RADIOLOGICAL PROTECTION

A Summary Handbook of ICRP Publications and Recommendations

A. NAGARATNAM

Radiological Protection : A Summary Handbook of ICRP Publications and Recommendations

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FOREWORD

No technology evokes such strong emotions as nuclear energy. The immense possibility of harnessing the power of the atom to produce limitless power, and also to unleash its fury through nuclear weapons that would destroy humankind are really two faces of the same technology. While the world is slowly moving to a better realization of the destructive power of nuclear weapons and evolving agreements to control and finally eliminate them, it is also getting increasingly restive about the safety of nuclear technology. Recent accidents at Three Mile Island and most notably at Chernobyl have shaken our faith on the very applications using nuclear energy. The industrial and healing power of the atom is today seen through a veil of concern and fear. The new Luddites are busy damning any application using nuclear energy. More than ever it is now necessary that we understand the power of radiation as well as its safe limits.

The International Commission on Radiological Protection (ICRP) is actually playing this role, suggesting possibilities, and warning of the dangers from radiation exposure. Such is the expertise and maturity of ICRP that in spite of it being only a recommendatory body, its advice is sought and taken seriously by all concerned, including international organizations like WHO, FAO, ILO and IAEA. The mission of ICRP is to develop a coherent philosophy and a system of radiation protection that primarily takes into account the justification for radiation exposure and works to calculate an appropriate limit of radiation dosage for that exposure. More, it also suggests optimization of the system of protection so that the benefits far exceed possible hazards. The aim is to evolve a dosage as low as reasonably achievable for that objective. This has evolved into the famous ALARA principle.

The scope of ICRP publications covers a wide canvas: philosophy of perception, evaluation and management of risks; understanding of biological and genetic effects of radiation; technical measures to control radiation hazards; engineering aspects of design and operation of equipment; procedures for monitoring safety; accident evaluation and response; organization and management systems and, public awareness. ICRP has enlisted the services of experts from many countries to carry out this vast mandate.

The recommendations of ICRP are regularly published and updated. From 1959 up to now, it has produced 64 publications that run to 9000 pages! How does one wrestle with such an ocean of information? Mr Nagaratnam's Handbook is a response to this challenge. Using the language of ICRP, he communicates clearly and concisely the salient features of the information given in ICRP publications, exercising critical judgement in choosing relevant areas. By all standards, this is a daunting task, and Mr Nagaratnam has responded to it with his characteristic efficiency and insight.

Mr Nagaratnam is the ideal author for a publication of this kind. For over four decades he has worked in areas related to radiation, first as a scientist at the Institute of Nuclear Medicine and Allied Sciences in Delhi, and later as a Director of the Defence Laboratory at Jodhpur where he concerned himself with the industrial applications of radiation. In both these institutions, he has nurtured and sustained competent groups of engineers and scientists working on problems associated with the peaceful applications of nuclear energy. His experiences in working with scientists of the Bhabha Atomic Research Centre and the Atomic Energy Regulatory Board have also contributed to the usefulness of this Handbook.

Defence Scientific Information and Documentation Centre (DESIDOC) of the Defence Research and Development Organization (DRDO) has come forward to publish this volume as a symbol of their continuing commitment to help the scientists and engineers working in this area. I congratulate DESIDOC for this effort and am confident this volume will soon become a ready reference manual to all workers concerned with nuclear radiation not only in India but in other countries as well.

Pittsburgh
July 1994

VS ARUNACHALAM

PREFACE

Mankind is reaping enormous benefits from the peaceful applications of nuclear energy in various fields including power production, medicine, industry, agriculture and research. On the other hand, we know that excessive exposure to ionizing radiations can lead to adverse biological effects. In this respect, radiation is no different from other risks in modern life, since all facets of human advance almost invariably entail some concomitant risks. Wisdom lies in striking a happy and judicious balance in order to ensure that we continue to utilize radiation for human benefit while keeping the potential risk to an acceptable minimum. Radiation should be handled with care, but not fear.

