NBS HANDBOOK 107

Radiological Safety in the Design and Operation of Particle Accelerators

AMERICAN NATIONAL STANDARD N43.1-1969

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[2] Located at Boulder, Colorado 80302.
[3] Located at 5285 Port Royal Road, Springfield, Virginia 22151.

UNITED STATES DEPARTMENT OF COMMERCE • Maurice H. Stans, *Secretary*
NATIONAL BUREAU OF STANDARDS • Lewis M. Branscomb, *Director*

American National Standard

Radiological Safety in the Design and Operation of Particle Accelerators

By

American National Standards Institute
Subcommittee N43-4 on Particle Accelerators

Under the sponsorship of the
National Bureau of Standards
Washington, D.C. 20234

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Foreword

This Handbook contains recommended safety standards for the design and operation of particle accelerators. It was developed by American National Standards Committee N43, Equipment for Non-Medical Radiation Applications, and the text has been approved by ANSI as an American National Standard. The National Bureau of Standards serves as the Secretariat of Committee N43 and provides the publication outlet for standards produced by the Committee.

NBS is authorized by Congress to cooperate with other governmental agencies and with private organizations in the establishment of standard practices, and to investigate the uses of radiation and means of protection of persons from its harmful effects. An outstanding example of such cooperation is the Bureau's support of the work of ANSI Standards Committee N43 and the precedent ASA Sectional Committee Z54. The Bureau is pleased to increase the usefulness of American National Standards by publishing them as NBS Handbooks.

Lewis M. Branscomb, *Director*

Preface

The American National Standards Institute (ANSI) Main Committee N43 (Equipment for Non-Medical Radiation Application) examined the need and approved the development of this standard at its February 1968 meeting. A Chairman was appointed to a subcommittee designated as N43–4 to develop the standard. Three subcommittee meetings were held during the period April 1968 to March 1969. During this period the standard was reviewed by organizations, laboratories, and universities and their comments were considered. The standard was then unanimously approved by the Main Committee N43 and subsequently submitted to the ANSI Nuclear Standards Board (NSB) where final approval was received December 23, 1969.

Basically, this standard recognizes that design and operational requirements are inseparable elements of safety. Guidance is provided in those basic considerations essential to the safe operation of a particle accelerator. Budgetary provisions should be made to include equipment and personnel to assure adequate protection of workers in accordance with the recommendations of this standard.

Realizing that questions may arise from time to time concerning interpretations of this standard, provisions have been made for an Interpretations Committee in order that uniform handling of questionable cases may be provided. It is recommended that anyone using this standard and desiring an interpretation of a questionable case communicate with the American National Standards Institute.

Suggestions for improvement gained in the use of this standard will be welcome. They should be sent to the American National Standards Institute, 1430 Broadway, New York, New York 10018.

The American National Standards Committee, N43, on Equipment for Non-Medical Radiation Applications, which processed and approved this standard, had the following personnel at the time it approved this standard:

Leonard H. Horn, *Chairman*
(Underwriters' Laboratories)

Elmer H. Eisenhower, *Secretary*
(National Bureau of Standards)

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American Conference on Governmental Industrial Hygienists	Robert H. Duguid
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The Subcommittee N43–4 on Particle Accelerators which had the responsibility for developing this standard consisted of the following personnel:

Edward J. Vallario, *Chairman*
(U.S. Atomic Energy Commission)

E. Alfred Burrill	Consultant
C. J. Karzmark	Stanford Medical Center, Stanford University
Richard C. McCall	Stanford Linear Accelerator Center
Richard Boggs	Bureau of Radiological Health
H. Wade Patterson	Lawrence Radiation Laboratory (Berkeley)
John H. Scotney	High Voltage Engineering Corp.
Harry J. Howe	Argonne National Laboratory

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i. Scope

This standard applies to particle accelerators principally with primary energies less than 100 MeV. It considers the characteristics of and controls for radiation as they affect accelerator design, operating procedures, and exposure evaluation.

ii. Definitions [1]

Qualified Expert. A person having the knowledge and training to measure ionizing radiation, to evaluate safety techniques, and to provide advice on radiation protection needs. (Where guidance is needed as to the competence of an individual to discharge the responsibilities of a qualified expert, it may be obtained from the American Board of Health Physics, the American Board of Radiology, or the American Board of Industrial Hygiene.)

Radiation Control Officer. That individual who is responsible for the radiation protection program.

Bioassay. The analysis of biological material to determine the presence and quantities of internally deposited radionuclides.

NOTE: This definition is specific to the field of radiation protection. This term has a different definition when used in other fields, such as biology or biochemistry.

Monitoring. (See *Radiation Monitoring.*)

**Radiation Monitoring.* The continuing collection and assessment of the pertinent information to determine the adequacy of radiation protection practices and to alert to potentially significant changes in conditions or protection performance.

**Smear Test.* A procedure in which a swab is rubbed on a surface and its radioactivity measured to determine if the surface is contaminated with loose radioactive material.

**Radiation Survey.* An evaluation of the radiation hazard potential associated with a specified set of conditions incident to the production, use, release, storage, or presence of radiation sources.

**Maximum Permissible Concentration* (MPC). An accepted upper limit for the concentration of a specified radionuclide in a material taken into the body below which continuous exposure (or in the case of occupational maximum permissible concentration exposure for 40 hours per week) to the material is not considered biologically harmful.

Maximum Permissible Dose (MPD). The amount of exposure to ionizing radiation established by authorized groups (such as NCRP, ICRP, FRC) which carries an acceptably low probability (risk) of resulting in appreciable bodily injury to a person at any time during his lifetime.

Threshold Limit Value (TLV). The TLV as defined by the American Conference of Governmental Industrial Hygienists refers to "airborne concentrations of substances and represents conditions under which it is believed that nearly all workers may be repeatedly exposed day to day."

Quality Factor (QF). A linear-energy-transfer dependent factor by which absorbed doses are to be multiplied to obtain the Dose Equivalent.

Dose Equivalent (DE). The term Dose Equivalent is used in radiation protection as denoting the rem. It is the product of absorbed dose (d), Quality factor (QF), dose distribution factor (DF), and other necessary modifying factors.

Accelerator. A machine that accelerates electrically charged particles to high velocities.

Interlock. A device which automatically shuts down the accelerator under certain conditions of system malfunction and where there is penetration of barriers containing such devices.

Uncontrolled Area. Any area to which access is not controlled for purposes of radiation protection.

