

VIII/4 Radiological Protection

Contents

1	The development of the organizational and the conceptual basis of radiological protection	1-1
2	Biological effects of ionising radiation	2-1
2.1	Introduction	2-1
2.2	Cellular effects	2-2
2.2.1	Primary events following exposure to ionising radiation	2-2
2.2.2	Cellular damage and repair following the primary radiation events	2-3
2.2.3	Classification of radiation-induced damage	2-5
2.2.4	Implications of cellular damage for whole or partial body exposure	2-9
2.3	Deterministic effects	2-9
2.3.1	Tissue and organ development	2-9
2.3.2	Dose-response relationships for radiation damage	2-10
2.3.3	Deterministic effects in humans following acute whole-body irradiation	2-11
2.3.4	Deterministic effects following partial body irradiation	2-12
2.4	Radiation-induced cancer	2-15
2.4.1	Cancer development	2-15
2.4.2	Dose-response relationships	2-16
2.4.3	Exposures to external radiation	2-18
2.4.4	Exposure to internally incorporated radionuclides	2-20
2.4.5	Dose and dose rate effectiveness factors (DDREFs)	2-23
2.4.6	Risk coefficients for protection	2-23
2.4.7	Low dose studies	2-25
2.5	Hereditary disease	2-27
2.5.1	Categories of genetic damage	2-27
2.5.2	Risk coefficients for hereditary disease	2-28
2.6	Irradiation in utero	2-29
2.6.1	Deterministic effects	2-30
2.6.2	Brain function	2-30
2.6.3	Risk coefficients for cancer	2-31
2.6.4	Hereditary disease	2-31
2.7	Summary of risk factors for cancer and hereditary disease	2-32
2.8	Conclusions	2-32
2.9	References	2-34
3	Physical fundamentals	3-1
3.1	Natural radioactivity	3-1
3.2	Elements, isotopes and radionuclides	3-2
3.2.1	Atoms, electrons and the Periodic Table of Elements	3-2
3.2.2	Atomic nuclei, nuclides and the Chart of Nuclides	3-3
3.3	The structure of the atomic nucleus	3-4
3.3.1	Elementary particles	3-4
3.3.2	Nuclear transformations	3-6
3.4	Radioactive decay	3-10
3.4.1	Basic properties	3-10
3.4.2	Decay modes	3-15
3.4.3	The natural radioactive decay families	3-18
3.5	Radioactive radiation	3-24

3.5.1	Types of radiation	3-24
3.5.2	Physical properties of radiation	3-26
3.6	Nuclear fission and fission products	3-30
3.6.1	Particle induced nuclear fission	3-30
3.6.2	Fission products	3-30
3.6.3	Nuclear reactors	3-32
3.6.4	Nuclear explosives	3-32
3.6.5	Radioactive inventory and nuclear waste	3-33
3.6.6	Release of radionuclides from the radioactive inventory of a nuclear reactor	3-38
3.7	References	3-39
4	Radiological quantities and units	4-1
4.1	Introduction	4-1
4.2	Radiation field quantities	4-2
4.2.1	Scalar radiation field quantities	4-2
4.2.2	Vectorial radiation field quantities	4-4
4.3	Interaction coefficients and quantities	4-5
4.3.1	Cross section	4-5
4.3.2	Mass attenuation coefficient and mass energy transfer coefficient	4-5
4.3.3	Mass stopping power and linear energy transfer (LET)	4-6
4.3.4	Mean energy expended in a gas per ion pair formed	4-7
4.4	Quantities related to energy transfer	4-7
4.4.1	Stochastic quantities	4-7
4.4.2	Non-stochastic quantities	4-8
4.5	Dose quantities in radiation protection	4-10
4.5.1	Concept of radiation protection quantities	4-10
4.5.2	Protection quantities	4-11
4.5.3	Operational quantities	4-14
4.6	Radioactivity quantities	4-18
4.6.1	Activity, specific activity, activity concentration, activity per area	4-19
4.6.2	Specific quantities for radon, thoron and their progeny	4-19
4.7	Quantities for internal dosimetry	4-22
4.8	Limits, constraints, action levels	4-23
4.9	References	4-27
5	Shielding against ionizing radiation	5-1
5.1	Introduction	5-1
5.2	Stopping power and range	5-1
5.3	Penetration depths of charged particles	5-2
5.3.1	Heavy charged particles	5-2
5.3.2	Electrons and positrons	5-4
5.4	Photons	5-5
5.4.1	Basic shielding concept	5-5
5.4.2	Attenuation data of radioactive sources in shielding materials	5-6
5.4.3	An example of the calculation of an ambient dose equivalent rate	5-9
5.5	Neutrons	5-16
5.5.1	Basic shielding concepts	5-16
5.5.2	Attenuation data of various neutron sources in shielding materials	5-16
5.5.3	Sample shield calculation	5-18
5.5.4	Induced activity	5-19
5.6	Computer codes and online nuclear data services	5-28
5.7	References	5-32