Our knowledge of the biological effects of radiation and potential risks therefrom far exceeds our knowledge of any other hazardous agent, whether in the industrial field, or in the general environment affecting members of the public. The International Commission on Radiological Protection (ICRP) has been playing a pioneering role for decades in this direction. The extensive database that has been established over the decades by the ICRP, the methodologies, techniques and the organizational structures that have been developed to control radiation hazards, and, above all, the philosophy of risk evaluation and management that has been evolved by ICRP, would serve as valuable guides not only to those concerned with radiological protection but to scientists, technologists and administrators involved in all facets of occupational and industrial safety, as well as those concerned with environmental protection.

From 1959 to the end of 1993 ICRP has brought out 64 publications running to around 9000 pages. It is important that everyone connected with the uses of ionizing radiations should be familiar with at least the basic features of the thinking of ICRP as embodied in these publications. The present Handbook attempts to give in a concise, consolidated and codified form the salient features of all the relevant information contained in the voluminous ICRP publications. As far as possible, the language of the original publications themselves has been used.

The suggestion that I take up this assignment came from Dr VS Arunachalam, former Scientific Adviser to the Minister of Defence. I am grateful to him for his constant advice and support, as well as for his kindly agreeing to write the Foreword to this Handbook.

Grateful thanks are due to the ICRP for generously agreeing, in conformity with its policy of encouraging wide dissemination of the information contained in its reports, to using material contained in the relevant ICRP publications for preparing this Handbook. To quote from the communication received from Dr H Smith, Scientific Secretary of ICRP, "On behalf of the International Commission on Radiological Protection I agree to you using the information contained in ICRP Publications 1 to 64 to prepare the monograph. In so doing, however, I stress that this does not necessarily imply that the ICRP will agree to the contents of your monograph or your interpretation of ICRP philosophy".

I would like to express my gratitude to Dr APJ Abdul Kalam, Scientific Adviser to the Minister of Defence, Sri K Santhanam, Chief Adviser on Technologies, Defence Research and Development Organization, Sri KN Singh, Chief Controller, DRDO, Prof P Rama Rao, former Director and Distinguished Scientist, and Sri SLN Acharyulu, the present Director, Defence Metallurgical Research Laboratory, Hyderabad, for their administrative and technical support. Thanks are also due to Sri R Seshadri, Chief Construction Engineer (R&D), Secunderabad; Col S Vasudevan, Director of Estates (R&D), Secunderabad; and Lt Col (Retd) ER Sadasivan, Project Manager, Office of DOE (R&D), Secunderabad for their administrative help. Special mention must be made of Dr SS Murthy, Director, Sri A Lakshmana Moorthy, Scientist and their colleagues at the Defence Scientific Information and Documentation Centre, Delhi, for their untiring efforts in bringing out this publication in an excellent form, and of Sri DS Sastry for his meticulous and fine editing of the manuscript. The help extended by Dr AR Reddy, Director, and the Design Drawing Staff of the Defence Laboratory, Jodhpur in the preparation of several tables and figures is gratefully acknowledged. Dr SC Jain, Scientist from the Institute of Nuclear Medicine and Allied Sciences, Delhi was of great help in several ways during the preparation of the Handbook. It is a pleasure to record my appreciation of and gratitude to my wife Sarasvati for her support in innumerable ways.

Several publishers have given permission for reproducing many tables and figures. Detailed acknowledgments are given separately.

The order of presentation followed in this Handbook does not follow the chronological order in which the publications have come out. The

material has been presented in 7 parts, each dealing with one major aspect of the recommendations, and summarizing the various publications connected with it. A separate note following the Preface gives a brief summary of the way the contents of the Handbook have been arranged.

