Executive Summary

The National Council on Radiation Protection and Measurements (NCRP) Report No. 51, published in 1977 and entitled, *Radiation Protection Design Guidelines for 0.1–100 MeV Particle Accelerator Facilities*, was one of the first comprehensive treatments of accelerator radiological-protection concerns. The present Report is a substantial revision and expansion of that earlier report and includes new information on source intensities, shielding, dosimetry, and the environmental aspects of particle accelerator operation. It is primarily concerned with radiological safety aspects that are special to the operation of particle accelerators having energies above about 5 MeV up to the highest energies available, while not neglecting low-energy neutron generators.

The purpose of this Report is to provide design guidelines for radiation protection, and to identify those aspects of radiological safety that are of major, or even unique, importance to the operation of particle accelerator installations and to suggest methods by which safe operation may be achieved. The Report is written from an engineering physics viewpoint and is intended to be useful to those engaged in the design and operation of accelerators particularly in smaller institutions and organizations that do not have a large radiological-protection staff. Managers of institutional and industrial accelerator installations, health physicists, hospitals, radiological physicists, research scientists, government regulators, project engineers, and other similar specialists will also find the information contained in this Report useful.

Since 1977, NCRP has issued two reports that discuss specific radiological-protection issues at particle accelerators: NCRP Report No. 72, *Radiation Protection and Measurements for Low-Voltage Neutron Generators* and NCRP Report No. 79, *Neutron Contamination from Medical Electron Accelerators*. NCRP Report No. 88, *Radiation Alarms and Access Control Systems* is also of interest for those who operate accelerators. The International Atomic Energy Agency has issued three reports that specifically deal with the radiological safety aspects of the operation of low-energy neutron generators, electron linear accelerators, and proton accelerators. In 1988, the U.S. Department of Energy issued its *Health Physics Manual for Good Practices for Accelerator Facilities*. In 1990, the European

Organisation for Nuclear Research (CERN) published a comprehensive volume on shielding against high-energy radiation. One aim of this Report was to revise NCRP Report No. 51 in such a way that access to much of this new material was brought together in one volume.

The first of this Report's seven sections provides a general introduction, sets out the scope of the Report, and provides information on radiological-protection standards, and international, national and state regulatory agencies.

The second section of the Report, Particle Accelerators and Accelerator Facilities, defines and classifies particle accelerators by their functional and radiological characteristics. A brief historical review of accelerator development is followed by a discussion of the ionizing radiation produced by the separate components of accelerator systems. The special problems of ion sources, radiofrequency (RF) systems, beam-handling systems, beam stops and auxiliary systems, such as high-voltage and microwave power supplies, and cooling and vacuum systems are briefly described. Guidance for the siting and layout of accelerator facilities is provided.

Section 3, entitled The Sources of Ionizing Radiations from Accelerators, provides a fundamental overview of the production of ionizing radiations by accelerated particles. After a brief review of the basic atomic and nuclear-physics concepts, the radiations produced by energetic electrons, protons and ions are separately described. Radiation yield data are presented in analytical and graphical form. The Section ends with a discussion of the production of radioactivity in materials. Bremsstrahlung yields, including angular distribution data, from thick and thin targets bombarded by electrons from the lowest energies up to the giga-electron volt region are given. Similar data are given for neutron production. Muon yields, important at the higher energies, are briefly discussed. The electron subsection ends with a description of the transport of the initial particle energy *via* the electromagnetic cascade. At energies above ~10 MeV, neutrons usually present the dominant source of occupational radiation exposure at proton accelerators. Neutron yields and angular distribution data for materials bombarded by proton beams are provided from the lowest energies up to the multi-giga-electron volt energy region, usually in graphical form. For proton energies above ~10 GeV muon production becomes important and is discussed. Muon range-energy data are given. The degradation of the primary proton energy *via* the hadronic cascade is described and the radiation environment outside the shield of high-energy proton accelerators, particularly neutron spectra, is discussed. Neutron yields for ions of energies up to $\sim$100 MeV amu^{-1} are provided for a variety of targets and ions.

Section 4 is entitled Radiation Shielding at Accelerators and provides a description of shielding of electron, proton and ion accelerators up to the multi-giga-electron volt energy region. A special section is devoted to synchrotron radiation facilities. Theoretical and experimental aspects of shield design are discussed. Information is given on the properties of shielding materials. The efficient design of penetrations through shielding and the design of shield doors are also described. Specimen shield calculations are provided.

Section 5 is entitled Special Techniques of Radiation Measurement at Particle Accelerators. Personal and environmental monitoring, as well as field surveys are discussed. After a preliminary review of the purposes for which accelerator-radiation measurements are made and the quantities in which these measurements are expressed, radiation detectors are classified as *active (real time)*, *e.g.*, Geiger-Mueller (GM) counters, proportional counters, fission chambers, counter telescopes; and *passive*, *e.g.*, thermoluminescence dosimeters (TLD), nuclear emulsions, track-etch techniques, bubble dosimeters, and activation measurements. The special problems of operating active real-time detectors in the pulsed radiation fields of accelerators are discussed. Above primary energies of a few mega-electron volts the radiation environments of electron, proton and ion accelerators are of a "mixed" character, consisting primarily of photons and neutrons. At the highest energies neutrons are often the most significant component of the radiation environment and much attention is, therefore, given to neutron detection techniques. The determination of neutron spectra from field survey data is described.

The environmental impact of the operation of particle accelerators is discussed in detail in Section 6, Environmental Radiological Aspects of Particle Accelerators, and includes descriptions of skyshine and the production of radioactivity. The mechanisms of the transport of prompt radiation to distances far from the accelerator, generally known as skyshine, are described for both photons and neutrons. Simple examples of the calculation of appropriate overhead shielding to reduce radiation intensities due to skyshine are provided. Second only to skyshine, but several times smaller in magnitude, the potential for the exposure of members of the public to radioactivity produced by accelerator operation is an important concern. Exposure to the public to accelerator produced radioactivity might result from three pathways: air activation, groundwater activation, and radioactive accelerator components. The mechanisms for the production and migration of radionuclides are described in detail. Illustrative data tables and calculations are provided. Methods of evaluating estimates of the population collective dose equivalent from these potential sources of exposure are given. Finally, in this Section, there is a brief discussion of the production of nonradioactive toxic gases, such as ozone, and the oxides of nitrogen.

The seventh and final section outlines the basic needs for an Operational Radiation Safety Program for Accelerators. Much of the safety program includes elements common to other radiological installations and this Section draws attention only to those special elements required at accelerators. For example, the conflicts between the requirements for easy access and the need to limit radiation leakage through the external shielding are discussed. Differences between the types of radionuclides produced at accelerators (more positron emitters) compared with nuclear reactors and their spatial distribution in surrounding materials, are described. Contamination control requires radiation detection techniques capable of detecting positron and low-energy beta emitters.

The Report has two appendices, the first tabulating importance functions for both neutrons and photons, the second giving tabulations of kinematic data for electrons, muons, kaons, protons, deuterons and selected heavier particles up to ^{238}U. Finally, a detailed Glossary and a comprehensive list of references are provided.

Some of the material in this Report is historical and refers to studies made many decades ago. In such cases, the then contemporary quantities, units and references as formatted are retained. Some of the figures reproduced from older references are somewhat impaired in quality.