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Engineered and Administrative Safety Systems for the Control of Prompt Radiation Hazards at Accelerator Facilities

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Introduction

The ANSI N43.1 Standard, currently in revision (ANSI 2007), sets forth the requirements for accelerator facilities to provide adequate protection for the workers, the public and the environment from the hazards of ionizing radiation produced during and from accelerator operations. The Standard also recommends good practices that, when followed, provide a level of radiation protection consistent with those established for the accelerator communities.

The N43.1 Standard is suitable for all accelerator facilities (using electron, positron, proton, or ion particle beams) capable of producing radiation, subject to federal or state regulations. The requirements (see word “shall”) and recommended practices (see word “should”) are prescribed in a graded approach that are commensurate with the complexity and hazard levels of the accelerator facility.

Chapters 4, 5 and 6 of the N43.1 Standard address specially the Radiation Safety System (RSS), both engineered and administrative systems, to mitigate and control the prompt radiation hazards from accelerator operations. The RSS includes the Access Control System (ACS) and Radiation Control System (RCS). The main requirements and recommendations of the N43.1 Standard regarding the management, technical and operational aspects of the RSS are described and condensed in this report.

Clearly some aspects of the RSS policies and practices at different facilities may differ in order to meet the practical needs for field implementation. A previous report (Liu et al. 2001a), which reviews and summarizes the RSS at five North American high-energy accelerator

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facilities, as well as the RSS references for the 5 labs (Drozdoff 2001; Gallegos 1996; Ipe and Liu 1992; Liu 1999; Liu 2001b; Rokni 1996; TJNAF 1994; Yotam et al. 1991), can be consulted for the actual RSS implementation at various laboratories. A comprehensive report describing the RSS at the Stanford Linear Accelerator Center (SLAC 2006) can also serve as a reference.

Radiation Safety System (RSS)

The systems that monitor, control, and/or mitigate the radiation hazard can include passive elements (e.g., shielding, fence), active elements (e.g., interlocked access control, beam interlocks, or radiation interlocks), and administrative elements (e.g., ropes and signs, area access locks, search procedure, operating policies and procedures).

A Radiation Safety System (RSS), consisting of an array of passive and active safety elements, may be required to reduce the prompt radiation hazard. The RSS can 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 and limiting personnel access to prompt radiation hazards inside accelerator housing or shielding. The RCS keeps radiation hazards away from people by using passive elements (e.g., shielding or fence) and/or active elements (e.g., beam and radiation monitoring/limiting devices).

Safety Assessment

The facility shall conduct safety assessment in the initial facility design stage by a safety professional safety. The assessment shall be reviewed and/or approved by the facility management, which includes the Radiation Safety Officer (RSO).

The safety assessment shall identify, analyze, and evaluate facility radiation hazards and form the basis for the design, construction, and operation of an accelerator facility that satisfies safety expectations.

In order to characterize the possible radiation doses throughout the machine, the safety assessment shall include evaluation of facility and operation modes such as the physical layout of the facility, normal and maximum beam parameters (e.g., particle types, energy, current, power), expected operational plans and schedule, and beam loss scenarios in both normal and abnormal operations. The needs for personnel occupancy throughout and around the facility during accelerator operation and maintenance shall be included.

The radiation output of the machine and the risks to the workers and the public under all normal and abnormal operations shall be analyzed and documented. Analysis of abnormal operations shall include evaluation of the Maximum Credible Beam Power that can be delivered and lost at any point in the facility (given various reasonable combinations of failures of the beam controls), the resulting maximum radiation source term, and the potential radiation fields in occupiable areas. The estimated radiation output should be compared (and comparable as well) with that from similar existing machines.

Radiation safety design including the RSS considerations shall be included in the facility safety assessment. With the safety assessment, the Operation Envelope and Safety Envelope can be specified.

Safety Envelope and Operation Envelope

The Safety Envelope and/or Operation Envelope shall specify the operational bounding conditions and safety control measures that are to be followed and/or monitored by the facility.

The Safety Envelope shall set forth the facility configuration and operating conditions (normal and abnormal), within which the radiation risks to the workers, the public, and the environment are acceptable. The Safety Envelope shall state the maximum permissible or allowable levels of radiation exposure to the worker and public.

The Operation Envelope should be established to ensure that the Safety Envelope is not exceeded during normal operations. Accelerator operations within the Operation Envelope should provide safety margins within the Safety Envelope.

The Safety Envelope and Operation Envelope shall specify or reference the RSS configuration in sufficient detail so that periodic verification of safety controls and/or monitoring of hazards can be performed.

Quality Assurance, Quality Control, and Configuration Control

Quality assurance (QA) and quality control (QC) shall be part of the facility safety program processes, so that the RSS can be designed, implemented and conducted with high performance, quality, reliability, and efficiency. The main elements of a QA program include clear roles and responsibilities, trained and competent individuals, documented programs and procedures, configuration control, readiness review, self-assessment, and peer review.

The accelerator facility shall also develop and implement a configuration control (CC) program to ensure that each safety system is in place as designed (for passive systems) or is operated as designed (for active systems).

Radiation Safety System (RSS)

A Radiation Safety System (RSS) comprising the physical (engineered) and administrative features shall be used to prevent exposure of individuals to non-permissible prompt radiation levels in and around an accelerator facility.

The prompt radiation produced by accelerator operation can be pervasive and very intense, but can be readily terminated by turning off the power sources. These characteristics make it desirable and feasible to establish specific accelerator standards that differ from those applying to induced radioactivity and radiation from devices using radioactive sources.

General requirements and guidance for the RSS can be found in this section, while detailed requirements and guidance for ACS and RCS are given in the following sections. In these sections, the term *radiation* means *prompt radiation* unless otherwise specified.

RSS Features

The RSS can have two complementary sub-systems:

1) The Access Control System (ACS): A system that prevents or controls personnel access to hazardous areas deemed unsafe due to the production of prompt radiation. The ACS may be an engineered, interlocked-type ACS or an administratively locked gate in a fence to keep people away from high radiation levels, or simply a rope with appropriate posting to warn people of the existence of radiation, etc. Higher levels of hazard will obviously lead toward the employment of more stringent systems as discussed further in this document.
2) The Radiation Control System (RCS): A system to ensure that prompt radiation in occupiable areas does not exceed permissible limits under all normal and abnormal accelerator operation conditions. The RCS may include passive elements (like shielding walls and fence) and/or active systems (like beam interlock systems and radiation interlock systems).

Fig. 1 illustrates the ACS and RCS system components that are typically used at a large, complex accelerator facility. Typical features of the entry module for the ACS are also shown.

The ACS keeps people away from prompt radiation while the RCS keeps prompt radiation away from people. The required features of the RSS (i.e., both the ACS and RCS) should be commensurate with the level of hazard. In a small facility, these two sub-systems might not be distinct and a single RSS is sufficient. In a large facility, the ACS and the RCS are likely to be two separate but connected systems (an example of an interlocked-type RSS is shown in Fig. 2).