Subjective judgement had necessarily to be exercised in the choice and emphasis of the subject matter. The author hopes that no important aspect has been left out. The part dealing with radiological protection in the medical applications of radiation has deliberately been made rather exhaustive. Very few medical colleges or leading hospitals in our country seem to have access to ICRP publications. Since it is well known that medical exposure contributes the largest share to population exposure from man-made radiation sources, and since significant reductions in exposure levels, particularly in diagnostic radiology, can be effected by the utilization of simple and cost-effective protection measures without reduction in the diagnostic information of interest, it was considered worthwhile to deal with this subject somewhat elaborately.

ICRP periodically reviews and updates its database in the light of recent information, particularly in the field of biological effects of radiation. The Commission also regularly revises its reports and recommendations, incorporating newer thinking; this is a continuing exercise. Among the immediate tasks ICRP is currently engaged in are revision of earlier reports to bring them into conformity with the latest main (1990) recommendations, revision of several dosimetric models including those of the respiratory tract, Reference Man, embryo and fetus, and radon exposures, as well as extending the age-dependent dosimetric computations to more radionuclides for exposure of members of the public from internally incorporated radionuclides. In the present Handbook, the author had necessarily to content himself with summarizing reports that were brought out by ICRP till the end of 1993.

Hyderabad
20 June 1994

A. NAGARATNAM

SUMMARY OF THE CONTENTS OF THE HANDBOOK

Part I is an extended summary of the latest main recommendations, as brought out in the text of ICRP Publication 60 (1991), using the language of the original publication itself to the extent possible. The order of presentation is the same as that of ICRP 60. Starting from a brief history of the ICRP and the development of ICRP recommendations (Chapter 1), a summary is next given (Chapter 2) of the quantities and units in radiological protection. Chapter 3 summarizes current knowledge on the biological effects of radiation. Chapter 4 deals with the conceptual framework of radiological protection, an area in which ICRP has thoughtfully developed a unique, logical and comprehensive system. Chapter 5 deals with the application of the system of protection for proposed and continuing practices. The basis for the currently recommended numerical values for the dose limits is explained. Chapter 6 is concerned with the application of the system in the case of intervention (following emergencies and accidents). Chapter 7 deals with the implementation of the recommendations, with special reference to the organizational aspects. Chapter 8 is a summary (as given by the ICRP itself) of the recommendations.

Appendix 5.1 deals with the conceptual framework of protection from potential exposures (for which there is a possibility but no certainty of occurrence). Appendix 8.1 (written by the author) gives in somewhat greater detail than in chapter 1 the history and organization of ICRP. Appendix 8.2 (also written by the author) gives a fairly detailed account of the historical evolution of the recommendations. Appendix 8.3 is an updated version of the list of ICRP publications given in ICRP 60.

Part II deals with the biological effects of radiation. It starts (Chapter 9) with a discussion of basic radiobiology at the cellular level. Chapter 10 discusses deterministic effects in various tissues and organs. Chapters 11 and 12 are concerned respectively with the two main types of stochastic effects, viz. induction of cancer and hereditary effects. The sources from which our knowledge of biological effects of radiation is derived, including human experience and results of animal experiments, are discussed. Numerical values of risk estimates are given, and the margin of uncertainty in these figures is indicated. To give a sense of perspective, Appendix

12.1 tabulates data (taken from the 1988 Report of the United Nations Scientific Committee on the Effects of Atomic Radiation) on the current levels of doses from radiation sources, natural and man-made. It is natural that great interest is being evinced on the effects of radiation on the embryo and fetus, and Chapter 13 is devoted to this aspect. The main concern today in radiological protection is in relation to the effects of low dose exposure. The subject is beset with difficulties and uncertainties, and Chapter 14 summarizes the current situation. Chapter 15 discusses the biological effects of inhaled radionuclides, a subject of relevance in certain important stages in the operation of the nuclear fuel cycle.

