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**Radiation Safety for the Design
and Operation of Particle Accelerators**

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American National Standards Institute, Inc.



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Preface

The previous ANSI N43.1 standard was published for use in December 1969 and covered mainly technical aspects with a stipulation that the standard applied principally to accelerators with energies less than 100 MeV. In 1974, a review of the standard was conducted that resulted in changes (principally dosimetric quantities) and a revised standard that was approved in July 1978. Currently, accelerators exist in a variety of types, sizes, power capabilities, operational modes, and applications. Therefore, accelerators can vary widely in their radiation hazard producing capacity and diversity, and the hazard analysis and control are more complex and challenging. The regulatory environment is also more demanding.

This new N43.1 standard is developed to address the hazards and controls for accelerators in the current technical, operational, and regulatory environment. The goal is to provide a consistent and sound radiation protection framework for accelerator community.

The new N43.1 standard has the following major new elements and/or changes:

1. It covers most fixed, non-medical accelerators, encompassing most particle types and energies.
2. It covers all phases of the accelerator facility (the life-cycle approach).
3. It addresses both technical and management aspects of the radiation safety program.
4. It sets requirements and recommends good practices for the protection of workers, the public, and the environment.
5. It takes a graded approach for the hazard control that is commensurate with the risk levels.
6. It addresses the subjects of engineered and/or interlocked safety systems for prompt radiation and accelerator operations in more detail.

Radiation Safety for the Design and Operation of Particle Accelerators

1.0 Purpose, Scope, and Introduction

1.1 Purpose

This standard sets forth accelerator facility ionizing radiation safety requirements for workers, public, and the environment produced during and from accelerator operations. This standard also recommends good practices that provide a level of radiation protection consistent with those established across the accelerator community.

1.2 Scope

This standard applies to all phases of the accelerator facility's life cycle, including design, installation, commissioning, operation, maintenance, upgrade, and decommissioning. This standard specifies requirements and recommendations for radiation safety program management and technical aspects.

This standard is suitable for all accelerator facilities using electron, positron, proton, or ion particles capable of producing ionizing radiation hazards. However, accelerators used within a formalized medical setting directly for diagnosis and/or therapy, such as medical accelerators used for radiotherapy and radio-diagnosis in hospitals, are not covered by this standard.

Accelerator facilities covered by this standard include, but are not limited to, the following accelerator systems:

- Small table-top accelerators
- Radiography machines > 1 MeV (inspection systems for security, contraband, etc.)
- Industrial accelerators (ion implanters, electron beam welders, medical sterilization accelerators, etc.)
- Accelerators such as cyclotrons producing radioisotopes for medical or non-medical uses
- Facilities manufacturing and testing medical or industrial accelerators

- Multi-use facilities that use accelerators for both medical and non-medical purposes (sub-facilities used only for medical purposes are excluded)
- Van de Graaff and other DC-type accelerators
- Pulse beam machines providing high peak currents at low duty factors
- Large, high-dose-rate R&D machines
- Synchrotron light and free electron laser (FEL) facilities
- Heavy ion accelerators

1.3 Introduction

Accelerators of varying types and sizes have different power capabilities, operational modes, and/or applications and can vary widely in their potential to pose a hazard. Therefore, this standard takes a graded approach and sets forth requirements and recommended practices based on the accelerator facility's complexity and hazard levels.

For example, an accelerator may be low-power, small, and self-shielded and have incorporated engineered controls limiting access to radiation levels of concern. These accelerators may be obtained as a pre-manufactured unit with safety operating procedures provided by the manufacturer or may be assembled from component parts in a small room. Due to their inherently safe nature (limited maximum radiation output and/or shielding containment), these accelerators may have simple radiation safety programs that require minimal radiation safety support and limited user training or operational requirements.

The other end of the spectrum includes complex accelerator facilities covering up to several square kilometers delivering kilowatt to megawatt peak or average beam power and involving many distinct beam enclosures. These large accelerator facilities typically require extensive radiation safety programs as well as significant support by radiation safety professionals and well-trained accelerator operation staff (Operations). Within a complex, high-hazard accelerator facility, there may be sub-facilities or secondary beamlines with low radiation hazard and uncomplicated safety

requirements. However, the principles of radiation safety should be consistently applied across the entire facility.

This standard uses the word “shall” to identify a required practice or the minimum acceptable level of performance. The word “should” is used to identify good practices (preferred practices) recommended by this standard. The word “may” is used to identify permitted practice (neither a requirement nor a recommendation). “Shall” is used in the non-normative appendices not to indicate mandatory practice but to indicate an elevated level of importance.

It should be noted that throughout the text the word “requirement” is intended to convey a practice that is necessary to meet the intent of this standard, not to convey any regulatory authority.

The requirements and recommendations in this standard are not intended to preclude alternative means of achieving the same radiation protection objectives. However, the responsibility of establishing alternative means sufficiency is borne by the facility.

Section 1.0 defines the purpose, scope and introduction. Section 2.0 provides common acronyms and defines common terms. Section 3.0 specifies the radiation safety programs for the accelerator facilities and sets forth the basis of the radiation safety program presented throughout the standard. Each main topic in Section 3.0 is presented in detail later in the document.

Section 4.0 provides details on radiation safety system (RSS) requirements and recommendations. The RSS includes the access control system (ACS) and radiation control system (RCS). Section 5.0 details the ACS, and Section 6.0 details the RCS.

Section 7.0 covers accelerator operations. The operational radiation safety (also called operational health physics) program is described in Section 8.0. Finally, Section 9.0 covers personnel training.