Examples of installations showing a range of RSS implementations might be:

- An accelerator (or beamline) with inherently limited radiation might have a single 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, both the RCS and the ACS are administrative type.
- A bench top accelerator might be fully enclosed by a metal shield (i.e., a passive element of the RCS) with no accessible opening. With the shielding secured (and/or interlocked) in place, there is no need for an interlocked ACS.
- A large facility might have several rooms receiving beam (or secondary radiation) independently. An interlocked RSS is generally used in this case. For example, the beam can be delivered from room A (the beam source area) to two target rooms B and C. A frequently occupiable area D is outside and adjacent to the rooms A, B and C. The ACS (e.g., interlocked and/or locked door entrance) prevents entry into rooms A, B, and C during beam delivery. Meanwhile, the RCS (e.g., the shielding between the area D and the 3 rooms, as well as an interlocked radiation monitor in area D) can protect personnel in area D. To make room A accessible, the beam source must first be turned off by the beam inhibiting devices (e.g., power supplies for the gun). If room B is made accessible while beam is delivered from room A to room C, the RCS shielding element and the beam inhibiting devices (beam shutters in this case) between room A and room B (as well as those between room B and room C) must be inserted into beamlines to keep the room B safe for access.
- Same as the approach for the primary beam areas, the RSS for secondary beamlines shall be designed and implemented according to the hazard level of the secondary beamlines.

RSS Requirements and Guidance

The general requirements and guidance for the engineered RSS elements, e.g., the interlocked ACS and RCS, are given in this section. In summary, the interlocked safety system shall be reliable, fail-safe, and tamper-resistant, designed and installed with high quality (e.g., meeting industrial standards), and subject to QA, QC and configuration control. Periodic certification and checks of the integrity and functionality of the RSS (i.e., the ACS and the RCS) shall also be performed to assure adequate system performance.

Reliability & Fail-Safe.

The RSS shall be reliable and fail-safe to meet its safety roles. The RSS should provide the required protection, while subject to all foreseeable aging and environmental conditions at the accelerator facility. Depending on the installation, these conditions may include weather extremes, high electromagnetic fields, high radiation fields, earthquakes, and the cumulative effects of aging on components, such as corrosion, dirt, and normal wear.

Features to ensure that the system is reliable and fail-safe shall include, but are not limited to: system redundancy, system self-checking, quality of material and workmanship, regular system testing and maintenance, and installation quality control. The QA program and the CC program should address these requirements. For complex interlock systems it may be appropriate to carry out fault tree analysis of the system.

In case of failure, the RSS shall maintain a safe condition. The RSS beam permit removal, due to a fault condition or function of its design, shall require manual RSS reset.

Tamper Resistance.

The RSS shall be tamper-resistant, meaning that it is secured from both inadvertent and intentional interference and/or alteration. Tamper resistance does not require protection against a deliberate attempt to defeat the systems.

Examples of tamper-resistant features include concealed door microswitches, interconnections in metal conduit, and system logic in inaccessible cabinets or locked cabinets with proper key control measures applied (combination locks should not be used). Examples of tamper susceptibility include a door switch that can be easily taped shut from the outside of the beam housing and electrical terminals exposed to misconnection. Examples of an attempt to defeat the system could be using a tool such as a screwdriver or an implement such as a ladder to climb over a tall fence clearly posted with warning signs.

Quality Assurance.

An accelerator facility shall develop and implement a documented quality assurance (QA) program for the RSS. The formality and detail of the program should be commensurate with the level of hazard. The program shall include, as a minimum, quality controls for system design, acquisition of components, system construction, periodic certification and checks, configuration control, and training of those who use, test, or modify the system.

Configuration Control.

A configuration control program shall be used to periodically verify and ensure that the RSS is in the configuration required by the Safety Envelope and/or Operation Envelope. A configuration control program shall be used to ensure that changes or additions made to the RSS meet the system requirements.

The authority and responsibility for the configuration control program shall be specified. Any change to the shielding and interlocked RSS elements shall require the review and approval by both the Operations and the radiation safety professional.

The configuration control program should provide sufficient documentation so that at any time it is easy to verify that installed safety features conform to the design. For example, the configuration control program should identify the documentation for shielding placement and beam control safety devices, and the procedures for ensuring conformance after change or maintenance.

The formality and detail of the configuration control programs should be suitable for the hazards and complexity of the facility.

Radiation Not Related To Accelerator Beam

The combination of high voltage and/or RF power and vacuum in some accelerator components can produce dark current and, thus, ionizing radiation even when the particle beam is off. This type of X-ray production has some of the characteristics of beam-related prompt radiation (e.g., it can be turned on and off). The RSS safety controls for this hazard shall be similar to those for the beam-related conditions with comparable hazards.

The accelerator facility shall have systems to protect the workers from excess exposure to, and production of, induced radioactivity in the machine components. Though induced activity hazards are more stable and predictable (thus more controllable by administrative measures) than the prompt radiation hazards, it may be appropriate to use the engineered RSS as the safety controls to address some potential hazards related to induced radioactivity after beam off. For example, interlocked access control into a beamline enclosure is allowed only after the exposure rate due to induced radioactivity or the radioactive concentration in the air is detected to be acceptable. Air ventilation is controlled during and/or after accelerator operation.

Access Control System (ACS)

This section provides requirements and recommendations for the Access Control System (ACS). The facility shall have an ACS(s) to control personnel occupancy in areas with prompt radiation above the acceptable levels.

Graded Approach

An ACS may range from a simple rope with appropriate posted warnings to a complicated engineered access control system. Higher levels of hazard will require the employment of more stringent systems as discussed below.

The 10CFR20 (NRC 1991) requires that the access control devices shall function automatically (or the area be locked) to ensure that no one is inside a High Radiation Area where a worker could receive more than 10 mSv in any one hour. The 10CFR835 (DOE 1998) requires that the access control devices shall function automatically (or the area be locked) to ensure that no one is inside a High Radiation Area where a worker could receive more than 10 mSv in any one hour.

Based on the NCRP-88 recommendations (NCRP 1986), Table 1 provides the graded physical features for the ACS, depending on the area’s dose level category. The dose rate values in the table refer to the maximum effective dose expected in any one hour of operation due to prompt radiation inside an area (operated within the Operation Envelope). The graded features in Table 1 are slightly tighter than those in NCRP-88.

Note that the ACS requirements in Table 1, as well as the dose rate levels, represent the minimum requirements. The facility should determine the reasonable and optimum approach, e.g., choosing a more stringent system when the associated cost of system implementation is not demanding.

An ACS is required for an area with dose rates > 0.05 mSv h^{-1} (5 mrem h^{-1}). Note that areas with dose levels ≤ 0.05 mSv h^{-1} (5 mrem h^{-1}) are not subject to the ACS requirements.

If an ACS is needed, more features are required per Table 1 for areas with higher dose levels, as explained below:

1) For the Minimum dose category (0.05 - 1 mSv h^{-1}), an administrative-type access control with rope and posted warnings is necessary and sufficient. Each entry gate can be left open or unlocked. The signage shall be explicit and clearly state the dose rate levels and the resulting access conditions.

2) For the Low dose category (> 1 and ≤ 10 mSv h^{-1}), additional requirements are visible and audible warnings prior to machine start-up and barriers (i.e., shielding wall or fence) to provide distance and deter access. The personnel entryway gate shall be locked (preferably via a captive interlocked key) or interlocked.

3) At dose level > 10 mSv h^{-1} (Moderate and High dose categories), the areas are classified as Exclusion Area (i.e., not accessible while the defining level of radiation can be present) and an Area Secure System (to ensure no one is left inside the area prior to operation) is required. In this case, the interlocked-type ACS shall be designed or approved by qualified experts and the RSO.

4) For the Moderate dose category (> 10 and ≤ 100 mSv h^{-1}), additional requirement is that the entryway shall be locked with a captive interlocked key. A redundant interlock is recommended.

5) For the High dose categories (> 100 mSv h^{-1}), additional requirements are that the entryway shall be locked and interlocked. Redundancy of the interlock is required. An emergency-off feature shall be included.