Part III deals with external and internal dosimetry, a topic whose importance in radiological protection hardly needs emphasis. Chapter 16 deals with quantities used in radiological protection, and is an elaboration and extension of Chapter 2. Considerable effort has gone into the development of the 'Reference Man', with well-defined anatomical, physiological and metabolic characteristics, for standardization of dosimetric protocols; Chapter 17 gives a fairly exhaustive account of the characteristics of the Reference Man. Chapters 18 to 20 discuss in detail the mathematical methodologies for internal dosimetry. Chapters 21 to 24 give details of the dosimetric models (lung, GI tract, bone, and submersion in a radioactive cloud). Chapters 25 and 26 give numerical values of internal dosimetric data for important radionuclides, for occupational workers and members of the public respectively. The impact, particularly on the public, of radionuclide releases into the environment is an important area, but subject to many difficulties in assessment. Chapter 27 deals briefly with the models developed by ICRP appropriate for such assessment. Chapter 28 is devoted to external dosimetry.

ICRP has evolved a realistic system of operational radiation protection in various applications for effective implementation of its recommendations; this forms the subject matter of Part IV. The general principles of monitoring, and monitoring programmes for protection of the workers and members of the public, both under normal conditions of operation and in the event of a major accident, are discussed in Chapters 29, 30 and 32. Chapters 31 and 33 discuss the procedures for handling accidents and emergencies, with respect to protection of the workers and members of the population respectively. ICRP has recently been concerning itself with principles of limiting exposures of the public to natural sources of radiation, and Chapter 34 summarizes the relevant guidelines. With the increasing use of devices and techniques involving ionizing radiation for the teaching of science (such as X-rays and radiotracers), ICRP has given guidelines for protection of the students which are summarized in Chapter 35. Chapter 36 deals

with the principles for the disposal of solid radioactive waste; such practices involve probabilistic assessments of events not only in the present but even in the far distant future.

In view of its historic association with the International Congress of Radiology, as well as the great relevance of radiological protection in medical applications (diagnostic radiology contributes the overwhelming share to population exposure from man-made sources of radiation), ICRP has devoted special attention to this area and given detailed recommendations on specific applications including diagnostic radiology, radiotherapy, nuclear medicine, and biomedical research involving radiation exposure. Part V (Chapters 37 to 41) discusses these aspects. (Appendix 37.1 gives the ICRP guidelines regarding radiological protection in biomedical research.)

Over the last two decades or so we have come to realize that exposure from the daughter products of radon and thoron forms the major proportion of exposure of every member of the human population from natural sources. Doses from this source are highly variable, depending upon geological factors and life styles, and can be very high to people living in certain geographic areas. Part VI (Chapter 42) deals with this subject, including guidelines for limiting exposures of the public from excessive exposure to radon and its daughters inside buildings.

A noteworthy feature of ICRP recommendations is the deep thought that has been given to the problem of risk evaluation and acceptance, as well as to the problem of judicious allocation of resources to radiological protection in the overall context of peaceful applications of nuclear energy in various fields. Part VII deals with these subjects. ICRP has developed elegant methodologies for optimizing and decision-making in radiological protection. These are not merely confined to broad generalities but appropriate techniques have been developed for practical application in specific cases. This is dealt with in Chapter 43. One of the difficult problems that ICRP has tackled is the attempt to evolve a quantitative basis for comparing risks of different kinds, to arrive at a generally applicable parameter for risk expression, as well as to evolve a consensus on what is a level of 'acceptable risk', whether for an occupational worker or a member of the public; these tasks involve not merely scientific but societal value judgements on the perception and acceptance of risk. It is only by a careful consideration of all these factors that it would be possible to arrive at dose limits for radiological protection implying acceptable levels of risk. These questions are discussed in Chapters 44 and 45.

It may be mentioned that in the list of references at the end of each chapter, those pertaining to the different ICRP publications (which have

been referred to in the individual chapters in the text) have not been included, since Appendix 8.3 gives the list of all ICRP publications to-date.

