HANDBOOK OF RADIOLOGICAL PROTECTION

PART I: DATA

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Prepared by a Panel of the Radioactive Substances Advisory Committee

Department of Employment

Department of Health and Social Security

Ministry of Health and Social Services, Northern Ireland

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1. Introduction

The objective of Part I of this Handbook is to provide in readily accessible form a collection of information likely to be of immediate use to those concerned with the radiological protection of workers and members of the public. In particular, it is intended as a supplement to the Code of Practice issued by the Department of Employment for the protection of persons exposed to Ionising Radiations in Research and Teaching, and that issued by the Department of Health and Social Security for the protection of persons against Ionising Radiations arising from Medical and Dental Use. It is intended that Part II of the Handbook will deal with the methods and techniques of radiological protection.

The field of radiological protection is a wide one and the problem of selection and rejection of data for the Handbook is therefore difficult. The compilers of Part I have aimed at including information which is likely to be needed fairly frequently, excluding material which is already contained in other compilations necessarily familiar to the health physicist. Thus, material included in the publications of the International Commission on Radiological Protection has been reprinted in this Handbook only when it adds completeness to a series of information obtained from other sources. All the data have been presented in the form most likely to be suitable for protection work and not necessarily in the form in which they were originally published.

The Handbook has been prepared in the international A4 paper size, which is large enough to do justice to material presented graphically. It has been presented in loose-leaf form so that further sections can be added if they are found to be appropriate, and corrections can be made without difficulty. The loose-leaf format also allows individuals to add additional data of their choice should they so wish. To simplify such additions, each section of the Handbook has its own numbering system for pages, tables, figures and references.

Acknowledgments

The information in the Handbook has been obtained as far as practicable from published sources, re-presented in a standard form. Original references are quoted wherever practicable, except where a review author has made a positive contribution in selecting information from a range of original publications.

The responsibility for the selection and presentation of the material has been that of a Panel of the Radioactive Substances Advisory Committee, who acknowledge with thanks the work of W. Binks during the early stages of assembling the data.

Contents

1.1 Other Compilations of Data of Use in Radiological Protection

ICRP Publications

The publications of the International Commission on Radiological Protection contain data on physical subjects (which are unlikely to change drastically), selected data representative of biological situations (which are more likely to change) and recommendations on the principles and practices of radiological protection (which are superseded as the subject develops). Much of the physical data published by ICRP is included in this Handbook but only a small part of the biological data has been used. This sub-section gives a general guide to the location of data in ICRP publications.

ICRP Publication 1: Recommendations of the International Commission on Radiological Protection (Adopted September 9, 1958). Pergamon Press, London (1959).

General recommendations (obsolete).

ICRP Publication 2: Recommendations of the International Commission on Radiological Protection. Report of Committee II on Permissible Dose for Internal Radiation (1959). Pergamon Press, London (1960).

Methods of calculation of internal doses

Physical and metabolic characteristics of the nuclides

Characteristics of Standard Man, including intakes of air and water, loss of water, chemical composition, mass of organs, behaviour of aerosols in the lung and models of the GI tract

Maximum permissible concentrations in air and water

Maximum permissible body burdens

(Many of these data are currently in process of revision. See also *ICRP Publication 6*)

ICRP Publication 3: Recommendations of the International Commission on Radiological Protection. Report of Committee III on Protection against X-rays up to Energies of 3 MeV and Beta- and Gamma-rays from Sealed Sources (1960). Pergamon Press, London (1960).

General recommendations

X- and γ-ray outputs and diffusion

Shielding requirements

(This report is currently in process of revision)

ICRP Publication 4: Recommendations of the International Commission on Radiological Protection. Report of Committee IV (1953–1959) on Protection against Electromagnetic Radiation above 3 MeV and Electrons, Neutrons and Protons (Adopted 1962, with revisions adopted 1963). Pergamon Press, Oxford (1964).

General recommendations

Quality factors for neutrons and protons up to 1000 MeV

Flux densities related to dose rate for neutrons and protons up to 1000 MeV

Linear energy transfer

Absorption coefficients for γ radiation

Build-up factors for γ radiation

Broad beam diffusion for γ radiation and neutrons

(This report is currently in process of revision)

ICRP Publication 5: Recommendations of the International Commission on Radiological Protection. Report of Committee V on the Handling and Disposal of Radioactive Materials in Hospitals and Medical Research Establishments. Pergamon Press, Oxford (1965).

