RADIATION BIOLOGY AND RADIATION PROTECTION

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Contents

Summary

Many essential modern technologies involve the application of ionizing radiation and radioisotopes. Scientists and other professionals increasingly understand more about the nature and dangers. Accordingly, proper safety measures must be provided for the radiation protection of occupationally exposed people as well as various population groups. A special case of the latter is the radiation protection of patients during the medical application of radiation. Besides the normal operation of radiation sources and facilities, sometimes incidents and accidents might occur. These produce interest and even controversy among the wider society. Therefore, the present chapter of EOLSS aims to present a concise overview of the most relevant and important data, processes and philosophy of radiation biology, as well as of radiation hygiene and protection, based on radiation-induced biological effects. Full details of these continuously developing scientific and technical branches cannot be included here. The authors of the chapter have focused on information which can orient the interested reader to further studies. The contents include sections on dosimetry, radiation types, dose quantities and units, radiation biology of cells, health effects of low and high doses (i.e. stochastic and deterministic effects), biological dosimetry, radiation protection of occupationally involved persons and the environment, and risk assessment.

1. Introduction

Since the discoveries of natural and artificial sources of ionizing radiation, more and more information is accumulating on their biological and health effects. The dose-dependent alterations might be beneficial or deleterious. For the safe use of ever growing radiation and nuclear technologies, deepening knowledge is required, and arguments are needed against misleading anti-radiological and antinuclear propaganda. The aim of the present article is to provide an introduction to contemporary knowledge on human radiation biology with special reference to those effects that serve as a basis for effective radiation protection. These branches of science are continuously developing; possible future trends are mentioned only to orientate the reader for further reading. The authors of this article have relevant experience in the research and application of radiation biology, in radiation hygiene as a part of public health, and in radiation protection of occupationally involved categories of people and the general public. Attention is paid also to environmental monitoring during normal operation of radiation and nuclear sources as well as in emergency situations.

2. Dosimetry

2.1. Radiation Types

Most of the harmful effects of *ionizing radiation* (skin burn, cataracts, cancer, etc.) appear only days, months, years or decades later in life after the exposure. With respect to protection against the effects of exposures, it is important to introduce proper quantities, measuring methods and tools to monitor the radiation type, energy, intensity, etc., in the living space, and to determine the potential health hazards associated with any proposed practice with radiation. It is necessary to establish when and where the

exposure is to be limited to permit working or living without any remarkable harmful effects.

2.1.1. Ionizing Radiation

Radiation is called ionizing radiation when the energy transferred to the orbital electrons is sufficient to eject electrons from the atoms, producing positively charged ions. The ejected electron may have sufficient kinetic energy to produce further ionization in the irradiated matter (Figure 1). Typical types of ionizing radiation include α-particles, β-particles and γ-rays. The radiation types with electrically charged particles are directly ionizing; others such as X-, γ- and neutron rays are indirectly ionizing. In living systems the minimum energy of radiation producing an ion is nearly 30 eV ($\approx$ 5 aJ). Experience shows that ionization is the major cause of biological effects of radiation.

2.1.2. Nonionizing Radiation

Radiation with low energy is incapable of removing electrons from atoms while passing through the matter. That kind of radiation produces mostly excitation of atomic or molecular vibrations and rotations. Typical nonionizing radiation includes electromagnetic waves in the range of UV, visible light, microwave and radiofrequency.

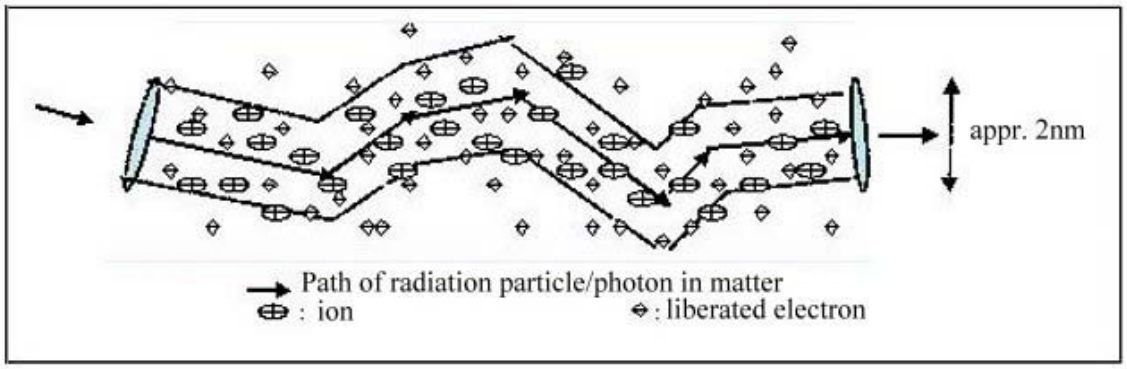

Figure 1: Production of free electrons and ions along the pathway of radiation.