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The author gratefully thanks the following for their kind permission to reproduce material from their publications:

Academic Press, Inc., USA, for the figure 'Observed biological effects of inhaled plutonium' modified from Bair, W.J. (1974). Toxicology of Plutonium. In: *Advances in Radiation Biology*, Vol. 4, edited by J.T. Lett, H. Adler and H. Zelle, 255-315;

Commission of the European Communities, Luxembourg, and Harwood Academic Publishers, Switzerland, for the figure 'Shape of dose responses for low LET and high LET radiations plotted on linear axes' from Sinclair, W.K. (1982). Fifty Years of Neutrons in Biology and Medicine: The Comparative Effects of Neutrons in Biological Systems. In: *Proceedings of the 8th Symposium on Microdosimetry*, EUR 6395; pp 1-37;

The Institute of Physics, UK, for the table 'Distribution of bone marrow spaces in adult bone' from Woodard, Helen Q. and Holodny, Edward (1960). A Summary of the Data of Mechanik on the Distribution of Human Bone Marrow. *Phys. Med. Biol.*, **5**, 57-59;

International Commission on Radiation Units and Measurements, for the table 'RBE values for fission (or optimum energy neutrons) vs gamma rays for stochastic end-points' from ICRU (1986). *The Quality Factor in Radiation Protection*, ICRU Report 40;

The US National Academy of Sciences, for the table 'Salient features of the major study: populations evaluated for derivation of numerical risk estimates', from *Health Effects of Exposure to Low Levels of Ionizing Radiation (BEIR V)*. Copyright 1990 by the National Academy of Sciences. Published by the National Academy Press, Washington, D.C.;

National Council on Radiation Protection and Measurements, USA, for the figure 'Schematic curves of incidence vs absorbed dose' from NCRP (1980). *Influence of Dose and its Distribution in Time on Dose-Response Relationships for Low LET Radiations*, NCRP Report 64;

National Radiological Protection Board, UK, for (a) the table 'Derived levels of surface contamination' from Wrixon, A.D., Linsley, G.S., Binks, K.C. and White D.F. (1979). *Derived Levels for Surface Contamination*, Report NRPB-DL2, and its supplement (1982); and (b) the figure 'Simplified version of the proposed new ICRP lung model' from Bailey, M.R. and Birchall, A. (1991). New ICRP Dosimetric Model for the Respiratory Tract: A Progress Report. *Radiat. Prot. Bull.*, **119**,13-20.

Nuclear Technology Publishing, UK, for (a) the table 'RBE_M values for fission (or optimum energy) neutrons vs gamma rays for stochastic end-points' from Sinclair, W.K. (1985). Experimental RBE Values of High LET Radiations at Low Doses and the Implications of Quality Factor Assignment. *Radiat. Prot. Dosim.*, **13**, 319-26; and (b) the figure 'Effective Q ($\bar{Q}$) as a function of photon energy' from Drexler, G., Veit, G. and Zanke, M. (1990). The Quality Factor for Photons. *Radiat. Prot. Dosim.*, **2**(2), 83-89;

Springer-Verlag GmbH, Germany, for the table 'Summary of the Weibel model of the tracheo-bronchial region' from Weibel, Ewald R. (1963). *Morphometry of Human Lung*;

University of Minnesota Press, USA, for the figure 'Four general post-natal growth patterns according to age' from Harris, J.A., Jackson, C.M., Patterson, D.G. and Scammon, R.E. (Eds) (1930). *The Measurement of Man*. Copyright 1930, University of Minnesota Press, Minneapolis; and

United Nations Scientific Committee on the Effects of Atomic Radiation, for the following:

(a) Table 'Skin doses in primary beam in diagnostic radiology (median values in cGy per examination)' from UNSCEAR (1979). *Sources and Effects of Ionizing Radiation*; (b) table 'Estimation of approximate thresholds for clinically detrimental non-stochastic effects in various tissues based on response of patients in conventionally fractionated therapeutic X or gamma radiation' from UNSCEAR (1982). *Sources and Biological Effects*; (c) table 'Main characteristics of the A-bomb survivor, ankylosing spondylitis, and cervical cancer series' from UNSCEAR (1988). *Sources, Effects and Risks of Ionizing Radiation*; (d) table 'Estimates of genetic risk arrived at by UNSCEAR in its 1988 report using the direct method: low LET low dose-rate (chronic irradiation conditions)' from UNSCEAR (1988). *Sources, Effects and Risks of Ionizing Radiation*; and (e) author's appendix containing two tables on 'Average doses to the world population from natural and man-made sources of radiation' from UNSCEAR (1988). *Sources, Effects and Risks of Ionizing Radiation*.