Appendices A–D provide detailed guidance and resources to assist accelerator facilities in addressing four key issues covered by this standard: 1) development of the safety

assessment document, 2) the interlocked-type ACS, 3) decommissioning program, and 4) measurements of radiation and radioactivity. Note that these four appendices are *informative* only and are, therefore, not part of this standard’s requirements and recommendations.

It is recognized that many parts of this standard address large and complex accelerator facilities with significant hazards. As discussed earlier, there are many commercially available, industrial, and/or production-type accelerators whose radiation hazards and radiation safety program for the facilities are much less complicated. In general, this type of facility is inherently safe and low-risk (due to the machine’s physical capabilities and/or engineered safety controls) and is operated by a limited number of staff. Therefore, it is desirable to give specific requirements and recommendations for this type of facility. Appendix E provides a summary of the minimum requirements and recommendations for these facilities, which allows the facilities to develop and conduct radiation safety programs in conformance with the standard. Appendix E follows the N43.1 standard layout and is *normative*, and therefore part of the standard requirements and recommendations.

Note that radiation safety requirements for single-purpose accelerators may be addressed by other ANSI standards that have been or are currently being developed. In that case, the general requirements for such types of accelerators may be covered by this standard, particularly Appendix E (if applicable), whereas detailed requirements are covered by the specific ANSI standard (if available).

At the end of this standard, some useful reports and documents are referenced and given as resources.

Note: Several accelerator design and operating characteristics, as well as associated prompt radiation hazards and engineered safety control/mitigation measures, are fundamentally different from nuclear facilities with nuclear weapons, nuclear reactors, or nuclear criticality potential. Therefore, the nuclear facility

radiation safety requirements should not be applied to accelerator facilities (and vice versa) without careful and thorough evaluation.

2.0 Acronyms, Abbreviations, and Definitions

2.1 Common Acronyms and Abbreviations

ABP: Allowed beam power
ACS: Access control system
ALARA: As low as reasonably achievable
ANSI: American National Standards Institute
BID: Beam inhibiting device
DOELAP: Department of Energy Laboratory Accreditation Program
IAEA: International Atomic Energy Agency
ICRP: International Commission on Radiological Protection
LCW: Low conductivity water
MARSSIM: Multi-Agency Radiation Survey and Site Investigation Manual
MCBP: Maximum credible beam power
NCRP: National Council on Radiation Protection and Measurements
NVLAP: National Voluntary Laboratory Accreditation Program
ORS: Operational radiation safety
PLC: Programmable logic controllers
QA: Quality assurance
QC: Quality control
RCS: Radiation control system
REP: Radiological environmental protection
RSC: Radiation safety committee
RSO: Radiation safety officer
RSS: Radiation safety system
SAD: Safety assessment document

2.2 Definitions

Abnormal Beam Loss: A beam loss in excess of that prescribed or normally anticipated and that occurs only infrequently. Examples include instances in which 1) a large fraction of allowed beam power is lost due to an RF trip or magnet failure (this is treated as part of normal operation within the operation envelope) or 2) the maximum credible beam power is lost (this is treated as part of abnormal operation within the safety envelope).

Abnormal Operation: Operation under conditions beyond normal operation defined by the operation envelope. Examples include delivering beam to unauthorized locations, delivering beam beyond authorized beam energy or current, delivering beam beyond conditions governed by the radiation safety system (RSS), and delivering beam to an area with deficient shielding.

Accelerator: A machine or apparatus used to accelerate charged particles to sufficient energy to create secondary ionizing radiation.

Accelerator Facility: An installation or complex of building(s), equipment and support structure(s) used to house and operate an accelerator, or a facility with subfacilities containing an accelerator.

Access Control System (ACS): A control system that prevents or controls access by personnel to hazardous areas deemed unsafe due to prompt radiation production. It includes engineered and/or administrative systems.

Active Systems: Systems or elements of a system used to monitor conditions and triggered to take action when they measure an inappropriate signal initiated by an abnormal or unexpected condition.

Administrative Controls: Controls employing human actions such as access control using rope(s) or warning sign(s), search procedures, administrative locks, etc.

Allowed Beam Power (ABP): The maximum beam power allowed by the operation envelope. It is generally monitored and/or limited by electronic means, and it is based on normal operation shielding design limits.

Area Secure System: A system that facilitates and enforces an area sweep by personnel (Operations in general) to make the area ready (secured) for accelerator operation, which ensures that personnel are not left inside the accelerator housing during operation.

As Low As Reasonably Achievable (ALARA): A radiation safety guiding

principle that requires that the potential or actual radiological impacts to the workers, public and/or environment associated with a facility process or practice should be kept as low as reasonable, taking into account economic, technical, practical, and social factors.

Attenuation: The process by which radiation particle energy and/or fluence is reduced when passing through a material.

Barrier: A structure (shielding wall or fence) that prevents or controls access to an area where radiation hazard is unacceptable.

Beam: The flow of particles or electromagnetic radiation that is either collimated (generally unidirectional) or divergent from a small source but restricted to a small solid angle (NCRP-144, p. 406).

Beam Inhibiting Device (BID): A mechanical or electronic device capable of terminating prompt radiation hazards by either blocking or terminating the beam.

Beam Interlock: A device that monitors beam current or energy and acts to terminate or reduce radiation hazards when predetermined unacceptable beam conditions are measured.

Beam Parameters: Beam characteristics that include, but are not limited to, particle type, size, power, current, energy, pulse repetition rate (macro and micro pulse rates), and so on.