General recommendations and procedures

ICRP Publication 6: Recommendations of the International Commission on Radiological Protection (as Amended 1959 and Revised 1962). Pergamon Press, Oxford (1964).

General recommendations (now obsolete)

Revised and extended data supplementing *ICRP Publication 2*

ICRP Publication 7: Principles of Environmental Monitoring Related to the Handling of Radioactive Materials: A Report Prepared by a Task Group of ICRP Committee 4. Pergamon Press, Oxford (1966).

General recommendations

ICRP Publication 8: The Evaluation of Risks from Radiation: A Report Prepared for Committee 1 of ICRP. Pergamon Press, Oxford (1966).

Quantitative estimates of somatic and genetic risks from radiation

ICRP Publication 9: Recommendations of the International Commission on Radiological Protection (Adopted September 17, 1965). Pergamon Press, Oxford (1966).

General recommendations and maximum permissible doses (Current values, 1969)

ICRP Publication 10: Evaluation of Radiation Doses to Body Tissues from Internal Contamination Due to Occupational Exposure: A Report Prepared by a Task Group of Committee 4. Pergamon Press, Oxford (1968).

Detailed methods of interpretation, including separate appendices for twenty-four nuclides

ICRP Publication 11: A Review of the Radiosensitivity of the Tissues in Bone: A Report Prepared by a Joint Task Group of Committees 1 and 2. Pergamon Press, Oxford (1968).

General review and recommendations

ICRP Publication 12: General Principles of Monitoring for Radiation Protection of Workers: A Report Prepared by a Task Group of Committee 4. Pergamon Press, Oxford (1969).

General recommendations

ICRP Publication 13: Radiation Protection in Educational Establishments: A Report Prepared by a Task Group of Committee 3. Pergamon Press, Oxford (1970).

General recommendations

ICRP Publication 14: Radiosensitivity and Spatial Distribution of Dose: A Report Prepared by Two Task Groups of Committee 1. Pergamon Press, Oxford (1969).

General review and recommendations

Task Group Reports published in *Health Physics*, *12*, 2 (1966):

Deposition and Retention Models for Internal Dosimetry of the Human Respiratory Tract: A Report of the Committee II Task Group on Lung Dynamics (p.173)
(The details of these models are still under review)

Radiobiological Aspects of the Supersonic Transport: A Report Prepared by the Committee 1 Task Group on the Biological Effects of High-Energy Radiations (p.209)

Calculation of Radiation Dose from Protons and Neutrons to 400 MeV: A Report Prepared for Committee III of ICRP (p.227)

The Evaluation of Risks from Radiation: A Report Prepared for Committee 1 of ICRP (p.239) (Also issued as *ICRP Publication 8*)

ICRU Publications

The International Commission on Radiation Units and Measurements publishes reports which contain physical data and methodology of importance to radiological protection. Some of these data have been used in this Handbook. The current ICRU reports are listed below. They are available from ICRU Publications, PO Box 4869, Washington DC 20008, USA.

ICRU Report No. 10b. Physical Aspects of Irradiation, NBS Handbook 85. Washington (1964)

ICRU Report No. 10c. Radioactivity, NBS Handbook 86. Washington (1963)

ICRU Report No. 10d. Clinical Dosimetry, NBS Handbook 87. Washington (1963)

ICRU Report No. 10e. Radiobiological Dosimetry, NBS Handbook 88. Washington (1963)

ICRU Report No. 10f. Methods of Evaluating Radiological Equipment and Materials, NBS Handbook 89. Washington (1963)

ICRU Report No. 11. Radiation Quantities and Units (supersedes ICRU Report No.10a, NBS Handbook 84). Washington (1968)

ICRU Report No. 12. Certification of Standardized Radioactive Sources. Washington (1968)

IAEA Publications

The International Atomic Energy Agency issue reports giving practical guidance concerning radiological protection in the Safety Series of reports. Some of the Technical Reports Series are also concerned with radiological protection. Most of these reports are concerned with procedures and techniques of protection and will be listed in Part II of the Handbook. Several of the reports are, however, relevant to Part I and are listed below. They are available from Her Majesty's Stationery Office, 49 High Holborn, London WC2 and branches.