Radiation Area. Any area, accessible to personnel, in which there exists radiation at such levels that a major portion of the body (whole body, head and trunk, active blood-forming organs, gonads, or eye lenses) could receive in

[1] Terms identified by an asterisk (*) have definitions identical to those in ANSI N1.1–1967 USA Standard Glossary of Terms in Nuclear Science and Technology. All other definitions are specific to this standard.

any one hour a dose equivalent, DE, in excess of 5 mRem or in any 5 consecutive days a dose equivalent, DE, in excess of 100 mRem. Each radiation area shall be conspicuously posted with a sign or signs bearing the radiation caution symbol and the words "Caution: Radiation Area."

High Radiation Area. Any area, accessible to personnel, in which there exists radiation at such levels that a major portion of the body (whole body, head and trunk, active blood-forming organs, gonads, or eye lenses) could receive in any one hour a dose equivalent, DE, in excess of 100 mRem. Each high radiation area shall be conspicuously posted with a sign or signs bearing the radiation symbol and the words "Caution: High Radiation Area."

Airborne Radioactivity Area. Any area in which airborne radioactive materials exist in concentrations in excess of the recommended concentration guides (MPC) or any area in which airborne radioactive materials exist in concentrations which, when averaged over the number of hours in any week during which individuals are in the area exceed 25 percent of the exposure guides specified in section 4.3 of this standard. Each airborne radioactivity area shall be conspicuously posted with a sign or signs bearing the radiation symbol and the words "Caution: Airborne Radioactivity Area." (Note: ANSI N2.1, Radiation Symbol.)

Toxic Material Area. Any area in which toxic materials exist such that the toxicity concentrations exceed the threshold limit values (TLV). Each toxic material area shall be conspicuously posted with a sign or signs bearing the words "Caution: Toxic Material Area."

Exclusion Area. An area defined by a qualified expert to be restricted to all personnel during operation of the accelerator.

American National Standard

Radiological Safety in the Design and Operation of Particle Accelerators

This American National Standard provides the basic considerations essential to the safe operation of a particle accelerator. It applies principally to particle accelerators with primary energies less than 100 MeV. It considers the characteristics of and controls for radiations as they affect accelerator design, operating procedures, and exposure evaluation. The section on radiation protection design criteria includes radiation shielding considerations and the use of safety systems. Operational health physics requirements are treated extensively, and radiation measurements are discussed in terms of the types of radiation that may be produced and proper techniques for monitoring. The final section, on dose assessment, includes basic exposure considerations such as maximum permissible dose and dose equivalent.

Key words: Accelerator design; accelerator operation; health physics; particle accelerators; radiation measurements; radiation protection; standard.

1. Radiation Protection Design Criteria

1.1 Radiation Shielding Considerations

1.1.1 *General Considerations*

1.1.1.1 The purpose of providing radiation shielding around a particle accelerator installation is to insure that *all* radiations from *all* sources within the radiation enclosure are attenuated to levels such that the maximum permissible dose (MPD) is not exceeded (a) for radiation workers, in controlled areas, or (b) for the general public, in uncontrolled areas. See Section ii, page , for definitions.

1.1.1.2 Radiation attenuation can be accomplished by a reasonable combination of (a) distance from the sources of radiation and (b) physical shielding barriers, provided that radiation workers or the general public are restrained from all areas in which the respective MPD could be exceeded during operation of the accelerator.

1.1.1.3 A qualified expert shall be consulted in the design of a particle accelerator installation and called upon to perform a radiation survey when the accelerator is first ready to produce radiation.

1.1.1.4 The accelerator designer should provide all possible information concerning the sources of primary and secondary radiations (as defined in section 3.1) from the specific accelerator under consideration. In the absence of sufficient information, the accelerator facility designer should assume that the radiation characteristics are the same as for equivalent or larger accelerators operating according to the same principle of operation.

1.1.1.5 The shielding design shall be based on the maximum radiation output of the accelerator, considering whichever combination of primary or secondary radiation energy, intensity, and species would require the most shielding. The possibility of operating later at higher energies and/or intensities should be anticipated in the original facility design, within reasonable extrapolations of the expected performance.

1.1.1.6 The shielding design shall also be based on continuous operation of the accelerator at maximum radiation output during an 8-hour day for 5 days per week. If it is planned that the accelerator will be in operation in excess of this period, the schedules of the associated radiation workers shall be arranged so that no worker occupies the controlled areas surrounding the accelerator facility for more than 8 hours per day, 5 days per week. Alternatively, the shielding design shall be increased so that personnel occupying the controlled and uncontrolled areas more than 8 hours per day, 5 days per week. will not receive more than the applicable MPD.

1.1.1.7 The shielding design shall conform to all applicable federal and state regulations

pertaining to the specific accelerator installation under consideration, its intended use, and its ancillary apparatus and materials.

1.2 Radiation Damage

1.2.1 Intense fluxes of ionizing radiation can cause deterioration of the characteristics (mechanical and electrical) of insulating materials, particularly plastics and certain composites of plastic and fiber. Special attention should be given to the use of radiation-resistant insulating materials, such as ceramics or mineral-oil insulated wire, where exposure to intense radiation fluxes is to be expected. If plastic materials are necessary, they should be shielded from the intense radiation. Plastic material should not be used in those regions where accumulated doses over 10 megarad can be absorbed by the material in a shorter time than the interval between periodic inspections of the accelerator facility. Polytetrafluoroethylene should not be subjected to high radiation doses.

1.2.2 Components of electrical and electronic devices used for safety that are to function in the presence of intense radiation fluxes shall be chosen for their resistance to radiation damage. Interlock switches, fire detectors, area monitors for radiation or radioactivity, ozone monitors, emergency off-switches, and similiar safety devices shall be designed into "fail-safe" circuits, so that radiation-damage effects are positively indicated. The damage may affect the mechanical or electrical integrity of the apparatus or instrument, particularly if plastic materials or solid-state devices are used. Sensitive electronic circuits may become inoperative when exposed to the intense radiation fluxes. Whenever possible, safety devices should be protected from the intense radiation. In any event, they should be periodically tested to insure that they are functioning properly in their radiation environment.

1.3 Safety Systems

1.3.1 *General Considerations*

1.3.1.1 The purpose of this section is not to design or specify safety systems required in various circumstances, but to indicate methods by which the required protection may be achieved. The recommendations are not intended to preclude alternative methods of achieving the radiation protection objectives. They may be modified upon the advice of a qualified expert.