Beam Shutter: A movable physical or mechanical device capable of blocking the beam when inserted into a beamline and keeping downstream areas within established radiation limits.

Beam Stop: A physical or mechanical device fixed in place, generally at the end of a beamline, and capable of absorbing the ABP while keeping the downstream areas within established radiation limits.

Configuration Control: A program or process that maintains a safety system's viability by ensuring that no unauthorized and undocumented changes occur.

Commissioning: Initial testing and phased accelerator system activation ensuring safe operation within specifications prior to routine operation.

Controlled Area: An area where access is managed to control radiation exposure.

Dark Current: Charged particles generated within accelerator cavities or RF waveguides with RF power generating high-voltage gradients.

Decommissioning: Administrative or technical actions to remove or reduce the radioactivity of facility components leading to the release or demolition of the component or facility.

Duty Factor: The fraction of actual beam-on time over the length of an accelerator beam cycle. For example, a 1-ms-long beam pulse with a repetition rate of 10 Hz would have a duty factor of 0.01.

Effective Dose: The sum of the equivalent doses for all human organs or tissues, weighted by the respective tissue weighting factors (w_T , unitless). The SI unit of effective dose is the sievert (Sv); the traditional unit is the rem ($1 \text{ Sv} = 100 \text{ rem}$). See ICRP-60 (1991) and ICRP-103 (2007) for details. In this standard, the terms *effective dose*, *equivalent dose*, and *dose* may be used interchangeably for personnel protection. This standard also acknowledges that, though the latest ICRP-recommended personnel dosimetric quantities have not been universally adopted and used in the United States, the numerical dose values quoted in this standard can be applied without correction for the small differences between different types of quantities.

Equivalent Dose: The product of the dose, in SI unit of gray (Gy) or traditional unit of rad ($1 \text{ Gy} = 100 \text{ rad}$), in an organ or tissue and the radiation weighting factor (w_R , unitless) for the radiation incident on the human body. The SI unit of equivalent dose is the sievert (Sv); the traditional unit is the rem ($1 \text{ Sv} = 100 \text{ rem}$). See ICRP-60 for details.

Exclusion Area: An area in which access by personnel is prohibited and/or restricted

by physical barriers with at least a locked entryway door/gate (interlock is also recommended). Areas with a prompt radiation dose level $> 10 \text{ mSv h}^{-1}$ (1 rem h^{-1}) are classified as exclusion areas. An area secure system is required to ensure no one is left inside the exclusion area prior to accelerator operation.

Expert (Qualified Expert): An individual who has the appropriate combination of education and work experience to make sound judgments regarding specific work areas to which he/she has been assigned. Minimum qualifications should include a bachelor's degree in a science/engineering field and three years of relevant work experience at accelerator or industrial facilities. A higher degree of education can substitute for some working experience. For example, a worker authorized to design and/or certify an interlocked access control system shall have education, experience and training that is commensurate with the tasks assigned. A radiation safety professional is a qualified expert in the areas of radiation safety.

Fail-safe: A feature of an interlocked safety system that renders the accelerator system safe when a component of the safety system fails.

Failure Resistant: A safety system in which some components have been backed-up, reinforced or selected to lessen the probability of failure but not to the extent required for a fail-safe designation.

Gate: A device allowing controlled access to areas that are not normally occupied.

Graded Approach: An approach that provides enhanced radiation safety by incrementally augmented restrictive safety measures as radiation risks increase.

Hazard: A source of danger (material, energy source, or operation) with potential to cause illness, injury, death, or damage to the facility and/or environment (without considering the likelihood or credibility of accident scenarios or consequence mitigation).

High Radiation Area: An area accessible to individuals in which radiation levels from radiation sources external to the body could result in an individual's receiving an effective dose in excess of 1 mSv (0.1 rem) in 1 h at 30 cm from a radiation source or from any surface that radiation penetrates.

Induced Radioactivity: Radioactivity produced in materials exposed to an accelerator beam and/or its secondary particles.

Interlock: A device or device group arranged to sense a limit, an off-limit condition, or improper event sequence that function(s) to shut down the equipment or prevent its operation. Interlocks are specifically designed to prevent and/or terminate a hazardous condition.

Interlock System: An engineered control system that includes interlock devices and interlock logic. It continuously receives feedback information from sensors, makes decisions about the safety of the area and activates mitigation or beam inhibiting devices. In general, the interlock system in this standard refers to personnel protection, though there are also interlock systems for machine (or equipment) protection (machine protection system).

Logic System: A system that relates sensors, feedbacks, and active elements that functions in relation to a given set of input conditions to trigger a given set of actions. The system is usually documented by including an architectural flow diagram.

Maximum Credible Beam Power (MCBP): The maximum power that can be imparted to accelerated beam particles without making significant beam source or accelerating structure changes. The MCBP is used to evaluate the RCS requirements under abnormal operation. The MCBP is greater than or equal to the ABP.

Normal Beam Losses: Beam losses that are anticipated as part of routine and planned operation, such as a 100% beam loss in a beam stop (or shutter) or a fraction of beam loss in a collimator. This is treated as part of normal operation and included in the operation envelope.

Normal Operation: Operation under conditions consistent with those set forth by the operation envelope, which includes normal beam losses and infrequent beam losses due to mis-steering or failure of equipment that is not part of the engineered radiation safety system (RSS).

