# INTRODUCTION TO RADIOLOGICAL HEALTH

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# Preface

This text originated in a series of lecture notes used for a course on the Introduction to Radiological Health given for many years at the New York University Medical Center. Some of the material was originally prepared for the training of radiation inspectors in the New York City Health Department.

In 1954, Congress amended the Atomic Energy Act to release many aspects of atomic energy and its applications from exclusive ownership and control by the Atomic Energy Commission. Many industries, universities, educational institutions, hospitals, and physicians were faced with the need of assuming an increased degree of responsibility for the health and safety aspects of radiation applications in order to qualify for AEC licenses. In many cases, the activities involved did not justify engaging the fulltime services of a professionally trained health physicist. In addition, many branches of Federal, state, and local governments, as well as insurance companies and others, found themselves in need of specialized training in this field. Many of the persons selected for training were engineers, scientists, physicians, and public health workers who were trained and experienced in their own fields but were being given the additional responsibility of radiological health. One of the reasons for the sudden need for such training was that for years many aspects of radiological health were restricted by security considerations during the war and postwar periods. Another reason for the need of training resulted from the great attention focussed on the biological effects of radiation, which had the effect of changing the attitude of public health authorities and the public toward radiation and radiation exposure. Considerable activity among Federal and state agencies to formulate radiation-protection regulations drew attention to many deficiencies in the previously unregulated use of X-rays and radium which had existed for many years.

It should be recognized that the scope of this text differs considerably from other material prepared for the academic training of professional health physicists, although it can well serve as an introduction to the field. Most such training has been sponsored by the AEC and is primarily concerned with atomic energy applications. The course for which this test was prepared presumes the student (1) has a working knowledge of nuclear physics and the elements of biology, (2) will take courses or has access to textbooks covering such subjects in considerably more detail than possible here. The material has also been influenced by the fact that most of the students have had considerable practical experience in related fields after completing their professional training.

An attempt has been made to give serious consideration to the relative importance of the various aspects of radiological health and the control of radiation exposure of both radiation workers and the general public. Some details, although of scientific interest and importance, have been omitted if not closely related to activities involving significant individual or population radiation exposure. Some such material believed important to assist the student in gaining a more comprehensive understanding of the field has been selectively included.

It is readily acknowledged that the subject of the medical and dental use of X-rays receives considerably more attention in this text than would normally be expected in a book devoted to the comprehensive subject of radiation hygiene. This has been done for two reasons: (1) It is generally agreed that the medical and dental use of X-rays constitutes by far, the greatest radiation exposure of the population, the one that can most readily be reduced without serious interference with the practice of radiology. (2) The vast majority of works published on the subject of health physics or radiation protection have been related to the field of atomic energy, largely because of the financial support given by national governments throughout the world. In most of these publications the subject of nonatomic energy radiation sources, such as X-ray equipment and radium, has to a great extent been neglected.

In the introduction to the book an attempt has been made to consider briefly all possible sources of radiation and put them into proper perspective. In the first chapter the various sources and their characteristics are dealt with in greater detail, followed by a general discussion of radiation and its interaction with matter.

The chapter on the biological effects of radiation is taken almost in its entirety from a guide originally prepared for the use of those public health workers faced with problems of radiation control but having had little academic training in medicine or biology. In most attempts to deal with a complex subject in simple nontechnical terms, there is some risk of scientific inaccuracies through oversimplification. This we believe has been avoided. Discussion of the historical development and details of current maximum permissible doses and concentrations in terms of biological effects follows. In this area it is important to remember that concepts and opinions are frequently changing and that the latest established radiation exposure limits should always be consulted. This would also apply to the section appearing later in the text on the legal aspects of radiation control, particularly with regard to any details concerning regulations. A section on radiation shielding has been prepared from a practical standpoint and is particularly directed at those problems which the average administrator or radiation safety officer must face without professional assistance.

Additional sections are devoted to radioactive contamination of the air, water, and foodstuff; they include a brief summary of the latest opinions and controversies regarding radioactive fallout from nuclear weapons tests. The section on radioactive waste disposal is intended as a guide to those who are faced with a wide variety of waste-disposal problems. One chapter devoted to the control of radiological hazards is believed unique in that it attempts to establish step by step the procedures necessary to assure an adequate and economical program of maintaining radiological health in industrial, educational, and medical facilities. The discussion of the legal aspects of radiation control results from the author's many years of experience in assisting in the preparation of AEC regulations and many state and local health and industrial radiation codes. This section also includes some consideration of the insurance aspects of radiation exposure. The section on accidents and incidents includes material which should be helpful to anyone faced with the responsibility of establishing an organization and preparing standard operating procedures for handling radiation incidents. This is another area in which the author has had considerable experience both at the Federal and local level.