2.1.3. Effects of Ionizing Radiation on Molecules, Cells, Tissues and Organs of Living Systems

The effects of radiation appear in multiple ways (Figure 2). The process of ionization necessarily changes atoms and molecules, at least transiently, and may rupture chemical bonds in the molecules important in a living cell, for example, the DNA macromolecule. Most of the free electrons and ions that are produced recombine to neutral atoms and molecules without any late effects on the function of the DNA or of cells. Others of them result in chemical radicals, harmful compounds and dissociated water molecules (radiolysis) in a very short time (ns to ms). Both the direct radiation and, hours later, the new and harmful chemical entities may induce damage in the DNA, e.g., single and double strand breaks. If only one strand is damaged, the other serves as a model (template) for repair, and the repaired macromolecule functions normally. Double strand breaks in DNA may induce chromosome aberrations in cells, and in cell nuclei they

may alter the information about the tasks of the cell or reprogram the genetic material. Mostly those kinds of faults may be repaired through cell division, when the daughter cells from normal cells replace the damaged cell. Usually that kind of process takes hours or days. Damage to cells may lead to different consequences; however, the body's capacity for different types of repair will correct most of the defects before the construction of the new cell is completed and the tissue is renewed.

2.2. Dose Quantities and Units

When radiation passes through matter, part of the energy is deposited in the matter; the rest is lost after collisions or without any interaction with the atoms. Experience indicates that the biological effect of the radiation is proportional to the amount of energy deposited in a unit mass of matter, such as in human tissue. In addition the effect depends on the type and energy of ionizing radiation and on many other factors both of radiation and the absorbing matter. Therefore to find proper quantities that characterize the harmful effects of radiation and that are measurable by use of common detectors is not easy. It is necessary to use additional types of quantities (called radiation doses), and, depending on the type and energy of radiation, different detectors must be introduced. Only the most frequently used quantities of doses are reviewed here.