Note that the required graded features are based on potential consequences from unauthorized or inadvertent exposure inside a beamline area. For example, at levels ≤ 1 mSv h^{-1}

(the Minimum dose category), an accidental exposure lasting for 1-h in the area (which is not likely) will receive a dose no more than 1 mSv (100 mrem, which is the legal limit for the public) and much lower than the occupational dose limit of 50 mSv (5 rem). These levels of prompt dose rate are also frequently seen around beamline components with induced radioactivity in high-power accelerator facilities. Therefore, the hazard can be managed by administrative-type access control (rope and posted warnings).

At the level of the Low dose category (1-10 mSv h^{-1}), an accidental exposure under an hour (which gives a maximum of 10 mSv) gives only a fraction of the permissible annual limit for occupational exposures (i.e., 50 mSv), so the hazard is considered manageable by an area enclosure (i.e., barrier) with either locks or interlocks on entryway gates.

Accidental access to an area with the Moderate dose category (10 - 100 mSv h^{-1}) could result in reaching or exceeding the permissible annual limit within one hour. Locks on entryway gates are required and additional interlocks are recommended. Also at the Moderate and High dose categories, the area is to be an Exclusion Area during accelerator operation, and an Area Secure System is required to ensure that persons are not left inside prior to beam delivery.

Accidental exposures to High dose category (> 100 mSv h^{-1}) could result in serious health effects. Therefore, entryway gates must have interlocks and be kept locked when the defining level of radiation may be present. Lethal exposure could occur before a person exits the area, so an emergency-off feature is an added requirement. The emergency-off feature is highly recommended for the areas at the Moderate dose category (10 - 100 mSv h^{-1}), when the cost is not an issue.

Access controls into an area shall be used for both the beam-on and beam-off conditions as specified in Table 1. For example, suppose the High dose category exists when beam is on in the area, but when beam is off the area has the Low dose category due to nearby beam operations. Then, the area is required to have an ACS for the High dose category when the beam is on and to have an ACS for the Low dose category when the beam is off.

An area may switch between different dose categories in various beam delivery conditions. In that case, the area should be equipped with access control features for the highest dose category.

Typically, an accelerator area will switch between at least two access conditions: 1) machine on / high prompt radiation / personnel exclusion, and 2) machine off / no prompt radiation / free access. Frequently there is another intermediate controlled access state between the 2 conditions above. The ACS should be designed for safe and efficient switching between the access states, which helps counter the tendency to circumvent inconvenient precautions.

The graded ACS features for prompt radiation may also be applied to the access control to limit exposure hazards from induced activity. However, it should be noted that the prompt radiation hazard is generally more dynamic and less predictable than the induced activity hazard. Therefore, at the same dose level, the ACS requirements for induced activity hazard can be less than those for prompt radiation (e.g., the ACS requirements in the Moderate dose category for induced activity can use those in the Low dose category for prompt radiation).

Administrative access control requirements and recommendations to areas with dose rate ≤ 0.05 mSv h^{-1} (5 mrem h^{-1}) shall be part of the operational radiation safety program.

ACS Features

Typical features of an entry module for an area with interlocked access control, as illustrated in Fig. 1, can include:

1) An interlocked, and lockable, outer door (with emergency entry and exit),
2) A maze and an interlocked, but not locked, inner gate,
3) A keybank with keys. In the Controlled Access or Restricted Access state, everyone entering the area is required to take a key from the keybank and carries it with him/her during the period of access,
4) A key switch and push button for door release (controlled by operator),
5) An access and beam status display, as well as radiation warning light and sign,
6) Intercom or telephone for communication with operator, and
7) TV camera to facilitate access control by operator.

These features allow the accelerator operators to maintain access control and allow people a safe entry.

Warnings and Signs.

In areas with the Low dose category or higher (> 1 mSv h^{-1}), pre-start-up notification using audible and visible warnings (such as horns, buzzers, public address system announcements, or distinct lighting) shall be given by the Operators before prompt radiation can be potentially produced in the area. The characteristics of audible and visible warnings shall be distinct so that the warning is unambiguous. Pre-start-up warning(s) shall be suitable for the ambient work area conditions. Warnings shall be adequate for hearing impaired workers. The lead-time shall be long enough to allow personnel to reach an emergency-off switch (when provided) or to safely evacuate an area before radiation is produced.

The following three phases of informing the workers of the operation status and hazards may be appropriate: 1) warning which indicates when the accelerator is preparing to produce radiation, 2) a signal when the radiation is about to be produced, and 3) a distinguishable signal when the radiation emission is underway.

The locked or interlocked personnel entryways shall be equipped with clearly visible signs indicating the access state and potential radiation hazard. Equipment entryways or non-routine personnel entryways, not equipped with entry/egress systems, are subject to the same requirements as Table 1; however, the postings for access state and radiation hazard may not be needed. When personnel entryways are interlocked, they shall be equipped with status lights and signs.

Areas with the High dose category (> 100 mSv h^{-1}) shall have easily accessible and clearly identified emergency-off switches, which enable a person inside to prevent or terminate radiation production in the area. Opening of exit doors shall inhibit radiation production in the area and can constitute the emergency-off switches if properly indicated as such.

The color(s) of the radiation warning and access status lights shall be consistent within each facility and radiation warning lights should be red or magenta.

A sign that describes the significance of the warning light, as well as any access control requirement, should be installed adjacent to the light or otherwise incorporated into the light.

The systems of warning signs, status signs and indicator lights should be made such that the Operator is aware of the access and occupancy conditions, particularly the areas that are going to have beam, so that effective control of the operations and response to abnormal conditions can be made.

Enclosures.

Any area with the dose category of Minimum or above (> 0.05 mSv h^{-1}) shall have a marked physical boundary around the area for the purpose of controlling access and informing those who enter about the hazard. The boundary requirements are specified in Table 1 and described in more detail below. None of the below enclosures shall be established that would prevent rapid evacuation of personnel.

The enclosure for an area not higher than the Minimum dose category (≤ 1 mSv h^{-1}) can be a rope with warning signs. The purpose of the rope is to provide a warning perimeter rather than to prevent entry. The access and dose controls for areas in this dose category shall be addressed in the operational radiation safety program.

Areas with the Low dose category or above (> 1 mSv h^{-1}) shall be enclosed by a barrier that is sufficient to prevent accidental, inadvertent or unauthorized entry (except with deliberate attempt to defeat the ACS). Examples of a suitable barrier include a wall of shielding material, a building wall, and a chain link fence. The barrier shall have sufficient height above any adjacent surface on which a person could normally stand to prevent unauthorized entry.

The configuration control program shall ensure the integrity of the barriers. If a barrier may be climbed or reconfigured with means available within the facility such as ladders, cranes, and forklifts, the barrier shall be posted with warning signs. Potential exposure issues (e.g., skyshine radiation to near-by areas or an individual standing on an elevated surface next to the barrier) beyond the top of barrier shall also be considered.

For the narrow beam geometry in which the potential radiation exposure is only a small portion of the whole body, the barrier can be in a form of exclusion zone around the beam, which prevents the exposure to the beam. However, consideration must be given to potential scattered radiation, which may need specific shielding.

Personnel Entryway Gates.

The gate (or door) of each personnel entryway of a barrier shall be locked or interlocked for areas with the Low dose category or above (> 1 mSv h^{-1}).

For areas with the Low and Moderate dose categories (1–100 mSv h^{-1}), the use of gate interlocks is optional (recommended for the Moderate dose category). In general, higher radiation levels, frequent access, and larger numbers of people making entries make a higher level of automation preferable.

Each gate providing entry into a High dose category (> 100 mSv h^{-1}) area shall be locked and interlocked so that the radiation hazard is terminated and inhibited when the gate is unlocked.