1.3.1.2 The safety system to be provided at any particular accelerator facility will depend upon the type of accelerator, its use, and the particular details of the site. There are two main categories of accelerator facility, and these might be termed "simplex" and "multiplex." The term "simplex" would describe those accelerator facilities where the beam is available at only one target position or within one controllable space. The term "multiplex" would describe those facilities where there are more than one target position, with independently controllable space associated with each target position. The usual concept is that with simplex facilities all high radiation areas are evacuated and controlled while the beam is ON, whereas in multiplex facilities access to unused target positions is usually available while the beam is ON at some other preselected target position.

1.3.1.3 The objective of a safety system is to prevent injury or damage by radiation, and its success depends inevitably on the understanding and control of the people who will be associated with it.

1.3.1.4 Materials and workmanship utilized in the design and installation of the safety system should be of the highest grades for dependability and long life. Fully enclosed components should be used wherever practicable, and methods of actuation shall be as failureproof and tamperproof as possible.

1.3.1.5 The principle of fail-safe shall apply whenever practicable in the design and execution of safety systems. Duplication of methods or redundancy of devices should be considered when it would seem that dependability can be justifiably enhanced.

1.3.1.6 Maximum reliance should be placed on passive rather than active elements of a safety system. Where possible, wall barriers and locks should be relied upon as compared with warning lights, bells, radiation detection devices or electrical surveillance systems.

1.4 Accelerator Controls and Interlock Systems

1.4.1 Primary controls governing the production of radiation shall be capable of being secured (locked) to prevent unauthorized use.

1.4.2 The operational positioning of controls and the use of colored indicators should comply with the prevailing conventions in the electrical and electronics industries as reflected in applicable ANSI Standards and the National Electrical Code [1, 2, 3].[2]

1.4.3 Instrumentation, readouts, and controls on the accelerator control console shall be clearly identified and easily discernible.

1.4.4 Provisions shall be made in radiation control circuits for the safety interlocks and warning systems. These provisions should not be dependent upon the operation of a single circuit and should be designed so the specific inter-

[2] Figures in brackets indicate the literature references at the end of this Handbook.

lock triggering an alarm condition is readily identifiable.

1.4.5 When an interlock system has been tripped, it shall only be possible to resume operation of the accelerator by manually resetting controls at the position where the interlock has been tripped, and lastly at the main control console.

1.4.6 All entrances into a target room or exclusion area shall be provided with interlock systems.

1.4.7 A scram switch, pull-chain, or other emergency power cutoff switch, shall be located within easy reach, and be easily identifiable, in exclusion areas. Such a cutoff switch shall have positive indication as to the operative position of the switch, and shall include, at the same location, a manual reset, so that the accelerator cannot be restarted from the accelerator control console without manually resetting the cutoff switch. (See paragraph 1.4.5.)

1.5 Warning Devices

1.5.1 All locations designated as high radiation areas, and entrances to such locations, shall be equipped with easily observable flashing or rotating purple warning lights that operate automatically when, and only when, radiation is being produced. Lights of a different color shall be used for other visual indicators when they are required. Redundancy shall be built into the system such that an alarm will sound in the event radiation is produced and the warning light has malfunctioned.

1.5.2 The purple color of the warning lights shall be in accord with ANSI Z53.1.1967, Safety Color Code for Marking Physical Hazards.

1.5.3 Barriers, temporary or otherwise, and pathways leading to high radiation areas, shall be identified in general accord with ANSI Z53.1.1967.

1.5.4 In a large facility audible warnings shall be given prior to startup of the accelerator. Horns or buzzers should be located in areas with readily accessible scram switches (see also section 2.6.4). There shall be no possibility of confusion between the tone and characteristics of these audible systems and the Immediate Evacuation Signal. The audible warning should have a duration such that a person's attention would be attracted above ambient noise, and that he would have time to reach a scram switch or to safely evacuate the space. In a small facility a public address (P.A.) system may satisfy the above requirement.

1.5.5 Continuous radiation monitoring devices should be operating in or adjacent to high radiation areas, or in other areas where radiation intensity may increase with the operational level of the accelerator. Such monitoring devices shall provide an audible warning to personnel in the vicinity when preset levels are exceeded.

1.5.6 The conditions under which immediate evacuation is required are not specified herein. However, it is assumed that evacuation alarms would be provided in general accord with ANSI N2.3, "USA Standard—Immediate Evacuation Signal For Use In Industrial Installations Where Radiation Exposure May Occur."

1.6 Reliability Tests

1.6.1 All safety and warning devices including interlocks shall be serviced and checked for proper functioning at intervals not to exceed six months.

2. Operational Health Physics

2.1 General Considerations

2.1.1 The responsibility for the protection of the worker and environment in its broadest sense rests with management.

2.1.2 A radiation safety program shall be developed in accordance with federal and state regulations.

2.1.3 ANSI standards and recommendations of authoritative bodies such as the Federal Radiation Council (FRC), The National Council on Radiation Protection and Measurements (NCRP), and the International Commission on Radiological Protection (ICRP) should be considered, as appropriate, in the development of a radiation safety program.

2.1.4 Cognizant personnel should be kept informed of new technological developments in radiation safety equipment and instrumentation as well as the most recent recommendations of the FRC, NCRP, ICRP, and ANSI.

2.2 Radiation Safety Organization and Responsibility

2.2.1 When implementing a radiation protection program, management shall appoint a radiation control officer and, if appropriate, a radiation safety committee.

2.2.2 The qualifications of the radiation control officer should be determined by the technical requirements dictated by the work as well as the complexity and size of the operations, and shall include a basic understanding of radiation protection principles.

2.2.3 As a minimum requirement, the services of a qualified expert shall be obtained dur-

ing the early planning stages or engineering phase of any new accelerator.

2.2.4 The radiation control officer shall develop and promulgate an effective radiation protection program, consistent with appropriate federal, state, and local regulations. He shall advise management and accelerator operators on all matters pertaining to radiation safety.

2.2.5 The accelerator operator shall be responsible for all operations connected with the accelerator, including radiation safety. The radiation control officer shall have the authority to cease operations when necessitated by radiation safety considerations.

2.3 Radiation Safety Procedures

2.3.1 Written operating and emergency procedures pertaining to radiation safety shall be developed and reviewed periodically by a qualified expert or radiation control officer for each accelerator facility and approved by the accelerator operator and management.