The author of any work attempting to cover such a broad subject as this and embracing so many different disciplines depends upon the assistance and advice of many others. This author has been fortunate in receiving the generous constructive criticism of some of our leading experts in the various fields. They include Merril Eisenbud, James E. McLaughlin, James H. Lade, Francis J. Weber, Clifford E. Nelson, Dade W. Moeller, Hertzel H. E. Plaine, Daniel E. Lynch, and Leonard R. Solon. Various publications and documents of the United States Atomic Energy Commission and the Public Health Service of the U.S. Department of Health, Education, and Welfare have been drawn upon for basic

data. In particular, the resources of the U.S. Department of Health, Education, and Welfare, the "1960 Radiological Health Handbook" edited by Simon Kinsman and the "Radiation Hygiene Handbook" edited by the author have been utilized. To Josephine Jones for assistance in preparing the manuscript and to my wife Elizabeth for her patience and sympathy, I am deeply grateful.

*Hanson Blatz*

# Contents

# Introduction

## RADIOLOGICAL HEALTH

In the rapidly developing areas of occupational and public health devoted to the protection of people from the immediate and long-term harmful effects of radiation exposure, a confusion of terminology has arisen. There has been a tendency for existing professional groups, principally radiological physicists, industrial hygienists, and radiologists, to assume the additional responsibilty of protection against radiation. There has also been a movement to develop a new field called health physics or radiation hygiene, at both the professional and technical levels, devoted exclusively to protective measures against radiation. There is undoubtedly a part to be played by all such groups, as well as by those concerned with public health education and legal questions.

Since radioactive materials and radiation-producing devices have become an accepted element of modern society, the field of radiological health can be considered the protection of humanity against undue health hazards to the extent that it does not interfere unreasonably with the beneficial utilization of nuclear energy or other activities involving radiation. The objective should be to gain the maximum benefits of these new forces without risking the public health. Although radiation is known to be a serious health hazard if encountered in large doses, little is known of its effect in small doses on human organisms. The degree of risk involved, therefore, in terms of benefits derived in any particular application is very difficult to determine.

Based on relatively few occupational mishaps in which persons have been harmed and in some cases killed by radiation, there has been sufficient experience to establish certain maximum permissible doses that should not be exceeded without an important reason. This feature of the practice of "radiological health" is relatively straightforward and applies similarly to many other known industrial hazards.

There is a different aspect involving the statistical consideration of the possible harmful effects of radiation in small doses. The question here is whether an individual who has been exposed to relatively small doses of radiation has a statistically significant increased likelihood of developing one of the many effects known to be caused by radiation at relatively high doses. Among such effects are leukemia, bone cancer, and genetic damage. This is actually not dissimilar to exposure to many other toxic or carcinogenic materials, but greater attention seems to have been focused on radiological hazards.

## IONIZING RADIATION

What is radiation, where does it come from, and what does it do?

In spite of the rapidly increasing attention to radiation in recent years, inquiries received by public health agencies indicate a surprising degree of ignorance on the subject, even among many educated persons. Although providing the answers constitutes an important purpose of this text, a very brief and general discussion is presented by way of introduction to indicate the scope of the problem.

When we speak of radiation, we mean radiation which has the property of ionizing matter through which it passes, either directly or indirectly. There are two general classes of ionizing radiation, electromagnetic and particulate, each of which will be described in detail subsequently. In addition to the ability to ionize matter, its other important general characteristic is that it will pass through material substances. These two properties result in certain biological, physical, and chemical changes in the material through which radiation passes.

## SOURCES OF RADIATION AND THEIR GENERAL CLASSIFICATION

Radiation occurs in a wide variety of forms and characteristics. This is because radiation can be produced in many ways from many different sources. Radiation and radiation sources can be classified in several ways; but in order to relate the various radiations to the subject of hazard control, their sources can perhaps best be placed in five general classifications: radioactive materials (natural and artificially produced), particle accelerators producing radiation (including X-ray machines), particle accelerators producing radiation and radioactive materials, nuclear fission (reactors, critical assemblies, and weapons), and secondary sources. Each is discussed here briefly but treated in greater detail in Chap. 1.

***Radioactive Materials.*** In 1896, Becquerel discovered that uranium had the ability to darken a photographic plate. Subsequent experiments by himself and also by Madame Curie resulted in the knowledge that uranium emits a type of radiation, and the material was therefore called radioactive. Subsequent experiments showed that many natural materials have the property of radioactivity. In addition to the natural radioactive materials, it has been found possible to produce man-made radioactive materials by transmutation caused either by splitting natural atomic nuclei or by bombarding stable atoms with high-energy particles.