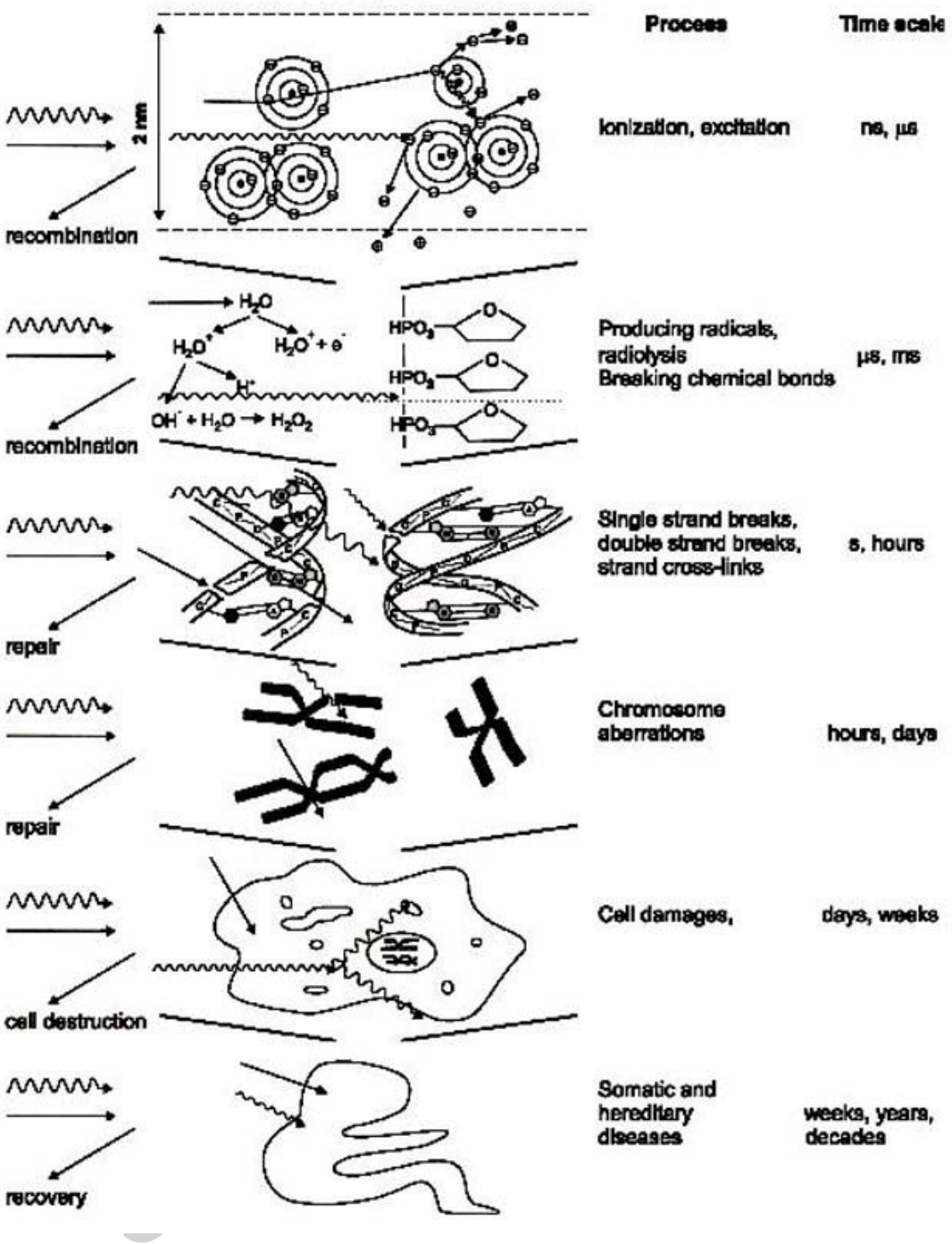

Figure 2: Development of early and late effects in a living system and the time scale of the processes.

2.2.1. Absorbed Dose (symbol: *D*)

The deposited energy per unit mass of a volume, in which the energy is absorbed in the matter, is called the absorbed dose. Using the symbols of Figure 3, the absorbed dose D can be written in mathematical form as

$$D = \frac{\varepsilon_{\text{dep}}}{m}.$$

Usually the absorbed dose in a human is an average dose for a tissue or organ.

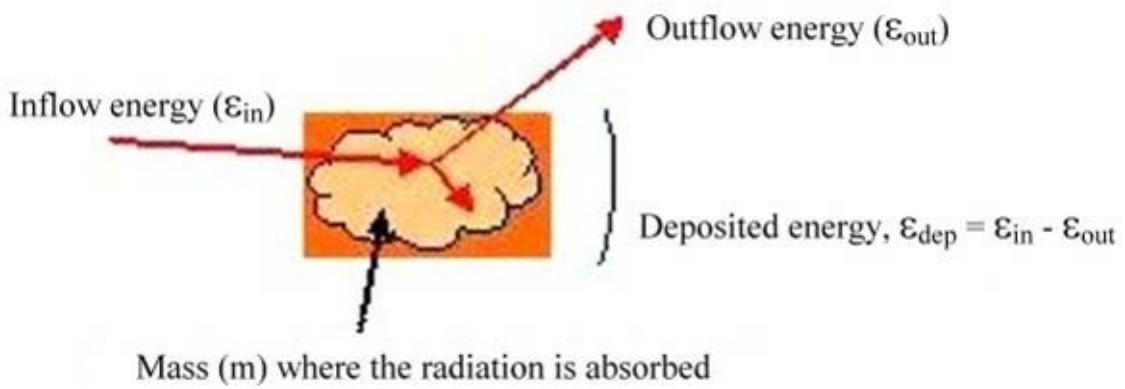

Figure 3: Absorption of energy from radiation in matter.