2.3.2 Operators and other appropriate personnel shall be familiar with and be given a copy of the written operating and emergency procedures pertaining to radiation safety. In addition, such procedures should be posted near the accelerator control console and other areas as appropriate.

2.3.3 Operators and other appropriate personnel shall be responsible for: (1) keeping occupational exposure to radiation as low as practicable; (2) wearing personal radiation dosimeters in the prescribed manner; (3) following radiation safety rules and regulations; (4) reporting radiation accidents, incidents, and unsafe working conditions; and (5) keeping a written log of interlock shutdowns or other indications of hazardous radiation conditions.

2.3.4 Unescorted access to radiation areas should be limited to personnel directly concerned with the operation and maintenance of the facility, experimental or production work, and radiation safety.

2.3.5 Procedures for control of radioactive materials shall be established by the radiation control officer.

2.4 Personnel Monitoring Requirements

2.4.1 The radiation control officer or his designated alternate shall supply appropriate personnel monitoring devices and shall require the use of such devices by:

2.4.1.1 Each individual who is likely to receive a dose equivalent, DE, in any calendar quarter in excess of 25 percent of the MPD specified in section 4.3 of this standard.

2.4.1.2 Each individual under 18 years of age who is likely to receive a dose equivalent, DE, in any calendar quarter in excess of 60 mRem.

2.4.1.3 Each individual who enters a high radiation area.

2.4.2 Appropriate personnel monitoring devices are devices designed to be worn or carried by an individual for the purpose of measuring the dose equivalent, DE. Examples of such devices are film badges, pocket ionization chambers, thermoluminescent dosimeters, chemical dosimeters, activation foils, photoluminescent devices, fission track recorders, etc.

2.4.3 The devices employed shall be capable of providing estimates of the dose equivalent, DE, received by the wearer, including a separation of the dose equivalent received in a mixed radiation field into its component parts, i.e., beta, gamma, x ray, thermal neutron, fast neutron, etc.

2.4.4 The personal monitoring devices employing film shall be capable of providing an estimate of the dose equivalent within those limits suggested by the National Sanitation Foundation or Pacific Northwest Laboratory [4, 5].

2.4.5 Periodic calibration of personnel monitoring devices shall be performed according to section 3.6 of this standard, preferably in a radiation field of composition similar to that to which the person may be exposed.

2.5 Area Monitoring Requirements

2.5.1 Before a new installation is placed in routine operation, a radiation protection survey shall be made by a qualified expert.

2.5.2 A radiation protection survey shall be performed and documented when changes have been made in shielding, operation, equipment, or occupancy of adjacent areas, and periodically to check for unknown changes and malfunctioning equipment.

2.5.3 Radiation levels in all radiation areas (see definition of areas) shall be determined and recorded during each operating shift in accordance with the requirements specified in section 3.4.4 of this standard. Results of these surveys shall be related to operating and targeting conditions where possible and shall be made easily available to personnel.

2.5.4 Radiation levels in all high radiation areas should be continuously monitored. The monitoring devices shall be capable of providing a remote and local readout with visual and audible alarms at both the control panel and monitoring locations. The monitoring device

should be equipped with a bright purple rotating light visible to any personnel entering the area.

2.5.5 Radiation levels in all exclusion areas should be continuously monitored. The monitoring devices shall be capable of providing a remote readout at the control panel and shall be interlocked at all entrances to the areas such that unsafe entry is rendered impossible during operation.

2.5.6 Periodic surveys should be made to determine the amount of airborne particulate radioactivity present in areas of airborne hazards.

2.5.7 An inventory of toxic materials in use at the facility shall be maintained, and a periodic survey should be made to ascertain that in using such materials the Threshold Limit Values of the American Conference of Governmental Industrial Hygienists [6] are not exceeded.

2.5.8 All area surveys shall be made in accordance with the written procedures established by a qualified expert or the radiation control officer of the facility and should include those items listed in section 3.4.4 of this standard.

2.5.9 In special cases, area monitoring shall include monitoring for surface contamination as follows:

2.5.9.1 Periodic smear surveys shall be made to determine the degree of contamination, especially in target and scattering chamber areas. As a preliminary estimate, a smear should be made by wiping an area of about 1 ft^2 with an absorbent material and counting the material with a suitable survey meter probe.

2.5.9.2 Should contamination be indicated by the method noted in 2.5.9.1 above, then additional surveys shall be made to determine the amount of removable contamination.

- Whenever feasible, the isotopic composition of the contaminant should be determined.
- A smear should be made by firmly rubbing a 100 cm^2 area of the surface with a slightly dampened piece of absorbent material. The smear should be counted on a laboratory type instrument and reported in $d/m/100\ cm^2$.

2.5.9.3 Areas of high contamination probability shall have the proper safeguards to minimize any spread of contamination. This may include positive ventilation, hoods, protective clothing, hand and foot monitors, proper work surfaces, etc.

2.5.9.4 Decontamination should be performed for worker protection and to minimize the spread of contamination to other areas of the facility.

2.6 Systems

2.6.1 *Ventilation Systems*

2.6.1.1 Air exposed to any form of ionizing radiation (γ rays, x rays, electrons, protons, etc.) will form toxic gases, mainly ozone. If the energy is sufficiently high radioactive gases can be formed. Both of these situations shall require adequate control of ventilation.

2.6.1.2 Provisions shall be made for adequate ventilation of irradiated areas where exposures to airborne radioactivity are expected to exceed the MPC or whole body dose equivalents greater than the MPD.

2.6.1.3 The air vented from irradiated areas shall be dispersed in the atmosphere in a manner to meet existing state, local, and federal air pollution laws. In particular, dispersion should be planned to eliminate the possibility of the exhaust air being immediately drawn into neighboring air intakes.

2.6.2 *Waste Disposal Systems*

2.6.2.1 Materials may become radioactive if exposed to high energy (greater than $\approx$ 8 MeV) photons or electrons, and neutrons or charged particles of any energy. If such material is considered waste, it should be treated as radioactive waste according to the requirements of appropriate state and federal regulations.

2.6.3 *Radioactive Materials Handling Systems*

2.6.3.1 Materials which are heavily irradiated may become highly radioactive, especially targets, windows, collimators, etc. If it is necessary to handle these for replacement or repair purposes, control of exposure may require such techniques as shielding or remote handling. For most accelerator components, the radioactivity levels decay rapidly after the accelerator is turned off and handling problems can be decreased considerably by allowing a 24-hour decay period before work proceeds. Procedures for machining, welding, or cutting of radioactive materials should be reviewed by a qualified expert to avoid problems of ingestion or inhalation of particulate or gaseous radioactive materials and to prevent the spread of contamination.

