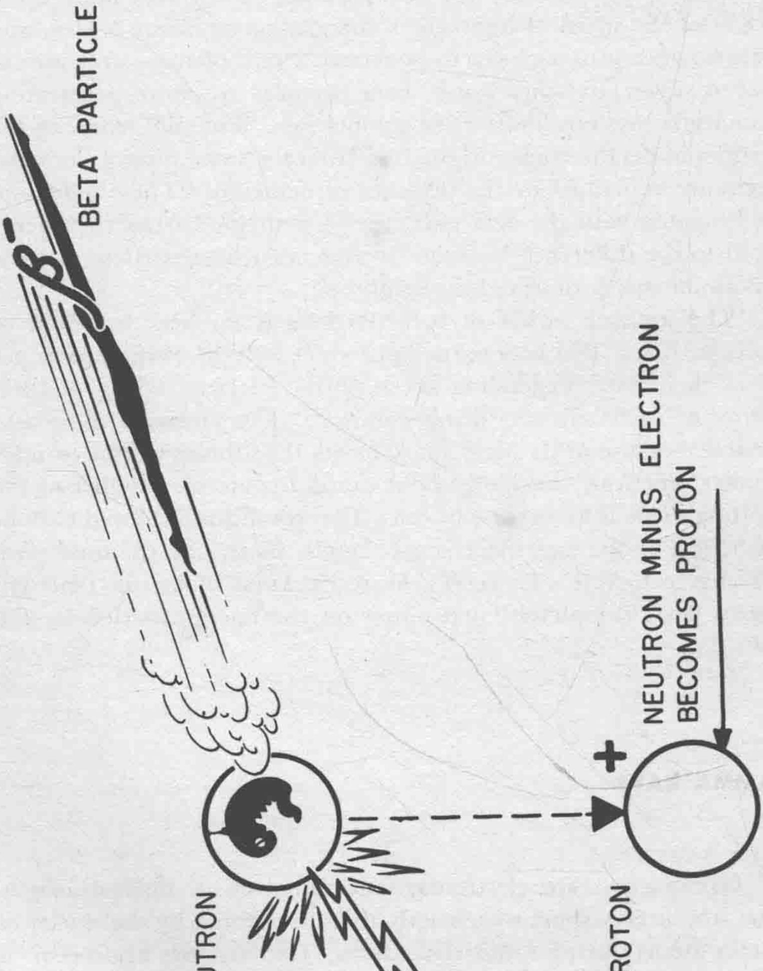


Fig. 1-4. Mechanism of beta decay.

and ranges. The velocities of beta particles can be very high, up to 99.8% of the speed of light, their energies up to about 3 Mev, and their ranges up to a power to penetrate 2 mm of brass or 1 mm of lead or silver. In other words, beta particles are more penetrating than alpha rays but less so than gamma rays. The differences in the energies of beta particles originating from the same type of decaying atoms are explained by the presence of neutrinos. These neutrinos are liberated with the beta particles. A neutrino carries the energy equal to the difference between its associated beta particle and the maximum energy observed in the isotope.

The ionizing power of beta particles is far less than that of alpha particles. Fast beta particles produce only 50–100 ion pairs per cm of their path, expending about 60 ev (electron volts) of their energy in each pair-producing collision. The emission of a beta particle, because of its slight mass, leaves the atomic weight or mass number practically unchanged but causes the atomic number of the emitting nucleus to increase by one. This condition is brought about by the loss of one negative charge, thereby increasing the total positive charge by one. There is a finite thickness of matter that will absorb betas completely, depending on the energy carried by the particles.

GAMMA RAYS

Gamma rays are electromagnetic radiation of nuclear origin. They are of very short wavelength and are emitted by the nuclei of certain atoms during radioactive decay. Gamma rays also occur as a result of various nuclear reactions. They are not composed of particles, in the sense of protons or neutrons, but consist of high-energy photons. Gamma rays have the speed of light, but have no electric charge and no rest mass. However, they simulate a slight mass owing to their motion and velocity. Their range, both in air and matter, is much longer than that of either alpha or beta par-