When the gate is closed, it shall meet the Barrier requirements stated above. If a gate can be locked, emergency egress shall be provided, e.g., the locked gates/doors shall be capable of being easily opened (i.e., not padlocked) from inside in case of an emergency.

If a gate is locked (e.g., under controlled access or no access states), the entry mechanism (keys, security cards, etc) shall be under administrative or automatic control so that the radiation hazard is inhibited before the gate can be unlocked and opened. The hazard shall remain off until the area is secured for operation. To enforce this sequence, an exchange key system (or the equivalent) shall be included in the ACS. The system shall also allow the operators to control the entry.

An example of an administrative control might be the checking out a key from the Operations or radiation safety professionals, which may be suitable for small facilities. Examples of automatic control are an interlocked key release system or a security identification system.

Exclusion Area.

Any area with the Moderate dose category or above (> 10 mSv h^{-1}) shall be an Exclusion Area. An Exclusion Area needs to have locked personnel entryway gate and interlock is also recommended. An Exclusion Area also requires an Area Secure System that uses interlocked equipment and written procedures to enforce the correct completion of the sequence to make the area ready (secured) for the hazard to be turned on and to ensure that persons are not left inside during changeover of access states.

The area secure sequence shall include steps confirming that personnel have left (e.g., using search pre-set, search switches, search reset), gates are locked, and hazard warning has been issued. The Area Secure System shall keep the hazard inhibited if the search sequence is not correctly executed and for a preset time (at least 30 seconds) after the warning so that a person left inside can exit or actuate the emergency-off switch (when provided). Search switches are required for any area where the presence of a person is not obvious to verify and are recommended for areas where the presence of a person is obvious to verify.

When practical (e.g., a single-room facility), a video monitoring system can be used to check the personnel presence inside an Exclusion Area.

Beam-Inhibiting Devices.

The RSS beam-inhibiting device is a device capable of terminating the hazards in an accessible area. Examples of suitable beam-inhibiting devices may include:

- A power supply for the gun or accelerator RF system, which can be used to remove the beam source.
- A beam shutter, which can be inserted into the beamline to make the downstream area safe for access.
- An electromagnet that, when it is off, renders beam passage impossible.

An example of a device that would be difficult to qualify as an RSS beam-inhibiting device is an electromagnet that is powered on to stop beam passage, because it is not intrinsically fail-safe.

The beam-inhibiting devices and interlocked doors/gates are critical safety system devices that shall meet a high standard of reliability and fail-safe requirements.

The use of at least two dissimilar beam-inhibiting devices to avoid common-mode failures is recommended. The inhibit status of the device shall be signaled to the interlock system by indicators (switches) that read the actual state of the device (in/out, on/off) and are independent of the device command signals.

The RSS beam shutters (or a beam stop fixed in the end of a beamline) shall have sufficient lateral size to intercept any mis-steered beam. If a shutter is inserted to intercept and block the beam, it shall be capable of providing the required Allowed Beam Power heat-load protection for at least an hour. If a shutter intercepts the beam only when a prior safety device fails (e.g., the downstream shutter of a redundant 2-shutter system), it may not need the heat-load protection.

The shutter shall include a secondary means to terminate beam delivery when excessive beam power is detected. Examples of an acceptable secondary method include, but are not limited to, a radiation detector located next to the beam shutter, the beam shutter's internal water circuits or air passages that release air into the accelerator beam pipe if the beam burns through or melts the beam shutter, vacuum or temperature interlocks, or a switching system to shut down the accelerator or switch beam to a full power beam blocking system.

ACS Interlocks

The ACS interlock system makes connections between the beam inhibiting devices and area access controls so that only intended configurations are possible. A typical implementation of the interlock system prevents beam inhibit removal or restoring the beam permit when an entryway is open to the Moderate dose category area or above (> 10 mSv h^{-1}).

In addition to the general RSS requirements, the interlocked ACS system shall meet the following functional requirements.

General Requirements.

The ACS interlock system shall keep the beam-inhibiting devices in place and performing their intended functions until personnel have left the area and entryways are closed (and area secure logic is satisfied, when required). When conditions change from area open to area closed, a non-permissible configuration shall not exist (e.g., beam can be on with entryway not closed), even momentarily.

The ACS shall not be designed so that its interlocks are used as the normal accelerator on-off control function. Normally, the standard accelerator control system should be used to enable/disable operations. However, the interlocks shall be capable of terminating/preventing operations under fault conditions. Manual shutdown capability shall also be provided to override the interlock controls.

An important consideration should be the balance between the testability and reliability inherent in functionally simple interlocks and the added complexity and overhead associated with redundancy and operational flexibility which may allow multiple operational modes such as the ability to deliver beam to some Exclusion Areas while others remain open.

Redundancy.

When an interlock system is used, a redundant system is recommended and, in the High dose category (> 100 mSv h^{-1}), a redundant system is required.

The ACS redundancy requirement shall be met through the use of at least two entirely independent interlock chains (with no shared components). Redundant components shall include, but are not limited to, separate sensing devices on entryway gate(s), beam inhibiting device(s), connecting wire interfaces, system logic, and beam termination means. If the whole system is subject to a single point failure, the system is not redundant. The systems can be identical or can use different components. In case of an ACS violation (e.g., door is opened accidentally) or a RCS violation (e.g., interlocked radiation monitor trips), the hazard shall be removed by at least two independent means.

A beam area access door (or a single mechanical beam shutter between two beam areas) with two independent micro-switch chains is an acceptable example of redundancy, but a double-pole micro-switch does not meet redundancy requirement.

If the ACS uses two beam shutters inserted by independent air pressure systems, the loss of air pressure is not a common-mode failure. However, even though the system is redundant, it is not acceptable because it is not fail-safe.

Design Considerations.

The ACS at large facilities will usually incorporate an extensive network of sensors (such as switches), signal distribution (wiring), logic (often relay logic), and outputs to numerous controlled devices (such as beam inhibiting devices and door locks). An effective design process should consider a range of means of implementation and make choices suitable for the facility. The design criteria shall include reliability, maintainability, testability, and simplicity.

In addition to the required redundancy features, additional means for secondary or backup protection may be considered. Examples include administrative measures such as personnel count when securing an Exclusion Area, or engineered measures such as motion detectors active when Exclusion Areas are closed and radiation detectors active when Exclusion Areas are open.

Use of Computer-Based Logic Systems.

Computer-based logic systems, e.g., the Programmable Logic Controllers (PLC), used in the ACS shall be subject to the same requirements and recommendations as those for relay-based logic systems.

In addition, the following design and operational considerations shall be made in applying appropriate computer-based logic systems:

1) The system shall be maintained in proper configuration control. For example, the computers used shall be dedicated solely for the ACS. No external interferences, e.g., connection to external network, shall be allowed. The system or its underlying programming shall be completely isolated from such networks, including the World Wide Web.

2) Multiple applications installed on a single computer have a potential for interacting. These interactions may not be predictable. Therefore, all results of the interactions may not be testable. Significance should be placed on defense-in-depth against the propagation of common-cause failures within and between functions.

3) Redundancy requirements should be achieved by using independent computer systems and may include different programmers working independently in writing the logic software for the systems.

4) Software program requirements shall follow a pre-determined set of specifications.

5) The expected functional behavior of the computer-based logic systems shall be specified to consider both normal and abnormal operation. When the system fails, the system as whole shall remain in or move to a safe state.

6) In special cases where the computer-based system unavoidably represents a single point or common cause failure mode, additional measures shall be used to mitigate, control, or lockout the hazard.