6	External dosimetry	6-1
6.1	Protection and operational quantities	6-1
6.1.1	Protection quantities	6-1
6.1.2	Operational Quantities	6-1
6.2	Dosimetric models	6-2
6.2.1	Models and phantoms of the human body	6-2
6.2.2	Idealized geometries representing occupational exposures	6-4
6.2.3	Environmental source geometries	6-4
6.2.4	Methods of calculating protection quantities in computational models	6-5
6.3	Conversion coefficients for photons	6-6
6.3.1	Occupational	6-6
6.3.2	Conversion coefficients for environmental gamma ray fields	6-13
6.4	Conversion coefficients for neutrons	6-20
6.5	Conversion coefficients for electrons	6-21
6.5.1	Occupational exposure	6-21
6.5.2	Environmental exposure	6-23
6.6	Doses from external exposure of radionuclides in the environment	6-23
6.7	References	6-42
7	Internal dosimetry of radionuclides	7-1
7.1	Introduction	7-1
7.2	Biokinetics of radionuclides in the body	7-2
7.2.1	Inhalation	7-3
7.2.2	Ingestion	7-10
7.2.3	Cuts and wounds	7-14
7.2.4	Absorption through intact skin	7-15
7.2.5	Systemic behaviour of radionuclides	7-15
7.2.6	Excretion	7-21
7.2.7	Embryo and foetus	7-21
7.2.8	Transfer in maternal milk	7-24
7.3	Dosimetric models	7-25
7.3.1	Introduction	7-25
7.3.2	Absorbed fraction and specific absorbed fraction	7-26
7.3.3	Computational models of the human anatomy	7-28
7.3.4	Dose rate per unit activity, S-factor	7-31
7.3.5	Specific absorbed fractions for various radiations	7-32
7.3.6	Calculation of doses to soft tissues and the skeleton	7-36
7.4	Dose coefficients	7-37
7.4.1	Method of calculation	7-38
7.4.2	Sources of dose coefficients	7-41
7.4.3	Dose coefficients for selected radionuclides	7-43
7.5	Internal monitoring	7-46
7.5.1	Methods of individual monitoring	7-47
7.6	Monitoring programme	7-51
7.6.1	Need for a monitoring programme	7-51
7.6.2	Routine monitoring	7-51
7.6.3	Special or task-related monitoring	7-52
7.6.4	Confirmatory monitoring	7-52
7.6.5	Wound monitoring	7-52
7.7	Dose Assessment	7-53
7.7.1	Estimation of intake and dose	7-53
7.7.2	Control of worker doses	7-54
7.8	Monitoring data for radionuclides (H-3, Co-60, Sr-90, Ru-106, I-131, Cs-134, Cs-137, Ce-144, U-234, Pu-239, Am-241)	7-55
7.9	References	7-68