Occupancy Factor: The fractional factor (≤ 1) by which the radiation quantities in an area may be multiplied to correct for the degree or type of occupancy of the area specified in an effort to obtain the best dose estimate. Occupancy factor is used in shielding design and is the fraction of time an area is occupied. Areas with 2,000 hours per year occupancy are considered to have an occupancy factor of 1. Areas with continuous or frequent occupancy such as offices or laboratories shall also be considered to have an occupancy factor of 1. See NCRP-144 (p.185) for suggested occupancy factor values for different types of areas.

Occupiable Area: Any room or other space, indoors or outdoors, that is likely to be occupied during accelerator operation by any person, either regularly or periodically, during the course of the individual's work, habitation, or recreation (NCRP-144, p. 410).

Operation Envelope: Limiting parameters and/or conditions within which the accelerator is expected to operate under normal operation. These parameters/conditions include routine beam losses and anticipated occasional beam spill or mis-steering but do not include the unlikely beam losses under engineered RSS failure conditions. The operation envelope is designed to maintain an acceptable level of risk to both workers and the general public. The operation envelope shall be within the safety envelope.

Operations (Accelerator Operation Group): The facility group charged with responsibility for the operation of the accelerators, beamlines, and associated equipment.

Operators (Accelerator Operators): Individuals who commission, tune, and/or operate the accelerators or a beamline.

Primary Beamline: A beamline that handles an accelerated beam directly without an intervening target (see also secondary beamline).

Programmable Logic Controller (PLC): A digital computer used for automation of electromechanical processes. The PLC is designed for multiple input and output arrangements. A PLC is an example of a hard real-time system since output results must be produced in response to input conditions within a bounded time; otherwise, unintended operation will result.

Prompt Radiation: Radiation generated as a direct result of an accelerator beam's interacting with matter. When the beam is off, prompt radiation is not generated.

Public (General Public): The general population not regarded as facility employees. Contractors, users, and visitors should not be treated as the general public in terms of training requirements but may be subject to the same dose limits as the general public.

Radiation (Ionizing Radiation): Energy in the form of particles or waves resulting from the acceleration of charged particles (bremsstrahlung x-ray from electrons interacting with the nucleus or synchrotron radiation from electrons in a magnetic field) or from unstable nuclei in the form of charged particles (alpha, beta, and positrons), neutrons, x-rays, and gamma rays.

Radiation Area: An area accessible to individuals in which radiation levels could result in an individual's receiving an effective dose in excess of 0.05 mSv (5 mrem) in 1 h at 30 cm from a radiation source or from any surface that the radiation penetrates.

Radiation Control System (RCS): An engineered system consisting of passive and active elements that contain/limit the beam and/or radiation to ensure that individuals outside the beamline housing or barrier do not receive excessive radiation dose.

Radiation Interlock: A device that acts to terminate or reduce radiation hazards when

pre-set levels of radiation are detected.

Radiation Safety Officer (RSO): An individual assigned the responsibility of developing, executing, and maintaining the accelerator facility's radiation safety program. The RSO may be known by other names, such as radiation protection manager, radiological control officer, and so on.

Radiation Safety Professional: An individual possessing a minimum of a bachelor's degree in a field of science or engineering and who has experience (minimum of three years) and training commensurate with the radiation hazard associated with the accelerator facility.

Radiation Safety System (RSS): An engineered and administrative system acting to protect individuals from prompt radiation exposure due to accelerator operation. It includes the ACS and RCS. The engineered-type RSS may also be used to control induced radioactivity hazards.

Radiation Warning Light (Warning Light): A visual system (generally a flashing magenta, red, yellow, or purple light) that denotes radiation hazards and alerts operators and/or personnel of potential exposure to radiation.

Radiation Worker: An individual who is likely to receive an annual occupational effective dose above 1 mSv (100 mrem) or whose routine job assignment involves operating accelerators, beamlines, or radiation-generating devices or working with radioactive materials.

Redundancy: Duplication or repetition of elements to provide alternative functional channels in case of failure.

Redundant Systems: Two or more complete, independent safety systems configured such that a single failure cannot disable both systems.

Reliability: The characteristic that a device or system will function as designed and when required.

Risk: Quantitative or qualitative expression

of assessment and consequences of a hazard.

Safety Assessment: A complete accelerator regulatory and safety systems evaluation to ensure that the facility falls within current worker and public-domain safe-operation requirements.

Safety Assessment Document (SAD): A facility document that records the radiation safety assessment and radiation safety system control implementation.

Safety Envelope: Limiting parameters within which the accelerator is required to operate without causing unacceptable dose consequence. These generally include maximum beam energy and current (MCBP), maximum beam loss, radiation safety system constraints or failures, dose limits to workers and the public, environmental restraints, and so forth. In short, the safety envelope encompasses any regulatory, management, or machine-imposed limitations that govern safe operation of an accelerator facility.

Search: A search of an accelerator housing, beamlines, or experimental areas conducted by trained individual(s), usually operators or radiation safety professionals, to ensure no personnel are left in hazardous areas before the accelerator begins operation (called a sweep in some facilities).

Search Switches: A series of switches located in a predetermined pattern. If installed, switches shall be activated, preferably in an ordered sequence, to verify that search personnel have accessed each area requiring a search to secure the area.

Secondary Beamline: A beamline downstream of a target such that the intensity is generally reduced and the beam particles are often different from those in the original accelerated beam.

Secured Area: A searched and locked area where the ACS would prevent entry by personnel who have not been given an area release by the operator.

Shielding: Physical or mechanical structures used to attenuate radiation and reduce

dose rates.

Status Light and/or Sign: A visual communication system used to broadcast current accelerator operation status and potential radiation hazard levels.