Safety Series No. 9. Basic Safety Standards for Radiation Protection (1967 Edition). STI/PUB/147, IAEA, Vienna (1967)
Safety Series No. 21. Risk Evaluation for Protection of the Public in Radiation Accidents. STI/PUB/124, IAEA, Vienna (1967)
Technical Reports Series No. 15. A Basic Toxicity Classification of Radionuclides. STI/DOC/10/15, IAEA, Vienna (1963)

2. Constants and Conversion Factors

2.1 Constants

Most of the constants in this section have been taken from or calculated from values given in Kaye and Laby.[1] Exceptions are noted. Preference has been given to SI units where appropriate.

Avogadro's number, N_A	$6 \cdot 02252 \times 10^{23}$ (^{12}C scale)
Inverse of N_A (1 atomic mass unit in grammes)	$1 \cdot 66043 \times 10^{-24}$
Electron charge	$1 \cdot 60210 \times 10^{-19}$ coulombs $4 \cdot 805 \times 10^{-10}$ esu
Electron rest mass	$9 \cdot 1091 \times 10^{-31}$ kg
Electron rest energy	0·51101 MeV
Proton rest mass	$1 \cdot 67252 \times 10^{-27}$ kg
Neutron rest mass	$1 \cdot 67482 \times 10^{-27}$ kg
Alpha particle rest mass	$6 \cdot 6424 \times 10^{-27}$ kg
Planck's constant	$6 \cdot 6256 \times 10^{-34}$ Js
Velocity of light	$2 \cdot 997925 \times 10^{8}$ m/s
Average energy per ion pair (W)[2]	
Alpha particles in air	$34 \cdot 98 \pm 0 \cdot 05$ eV
Electrons in air	$33 \cdot 73 \pm 0 \cdot 15$ eV
Alpha particles or electrons in argon	$26 \cdot 2 \pm 0 \cdot 2$ eV

References for Section 2.1

2.1 (1) KAYE, G. W. C. and LABY, T. H. *Tables of Physical and Chemical Constants* (Thirteenth Edition). Longmans, Green & Co Ltd, London (1966).

2.1 (2) International Commission on Radiological Units and Measurements: Physical Aspects of Irradiation. ICRU Report 10b (1962). *NBS Handbook* 85, US Government Printing Office, Washington DC (1964).

2.2 Decade Prefixes[1]

TABLE 2.2 (1): Decade Prefixes

Name[1]	*Symbol*	*Equivalent*
(*multiples*)		
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
hecto	h[2]	10^{2}
deca	da[2]	10
(*sub-multiples*)		
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ[3]	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}

NOTES

(1) Compound prefixes should not be used.

(2) To be restricted as much as possible.

(3) μ is widely employed as an abbreviation of μm (10^{-6} or micrometre) and is then called *micron*, but μm is the correct symbol to use for 10^{-6} m.

References for Section 2.2

2.2 (1) KAYE, G. W. C. and LABY, T. H. *Tables of Physical and Chemical Constants* (Thirteenth Edition). Longmans, Green & Co Ltd, London (1966).

2.3 Conversion Factors

The principal conversion factors in this section have been taken from Kaye and Laby.[1] Other values have been obtained by calculation. The accuracy is that which is readily available and is always considerably more than that normally required for protection purposes.