The nucleus of each atom has a certain degree of stability, depending upon its makeup. Early in the twentieth century, scientists found that the mass of the nucleus of an atom was less than the sum of the masses of all of the particles that it was known to contain. This difference in mass was found to represent the energy required to subdivide the nucleus into its component parts. The nucleus is said to be held together by a certain amount of binding energy. This energy and its relationship to the difference in mass of all the components and the total nucleus was given by Einstein in his now famous equation $E = mc^2$.

The more stable an atom, the greater is its binding energy, and, in general, if an atom of one type with a given binding energy can through some process change itself into an atom with a greater amount of binding energy, it will do so. Atoms which do this are unstable and are commonly said to be *radioactive*. The radioactive characteristics of an atom depend upon its degree of instability as well as the relative distribution of its component parts. For example, the instability of the naturally occurring heavy radioactive elements, such as uranium, is very small. For this reason it may be many years before a uranium atom will transform itself into another atom having a greater binding energy. We thus say that such materials have long lives or that they are long-lived. It is for this reason that many of the naturally radioactive materials are still present in nature, in spite of the fact that they have always existed. Some fission products caused by a nuclear explosion are very unstable and consequently have extremely short lives, some having half-lives of small fractions of seconds.

Most atoms are stable but can be converted or transmuted into unstable ones by being struck by a neutron or in some cases by another particle that can enter the nucleus. Fissionable materials which all have heavy nuclei, when struck by neutrons, split up into two or occasionally more parts, each of which is usually radioactive. These parts are called *fission products.*

One reason for the importance of radioactive materials in the subject of radiological health is that virtually every element can be found or produced in a radioactive form and it can occur in any one of the possible chemical or physical forms in which the corresponding stable element can occur. This means that radioactive materials could be mixed with their stable counterparts, enter the air we breathe, the food we eat, and the water we drink in significant quantities if sufficient care were not exercised. In addition, concentrations of radioactive materials can constitute significant sources that may radiate into our bodies even though the sources are external. A concentrated source, such as radium or radioactive cobalt, can constitute such an external hazard. Widespread radioactive contamination on the surface of the ground can also constitute a source of external radiation that may reach hazardous levels. One of the problems in dealing with radioactive materials as radiation hazards is that they often occur in finely divided or even gaseous forms. If they enter our environment, they are usually very difficult to remove.

***Electrical Sources of Radiation.*** An important source of radiation is through the conversion of the kinetic energy of a rapidly moving particle into radiant energy when the particle is suddenly stopped. In some cases, the radiation is produced by a nuclear transformation when the particle strikes its target. The most common type of particle accelerator is an X-ray machine. In this device, electrons are electrically accelerated with energies from a few thousand volts up to many millions of volts and then stopped abruptly by striking a massive target. In accordance with Maxwell's electromagnetic theory, the deceleration of the moving electric charge must be accompanied by the emission of radiation. Such radiation is generally called X-rays, but, under certain circumstances, is often referred to by the German name *bremsstrahlung,* which literally translated is "braking, or slowing down radiation." One important characteristic of X-rays, insofar as radiological health considerations are concerned, is that they are emitted only during the time when the equipment is electrically energized. When the machine is turned off, the X-ray production, both primary and secondary, is immediately stopped.

We may group with X-ray equipment those other accelerators that produce radiation only while they are in operation, as distinguished from those that produce radioactive materials which continue to emit radiation even after the equipment is deenergized. In general, these comprise principally the various types of electron accelerators, such as the betatron, the Van de Graaff electrostatic generator, and the linear electron accelerator. Although many such high-energy accelerators are designed and used to produce nuclear transformations in the targets, the principal radiation hazard is from X-rays produced by the deceleration of electrons, as in an X-ray tube.

***Electrical Sources of Both Radiation and Radioactive Materials.*** Accelerators, both linear and circular or spiral types that are used to accelerate heavy particles, generally present a dual problem. They are important sources of radiation during operation and, in addition, produce artificial radioactive materials that are sources of considerable residual radiation after the accelerators stop operating. In heavy-particle accelerators, the structural material often becomes radioactive to the extent that safeguards must be provided for those who must use and service the equipment. The storage and handling of used target materials, particularly, may present radiological health problems. Such accelerators generally include cyclotrons, linear proton accelerators, synchrocyclotrons, and proton synchrotrons, also known by a variety of other names such as bevatrons and cosmotrons. The more sophisticated types of extremely high-energy accelerators like the alternating gradient synchrotrons (AGS) are included in this group.