2.6.4 *Interlock and Warning Systems*

2.6.4.1 Particle accelerators shall be secured when not in operation to prevent unauthorized use.

2.6.4.2 A continuous radiation monitoring system shall be operational and located in proximity to the accelerators with associated readout and preset alarm devices located within the machine area, and at the control console.

2.6.4.3 A control switch on the accelerator control console shall be used to turn the accelerator beam on and off. The safety interlock system shall not be used to turn off the accelerator beam except in an emergency. If the interlock system turns off the accelerator, it shall not be possible to resume operation without resetting the accelerator "ON" switch at the control console.

2.6.4.4 All safety and warning devices, including interlocks, shall be checked for proper operability at intervals not to exceed 6 months.

2.6.4.5 If, for any reason, it is necessary to intentionally bypass a safety interlock or interlocks, such action shall be: (1) authorized by the accelerator operator and radiation control officer on each shift, (2) recorded in a maintenance log or other record and posted at the accelerator control console; and (3) terminated as soon as possible.

2.7 Education and Training

2.7.1 Operating personnel shall (1) receive appropriate radiation safety training; and (2) demonstrate competence to use the accelerator, related equipment, and radiation survey instruments.

2.7.2 Training should include but not be limited to the following:

2.7.2.1 *Fundamentals of Radiation Safety:*

- Characteristics of particulate and electromagnetic radiation.
- Units of radiation dose and quantity of radioactivity.
- Biological hazards of exposure to radiation.
- Measurement of radiation.
- Methods of controlling radiation dose.
- Radiation safety procedure, interlock systems, and warning systems.

2.7.2.2 *Fundamentals of Radiation* **Detection:**

- Use of radiation survey instruments.
- Survey techniques.
- Use of personnel monitoring equipment.

2.7.2.3 *Equipment:*

- Operation and control of accelerator equipment.
- Remote handling equipment.
- Handling of activated materials.
- Use of shielding.

2.8 Record Keeping

2.8.1 Records shall be kept concerning individual radiation exposures. These records shall include, as appropriate, results from individually worn dosimeters, calculated results, bioassay, and whole body counting data.

2.8.2 The guidance provided in ANSI N2.2–1966, "American Standard Practice for Occupational Radiation Exposure Records Systems" shall apply for the purposes of this standard.

2.8.3 Up to date interlock system circuit diagrams shall be maintained.

3. Radiation Measurements

3.1 Prompt Radiation— (Primary and Secondary)

3.1.1 Operation of any accelerator will result in radiation called "prompt" radiation to distinguish it from that due to induced radioactivity. Prompt radiation, which by definition stops as soon as the accelerator is turned off, is subdivided into two categories—Primary and Secondary. Exposure to both primary and secondary radiation shall be governed by pertinent state or government regulations. Useful data has been developed by national authorities [7, 8, 9].

3.1.2 Primary radiation may be comprised of electrons, protons, alpha particles, or other heavy particles. In the case of machines having the primary function of generating x rays, the bremsstrahlung produced would be considered the primary radiation. Neutrons resulting from (d,t) or (d,d) reactions should not be considered primary radiation even though their production is the primary purpose of this type of accelerator. In general, the primary radiation is accelerated in a vacuum chamber and is not a hazard until it is brought out into the air. Characteristically, an accelerator beam is fairly well-collimated and travels in a straight line unless deflected by a magnet. Primary radiation fields are usually extremely high intensity but of limited area. The major concern is to prevent exposure of personnel to these beams since even a momentary exposure can cause severe injury or death. When the beam strikes a solid object, e.g., a target, a target holder, or beam stopper, many of the particles

may scatter, even in the backward direction. This is especially true of electrons. Any area traversed by the beam, including the target area, shall be defined as an exclusion area while the beam is on.

3.1.3 Secondary radiation is produced by the interaction of the primary beam with matter. The secondary radiation is usually either bremsstrahlung (x rays) or neutrons. Often the secondary radiation may be the product of interest for the accelerator, e.g., x rays from electron accelerators (except x-ray machines) or neutrons from (d,t) or (d,d) generators.

3.1.3.1 Bremsstrahlung is produced mostly by electrons and is usually negligible for heavy particle accelerators. Bremsstrahlung production is minimized by stopping electrons in materials of low atomic number, e.g., aluminum, water, or concrete. It is absorbed most efficiently by materials of high atomic number such as iron, copper, or lead.

3.1.3.2 Neutrons are usually generated in all directions with a high energy component in the forward direction, which becomes more important as the accelerator energy increases. Neutrons are stopped most efficiently by materials containing hydrogen; concrete, water, and earth are most frequently used. Where space or weight are at a premium, polyethylene with an outer lining of cadmium, or polyethylene loaded with boron are frequently used. Neutrons involve special monitoring considerations as described in section 3.4.

3.2 Induced Radioactivity

3.2.1 High levels of radioactivity may be induced in target materials that are irradiated by a beam of primary radiation, to an extent that depends on the primary-radiation energy and intensity. Many of the nuclear reactions that can cause induced radioactivity may also yield secondary radiations which, in turn, may induce significant levels of radioactivity in the target and in materials near the secondary-radiation source, such as structural walls, experimental apparatus, or the atmosphere. In the context of this section, the target of the primary radiation may lie anywhere along the trajectory of the particle beam, including acceleration-tube electrodes and insulators, cyclotron dees, tandem-accelerator stripper canal or foil holder, beam collimators, beam stops, or beam-tube piping.

3.2.2 The following table categorizes the many kinds of accelerated particles (or primary radiations) according to their propensity for inducing radioactivity, either directly or through their secondary radiations:

Table 1.

Particle	Energy range	Induced radioactivity in	
		Target	Vicinity
Electrons	below 1.67 MeV	none	none
Electrons	1.67 to 10 MeV	limited	very slight
Electrons	above 10 MeV	probable	suspect
Protons, Helium ions	below 1 MeV	limited	none
Protons, Helium ions	1 to 10 MeV	limited	suspect
Deuterons, tritons	any energy	limited	suspect
All ions of light atomic weight	above 10 MeV	probable	suspect

At energies below 1 MeV, deuteron-initiated nuclear reactions are limited to the following: D (d,n) ^{3}He, T (d,n) ^{4}He, ^{9}Be (d,n) ^{10}B, ^{12}C (d,n) ^{13}N. Except for ^{13}N, all residual nuclei are stable. At any deuteron energy, however, there is the probability that deuterium will be driven into the target material thus causing neutrons to be produced from the D (d,n) ^{3}He reaction. The problem of accelerated tritium ions is discussed in section 3.3.1.5 because its inherent radioactivity causes contamination in the accelerator system.