TABLE 2.3 (1): Conversion Factors

Multiply quantity in units given	*by*	*to obtain same quantity in units required*
Time		
Days (d)	86400	seconds
Days	$2{\cdot}7379 \times 10^{-3}$	years
Hours (h)	$1{\cdot}141 \times 10^{-4}$	years
Seconds (s)	$1{\cdot}1574 \times 10^{-5}$	days
Seconds	$3{\cdot}1689 \times 10^{-8}$	years
Years (y)	365·22	days
Years	8765·8	hours
Years	$3{\cdot}15569 \times 10^{7}$	seconds
Length		
Angstroms (Å)	10^{-8}	centimetres
Angstroms	10^{-10}	metres
Centimetres (cm)	10^{8}	Angstroms
Centimetres	0·032808	feet
Centimetres	0·393701	inches
Centimetres	10^{4}	micrometres
Fathoms	1·8288	metres
Feet (ft)	30·480	centimetres
Feet	0·30480	metres
Inches (in)	2·540	centimetres
Inches	$2{\cdot}54 \times 10^{-2}$	metres
Inches	25400	micrometres
Kilometres (km)	0·621371	miles
Metres (m)	10^{10}	Angstroms
Metres	0·546807	fathoms
Metres	3·28084	feet
Metres	39·3701	inches
Metres	1·09361	yards
Micrometres (μm)	10^{-4}	centimetres
Micrometres	$3{\cdot}937 \times 10^{-5}$	inches
Yards (yd)	0·91440	metres
Area		
Acres	0·404686	hectares
Acres	4046·86	square metres
Barns	10^{-24}	cm^2
Barns	10^{-28}	m^2
Hectares	2·47105	acres
Square centimetres	10^{24}	barns
Square centimetres	0·00107639	ft^2
Square centimetres	0·15500	in^2
Square feet	929·03	cm^2
Square feet	0·092903	m^2
Square inches	6·4516	cm^2
Square inches	$6{\cdot}4516 \times 10^{-4}$	m^2
Square kilometres	0·386102	$mile^2$
Square metres	$2{\cdot}47105 \times 10^{-4}$	acres
Square metres	10^{28}	barns
Square metres	10·7639	ft^2
Square metres	$1{\cdot}5500 \times 10^{3}$	in^2
Square metres	1·19599	yd^2
Square miles	2·58999	km^2
Square yards	0·836127	m^2

Table 2.3 (1) (cont.)

Multiply quantity in units given	*by*	*to obtain same quantity in units required*
Volume		
Cubic centimetres	$3 \cdot 53147 \times 10^{-5}$	ft^3
Cubic centimetres	0·0610237	in^3
Cubic centimetres	$2 \cdot 19969 \times 10^{-4}$	gallons (Imperial)
Cubic centimetres	$2 \cdot 64172 \times 10^{-4}$	gallons (US)
Cubic feet	28316·8	cm^3
Cubic feet	0·0283168	m^3
Cubic feet	6·229	gallons (Imp.)
Cubic feet	7·4805	gallons (US)
Cubic inches	16·3871	cm^3
Cubic inches	$1 \cdot 63871 \times 10^{-5}$	m^3
Cubic metres	35·3147	ft^3
Cubic metres	$6 \cdot 10237 \times 10^{4}$	in^3
Cubic metres	1·30795	yd^3
Cubic metres	219·969	gallons (Imp.)
Cubic metres	264·17	gallons (US)
Cubic yards	0·764555	m^3
Cubic yards	168·18	gallons (Imp.)
Cubic yards	201·97	gallons (US)
Litres	1·0	cubic decimetre (exactly)
Gallons (Imp.)	4546·092	cm^3
Gallons (Imp.)	0·16054	ft^3
Gallons (Imp.)	1·20095	gallons (US)
Gallons (Imp.)	0·004546092	m^3
Gallons (Imp.)	0·005946061	yd^3
Gallons (US)	3785·43	cm^3
Gallons (US)	0·13368	ft^3
Gallons (US)	0·83267	gallons (Imp.)
Gallons (US)	0·0037854	m^3
Gallons (US)	0·0049511	yd^3
Mass		
Grammes (g)	0·035274	ounces (avoirdupois)
Grammes	0·00220462	pounds (avoirdupois)
Ounces (avoirdupois) (oz)	28·3495	grammes
Ounces (avoirdupois)	0·0283495	kg
Pounds (avoirdupois) (lb)	453·59237	grammes
Pounds (avoirdupois)	0·45359237	kg
Pounds (avoirdupois)	$4 \cdot 5359 \times 10^{-4}$	tonnes (metric)
Pounds (avoirdupois)	$4 \cdot 4643 \times 10^{-4}$	tons (long, British)
Pounds (avoirdupois)	5×10^{-4}	tons (short, US)
Tonnes (metric)	2204·6	pounds (avoirdupois)
Tonnes (metric)	0·984207	tons (long, British)
Tonnes (metric)	1·1023	tons (short, US)
Tons (long, British)	2240	pounds (avoirdupois)
Tons (long, British)	1·01605	tonnes (metric)
Tons (long, British)	1·1200	tons (short, US)
Tons (short, US)	2000	pounds (avoirdupois)
Tons (short, US)	0·90718	tonnes (metric)
Tons (short, US)	0·89286	tons (long, British)
Velocity		
Feet/minute	0·0050800	m/s
Feet/second	1·09728	km/h
Kilometres/hour	0·91134	ft/s
Kilometres/hour	0·53959	knots
Kilometres/hour	0·277778	m/s
Kilometres/hour	0·621371	mile/h
Knots (UK)	1·15151	mile/h
Knots	1·8533	km/h
Metres/second	196·85	ft/min
Metres/second	3·6000	km/h
Metres/second	2·2365	mile/h
Miles/hour	1·609344	km/h
Miles/hour	0·868423	knots
Miles/hour	0·44704	m/s