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Part I

Main Recommendations of ICRP

(1990 Recommendations, ICRP Publication 60)

CHAPTER 1

INTRODUCTION

Ionizing radiation is the term used to describe the transfer of energy through space in the form of either electromagnetic fields or subatomic particles that are capable of causing ionization in matter. Ionization is the process by which atoms lose, or sometimes gain, electrons and thus become electrically charged, being then known as ions. When ionizing radiation passes through matter, energy is imparted to the matter as ions are formed.

Ionizing radiations and radioactive materials have always been features of our environment, but, owing to their lack of impact on our senses, we have been aware of them only since the end of the 19th century. Since that time, we have found many important uses for them and have developed new technological processes which create them, either deliberately or as unwanted side effects. The primary aim of radiological protection is to provide an appropriate standard of protection for man from the harmful biological effects of these radiations without unduly limiting the beneficial practices giving rise to radiation exposure. This aim cannot be achieved by the use of science alone. All those concerned with radiological protection have to make value judgements about the relative importance of different kinds of risk and about the balancing of risks and benefits. In this they are no different from those working in other fields concerned with the control of hazards. The International Commission on Radiological Protection (ICRP) concerns itself with the formulation of appropriate recommendations in matters of radiation protection.

1.1 THE HISTORY OF ICRP

The International X-ray and Radium Protection Commission was established in 1928, following a decision by the Second International Congress of Radiology. In 1950 it was restructured and acquired its present name of International Commission on Radiological Protection. Over the years, ICRP, while still retaining a relationship with the International Congress of Radiology, has greatly broadened its interests to take account of the increasing uses of ionizing radiation and of practices that involve the generation of radiation and radioactive materials.

ICRP works closely with its sister body, the International Commission on Radiation Units and Measurements (ICRU), and has links with the World Health Organization, the International Atomic Energy Agency, and other United Nations bodies like the United Nations Scientific Committee on the Effects of Atomic Radiation, the United Nations Environment Programme, the International Labour Organization, the International Standards Organization, the International Electrotechnical Commission, and the International Radiation Protection Association.

ICRP recommendations are confined to protection against only ionizing radiations. (ICRP considers that non-ionizing radiation is a subject outside its own field of competence.) ICRP emphasizes that ionizing radiation needs to be treated with care rather than fear and that its risks should be kept in perspective with other risks. The procedures available to control exposures to ionizing radiation are sufficient, if used properly, to ensure that radiation remains a minor component of the spectrum of risks to which all are exposed.

ICRP believes that the standard of environmental control to protect man will ensure that other species are not put to risk. Occasionally, individual members of non-human species might be harmed, but not to the extent of endangering whole species. ICRP concerns itself with mankind's environment only with regard to the transfer of radionuclides through the environment, since this directly affects the radiological protection of man.

ICRP issued its first report in 1928. The first report in the current series, Publication 1 (1959), contained the recommendations approved in 1958. Subsequent general recommendations have appeared as Publication 6 (1964), Publication 9 (1966), and Publication 26 (1977). Publication 26 was amended and extended by Statements in 1978, 1980, 1983, 1984, 1985 and 1987. Reports on more specialized topics have appeared as intermediate and subsequent publication numbers.

A somewhat more detailed account of the history and organization of ICRP is given in Appendix 8.1.

1.2 THE DEVELOPMENT OF ICRP RECOMMENDATIONS

The method of working of ICRP has not changed greatly over the last few decades. Since there is little direct evidence of harm at levels of annual dose at or below the limits recommended by it, a good deal of scientific judgement is required in predicting the probability of harm resulting from low doses of radiation from the observed data obtained at higher