8	Decontamination	8-1
8.1	Decontamination of materials	8-1
8.1.1	General approaches to decontamination	8-2
8.1.1.1	Contamination	8-2
8.1.1.2	Characteristics of oxide layer in BWRs and PWRs	8-2
8.1.1.3	Other types of contamination	8-3
8.1.1.4	Decontamination	8-4
8.1.1.5	The use of decontamination in decommissioning	8-4
8.1.1.6	Identification of decontaminable components	8-5
8.1.1.7	Effectiveness of decontamination, decontamination factor	8-6
8.1.1.8	Decontamination techniques (processes)	8-7
8.1.1.9	Decontamination and secondary waste generation	8-8
8.1.2	Decontamination techniques for large volume closed systems	8-8
8.1.2.1	Reactor decontamination in BWRs and PWRs	8-8
8.1.2.2	Fuel assemblies and decontamination	8-12
8.1.2.3	Decontamination of sodium cooled systems	8-12
8.1.2.3	Gas cooled reactors (WAGR)	8-13
8.1.3	Decontamination techniques for segmented parts	8-13
8.1.3.1	Chemical decontamination	8-13
8.1.3.2	Electrochemical decontamination	8-15
8.1.3.3	Jetting decontamination techniques	8-18
8.1.3.4	Ultrasonic decontamination	8-19
8.1.3.5	Decontamination by foams	8-21
8.1.3.6	Decontamination by gels	8-21
8.1.3.7	Decontamination by pastes	8-21
8.1.3.8	Mechanical decontamination techniques	8-21
8.1.3.9	Decontamination by strippable coatings	8-22
8.1.3.10	Melting	8-22
8.1.4	Decontamination techniques for building surfaces	8-22
8.2	Decontamination of skin	8-24
8.2.1	Introduction	8-24
8.2.2	Transport of radioactive substances via the skin	8-24
8.2.2.1	Anatomy of the skin	8-24
8.2.2.2	Transport procedure	8-25
8.2.3	Skin dose at contamination	8-25
8.2.3.1	Calculation of the equivalent dose to the skin	8-25
8.2.3.2	Equivalent dose rate conversion coefficients	8-26
8.2.4	Decontamination measures	8-30
8.2.4.1	Organisational and preliminary measures	8-30
8.2.4.2	First aid measures of skin decontamination	8-30
8.2.4.3	Specific decontamination procedures	8-31
8.2.4.4	Decontamination of specific body regions and organs	8-32
8.2.5	Procedure at residual contamination and fixing a reference value	8-32
8.2.5.1	Frequency of decontamination steps	8-32
8.2.5.2	Derivation of the reference value for residual contamination	8-32
8.3	References	8-34
9	Decorporation of radionuclides	9-1
9.1	Introduction	9-2
9.2	General considerations	9-2
9.2.1	Factors affecting the efficacy of treatment	9-2
9.2.2	Factors influencing treatment decisions	9-3
9.2.3	Decision levels	9-3

9.2.4	Perception of risk and its implications	9-4
9.2.5	Approaches to treatment	9-5
9.3	Methods of treatment	9-6
9.3.1	Non-specific procedures	9-6
9.3.2	Procedures to enhance systemic radionuclide excretion	9-7
9.4	General comments on the efficacy of chelating agents for the actinides	9-8
9.4.1	What are the factors that govern the efficacy of chelating agents ?	9-9
9.4.2	Can the efficacy of treatment be predicted from animal studies ?	9-9
9.4.3	Are chelating agents always most effective when the radionuclides are present in circulating blood ?	9-9
9.4.4	Is DTPA effective for all actinides ?	9-10
9.4.5	Will the administration of chelating agents result in enhanced tissue deposition ?	9-10
9.4.6	Is the administration of sodium carbonate effective for uranium ?	9-10
9.4.7	Must chelating agents be administered promptly to be effective ?	9-10
9.4.8	Is intravenous injection the best mode of administration ?	9-11
9.4.9	How can judgements on efficacy be made ?	9-11
9.4.10	When should treatment start ?	9-11
9.4.11	When should treatment stop ?	9-11
9.4.12	For which materials are chelating agents likely to be effective ?	9-11
9.4.13	For which materials are chelating agents unlikely to be effective ?	9-12
9.4.14	Is lung lavage more effective than chelation treatment for inhaled materials ?	9-12
9.5	Recent developments	9-13
9.5.1	Plutonium and americium	9-13
9.5.2	Thorium	9-13
9.5.3	Uranium	9-13
9.6	Optimum treatment protocols	9-14
9.6.1	Tritium	9-14
9.6.2	The alkaline earth elements, strontium, barium and radium	9-14
9.6.3	Iodine	9-16
9.6.4	Caesium	9-16
9.6.5	Plutonium and americium	9-18
9.6.6	Thorium	9-26
9.6.7	Uranium	9-27
9.7	Future research needs	9-29
9.8	References	9-31
10	Measuring techniques	10-1
10.1	Detectors for radiation protection	10-1
10.1.1	Overview and general characteristics of radiation detectors	10-1
10.1.2	Gas-filled ionization detectors	10-3
10.1.2.1	Ionization and gas amplification	10-3
10.1.2.2	Ionization chambers	10-4
10.1.2.3	Proportional counters	10-8
10.1.2.4	Geiger-Müller counters	10-10
10.1.3	Scintillation detectors	10-11
10.1.4	Semiconductor detectors	10-14
10.1.5	Thermoluminescence and radiophotoluminescence detectors	10-18
10.1.6	Photographic films	10-20
10.1.7	Detectors for neutrons	10-21
10.1.8	Biological dosimetry	10-23
10.1.9	References for 10.1	10-25
10.2	Radiological protection measurements: external exposure	10-27
10.2.1	Operational quantities	10-27