7) Software programs shall reside only in non-volatile memory. A sufficient Uninterruptible Power Supply (UPS) system shall be provided for long-term (minimum 24 hours) retention of the program state.

8) Watchdog timers shall be incorporated so that action can be taken if the program fails to reach appropriate checkpoints within a specified time.

9) High modularity and testability should be considered.

10) Safety-rated PLC systems shall be used.

11) An integrated risk assessment of the interlock systems shall be made in the design phase and before implementation.

12) Software quality assurance shall be performed.

13) The system shall be validated, verified and peer reviewed prior to use.

For detailed information on designing and using computer-based logic systems for the ACS, the guidelines given by the ANSI/ISA-84.01 (ANSI 1996), the European Workshop on Industrial Computer Systems, Technical Committee 7 (EWICS 1998), and the International Electrotechnical Commission reports (IEC 2000) may be consulted.

Review

This section only applies to the interlocked-type ACS, which is recommended for the areas with the Moderate dose category (> 10 mSv h^{-1}) and required for the High dose category (> 100 mSv h^{-1}).

Before a new ACS is accepted prior to routine operation, the system shall be reviewed and documented by drawings and a written functional description. System modification shall be documented, reviewed and approved. The Operations manager and the RSO shall pre-approve the ACS system documents and procedures for testing and use.

A new ACS or any significant ACS change for the High dose category (> 100 mSv h^{-1}) facilities shall require an independent qualified expert(s), internal or external, review.

Certification and Checks

This section only applies to the interlocked-type ACS, which is recommended for the areas with the Moderate dose category (> 10 mSv h^{-1}) and required for the High dose category (> 100 mSv h^{-1}).

An ACS certification and check program shall be developed in the system design and installation stage. The certification and check processes should be designed to be effective and efficient, as well as commensurate with the operation schedule.

The certification of the ACS shall be performed under each of the following conditions (in the order of comprehensiveness):

1) Prior to accelerator commissioning or major ACS changes, the whole system including all functions of the ACS logic, unintended functions, and potential common mode failures through errors in system design or implementation, and component failures, shall be certified. This comprehensive certification can be viewed as an acceptance test of the whole

interlock system.

2) The validity of certification is one year. Therefore, before accelerator operation past one year following the last successful certification continues, the ACS hardware and functionality shall be certified to operate as intended. A grace period of 1-2 month can be granted under special conditions. This can be viewed as the annual certification of the system.

3) Before restarting operation following the ACS modification, repair, or maintenance on specific system components, the potentially affected system parts shall be certified.

The completion of the ACS certification shall be reviewed and approved by the Operation manager before operation can commence.

The ACS certification shall be end-to-end, verifying that all input conditions are properly sensed and all consequent actions occur correctly according to the system design. Each component shall be exercised and each required system action be confirmed. Critical fail-safe features shall be tested (e.g., devices that require power to operate shall fail safely). Signal level (e.g., radiation or electrical current) inputs shall be verified for accuracy, and the reliability under extreme conditions such as extreme overload shall be confirmed. In redundant systems, all branches shall be tested.

More frequent and periodic checks of the interlocks by the Operations or qualified experts shall be implemented for system components (e.g., micro-switches, emergency-off, keybank, etc) that are subject to accidental damage or potential failures caused by frequent use or presence in a harsh physical environment.

The certification, checks, inspections, and maintenance of the ACS shall be conducted under formal written procedures by authorized personnel, and the results shall be documented.

The procedures shall be managed under a formal document control system with provisions for review and approval. Records pertaining to the ACS installation, modification, certification and check, and maintenance shall be retained.

Radiation Control System (RCS)

The facility shall have a Radiation Control System (RCS) to ensure that prompt radiation in occupiable areas does not exceed the expected levels under both normal and abnormal accelerator operation conditions.

As shown in Fig. 1, the main system elements of the RCS are shielding (both bulk and local), beam limiting devices, and radiation monitoring devices. The preferred implementation of the RCS uses passive elements (e.g., shielding and fences), to interpose mass and distance between radiation sources and personnel. Lower in preference is the use of active elements that monitor and terminate un-allowed beam or radiation conditions through interlocks. Examples of active systems may include the beam interlocks using current monitors and beam loss monitors as well as radiation interlocks using fail-safe radiation detectors.

If the shielding for a full beam loss at any point of the beamline does not require demanding architectural or engineering solutions and can be implemented, there is then no need for an active system. However, for many facilities a reasonable combination of passive and active systems can offer a robust and cost-effective solution to meet both the safety and operational requirements. A typical example of the combined use of passive and active systems is to: 1) use a shield wall for normal beam losses so that the annual worker dose is only a small fraction of the permitted dose, and 2) use radiation monitors placed inside and/or outside the shielding wall to detect and terminate high radiation levels, which occur from abnormal beam losses (e.g., a loss of a large fraction of beam at an unexpected location).

The active RCS systems shall follow the requirements and recommendations for interlocked-type ACS in the previous section. Independent (internal and/or external) reviews are essential and are necessary when active systems play extensive or major roles in the RCS.

Performance Requirements

The facility shall have a written policy in setting the performance goals and requirements for the RCS for both normal and abnormal operations.

Normal Operation.

For normal operation within the Operation Envelope, the RCS for an area shall limit the prompt radiation to the level allowed by the area's dose category (see Table 1).

The passive element of the RCS (shielding and fence) shall be used to control the prompt radiation so that the maximum annual dose in areas that only radiation workers can occupy frequently (i.e., an occupancy factor of 1) is no more than 10 mSv y^{-1} (1000 mrem y^{-1}). It is recommended that the maximum annual dose be no more than a fraction of the legal occupational dose limit. As the current US limit for occupational dose is 50 mSv y^{-1}, 10 mSv y^{-1} corresponds to a fraction of 20% of the legal limit.

For areas that may be occupied frequently by non-radiation workers (whose current dose limit is 1 mSv y^{-1}, the same as the visitors or general public), the RCS passive elements shall control the maximum annual dose to be no more than 1 mSv (100 mrem).

The ALARA principle should be observed in designing the RCS. For example, synchrotron light sources have many short-term users and visitors and, thus, a lower design limit of 100 mrem y^{-1} should be achieved by using the RCS passive elements (shielding and fence) so that the collective doses can be reduced and less comprehensive safety training requirements are needed. This principle also applies to industrial production-type facilities, in which the modes of operation are simple and the hazards are designed to be low (e.g., ≤ 1 mSv y^{-1} outside the accelerator housing) so that the facility can have minimum operational safety controls and the operators/users of the machine can have minimal safety training that is commensurate with the lower hazard levels.

The passive element of the RCS (shielding and fence) should also be used to control the off-site doses from direct or skyshine radiation so that the maximum exposed individual of the general public (who reside near the site boundary) receives an annual dose no more than 0.1 mSv y^{-1} (10 mrem y^{-1}). This corresponds to 10% of the current legal public dose limit of 1 mSv y^{-1}.

Note that the ALARA principle should also be observed in controlling the doses to the public. An occupancy period of ≥ 7200 h y^{-1} (a typical facility annual operation time, excluding machine down and maintenance) should be used to estimate the off-site doses to the public, who reside near the site boundary.

In general, the direct skyshine radiation to off-site public should be limited by the use of appropriate shielding.

The active RCS system elements shall be used to detect abnormal operation or beam loss situations (e.g., operation with beam higher than Allowed Beam Power or an unexpected loss of a large fraction of beam) and terminate/mitigate the resulting unacceptable high dose rates either to people (worker and public) or the environment.