The photodisintegration of deuterium (threshold = 2.20 MeV), beryllium (threshold = 1.67 MeV), and uranium (threshold = 6 MeV) yield neutrons of sufficient intensity that radioactivity may be induced in materials near the source of neutrons. Representative photodisintegration reactions of other materials having thresholds below 10 MeV are listed below. All are (γ,n) reactions.

TABLE 2.

Target	Threshold energy	Half-life
	MeV	
^{197}Au	8.0	5.6 d
^{181}Ta	7.7	8.0 h
^{141}Pr	9.4	3.6 m
^{121}Sb	9.2	17.0 m
^{107}Ag	9.5	24.5 m
^{82}Se	9.8	17.0 m
^{70}Zn	9.2	52.0 m

At electron energies less than 10 MeV, these reactions do not in general produce neutrons with sufficient intensity to induce radioactivity.

3.3 Other Radiations and Radioactivity

3.3.1 Primary and secondary radiations, as defined in section 3.1, are associated with the fully accelerated particle beam of a particular accelerator. There are other primary and secondary radiations that are generated by ancillary apparatus of the more complex accelerators.

3.3.1.1 *Accelerator Injectors:* In certain types of cyclotrons, electron linear accelerators, tandem-type accelerators, etc., the particle beam accepted by the main accelerator system is formed and preaccelerated in a separate apparatus. The injector usually produces its own primary and secondary radiations. In some cases, the injector is tuned locally before the entire accelerator is put into operation. Personnel must therefore be protected from these relatively low-energy radiations.

3.3.1.2 *Klystrons:* These microwave power amplifiers are utilized predominantly in connection with electron linear accelerators. Since they operate with their own electron-accelerating voltages of several hundred keV, the x rays that are consequently generated must be adequately contained, so that operating and maintenance personnel are not subjected to excessive radiation levels. In effect, klystrons are low-voltage x-ray generators, and they must be treated as such in any protective design and procedure. Microwave power is not necessary for the production of x rays.

3.3.1.3 *Transformer-Rectifier Power Supplies:* DC power supplies attached to high vacuum devices such as hard tube rectifiers, vacuum switches, etc., are sources of x rays. In general, transformer-rectifier sets are immersed in oil or in gas-pressurized tanks during operation. Care must be taken, however, to assure that the radiations from these power supplies are adequately attenuated, so that operating and maintenance personnel are not excessively exposed to the radiations.

3.3.1.4 *Secondary Radiations from DC Accelerators:* In addition to the secondary radiations from the formally established target or beam stop of a dc accelerator, there are other regions where the primary radiation strikes intentionally and must be considered in any facility design because of the secondary radiations that are generated from that locality. A prime example is the midterminal of a tandem-type accelerator, in which a charge-change gas or foil is situated to change the accelerated ion from negative to positive charge state "in flight." A small percentage of the ions accelerated to the midterminal falls outside the limit of the charge-change system. With sufficient ion energy, neutrons can be produced from nuclear reactions between these ions and the stripper material (a special target-material case). Along with the negative ions, electrons can also be accelerated by the same electrostatic fields. On impingement with the midterminal components, these electrons can produce bremsstrahlung x rays.

In a single-stage or tandem-type dc ion accelerator there is a distinct possibility that electrons will be accelerated in the reverse direction to the ion propagation. These electrons are released from the residual gas inside the acceleration tube or from the electrode structure by ion bombardment. As a consequence, the high-voltage terminal becomes a source of bremsstrahlung from the backward-directed electrons. Modern acceleration-tube designs tend to greatly reduce this secondary electron flow in intensity and energy.

3.3.1.5 *Tritium and Other Radioactive Materials:* Radioactive materials are occasionally used as targets in nuclear research. Tritium is of special interest because of its wide use, its gaseous nature, and its low energy beta activity. Tritium is used in accelerators, not only as a target material but also as an accelerated particle. Procedures must be adopted to insure that gases evacuated from the region in which the tritium is present are adequately trapped and contained. Pump oil in both diffusion and backing pumps must be carefully monitored for absorbed or assimilated tritium. Beam-tube piping must be similarly monitored when changes in the accelerator system are contemplated.

The acceleration of tritium ions imposes additional procedures for the safety of associated personnel. All portions of the accelerator system that have been exposed to tritium must be carefully monitored for tritium contamination. In certain cases, even meticulous smear tests are not adequate to determine the presence of absorbed or assimilated tritium. For example, the organic seals of some dc acceleration tubes can retain tritium without detection by conventional tests. Only after the tube has

been elevated in temperature is there a significant evolution of tritium. In general, therefore, ion sources, gas bottles, acceleration tubes, vacuum pumps, and similar components exposed to tritium ions should be considered as radioactive waste-disposal materials after their useful life.

3.4 Instrumentation and Radiation Measurement Techniques

3.4.1 Instrumentation requirements [7, 8, 9] will vary with the size, complexity, and versatility of the accelerator. However, the following capabilities must be available at any installation:

3.4.1.1 Measuring ability to determine if any area is safe to enter or occupy.

3.4.1.2 Measuring ability to show that the dose equivalent received by nonradiation workers in uncontrolled areas does not exceed the MPD for the general public.

3.4.1.3 Measuring ability to show that personnel in occupied areas are not exposed to excessive radiation levels due to incorrect or unusual accelerator operation.

3.4.2 Radiation due to induced activity can be measured with GM counters, scintillation counters, or ionization chambers. The measurement of prompt radiation requires special measuring techniques, especially the prompt radiation from pulsed accelerators. The advice of a qualified expert should be sought for measurements around pulsed accelerators.

3.4.3 Neutron monitoring is much more complicated and has no single, simple instrumental solution; and because of its complexities, the advice of a qualified expert shall be sought. Generally three different approaches are found to be acceptable. These are:

3.4.3.1 The use of a tissue equivalent ionization chamber to measure total absorbed dose in rads. The dose obtained is multiplied by a Quality Factor of 10 to obtain a safe overestimate of dose equivalent. [10, 11, 12, 13].