By definition, the SI unit for absorbed dose is the quotient of energy and mass, that is, J/kg. This unit has a special name in radiation dosimetry, *gray* (Gy), where 1 Gy = 1 J/kg (named for Harold Gray, 1905-1965, physicist from England). The old unit of absorbed dose is the *rad* (*r*oentgen *a*bsorbed *d*ose); 1 Gy = 100 rad. The absorbed dose may be used for any type of ionizing radiation (α-, β-, X-rays, etc.) and with respect to any type of matter (both living systems and nonliving materials), but it is not an unequivocal measure for an estimate of harmful effect, e.g., different types of radiation with the same absorbed doses may cause remarkably different damage.

2.2.2. Equivalent Dose (symbol: H_T)

The equivalent dose H_T to a tissue is defined as the product of the absorbed dose averaged over a tissue or organ (T) times the radiation weighting factor w_R, for radiation type R. In mathematical form:

$$H_T = w_R \cdot D_T,$$

where D_T is the absorbed dose over tissue T and w_R is the *radiation weighting factor* for radiation type and energy R. The weighting factor varies between 1 and 20. Table 1 contains values of the factors recommended by the ICRP (see Section 4.1.1.) for different types and energy ranges of radiation. The SI unit of equivalent dose is the *sievert* (Sv), where 1 Sv = 1 J/kg (named for Rolf Sievert, 1896-1966, physicist from Sweden).

It seems that the equivalent dose has the same fundamental unit (J/kg) as the absorbed dose. However, it is given its own special name, the sievert, in recognition that it is obtained from the Gy by multiplying by a dimensionless scale factor. (Actually, the

dimension of w_R should be Sv/Gy to avoid dimensional conflicts.) The equivalent dose expresses the fact that the biological effect (more precisely, the stochastic effect; see Section 3) depends on the type and energy of radiation, as well as on the absorbed dose.

Type and energy range of radiation	w_R
Photons, all energies	1
Electrons and muons, all energies	1
Neutrons, energy < 10 keV	5
10 to 100 keV	10
100 keV to 2 MeV	20
2 to 20 MeV	10
> 20 MeV	5
Protons, other than recoil protons, energy > MeV	5
Alpha particles, fission fragments, heavy nuclei	20

Table 1. Radiation weighting factors, w_R.

According to the radiation weighting factors in Table 1, a 1 Gy absorbed dose due to γ-radiation corresponds to 1 Sv equivalent dose, but for α-radiation, 1 Gy absorbed dose results in 20 Sv equivalent dose. Usually the values w_R are broadly compatible with the values of the *quality factor* (Q) and the *relative biological effectiveness* (RBE), terms which were used more frequently in the past and are still used with respect to personal dose measurements. When the radiation field is composed of different types of radiation with different values of w_R, the equivalent dose is the sum of the partial equivalent doses from each different type of radiation.

2.2.3. Effective Dose (symbol: *E*)

Additionally it is necessary to take into account the different sensitivities of various tissues and organs to the induction of health effects that are deleterious to the whole organism. The effective dose E is defined as a summation of the tissue equivalent doses multiplied by the appropriate tissue weighting factor w_T. According to this definition:

$$E = \sum_T w_T H_T$$

where H_T is the equivalent dose in organ or tissue T and w_T is the tissue weighting factor for the organ or tissue T. Recommended values of w_T are given in Table 2.

Tissue or organ	w_T
Gonads	0.20
Bone marrow, red	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05

Table 2. Tissue weighting factors, w_T .

According to the definition of the tissue weighting factor, the summation of the factors over all the tissues results in a value of 1, that is

$$\sum_T w_T = 1.$$

In other words, the same effective dose is produced either if the whole body is exposed homogeneously or if all the organs are separately irradiated by the same equivalent dose.

From these definitions, it follows that:

$$E = \sum_T w_T \left(\sum_R w_R D_{TR} \right),$$

where D_{TR} is the average absorbed dose in organ or tissue T due to radiation R. The last form indicates that the various doses due to the different types of radiation and different tissues are additive quantities without any cross-contributions or synergism among them. Very probably this is valid only for sufficiently small doses in the range of practices with ionizing radiation. By definition, both equivalent and effective doses are

calculated values by use of the radiation and tissue weighting factors, and not directly measured quantities.