As specified in Table 1, when any area entryway gate may be left unlocked, radiation levels within that area must be ≤ 1 mSv h^{-1} (100 mrem h^{-1}). That sets a minimum requirement for the RCS of the area. However, continuous exposure of a person to radiation near this level would rapidly exceed the permissible annual limit. Therefore, additional measures should be taken to control the worker exposure. If the area can be accessed or occupied frequently, the radiation level in the area should be reduced via the use of RCS, e.g., shielding. If the area will be accessed or occupied only infrequently, administrative access controls to limit the occupancy should then be in place.

Abnormal Operation.

A wide range of abnormal operating and beam loss conditions with different probabilities may occur during accelerator operations. Abnormal operations that should be addressed are the ones that are credible. Therefore, the facility shall evaluate and decide which abnormal operating conditions or abnormal beam loss scenarios are credible, based on the capabilities of the accelerator systems, modes of operation, and the features of the implemented RSS. Experience from peer accelerator facilities can serve as a useful guidance for this critical and essential decision-making process.

Examples of credible abnormal operations include full loss of beam higher than the Allowed Beam Power (when toroid fails and operators mis-tune the machine to have a higher current) and the loss of Maximum Credible Beam Power. Clearly, the former scenario has a higher probability than the latter. An example of an incredible abnormal operation is a full loss of the beam power delivered in excess of that specified in the Safety Envelope, which may only happen after a day's tuning by operators when the machine's RSS fails. A complete failure of an interlocked ACS is another example of an implausible abnormal operation.

The RCS shall limit any abnormal operation so that the maximum integrated dose per event is a small fraction of the permitted dose, e.g., no more than 10 mSv (1 rem) for unlikely events. Lower limits can be used for those abnormal operations that can occur with higher probabilities.

It is generally not practical for all parts of the facility enclosure to be designed to completely contain the radiation from all abnormal operations. Therefore, to meet the recommended limit of 10 mSv (1 rem) per event, shielding can be used to reduce the instantaneous dose rates generated from abnormal operations to acceptable levels (e.g., 10-1000 mSv h^{-1}, depending on the event probability) and then the beam loss interlock and/or radiation interlock are used to detect and terminate the abnormal event so that the integrated dose per abnormal event remains acceptable (i.e., $\leq$ 10 mSv or lower).

If it is not practical to use active interlocks to terminate an abnormal event, the operator's awareness of operation and his/her taking action to terminate the abnormal operations may be used as an argument to estimate the duration of an abnormal event, though this is not a preferred way.

The facility should address the risk and the controls for abnormal operations through the following steps:

1) Determine credible abnormal operational scenario, including the Allowed Beam Power and the Maximum Credible Beam Power (maximum beam energy and/or maximum beam current) the accelerator can generate at different locations throughout the facility, considering the potential output of the beam particle, modes of operations, the available accelerating system capability under potential system failure conditions, etc,
2) Estimate the dose rates outside of the Exclusion Area throughout the facility under various credible abnormal operations, by considering the potential beam power, points of beam escape or impingement, impacted material, and shielding enclosure weaknesses (for example, thin shielding or holes),
3) Potential occupancy in areas with significant radiation hazards,
4) Describe how the abnormal events are monitored, detected and mitigated/terminated, and
5) Demonstrate the adequacy of the RCS by showing that higher levels of radiation risk are mitigated by increasing layers of safety control (e.g., thicker shielding, more controls on the beam and/or radiation, as well as occupancy control).

Passive Systems: Shielding and Fences

Radiation attenuation can be accomplished by interposing mass (shielding) and distance (e.g., fences). These passive measures are the preferred means to achieve the goals of the RCS, because they are not dependent on the systems' capability in detecting an unsafe situation and reacting to it to terminate a radiation hazard.

The facility shall have a conservative shielding design policy and configuration control program for the passive elements. Conservative operation schedule and beam loss scenarios for the accelerator operation shall be used in the shielding design. Shielding design shall consider both normal and abnormal beam loss conditions, including the losses of the Allowed Beam Power and the Maximum Credible Beam Power. Possible use of different beam particles and target design, as well as different facility and beamline configurations, should be considered in the shielding design.

Reasonably conservative occupancy factor shall be considered in establishing the shielding requirements for normal beam loss scenarios. Experimental/working areas and offices shall use an occupancy factor of 1, i.e., the area is assumed to be occupied continuously and the occupancy period used to estimate the annual dose is generally 2000 h y^{-1}. Occupancy factors of less than 1 may be used for some areas (e.g., spaces designed for limited occupancy like roof, storage rooms, restrooms, parking areas), if the area occupancy can be managed or reasonably estimated, and the occupancy condition is not likely to change in the foreseeable future. Occupancy factors are only to be used for normal operating conditions and occupancy factors less than 1/16 should not be used. When an occupancy factor less than 1/16 is used, access to those areas with radiation shall have additional controls to avoid potential unacceptable doses.

Any penetrations (e.g., cable trays, ventilation) on the shielding walls and overlap between walls should receive similar attention as the wall itself.

A radiation safety professional shall be consulted for the shielding design, for shielding verification by radiation survey, and before extensive changes to the shielding are made which could alter the radiation fields in occupiable areas.

The shielding verification surveys should include measurements of normal and abnormal modes of operations. The survey should be adequate to characterize the fields for different radiation types and correlate with expected operation modes so that the doses to an individual around the facility and the public off-site can be estimated. Instruments used to complete the survey shall be capable of finding thin collimated radiation emanating from cracks and voids in the shielding.

To validate the shielding designs in the Safety Envelope, it may be necessary to make measurements under special operating conditions, such as causing deliberate impingement of the beam along the accelerator and beamlines where typical beam losses do not produce a useful reading. Such tests should be performed safely, carefully and accurately so that the basis of the shielding design can be validated. In general the interlocked safety system should not be bypassed to carry out these tests unless it is in a specially controlled condition.

Active Systems

Active RCS systems detect unwanted operating conditions (e.g., high beam power or radiation) and react to mitigate the radiation hazards (e.g., the systems stop beam delivery or reduce the radiation level). Typical systems use beam energy, beam current, beam loss, and/or radiation measuring equipment programmed with hard limits to prevent unwanted beam conditions from occurring.

The beam power and/or the beam losses of the accelerator should be physically limited or interlocked so that the shielding is adequate.

Active RCS systems shall meet the technical (reliability and fail-safe) and administrative requirements that apply to the ACS to the extent applicable. The requirements include high reliability, redundancy, tamper-resistance, quality assurance, configuration control, use of procedures, and annual system certification. In addition, the active systems shall be periodically calibrated and their active and operational status maintained and verified regularly during operations.

In addition to the active RCS elements for personnel protection, facilities generally have interlocked systems for machine protection purposes. These machine protection systems may not be subject to the same quality, testing, and configuration control requirements as those for the active RCS. These systems are in general controlled by the operators and may be by-passed for operational convenience without prior radiation review and approval. The differences between the two systems shall be accounted for when taking credit of the machine protection systems as part of the RCS.

Beam Interlocks.

If the accelerator can produce beam energy or current that exceeds the limits described by the Operation Envelope in any part of the facility, the limits should be automatically enforced. This can be done, for example, by implementing interlocked beam energy or current measurement devices.

If beam losses at any given point can cause radiation levels exceeding the acceptable levels, then the beam loss limit should be automatically enforced. Methods include interlocked beam loss monitors (e.g., beam current comparators) and radiation detectors placed either inside or outside the shielding.

Radiation Interlocks.