10.2.2	Reference levels	10-29
10.2.3	Types of exposure	10-29
10.2.3.1	Occupational exposure	10-30
10.2.3.2	Public exposure	10-30
10.2.4	Types of monitoring programs	10-31
10.2.4.1	Individual monitoring for external exposure	10-31
10.2.4.2	Area monitoring for external exposure	10-31
10.2.4.3	Calibration	10-32
10.2.5	Requirements for individual monitoring of external exposure	10-33
10.2.5.1	Operational requirements	10-34
10.2.5.2	Accuracy requirement	10-35
10.2.6	Personal dosimeters for individual monitoring in different radiation fields	10-36
10.2.6.1	Photon dosimetry	10-36
10.2.6.2	Beta dosimetry	10-37
10.2.6.3	Neutron dosimetry	10-37
10.2.6.4	Dosimetry in mixed field situations (photons and neutrons)	10-38
10.2.7	References for 10.2	10-39
10.3	Radiological protection measurements: internal exposure	10-41
10.3.1	Measurement of radon and its progeny	10-41
10.3.1.1	Measurement of radon in air	10-44
10.3.1.2	Measurement of radon progeny in air	10-47
10.3.1.3	Measurement of radon in the ground and in water	10-50
10.3.1.4	References for 10.3.1	10-51
10.3.2	In vivo measurements	10-52
10.3.2.1	Introduction	10-52
10.3.2.2	Requirements	10-53
10.3.2.3	Principles of γ spectrometry	10-56
10.3.2.4	Equipment	10-58
10.3.2.5	Spectrum evaluation	10-66
10.3.2.6	Measuring geometries	10-67
10.3.2.7	Calibration	10-71
10.3.2.8	Uncertainties and detection limits	10-77
10.3.2.9	Measurement procedure	10-79
10.3.2.10	Quality assurance and control	10-79
10.3.2.11	References for 10.3.2	10-81
10.3.3	In vitro measurements: excretion analyses	10-83
10.3.3.1	Introduction	10-83
10.3.3.2	Urine samples	10-83
10.3.3.3	Faeces samples	10-84
10.3.3.4	Exhalation	10-84
10.3.3.5	Other biological samples	10-85
10.3.3.6	Radiochemical analyses	10-85
10.3.3.7	Measuring techniques	10-88
10.3.3.8	Quality assurance	10-91
10.3.3.9	Examples for dose estimations from in vitro measurements	10-93
10.3.3.10	References for 10.3.3	10-97
11	Exposures from natural and man-made radiation sources	11-1
11.1	Introduction	11-1
11.2	Exposures by cosmic radiation and cosmogenic radionuclides	11-2
11.2.1	Origin and kinds of cosmic radiation	11-2
11.2.2	Exposures by cosmic radiations	11-2

11.3	Terrestrial radiation	11-4
11.3.1	External exposures	11-5
11.3.2	Internal exposures	11-6
11.4	Enhanced exposures from industrial activities	11-9
11.5	Worldwide average exposure from natural and man-made sources	11-10
11.6	References	11-12