Tamper Resistant: A feature of a safety system that protects the system from inadvertent or unintentional interference or alteration.

Testable: Operational capability, function, integrity, and action that can be observed, measured, and/or verified.

Verbal Announcement: An oral announcement given to convey imminent accelerator or beamline start-up such that personnel in the areas recognize the area is being searched (swept) prior to the beam operation.

Very High Radiation Area: An area accessible to individuals in which radiation levels from radiation sources external to the body could result in an individual's receiving a dose in excess of 5 Gy (500 rad) in 1 h at 100 cm from a radiation source or from any surface that the radiation penetrates.

Worker: A facility employee. This may include contractors and users who come on-site to perform work or experiments.

3.0 Radiation Safety Program

3.1 General

Hazards at accelerator facilities include ionizing and non-ionizing radiation as well as electrical, fire, chemical, vacuum, and cryogenic hazards, among others. This standard is devoted entirely to ionizing radiation safety only.

A facility radiation safety program shall be established to address and control risks from ionizing radiation to facility workers, the public, and the environment associated with the facility's life cycle, which includes design, installation, commissioning, operation, maintenance, upgrade, and decommissioning.

The objectives and scope of the radiation safety program shall be clearly defined. The radiation safety program should adopt relevant and applicable accelerator community practices and/or consensus approaches. The radiation safety program shall embrace the ALARA (As Low As Reasonably Achievable) principle to protect workers, the public, and the environment.

The radiation safety program shall be an integral part of the facility's research and development (R&D) and operational programs and should be integrated into the facility's safety program.

Resources invested in developing and implementing the radiation safety program should reflect the complexity and likelihood of radiation hazard and potential consequences. In large R&D facilities, the radiation safety program may be uniquely developed and matched to the facility. For single-purpose and/or fixed operational mode facilities using commercially produced accelerators, radiation safety programs may be simple and standardized and/or supplied directly by the manufacturer(s).

The radiation safety program shall, at a minimum, include the following elements (with contents appropriate to the scope, complexity, and hazard levels of accelerator operation):

1. Organization and safety program administration,
2. Radiological hazard identification and safety assessment,
3. Design and implementation of engineered and administrative safety controls and monitoring,
4. Accelerator and facility operations,
5. Operational radiation safety,
6. Training and qualification of personnel, and
7. Safety program review and performance evaluation.

Quality assurance (QA), quality control (QC), configuration control, and proper document/record management shall be incorporated in the development and implementation of the safety program.

3.2 Organization and Administration

The facility organization and radiation safety program roles, responsibilities, and authorities shall be clearly defined for facility management, line managers and supervisors, operators, radiation safety professionals, workers, contractors, users, visitors, and so on.

3.2.1 Facility Management and Operation

Responsibility for safe facility operation rests with the facility management, who shall commit resources to support the radiation safety program development and implementation and ensure that the safety program has sufficient fiscal, professional, and technical resources to address hazards.

Operations and radiation safety professionals should work together to develop and implement accelerator operation and maintenance activity safety control practices based on radiation safety program requirements.

Independence of radiation safety professionals shall be maintained such that pressures to meet design and operational targets will not compromise safety. Radiation safety professionals shall have no conflict of interest in their assigned safety duties.

3.2.2 Radiation Safety Professionals The radiation safety professional group's staffing level, training, and experience shall be commensurate with the complexity and level of hazard associated with the accelerator facility. The type and number of radiation safety staff should be consistent with the frequency, routine task complexity level, and the flexibility needed for unplanned operations.

The facility shall have access to a radiation safety professional, who is responsible for developing and/or evaluating the radiation safety program.

Self-contained commercial machines with few radiation hazards may require limited supervision or consultation by the radiation safety professional. Examples of accelerators appropriate for this control level may be found in Appendix E of this standard.

Facilities with significant potential hazards or complex programs should have one or more radiation safety professionals.

3.2.3 Radiation Safety Officer and Radiation Safety Committee The facility shall designate a radiation safety officer (RSO) who manages and is responsible for the radiation safety program. The RSO should have direct access and report to top facility management.

Large, complex facilities generally appoint an RSO from radiation safety professionals who are supported and/or guided by a facility radiation safety committee (RSC). The committee should include facility management representatives with an interest in facility productivity and application as well as technical, operational, and radiation safety personnel. Consensus recommendations from a committee with balanced composition provide strong guidance to top management and/or the RSO.

The RSO's and RSC's (if one exists) roles, authorities, and responsibilities and their interrelationship shall be clearly stated. The RSO and/or RSC shall have the authority to approve operations and to stop unsafe operations, and only top management can override the RSO/RSC's decision. The responsibilities of the RSO/RSC shall include the following: review and approval of major accelerator and safety system design, configuration, and operational changes, as well as major experiments and work activities having significant radiological impacts on personnel and the environment (e.g., approaching the facility's administrative limits). Periodic reviews focused on strengthening radiation safety and safe accelerator operation shall be assigned to the RSO/RSC.

3.3 Hazard Identification and Safety Assessment

Safety assessments shall be used to identify and evaluate an accelerator facility's radiation hazards as a basis for facility design, construction, and operation. Management shall ensure that accelerator designers and Operations work closely with radiation safety professionals to perform

hazard identification and assessment and determine radiation safety controls for machine design, prototyping, commissioning, operation, maintenance, and decommissioning.