***Reactors.*** Reactors are sources of a variety of radiological health problems, which are discussed in detail in another section. The fuel materials, even before being installed in an accelerator, can be sources of radiological problems because they are made of radioactive materials that require a great amount of handling, processing, and machining. In addition, enriched fuels (fuel elements having a higher than normal content of fissionable materials such as uranium 235) can constitute criticality hazards if they are not handled and stored properly. The design and operation of reactors generally present important shielding problems because reactors emit both neutrons and high-energy gamma radiation while in operation. Any materials in the core of a reactor, including target materials placed there deliberately for irradiation, structural materials, and cooling agents, are subject to induced radioactivity, and suitable precautions must be taken both in design and in operation. Fuel elements that have been utilized in a reactor, commonly referred to as spent fuel, present particularly difficult problems because of the high degree of radioactivity and the intense high-energy radiation emitted from them. In addition, freshly removed fuel elements from power reactors are often so hot, thermally, that special precautions must be taken to keep them cool by artificial means to avoid the volatilization of the elements which would permit the highly radioactive fission products to become airborne and thereby spread radioactive contamination.

***Critical Assemblies.*** Most of the serious occupational exposures to radiation have resulted from criticality accidents. Several have resulted in death. Either through malfunctioning of controls or through improper planning, a critical assembly or experimental reactor can sometimes initiate a chain reaction (go critical) unexpectedly, thereby exposing nearby unprotected workers to a burst of high-intensity neutron and gamma radiation. Improperly packed or stored fissionable materials could go critical if additional fissionable material or neutron-reflecting material were placed nearby. The flooding of a subcritical quantity of material by water could convert it to a critical quantity by neutron reflection.

Wherever significant quantities of fissionable materials are used, stored, or transported, the nuclear safety aspects should be reviewed and checked carefully because of the possible consequences of errors. The subject is dealt with in greater detail in Chap. 1.

***Secondary Sources.*** A number of miscellaneous secondary sources of radiation sometimes constitute troublesome radiological problems in that they may occur or appear unexpectedly if the users are not properly trained to expect them. That certain target materials in accelerators can become radioactive has been mentioned previously. In certain radioactive chains, particularly those found in the course of refining and separating natural radioactive elements, as well as in certain fission products, there can be an increase in radiation emission with time. This is caused by the fact that a parent radioactive material can disintegrate and produce daughter products that are more important sources of radiation. An example of this is thorium 234 (uranium $X_1$). It decays into a daughter product, protoactinium 234 (uranium $X_2$), which has a very high-energy beta emission. When placed in a container, the beta radiation of the daughter product can cause considerable emission of high-energy bremsstrahlung, which will cause a gradual increase in the external radiation from the container with time until it reaches an equilibrium condition and then decays. There are many similar examples of this phenomenon.

The production of bremsstrahlung by placing a beta-emitting material into a container made of a high-atomic-number material can produce unexpected radiation.

Another secondary source of radiation that may be unexpected is scattered radiation. An example of this is the case of an X-ray generator in a room having shielding up to the usual 7 ft height, but not in the ceiling or floor, where the radiation levels close to the shield may be within permissible levels. Radiation from the X-ray tube can frequently strike the ceiling of the next room or a basement floor, producing excessive radiation levels some distance away from the shielded X-ray room. The presence of zinc in an adhesive bandage plaster has been found a source of irritating secondary radiation to a patient undergoing X-ray therapy.

## EFFECTS OF RADIATION

Radiation, as mentioned previously, has physical, biological, and chemical effects. It can darken photographic films, enhance certain chemical reactions, and change physical properties of materials. We depend on its electrical, chemical, and physical effects to detect and measure it by ionization, photographic, calorimetric, and scintillation methods.

The effects we are most interested in here are biological. Those are the ones for which we are attempting to describe and evaluate safeguards. Radiation in large doses has been shown to kill, to produce cancer, to cause certain blood disorders, and to induce cataracts in the eye. It can cause skin burns, sterility, abnormal pregnancies, and malformed offspring. On the other hand, it is used by physicians to treat cancer and skin diseases; it often effects cures.

Even in relatively small doses, there is statistical evidence that radiation can cause certain damage to genetic materials. It is suspected of shortening man's life span and increasing his likelihood of suffering from certain illnesses like leukemia.

The important question, which may never be answered, is this: Since man has always been exposed to substantial amounts of radiation from nature, to how much additional radiation can he be exposed without an unreasonable risk to himself or to his progeny? As in the case of many occupational or environmental hazards, this will probably have to be answered in terms of the benefits which accompany the risks.