3.4.3.2 The use of various methods to obtain a neutron energy spectrum and assessment of total flux, and from these the calculation of the dose equivalent in rems [11, 13, 14].

3.4.3.3 The measurement of neutron dose equivalent with one of various instruments designed to measure dose in rems. Care must be taken to insure that the instrument responds correctly for the accelerator pulse width and duty cycle and is not affected by other types of radiation present [11, 13, 15].

3.4.4 The radiation measurements should be recorded and include:

3.4.4.1 Date and time of survey.

3.4.4.2 Beam particle energy and beam current.

3.4.4.3 Type of target.

3.4.4.4 Location of collimator and magnets.

3.4.4.5 Purpose of survey, radiation detector used.

3.4.4.6 Where the survey was performed.

3.4.4.7 Results and recommendations.

3.4.4.8 Person or persons performing the survey.

3.5 Airborne Radioactivity Monitoring Including Toxic Gas Detection

3.5.1 Monitoring methods [16, 17] used for the detection of radioactive gases or particulates shall be sensitive enough to detect the concentrations permissible for occupational and nonoccupational exposure as contained in NBS Handbook 69 (Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and Water for Occupational Exposure).

3.5.2 Monitoring methods used for the detection of toxic gases [17], such as ozone, shall be sensitive enough to detect the threshold limit value or concentration recommended for occupational exposure by the American Conference of Governmental Industrial Hygienists [6].

3.6 Test, Calibration, and Maintenance

3.6.1 Each radiation survey instrument shall be calibrated at intervals not to exceed three months, and after each servicing and repair.

3.6.2. Each quarterly calibration shall include a determination of the response of the radiation survey instrument or detector as a function of the total exposure or the rate of exposure to the radiation which it is designed to detect.

3.6.3 A record of the results of the last calibration shall be maintained. The date of calibration should be indicated on the instruments.

3.6.4 Performance data on the following items shall be available for each type of radiation survey instrument and detector:

3.6.4.1 Angular response.

3.6.4.2 Energy response.

3.6.4.3 Response as a function of the rate of radiation exposure or as a function of the total exposure.

3.6.4.4 Response to radiations other than the type the instrument is designed to detect.

3.6.4.5 Response to changes in temperature and atmospheric pressure.

3.6.5 Pocket ionization chambers shall be calibrated and checked for leakage at intervals not to exceed one year, and after each servicing and repair.

3.6.6 Daily or weekly operational checks of instrument and detector function shall be made for those instruments in regular or continuous use.

3.6.7 Calibrated and operable radiation survey detectors shall be available during operation and shut-down periods of the accelerator.

3.6.8 Personnel monitoring film calibration and interpretation procedures shall provide limits of accuracy and precision at least the equivalent to those recommended by the National Sanitation Foundation or Pacific Northwest Laboratory, Battelle Memorial Institute [4, 5].

4. Dose Assessment

4.1 General Considerations

4.1.1 The primary objective in establishing Maximum Permissible Dose Guides (MPD) for occupational workers is to insure that exposures are kept well below a level at which adverse somatic and/or genetic effects are likely to result. Thus, MPD values have been specified by national and international authorities [18, 19] and shall be followed during work associated with the operations of a particle accelerator.

4.1.2 Authorities [18, 19] make the cautious assumption that any radiation exposure may carry some risk. Therefore, in assessing the anticipated biological dose from a particular job function, the concept of "benefit versus risk" should be considered. Benefits to be derived from the work should be weighed against the radiation dose to be received.

4.1.3 This standard recognizes that small transient deviations in individuals' exposures above the recommended maximum permissible values are biologically insignificant; however, they should be regarded as indices of poor radiation protection practices.

4.1.4 Methods, assumptions, and recommendations developed by the national and international authorities [18, 19, 20] shall be considered in the context of this standard.

4.2 Basic Exposure Considerations

4.2.1 An assessment of the dose shall involve considering: (a) the accumulated absorbed dose, (b) the dose-rate, (c) the fraction or region of the body exposed, (d) penetrating power, and (e) linear energy transfer dependent factor (Quality Factor).

4.2.2 When it is known that the radiation field is entirely electromagnetic in character a Quality Factor (QF) of 1 should be used in assessing the Dose Equivalent (DE). In the absence of information concerning the energy distribution associated with other radiation, a conservative Quality Factor should be used in assessing the Dose Equivalent (DE). In the absence of information concerning the energy distribution associated with other radiation, a conservative Quality Factor should be used in assessing the Dose Equivalent (DE).

4.2.3 Methods of estimating dose equivalent to organs of interest shall be consistent with assumptions and recommendations of the National Council on Radiation Protection and Measurements (NCRP) and International Commission on Radiological Protection (ICRP).

4.2.4 The incremental dose equivalent values shall be summed for all types of exposures.

4.3 Maximum Permissible Dose (MPD)

4.3.1 The MPD is defined as the amount of ionizing radiation which carries an acceptably low probability (risk) of causing biological damage to a person during his lifetime. The MPD values specified herein have been established by international authorities and shall be followed. The dose equivalent values do not apply to diagnostic or therapeutic exposures.

4.3.2 The DE values specified for Occupational Workers (table 3) apply to individuals over age 18. Individuals under age 18 shall not exceed the MPD specified for Individuals and Population Groups (note section 4.3.4).

4.3.3 The total dose equivalent for Occupational Workers at any age past 18 shall not exceed 5 (N–18) rems where N is the age in years.

TABLE 3. *Maximum Permissible Dose Equivalent—Occupational Workers*

	Quarter (rem)	Year (rem)
Whole body, head and trunk, active blood forming organs, gonads, or lens of eye	3	5(N–18)
Skin, thyroid, and bone	10	30
Hands, ankles, forearms, and feet	25	75
Other organs	4	15

4.3.4 The annual dose equivalent for members of the public shall be limited to one-tenth of the corresponding annual DE for Occupational Workers noted in section 4.3.3 above. The annual whole body dose restriction for the public is given as 0.5 rem.

4.3.5 For operational purposes the dose equivalent received by individuals in uncontrolled areas shall not exceed 2 mRem in any 7 consecutive days or 500 mRem in any year.

4.4 Methods

4.4.1 For purposes of radiation protection the dose shall be determined using the quantity DE (Dose Equivalent). DE is defined [23] as the product of absorbed dose (d), quality factor QF, dose distribution factor (DF), and other factors as appropriate, or

$$DE = d\ (QF)\ (DF)\ \ldots$$

The unit of Dose Equivalent is the rem.