Initial accelerator facility designs shall consider radiation safety. Critical safety features such as shielding and interlocked radiation safety systems shall be incorporated. Cost and scheduling pressures can have significant bearing on facility design and engineering decisions, and consequently on radiation characteristics and outputs. In any case, emphasis shall be directed toward safety in the design phase. Future upgrades should be included in the initial facility design because retrofitting costs can be significant.

Accelerator facilities shall have a safety assessment document (SAD) that describes, at a minimum, facility, accelerators, beam parameters, operational modes and schedules, radiation hazards analysis, engineered and administrative safety systems to detect, control and/or mitigate hazards, and the hazards and risks to workers, the public, and the environment.

A large, complex facility may have a single SAD document system or one SAD for each subfacility. Industrial accelerator facilities with similar beam and operational modes, producing analogous hazards, or using vendor-supplied accelerator systems may use a standard SAD provided by the manufacturer/vendor.

The SAD shall be a practical safe operations guide and it shall be kept current throughout the facility's lifetime. The SAD shall be reviewed by the RSO/RSC and approved by facility management. The SAD should be reviewed at least annually against the current design and operational conditions.

Appendix A provides facility SAD development guidance meeting the requirements and recommendations in this standard.

3.4 Design and Implementation of Safety Controls and Monitoring

To characterize potential radiation hazards throughout the facility, the SAD facility

description should include physical layout; normal and maximum beam parameters (particle types, energy, current, power); operational modes, plans, and schedule; beam loss scenarios for normal and abnormal operations; and operation and maintenance occupancy conditions.

Machine radiation output shall be analyzed and include risks to workers and the public under normal and abnormal operations. Abnormal operation analysis shall include the maximum credible beam power (MCBP) evaluation (under credible beam control system failure scenarios), the resulting maximum radiation source terms, and radiation levels in occupiable areas.

Estimated beam parameters, operation modes, beam losses, and radiation outputs should be validated by comparing them with those of similar existing machines.

Personnel and environmental radiation protection shall include an analysis of accelerator-produced residual radioactivity in accelerator components, accelerator housing, and environmental media (such as air, soil, ground water, etc.).

Reasonable design and control system modification should be allowed as design or operation experience is gained. Likely beam current or energy upgrades, facility expansion, and new experimental protocols should be considered.

More technical guidance on accelerator facility design, including design details and shielding data, may be found in references (IAEA 1979, 1988; SLAC 1988; NCRP 2003).

3.4.1 Radiation Safety System (RSS) A radiation safety system (RSS) is used to control prompt radiation hazards. The RSS should include two complementary systems: the access control system (ACS) and the radiation control system (RCS). The ACS keeps people away from radiation hazards by controlling access to hazardous areas such as accelerator housings. The RCS keeps radiation hazards away from people by using passive and/or active elements.

The RSS can include passive elements

(shielding and fences), active elements (interlocked access control, beam interlocks or radiation interlocks), and administrative elements (ropes and signs, locks, search procedures, operating policies and procedures).

Section 4.0 of this standard specifies more detailed requirements and recommendations on RSS design and implementation. Section 5.0 details ACS systems, and Appendix B provides guidance for designing and implementing an interlocked-type ACS. Section 6.0 details the RCS.

3.4.2 Safety Envelope and Operation Envelope

The SAD shall describe the safety envelope and should describe the operation envelope and specify control systems, safety measures, and operational conditions needed to ensure operation is within the safety envelope. The SAD shall specify or reference sufficient facility configuration detail so that periodic verification of the hazard control to ensure compliance with the safety envelope and operation envelope can be performed.

The safety envelope shall set forth facility configuration and operating conditions (normal and abnormal) within which radiation risks to workers, the public, and the environment are acceptable. The safety envelope shall state the maximum permissible worker and public radiation exposure levels. The operation envelope should be established to ensure the safety envelope is not exceeded during normal operations. Accelerator operations within the operation envelope should provide sufficient safety margins within the safety envelope.

A risk assessment including justification for operation outside the operation envelope or safety envelope is required. Operation outside the safety envelope shall be approved by institutional management, the operations manager, and radiation safety professionals. Changes to the safety envelope may require regulatory agency approval. Accelerator operations outside the operation envelope shall require approval by the Operations manager and radiation safety professionals.

Examples of the safety envelope and operation envelope include the following:

- The safety envelope may specify a 2-kW MCBP limit, if no physically possible beam operation or abnormal operation can exceed 2 kW.
- The operation envelope may specify a 1-kW allowed beam power (ABP) limit that is ensured by administrative and/or interlocked means. Shielding for normal beam losses at ABP and controls for infrequent and unplanned full loss of ABP such as beam and/or radiation interlocks are part of the operation envelope.
- The operation envelope may specify yearly total beam particle numbers, as well as acceptable beam energy ranges, delivered to various areas within the facility so the integrated doses outside shielding will not exceed design limits, as well as the control systems used to monitor integrated particle numbers and beam energy.
- The safety envelope may specify a dose rate limit of 50 mSv (5 rem) in any 1 h for abnormal operation and a dose limit of 10 mSv (1 rem) for an abnormal event.
- The operation envelope may specify an annual dose limit of 10 mSv (1 rem) for a radiation worker and an annual dose limit of 1 mSv (0.1 rem) for users and the general public on-site.
- The operation envelope may specify an annual dose limit of 0.2 mSv (20 mrem) for the general public off-site.

3.5 Accelerator Operations

Accelerators should be operated in compliance with the operation envelope. A relevant RSS shall be in place and functioning properly before and during operation.