Radiation detectors should be used to detect and mitigate elevated radiation levels, particularly in frequently occupiable areas. When used, these detectors shall provide warnings to the operators and to personnel in the area where increased radiation levels have been observed, and should also terminate beam delivery or reduce the radiation levels.

When the radiation detector use is critical, e.g., it is used to detect and terminate high dose hazard in a frequently occupiable area, an interlocked system to enforce the termination/mitigation shall be used. In this case, a fail-safe system, e.g., a detector equipped with a self-check source, should also be considered.

The type, sensitivity and location of the detectors shall be suitable for the expected radiation hazard. Attention shall be paid to possible effects on detector response resulting from accelerator's pulsed radiation fields, the RF/magnetic field interference, and radiation damage to the detection system.

Administrative Controls

To stay within the Operation Envelope, machine characteristics such as the beam energy, beam current, number of integrated beam particles, pulses, bunches and particle type should be controlled by administrative means (e.g., computer control or operating procedures), if not by engineered means. Administrative controls may also be satisfactory to act in response to temporary excursions outside of the Operation Envelope for low-hazard conditions.

Miscellaneous Issues

Accelerator Operations Relevant to RSS

A readiness review shall be conducted by management and/or authorized individuals prior to the commissioning or the first operation of an accelerator facility. As a minimum, the readiness reviews shall demonstrate that:

1) The Radiation Safety System is in place and can operate properly,

2) The associated safety systems and certification/testing process are documented and approved,

3) The administrative responsibilities for operational safety are clearly defined, and

4) The personnel involved are trained at the appropriate level.

Control system design shall allow the operators to directly turn off the accelerator independently from the normal beam control system. This shutting down procedure or emergency-off system shall require a manual reset before beam operation can resume.

Records germane to the safety management, such as temporary or permanent changes in the ACS or the RCS, and notices of temporary operations outside the Operation Envelope, shall be readily available to the operators and other personnel. Changes to the ACS and/or RCS shall be posted either in the area affected, disseminated by email, and/or posted in the accelerator control room, or at some centrally recognized location in a way which will ensure that the information is available to those who need it.

There are special operation conditions (e.g., processing the RF cavities or klystrons without beam operation) that a facility may be operated without the operators being present in the operation center (or near the control panel). In this unattended operation mode, the operating parameters and the resulting hazards shall be monitored and controlled via engineered means. If operation or hazard exceeds the pre-set ranges, the operation shall be terminated automatically and cannot be resumed. Any emergency situation shall also be properly addressed before these unattended operations are allowed. Long-term unattended operations should require periodic status monitoring and verification.

Programs and approved processes to ensure the reliability and functionality of the Radiation Safety System shall be conducted as specified. Maintenance, installation, and repairs for safety-related items shall be part of the facility maintenance plan and process.

RSS Interlock Bypasses or Variances

No RSS interlock bypass or variances shall be made if it may in any way endanger personnel.

An example of variance, which has safety implications, is the continued operation after the failure of one channel of a redundant interlocked safety system. Policies and procedures shall be developed and used to govern and control interlock bypasses and variances.

All interlock bypasses or variances shall be justified and approved by authorized personnel (including an appropriate radiation safety professional, e.g., the RSO and the Operations manager) as defined in approved operating procedures. These processes shall be followed and completed before any interlock bypass or variance is implemented.

Details of any interlock bypass or variance shall be clearly documented so that it can be reconstructed or reproduced if necessary. Interlock bypass/variance documentation should reference `fault' or `service' report numbers so that broken or damaged devices are promptly repaired. The documentation shall specify the date and intended duration of the bypass/variance as well as any applicable limitations. Interlock bypasses/variance shall be posted at the affected device or system and at a location near the console.

Some form of alternative protection shall either exist or be substituted for any interlock bypass, which results in the removal of a level of personnel protection. Such alternate protections may involve, for example, immobilizing a device (which is usually freely moveable), implementing a tightly controlled administrative procedure for an engineered interlock, or administratively locking hazardous areas to prevent access. Padlocks, with appropriate key control can be used for this purpose but combination locks should be prohibited for this use. A description of the alternate protection shall also be documented.

Interlock bypasses should be made as close to devices as possible so as not to lose protection from other interlocks that may be in a chain.

Normal interlock protection should be restored as soon as a bypass/variance has served its purpose. The removal of any interlock bypass/variance - and the verification of the interlock, as appropriate - shall also be documented and approved by authorized personnel.

Interlock bypass/variance documentation shall be reviewed regularly to ensure the timeliness, sign-offs, and documentation of bypass removal.

There may be very special cases when an individual needs to enter some parts of an area to perform tasks while the prompt radiation hazards remain on in the area. This situation represents even a higher level of concern than the interlock bypass. This shall be treated with utmost caution and requires the approval by the facility management and the RSO. This shall not be allowed without a sound justification, e.g., hazards can be controlled and assured, there are no other alternatives, and the task is mission critical. This shall be performed only under tightly controlled conditions (e.g., the prompt radiation level in the accessed area is certain to be ≤ 10 mSv h^{-1}) with special procedures (e.g., both the beam and work conditions are continuously monitored by operators). It should be noted that the exposure control for prompt radiation is different from that for induced radioactivity, though the dose levels may be similar.

Conclusions

Some aspects of radiation safety problems at accelerator facilities are different from those of nuclear facilities, especially in the protection against the prompt radiation hazards. Currently there are no detailed standards for the establishment of radiation safety systems at accelerator facilities. It is hoped that the requirements and recommendations described in this report, which are basically the same as those of ANSI N43.1 Standard draft, will allow the accelerator community to have a sound, consistent and harmonized approach in establishing radiation safety systems amongst the accelerator community.

Common Terms

Abnormal Beam Loss: A beam loss in excess of that prescribed or normally anticipated and occurs only infrequently. Examples include: a large fraction of the Allowed Beam Power is lost (e.g., due to RF trip or magnet failure, which are treated as part of normal operation, i.e., Operation Envelope) or the Maximum Credible Beam Power is lost (which is treated as part of abnormal operation, i.e., Safety Envelope).

Abnormal Operation: Because of the RSS (Radiation Safety System) failure and/or inappropriate operator action, a situation in which the beam is sent to the wrong location, a location receiving higher than authorized beam current (e.g., exceeding the toroid limit), an area not currently authorized, or an area with deficient shielding.

Access Control System (ACS): A system that prevents or controls personnel access to hazardous areas deemed unsafe due to the production of prompt radiation.

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

Allowed Beam Power: The maximum beam power allowed by the Operation Envelope. It is generally monitored and/or limited by electronic means. Its value is related to shielding design for normal operation.

Area Secure System: A system that uses procedures and interlocked equipment to enforce the correct completion of the sequence to make the area ready (secured) for the hazard to be turned on and to ensure that persons are not left inside during changeover.

Barrier: A structure, e.g., shielding wall or fence, that prevents or controls access to an area or building where radiation levels or other hazards are unacceptable.

Beam Inhibit: An operational mode in which beam is stopped by mechanical or electronic means such that the potential hazards to workers are removed.

Beam Interlock: A device, which acts to terminate or reduce the radiation hazards when pre-set beam conditions, e.g., beam current is too high or beam energy is out of range, are detected.

Beam Parameters: Characteristics of the beam which include, but are not limited to, beam particle type, beam size, beam power, beam current, beam energy, the beam pulse repetition rate (macro and micro pulse rates), etc.

Beam Shutter: A physical or mechanical device capable of stopping the beam and keeping the downstream areas safe when inserted into a beamline.

Beam Stop: A physical or mechanical device fixed in place, generally at the end of a beamline, and capable of absorbing the Allowed Beam Power and keeping the downstream areas safe.