As an example of the calculation of an effective dose: The thyroid glands are exposed to 20 mGy absorbed dose of β-radiation, and the lungs to 10 mGy absorbed dose of γ-rays and 1 mGy of α-rays. The other parts of the body are not exposed. In this case the effective dose is calculated as follows:

$$E = 0.05 \times 1 \times 20 \text{ mGy} + 0.12 \times (1 \times 10 \text{ mGy} + 20 \times 1 \text{ mGy}) = 4.6 \text{ mSv}.$$

2.2.4. Exposure Dose (symbol: *X*)

The exposure dose X with its unit *roentgen* (abbreviated usually by R or r) was the first quantity used in radiology, for characterizing the potential damage by X-rays (1928). It refers to ionization in air only by X- (or γ-) rays, and its determination could be provided by a relatively simple technique, using an air-filled ionization chamber. The quantity does not conform to the ICRP concept and the SI system, but the unit is still not uncommon in practice, especially in medical fields. An exposure of 1 R produces ion pairs with a total – either positive or negative – electrical charge of 0.00026 C (coulomb) in an air volume of unit mass (1 kg). An exposure of 1 R corresponds to ~0.0088 Gy in soft tissues and ~0.01 Gy in bones, or 1 Gy corresponds to nearly 100 R.

2.2.5. External and Internal Dose

According to Figure 4, sources of radiation might be located either outside or inside the body. This permits classification of radiation and dose as either external or internal. Typical sources of external dose practices are the X-ray devices, including computed tomography (CT) for examining patients, industrial radiography by sealed sources (defectoscope), cosmic rays varying with height above sea level, and natural radionuclides dispersed in soils. Many radionuclides can come into the body from contaminated foods or drinking water and from inhalation of the atmosphere; these irradiate internally, producing an internal dose.

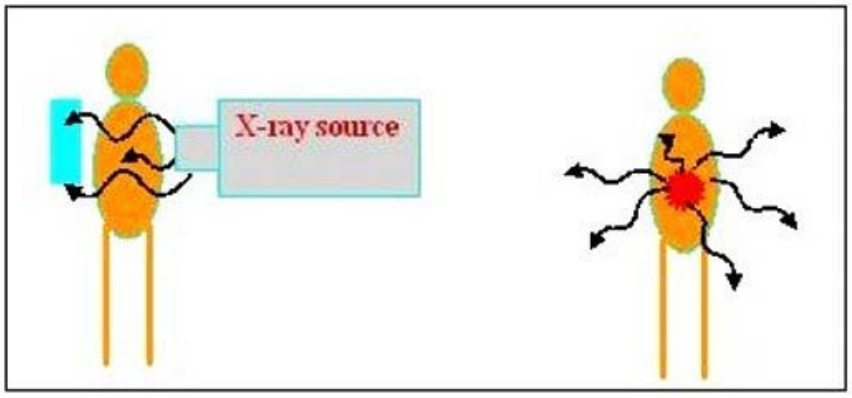

Figure 4. External and internal radiation.

In the case of external exposure, the individual is exposed only as long as he/she stays

in the radiation field. However, with internal contamination of the body, the individual carries the source within his/her body until the radioactivity is decayed or the radioactive material is excreted. Therefore the internal dose must be calculated by summing over properly short time intervals of the temporary doses (time integrated value); this is called the *committed dose*.

2.2.6. Individual and Collective Doses (symbol: *S*)

The dose incurred by an individual member of the population is an individual dose. The concept is used mainly for humans, but it can be extended to other living organisms as well, in general to biota. Taking into consideration the various viewpoints of society, the number of individuals exposed might be important, too. The collective dose as a dosimetric quantity represents the total consequences of exposures of a population or group. Therefore the collective dose of a group, S, is the sum of the individual doses. For practical use of the collective dose, the individuals of the proper group should be exposed by nearly the same dose, or subgroups should be identified. In most cases the quantity of *collective effective dose* is used, but occasionally the quantities of *collective absorbed dose* and *collective equivalent dose* are useful. The unit of the collective effective dose is person-Sv (also referred to as man-Sv in the literature).