Accelerator operation and maintenance shall be conducted by trained and qualified individuals following facility program schedules and using well-defined procedures or instructions. Machine operator and system maintenance personnel responsibilities, authorities, and safety functions shall be clearly defined.

Systems and communication channels ensuring effective and timely coordination among all parties involved in the facility's safe operation shall be developed and implemented.

Accelerator operation requirement and recommendation details are covered in Section 7.0.

3.6 Operational Radiation Safety

Detailed operational radiation safety (ORS) requirements and recommendations are described in Section 8.0 of this standard. The ORS program shall ensure that facility operations remain compliant with regulatory and facility requirements.

Radiation safety professionals shall develop and implement the ORS program with input from accelerator facility operation groups. Experience and lessons learned during the design and commissioning phases should be incorporated into the ORS program for routine operation. The ORS program should be formal and procedural, yet flexible enough to adapt to changing beam, target, and experimental parameters and operational conditions.

The ORS program shall include the following program elements commensurate with the facility's hazard levels and complexity:

1. Area and worker classification as well as access control,
2. Personnel dosimetry,
3. Measurements of area radiation levels and integrated doses,
4. Radiological work control,
5. Measurement and control of induced radioactivity,
6. Instrument selection, calibration, and use,
7. Management of radioactive sources, materials, and waste,
8. Measurements and/or evaluation of radiation and radioactivity, as well as the impacts, to people and the environment, and
9. Facility cleanup and decommissioning.

3.7 Training and Qualification

Facility employees, contractors, users, and visitors shall receive radiation safety training commensurate with the radiation hazards and controls associated with their duties and tasks.

A qualification program shall be used to evaluate training effectiveness, authorize work, and ensure tasks are completed in a safe and controlled manner.

Details of personnel training and qualification are given in Section 9.0.

3.8 Program Review and Performance Evaluation

Periodic program reviews shall be conducted and documented to ensure that 1) facility design and operation are in compliance with radiation safety program requirements and 2) the radiation safety program continues to meet applicable regulations, facility objectives, facility designs, operation status, and the latest international and national standards.

The performance of the facility radiation safety program should be comparable to that in peer facilities. Key program performance indicators (both leading and lagging) shall be developed, analyzed, and tracked as part of continuous program improvement. Examples of leading performance indicators include completion of training and qualification, completion of mandatory surveys, radiological work control evaluation, numbers of radiation areas and contamination areas, reported concerns, near misses, and so on. Examples of lagging performance indicators include the maximum individual doses to workers and off-site public, collective doses for critical groups, area and site boundary doses, environmental radioactivity releases (air, soil, ground water, waste water, surface water, etc.), safety incidents, abnormal occurrences, waste collection and disposal, and so forth.

A phased program and performance evaluation should be conducted by facility management, Operations, and radiation safety professionals. The program's scale

and complexity should mandate the evaluation's frequency. The whole program shall be reviewed once at least every three years.

Readiness review(s) shall be conducted to verify SAD implementation and adequacy prior to operation. Significant facility changes shall also be cause for review. The review shall include a design goal evaluation with respect to established policies and requirements, and the adequacy of safety control implementation. New installations and/or current installations with significant changes (modification of the safety envelope) should undergo an independent review by an external expert.

Systematic program review shall identify program weaknesses, determine root causes, document corrective actions and track them until closure. Deficiency resolution shall be scheduled, and finding corrections shall be validated. Program changes, additions, and improvements should be documented. A process should be in place to solicit, review, and incorporate feedback from employees, contractors, and users.

3.9 Quality Assurance, Quality Control, and Configuration Control

Facility program processes shall include QA and QC. A high-performance radiation safety program shall be designed, implemented, and conducted with quality, reliability, and efficiency. The QA program addressed in this standard includes ensuring clear roles and responsibilities, well-trained individuals, documented program policies and procedures, configuration control, readiness review, self-assessment, and peer reviews.

The facility shall develop a configuration control program to ensure that each safety system is constructed (for passive systems) or operated (for active systems) as designed. These requirements are addressed further in Section 4.0.

3.10 Document and Record Management

The facility shall develop and implement a document and record management system

such that 1) accelerator and radiation safety program processes (both design and operation) are conducted by individuals following written policies, procedures, and instructions, 2) associated activities are well recorded, and 3) program process and performance are auditable.

The documentation system hierarchy and inter-relationship shall be clearly specified. Procedures and records associated with radiation safety program administration (including periodic reviews, recommendations, and actions taken as a result of these reviews) shall be documented.

Vital radiation safety program records shall be safely stored for appropriate time periods and shall be readily retrievable. The vital records include, but are not limited to, the following:

- Facility design, layout, and revisions,
- SAD, safety envelope, and operation envelope,
- Experiments or operation review and approval,
- Accelerator operations records and logbooks,
- Accelerator operations outside the operation envelope or the safety envelope,
- Accelerator or support system changes (temporary or permanent),
- Equipment or operations changes that result in a radiation hazard change,
- Interlocked RSS (ACS and RCS) certification, testing, bypasses, and repairs,
- Radiation safety program reviews and audits,
- Technical basis documents, program manuals, and procedures,
- Radiation surveys and radioactivity measurements,
- Radioactive source control or inventory, radioactive materials and waste,
- Instrument calibrations and source checks,
- Individual training records,
- Personnel radiation dose records,
- Area dose monitoring records,
- Evaluation, monitoring, and releases of radiation and radioactivity to the public and environment,

- Public dosimetry records, and
- Facility cleanup or decommissioning activities records.