Table 2.3 (1) (cont.)

Multiply quantity in units given	*by*	*to obtain same quantity in units required*
Energy and Power		
Atomic mass units (u, ^{12}C scale)	931·478	million electron volts (MeV)
Calories (15°C)	$2·6125 \times 10^{13}$	MeV
Calories	4·1855	joules
Calories	$1·306 \times 10^{11}$	fissions (at 200 MeV/fission)
Curie MeV	0·005928	watts
Electron volts	See MeV	
Ergs	10^{-7}	joules
Ergs	$6·2419 \times 10^{5}$	MeV
Fissions (at 200 MeV/fission)	$7·657 \times 10^{-12}$	calories
Fissions (at 200 MeV/fission)	$3·2041 \times 10^{-11}$	joules
Fissions (at 200 MeV/fission)	$8·9058 \times 10^{-18}$	kilowatt hours
Fissions (at 200 MeV/fission)	$3·7108 \times 10^{-22}$	megawatt days
Joules (J)	0·23892	calories
Joules	10^{7}	ergs
Joules	$3·1211 \times 10^{10}$	fissions (at 200 MeV/fission)
Joules	$2·7778 \times 10^{-7}$	kilowatt hours
Joules	$6·2419 \times 10^{12}$	MeV
Kilowatt hours	$1·1236 \times 10^{17}$	fissions (at 200 MeV/fission)
Kilowatt hours	$3·6000 \times 10^{6}$	joules
Kilowatt hours	$2·24705 \times 10^{19}$	MeV
Megawatt days	$2·696 \times 10^{21}$	fissions (at 200 MeV/fission)
Megawatt days	$5·3916 \times 10^{23}$	MeV
MeV	0·001073562	atomic mass units
MeV	$3·8278 \times 10^{-14}$	calories
MeV	$1·6021 \times 10^{-6}$	ergs
MeV	$1·6021 \times 10^{-13}$	joules
MeV	$4·45 \times 10^{-20}$	kilowatt hours
MeV	$1·8547 \times 10^{-24}$	megawatt days
Watts	168·7	curie MeV
Volume flow rate		
Cubic centimetres/second	0·002119	ft^3/min
Cubic feet/minute	471·95	cm^3/s
Cubic feet/minute	1·6990	m^3/h
Cubic metres/hour	0·58858	ft^3/min
Cubic metres/second	19·0053	million gallons (Imp.)/day
Million gallons (Imp.)/day	0·052617	m^3/s
Pressure and mass per unit area		
Atmospheres	76·0	cm of mercury at 0°C
Atmospheres	1·013250	bars
Atmospheres	14·696	lb/in² (colloquial)
Atmospheres	101325	newton /m² (N/m²)
Bars	0·98692	atmospheres
Bars	100000	N/m²
Centimetres of mercury at 0°C	0·01316	atmospheres
Grammes/square centimetre	2·04816	lb/ft²
Grammes/square centimetre	0·0142233	lb/in²
Kilogrammes/square metre	0·00142233	lb/in²
Kilogrammes/square metre	9·80665	N/m²
Newtons/square metre	$9·8692 \times 10^{-6}$	atmospheres
Newtons/square metre	10^{-5}	bars
Newtons/square metre	0·10197	kg/m² (colloquial)
Newtons/square metre	$1·4504 \times 10^{-4}$	lb/in² (colloquial)
Pounds/square foot	0·488243	g/cm²
Pounds/square inch (colloquial)	0·068046	atmospheres
Pounds/square inch (colloquial)	$6·89476 \times 10^{3}$	N/m²
Pounds/square inch	70·307	g/cm²
Pounds/square inch	703·07	kg/m²