Configuration Control: A system that maintains the viability of safety systems by ensuring that unauthorized and undocumented changes are not made to the facility. The system shall be documented and maintained in accordance with safety system needs.

Exclusion Area: An area in which personnel access is prohibited and/or restricted by physical barriers with at least locked entryway gate and interlock is also recommended. Areas with a prompt radiation dose level > 10 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 operation.

Fail-safe: A safety system built to be in a safe mode in the event of any single point failure.

Graded Approach: A reasonable and sound approach to provide increased levels of radiation safety through the use of increasingly more restrictive, and/or layers, of safety measures based upon the need to protect personnel and environment from increasing radiation risks.

Interlock: A device or group of devices arranged to sense a limit or off-limit condition or improper sequence of events that functions to shut down the equipment or prevents operation. Interlocks are specifically designed to avoid and/or terminate a hazardous condition.

Interlock System: An engineered control system that includes the interlock devices and interlock logic at the heart of its system.

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

Normal Beam Losses: Beam losses that are anticipated as part of routine and planned operation, e.g., 100% loss in a beam stop, a small fraction (< a few percent) beam loss in an aperture like collimators. This is treated as part of normal operation, i.e., 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 RSS (Radiation Safety System).

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

Operation Envelope: The 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 (e.g., full beam loss in areas designed for such a scenario), but do not include the unlikely beam losses under safety system 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.

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, which acts to terminate or reduce the radiation hazards when pre-set levels of radiation are detected.

Radiation Safety System (RSS): An engineered and administrative system, consisting of the ACS and the RCS, which acts in concert to protect individuals from prompt radiation exposure due to accelerator operation. In some cases, the engineered-type RSS may be used to control high hazards from induced radioactivity.

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

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

Safety Envelope: The limiting parameters within which the accelerator is required to operate without causing unacceptable dose consequence. These generally include the maximum beam energy and current (i.e., the Maximum Credible Beam Power), maximum beam losses, the Radiation Safety System constraints, the dose limits to workers and public, environmental restraints etc.

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

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

Secured Area: An area that has been administratively swept of all personnel and locked (interlocked) to prevent entry to any personnel who have not been authorized and given a release to enter the area by the accelerator operations control room.

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As the N43.1 standard is not yet officially approved by ANSI as of 2007, the requirements and recommendations in this chapter should not be quoted as official ANSI positions. The authors also take full responsibility for any possible errors of this chapter and any discrepancies with the N43.1 standard.

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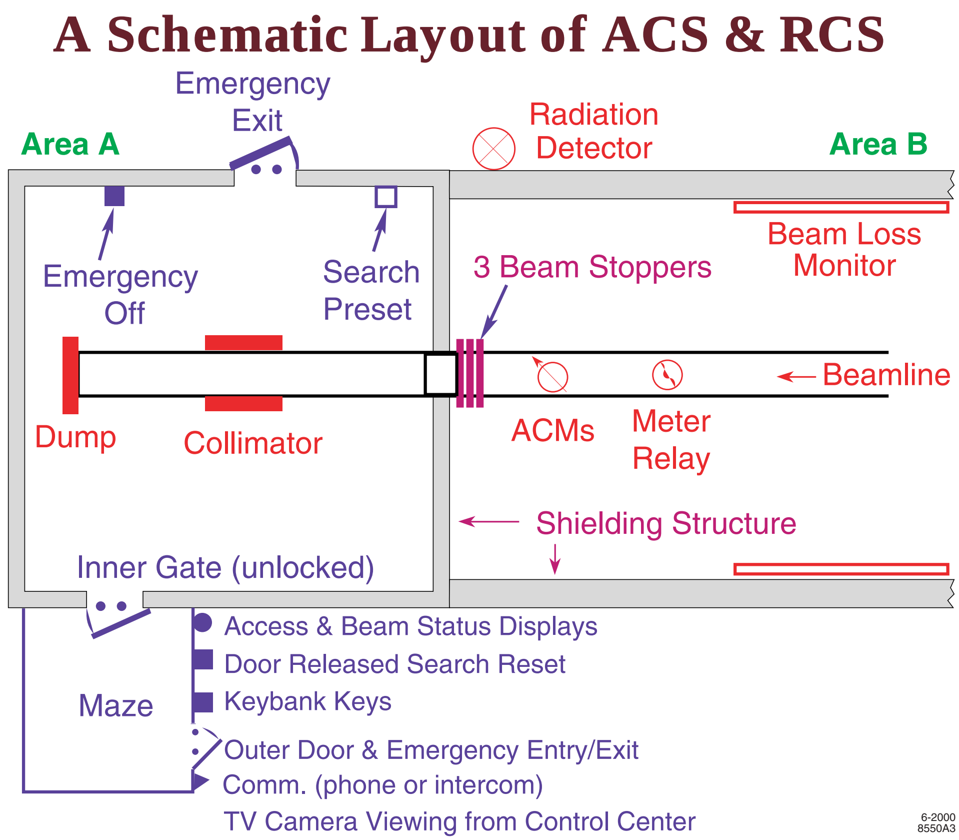

Fig. 1. A schematic layout of the ACS and RCS

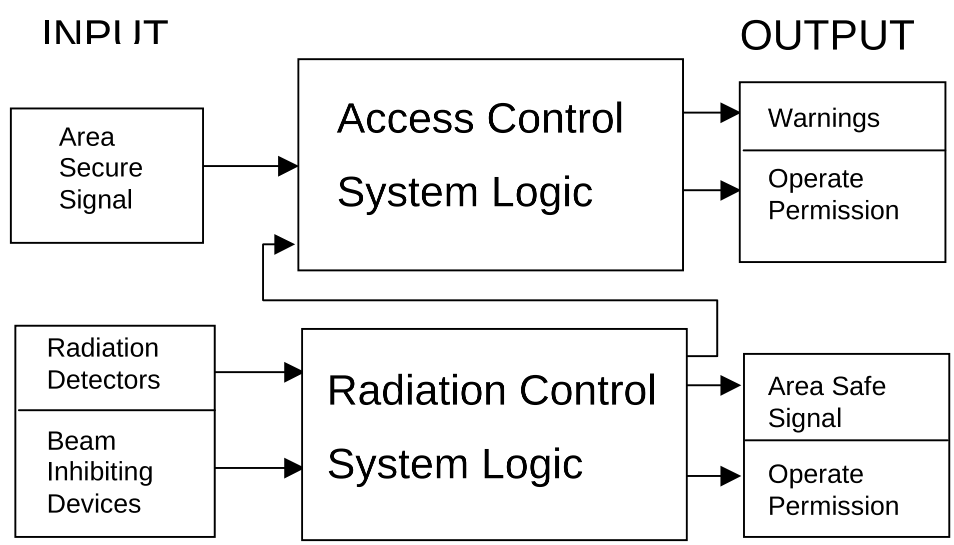

Fig. 2. Generic relationship of the ACS and the RCS in a complicated, engineered RSS

Table 1. Graded features required for the Access Control System (ACS) for prompt radiation.

Dose Rate ($mSv\ h^{-1}$)	Dose Category	Start-up Warning	Enclosure	Each Personnel Entryway Gate	Interlock Redundancy	Area Secure System
0.05–1	Minimum	None	Rope	No Restriction	None	None
1–10	Low	Visible/Audible	Barrier	Locked or Interlocked	Recommended	None
10–100	Moderate	Visible/Audible	Barrier	Locked; Interlock also Recommended	Recommended	Required
> 100	High	Visible/Audible; Emergency-Off	Barrier	Locked & Interlocked	Required	Required