All records should be maintained in accordance with National Archives and Records Administration (NARA) requirements and recommendations. ANSI N13.6 (1999), "Practice for Occupational Radiation Exposure Records Systems," should be used as a basis for maintaining the record-keeping system.

4.0 Radiation Safety System (RSS)

4.1 General

Non-permissible prompt radiation exposures around an accelerator facility shall be prevented through the use of a radiation safety system (RSS) composed of physical (engineered) and/or administrative features.

Accelerator-produced prompt radiation can be pervasive and intense but is terminated when the power is off. Thus, accelerator standards differ from those applying to induced radioactivity and radiation from radioactive sources. General requirements and guidance for the RSS can be found in this section, and detailed requirements and guidance are given in Sections 5.0 (ACS) and 6.0 (RCS). The ACS keeps people away from prompt radiation, whereas the RCS keeps prompt radiation away from people. In this chapter, the term *radiation* means *prompt radiation* unless otherwise specified.

4.2 Features of the Radiation Safety System (RSS)

The RSS has two complementary sub-systems:

1. Access Control System (ACS): A safety system to prevent or control personnel access to areas with potential prompt radiation hazard. The ACS controls area access with interlocked-type ACS, administratively locked gates/fences, or simply a rope with appropriate posting to warn people of a hazard's existence. Higher hazard levels will require employment of more stringent systems as discussed further in this document. Graded approach details are described in Section 5.0.
2. Radiation Control System (RCS): A safety system to ensure that radiation (prompt and induced) in occupiable areas does not exceed permissible limits under all normal and abnormal accelerator operating conditions. The RCS may include passive elements (e.g., shielding walls and fence) and/or active systems (beam interlock systems and radiation interlock systems).

The required features of the RSS (ACS and RCS) should be commensurate with the hazard level. In a small facility, these two subsystems might not be distinct and a single RSS is sufficient. In a large facility, the ACS and RCS are likely to be separate but interrelated systems. An example of a complicated, engineered RSS is shown in Fig. 4.1.

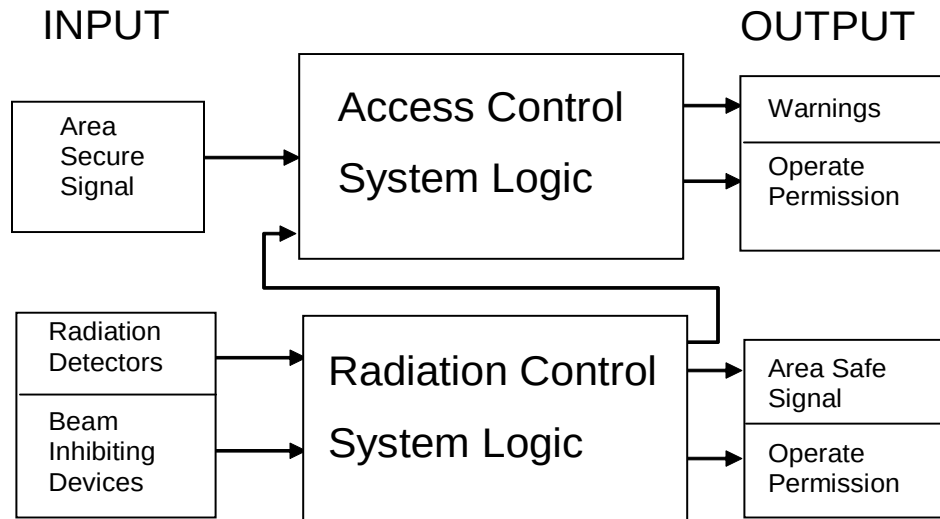


Fig. 4.1. Generic ACS and the RCS relationship in a complicated, engineered RSS.

Some RSS installation examples are given below:

- An accelerator (or beamline) with inherently limited radiation output might have a single radiation warning line around the accelerator area that serves as the RCS by interposing distance and, at the same time, serves as the ACS for controlled access. In this case, the RCS and ACS are administrative types.
- Metal shielding (a passive element of the RCS) may enclose a bench-top accelerator, leaving no accessible openings. With the shielding secured (and/or interlocked) in place, there is no need for interlocked ACS.
- A large facility has several rooms for primary beamline and secondary beamlines operating independently. An interlocked RSS is generally utilized in this case. For example, primary beam can be delivered from room A (the beam source area) to two target rooms B and C. Frequently occupied area D is outside and adjacent to the rooms A, B, and C. The locked and/or interlocked ACS prevents entry into rooms A, B, and C during beam delivery. Meanwhile, the RCS shield between area D and rooms A, B, and C, as well as interlocked radiation monitors in area D, can protect area D personnel. Making room A accessible requires turning the

beam source off using beam inhibiting devices (e.g., gun power supplies). Room B is made accessible during beam delivery from room A to C by utilizing RCS shielding and beam inhibiting devices (beam shutters) between rooms A and B and between rooms B and C.

4.3 Requirements and Guidance

This section provides general design requirements and guidance for an engineered ACS and RCS such as that shown in Fig. 4.1.

Interlocked RSS shall be reliable, fail-safe, tamper-resistant, designed and installed with high quality, and subject to configuration control. Periodic system certification and regular checks shall be conducted to ensure the system's integrity, functionality, and performance.

4.3.1 Reliability and Fail-Safe The RSS shall be reliable and fail-safe (the accelerator system is rendered safe when any single safety system component fails). The RSS shall provide required protection while the systems are subject to reasonable and foreseeable aging and environmental conditions, which may include temperature and humidity extremes, mechanical shock, high electromagnetic fields, high radiation