4.4.2 The Quality Factor in the above formula is the LET dependent factor by which absorbed doses are multiplied to obtain a quantity that expresses on a common scale the effect of all ionizing radiation. The QF's to be used for determining neutron and/or proton exposures from known energies are provided in column C of table 4.

4.4.3 If it is more convenient to assess the neutron component of the dose in neutrons/cm^2 rather than rads and where the energy spectrum is known, column B of table 4 may be used to assess the dose by relating Flux to Dose in rem as a function of neutron energy.

4.5 Dose Restrictions (Female Occupational Workers)

4.5.1 Exposures to women of reproductive capacity should be limited to 1.3 rem/quarter and 5 rems/year. It is expected that under these conditions the dose to the embryo during the first two months of pregnancy would be less than 1 rem which is considered an acceptable dose [18].

4.5.2 In those cases where pregnancy has been diagnosed and the exposure involves penetrating radiation, the exposure to the woman should be such that the dose to her fetus during the remaining period of her pregnancy does not exceed 1 rem.

4.5.3 In those cases where the abdomen is protected from or not exposed to radiation and where the fetal dose is estimated to be considerably less than that received by the woman, protection is considered adequate and exposures may be received at a rate not exceeding 1.3 rem/13 weeks.

TABLE 4. *Neutron flux density—dose equivalent conversion factors and maximum quality factors*

Column A	Column B	Column C
Neutron energy	Flux density equivalent to 1 millirem hr^{-1}	(QF)* max
(MeV)	*(n cm^{-2} sec^{-1})*	
2.5×10^{-8}	268	3
5	260	2.9
1 10^{-7}	250	2.8
2	242	2.7
5	233	2.6
1 10^{-6}	227	2.5
2	221	2.5
5	214	2.4
1 10^{-5}	210	2.3
2	206	2.2
5	202	2.1
1 10^{-4}	200	2
2	201	2
5	215	2.1
1 10^{-3}	222	2.2
2	235	2.3
5	228	2.7
1 10^{-2}	162	3.6
2	110	5.1
5	57	6.8
1 10^{-1}	36.5	8
2	21	9.2
5	12.2	10.3
1 10^{0}	9.2	10.3
2	8.7	8.8
5	7.2	7.5
1 10^{1}	6.8	6.7
2	6.4	5.9
5	5.8	5
1 10^{2}	5.5	4.4
2	5.1	3.7
5	4.5	3
1 10^{3}	4.1	2.4
2	3.8	1.9

*A QF of one (1) should be used for x and gamma radiation. A QF of 20 should be used for heavy recoil nuclei, for recoil fission fragments, and heavy particles from accelerators.

5. References

[1] *Marking Physical Hazards and the Identification of Certain Equipment* (Safety Color Code), ANSI, Z53.1–1967.

[2] *Electrical Safety Guides for Research*, U.S. Atomic Energy Commission, Kelly, John P. H., Sr., *et al.*, December 1967.

[3] *National Electrical Codes* (NFPA 70 1965), ANSI Standard C1.

[4] *The National Sanitation Foundation Standard #16*, Film Badge Services, May 4, 1966.

[5] *The Establishment and Utilization of Film Dosimeter Performance Criteria*, Unruh, C. M., *et al.*, BNWL–542, September 1967.

[6] *Threshold Limit Values*, 1968, American Conference of Governmental Industrial Hygienists.

[7] *Shielding for High Energy Electron Accelerator Installation*, Nat. Bur. Stand. Handb. 97 (July 1964).

[8] *Protection Against Betatron Synchrotron Radiation up to 100 Million Electron Volts*, Nat. Bur. Stand. Handb. 55, (Feb. 1954).

[9] *Medical X-ray and Gamma Ray Protection for Energies up to 10 MeV*, National Council on Radiation Protection Report No. 33, February 1968.

[10] *Measurement of Absorbed Dose of Neutrons and of Mixtures of Neutrons and Gamma Rays*, Nat. Bur. Stand. Handb. 75 (NCRP Report No. 25) February 1961.

[11] *Neutron Dosimetry*, Proceedings of Symposium on Neutron Detection Dosimetry and Standardization, International Atomic Energy Agency, Harwell, England, 1962.

[12] *Radiation Dosimetry for Protection Purposes Near High Energy Particle Accelerators*, Baarli, J., and Sullivan, A. H., Health Physics Journal, Vol. II, p. 353, May 1965.

[13] *Neutron Monitoring, Proceedings of Symposium on Neutron Monitoring for Radiological Protection Purposes*, International Atomic Energy Agency, Vienna, 1967.

[14] *Proceedings of the First Symposium on Accelerator Radiation Dosimetry and Experience*, U.S. Atomic Energy Commission Conf. No. 651109, available from the Clearinghouse for Federal Scientific and Technical Information, National Bureau of Standards, U.S. Department of Commerce, Springfield, Virginia 22151.

[15] *New Methods of Measuring Neutron Dose Equivalent Rates Around Pulsed Neutron Generators*, Leake, J. W., AERE–R–4883, 1965.

[16] *Radiation Hygiene Handbook*, Blatz, Hanson, McGraw-Hill Book Company, New York, 1959.

[17] *Air Sampling Instruments*, American Conference of Governmental Industrial Hygienists, 1967.

[18] *Radiation Protection*, International Commission on Radiological Protection (ICRP Publication 9) adopted September 17, 1965, First Edition 1966.

[19] *Dose Effect Modifying Factors in Radiation Protection* (Report of Subcommittee M–4–RBE), the National Council on Radiation Protection, BNL 50073 (T–471) August 1967.

[20] *Protection Against Electromagnetic Radiation above 3 MeV and Electrons, Neutrons and Protons* (ICRP Publication No. 4) 1964.

[21] *Biological Interpretation of Dose from Accelerator Produced Radiation*, Proceedings of the First International Symposium, U.S. Atomic Energy Commission Conf. No. 670305, available from the Clearinghouse for Federal Scientific and Technical Information, National Bureau of Standards, U.S. Department of Commerce, Springfield, Virginia 22151.

[22] *Particle Accelerators*, Livingston, M. S., and Blewett, J. P., McGraw-Hill Book Company, New York, 1962.

[23] *Radiation Quantities and Units*, International Commission on Radiological Units and Measurements (ICRU) Report 11, 1968.

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