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Biographical Sketches

György J. Köteles graduated at the Medical University, Budapest in 1958, as MD. He has got the Ph.D. degree in 1971 “The biochemistry and radiation biology of the human lens”, the DSc degree in 1987 from the Hungarian Academy of Science “The radiation biology of cellular membranes”, and the degree Dr. med. habil. from Semmelweis University, Budapest. Specializations: Radiation biology and radiation hygiene, 1984, Haynal Imre Postgraduate Medical School, Budapest, Preventive medicine and public health, 2002, Debrecen University Medical School. Jobs: 1958-1960: Biochemical Institute, Medical Faculty, Budapest, junior assistant, then assistant; 1961-1971: Frederic Joliot-Curie National Research

Institute for Radiobiology and Radiohygiene, Budapest, scientific co-worker, then head of laboratory; 1971-1974: National Atomic Energy Commission of Hungary, Head of Department; 1974-1979: International Atomic Energy Agency, Vienna, Radiation Safety Section, First Officer; 1979-1998: Frederic Joliot-Curie National Research Institute for Radiobiology and Radiohygiene, Budapest, Deputy Director General and Head of Laboratory for Diagnosis of Radiation Injuries; 1998-2004: Fodor József National Public Health Center, Frederic Joliot-Curie National Research Institute for Radiobiology and Radiohygiene, Director; 2004: retired and continuing scientific and teaching activities on contractual bases. University jobs: 1991-1999: Professor, Chairperson, Chair of Radiation biology and radiation hygiene, Postgraduate Medical School, Budapest; 1980-2004: Professor, Chair for Occupational and Environmental Medicine. Member of several foreign and Hungarian scientific societies, member of editorial boards of J. Radiat. Prot. (UK), Int. J. Low Radiation (France), coeditor-in-chief of Central Europ. J. Occup. Environm. Medicine (Hungary). Author of more than 150 scientific articles.

Béla Kanyár graduated in 1963 at Eötvös Loránd University, Faculty of Science, Budapest, as research physicist. His first specialization was the use of radioisotopes in biophysics and medicine, later on he turned to the computer methods in medicine at the University of Medicine, Budapest. In 1981 he obtained the title Candidate of Biological Sciences from the Hungarian Academy of Sciences and PhD degree at the University of Sciences. In 1982 he joined to the National Research Institute for Radiobiology and Radiohygiene, Budapest as head of Division of Measurements and Computing. His activity turned to the data processing in environmental radiation, later on to radioecology and modeling of radioisotope transfer in the environment. From 1990 as the head of Department of Radiohygiene he got involved in radiation protection, in general.

In 1995 Dr. Kanyár moved to the University of Veszprém as head of Department of Radiochemistry. He habilitated and as university professor his main lectures became radioecology, nuclear emergency and computer simulation of radionuclide transfer in the environment. In 2004 he retired and partly continued his research and educational work.

During the more than forty years work Dr. Kanyár has published nearly 100 scientific papers and given more than 150 lectures at conferences. He is the author/coauthor of 4 books and 5 special manuscripts for the university students in environmental and chemical engineering.
In frames of fellowships he has spent 1-3 months in institutes of Sweden, England, Germany, Denmark and USA. He was/is member of some special and scientific committees of the Hungarian Academy of Sciences and other organizations and has taken part in projects of the International Atomic Energy Agency and of the European Committees.

Kathleen Thiessen holds a Ph.D. degree in Genetics from the University of Tennessee—Oak Ridge Graduate School of Biomedical Sciences. She is a Senior Scientist with SENES Oak Ridge, Inc., Center for Risk Analysis, in Oak Ridge, Tennessee. She was previously a staff member of the Oak Ridge National Laboratory. Dr. Thiessen's major professional activities are in the fields of environmental transport of contaminants (radionuclides and chemicals), chemical toxicity, exposure assessment, and human health risk assessment. As a member of a National Research Council committee, she recently coauthored a major report on fluoride exposure and toxicology. Dr. Thiessen is involved in international efforts to improve the capabilities of environmental transport modeling for radionuclides, serving as a Working Group leader in two programs organized by the International Atomic Energy Agency. Dr. Thiessen contributed to the development of a risk-based screening approach to prioritize further investigation of contaminants and exposure situations in various assessment contexts, and she led an analysis of human exposures, doses, and health risks associated with waterborne releases of radionuclides from government facilities in Tennessee. She has also authored or contributed to reports published by the U.S. Environmental Protection Agency, the International Atomic Energy Agency, and the National Council on Radiation Protection and Measurements.