Radiation Safety Systems

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Approval

This document, *Radiation Safety Systems* (SLAC-I-720-0A05Z-002), has been reviewed, accepted, and approved for implementation by

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The requirements of this document take effect 23 October 2019.

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Acronyms

ACL	administrative control level
ALARA	as low as reasonably achievable
BCS	beam containment system
BSOIC	beam shutoff ion chamber
BTM	burn-through monitor
CC	credited control
DD	defense-in-depth control
FEL	free electron laser
HPS	hutch protection system
linac	linear accelerator
LCLS	Linac Coherent Light Source
LOTO	lockout/tagout
MCB	maximum credible beam
MCI	maximum credible incident
MPS	machine protection system
PLC	programmable logic controller
PPS	personnel protection system
RF	radio frequency
RSC	Radiation Safety Committee
RSO	radiation safety officer
RSS	radiation safety system
VVS	variable voltage substation

Glossary

allowed beam power. The highest primary power permitted for the beam line in question by administrative and/or electronic restraints. The radiation physicist responsible for the beam line determines the allowable beam power.

beam authorization sheet (BAS). Document authorizing the operation of an electron accelerator facility element.[1] The document is approved by the ALD (or designee) of the directorate responsible for operating that accelerator facility element and by the SLAC radiation safety officer (or designee).

beam containment shutoff system. This system utilizes two electronic summary modules that shut off the beam by two independent methods.

beam containment system (BCS). A beam channel defined by a system of devices – that is, shielding, dumps, collimators, stoppers, magnets, or electronic restraints - designed to contain the beam and/or limit the beam power and/or beam losses to prevent excessive radiation in occupied areas. The BCS confines a beam to an approved channel at an approved allowed beam power.

beam line authorization sheet (BLA). Document authorizing the operation of a photon accelerator facility element. The document is approved by the ALD (or designee) of the directorate responsible for operating that accelerator facility element and by the SLAC radiation safety officer (or designee).

beam line engineer. The engineer responsible for the design and/or operation of the beam line, including the provision of all safety devices such as collimators, dumps, ion chambers, and other containment devices

beam shutoff ion chamber (BSOIC). A device wired into the PPS interlock systems to put in beam stoppers or turn off beam if radiation is detected above a pre-set level

burn-through monitor (BTM). A device wired into the PPS interlock systems to turn off beam if the BTM mechanical beam containment device has burned through.

credited control (CC). An engineered or administrative control to mitigate high or medium risk to people or environment. These controls are considered to be essential for safe operation directly related to the protection of personnel or the environment.

defense-in-depth (DD) (control). An engineered or administrative control to mitigate low risk or to supplement/support credited controls (as an additional layer of defense) to further mitigate high or medium risk hazards

maximum credible beam (MCB). Highest beam power that the accelerator can deliver to a point. The MCB is the lower of (a) the maximum beam power that could be credibly created by machine capabilities and (b) the maximum beam power limited by credited control.

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1 For a definition of accelerator facility element, see *SLAC Conduct of Accelerator Facility Operations*.

maximum credible incident (MCI). Credible incident that may produce the highest radiation outside the shielding

mis-steered beam. Beam that is within the allowed beam power, but terminates partially or fully at a location that is not designed for beam losses

normal beam operation. Beam lines operated within the allowed beam power and with well steered beams

personnel protection system (PPS). A combination of devices and logic systems that includes access control, warning systems and beam stoppers. The PPS prevents access to secured areas when beam is possible or present, and prevents the radiation dose rate from exceeding the shielding design criteria inside secured areas when access is permitted. Hutch protection systems (HPS) are a sub-category of PPS.

protection device. Electronic circuit or module connected to beam line transducers, such as a toroid, flow switch, or ion chamber, that prevent the beam rate, beam power, temperature, beam loss, or other parameter from exceeding specified values. When out-of-tolerance conditions are detected by these electronic modules, beams are shut off by the associated interlock system.

radiation safety system (RSS). A combination of active and passive systems designed to protect personnel from prompt radiation. An RSS typically includes shielding, PPS, BCS, BSOICs and BTMs.

responsible radiation physicist. The member of the Radiation Physics staff assigned to a specific beam line responsible for the radiological aspects of the design and operation of the beam line.

safety envelope. The administrative guideline for facility design that limits the dose to an individual to 30 mSv (3 rem), or a dose rate to 250 mSv/h (25 rem/h)

secondary beam channel. A beam line in which the incoming beam is the result of an interaction of the primary beam with a target, or a synchrotron radiation or free electron laser beam line

secured area. Radiation containment area for which the doors or gates are locked with strictly controlled keys or are interlocked in the PPS

References

Title 10, *Code of Federal Regulations*, Part 835, "Occupational Radiation Protection" (10 CFR 835)

Department of Energy Order 420.2C, "Safety of Accelerator Facilities" (DOE 420.2C)

American National Standards Institute (ANSI) N43.1, "Radiological Safety in the Design and Operation of Particle Accelerators" (ANSI N43.1)

National Council on Radiation Protection and Measurements, "Radiation Alarms and Access Control Systems" (NCRP Report No. 88)

International Electrotechnical Commission (IEC) 61508, "Functional Safety of Electrical/Electronic/Programmable Electronic Safety-related Systems" (IEC 61508)

SLAC Conduct of Engineering Policy (ENG-2018-018)

SLAC Conduct of Accelerator Facility Operations (SLAC-I-010-003-001-00)

SLAC Radiological Control Manual (SLAC-I-720-0A05Z-001)

SLAC Environment, Safety, and Health Manual (SLAC-I-720-0A29Z-001)

- Chapter 1, "General Policy and Responsibilities"
- Chapter 9, "Radiological Safety"

ESH Course 116, Radiological Worker I (RWT I) (ESH Course 116)

1 Safety Systems for Prompt Radiation

This revision of the *Radiation Safety Systems* technical basis document specifies the criteria for radiation safety systems and describes the design of the various systems used at SLAC to meet those criteria. It has been written jointly by the Radiation Physics Group of the Radiation Protection Department, the Accelerator Department Safety Office, and the Controls Department. The radiation safety officer is responsible for maintaining the document. Policies and guidelines for the design and use of the safety systems as well as descriptions of SLAC-specific implementation are included.

This section describes the components of the radiation safety systems at SLAC and the major policies for each and their design and documentation requirements. Sections 2 through 4 describe the components in greater detail.

1.1 Introduction

During operation of accelerators at SLAC, radiation is produced when the electron or positron beam interacts with any material in its path. Secondary particles and photons produced in targets, and synchrotron radiation and free electron laser (FEL) photons, can also produce radiation through atomic or nuclear interactions, including scattering.

The instantaneous radiation produced from these interactions is referred to as prompt radiation. Prompt radiation consists primarily of photons, neutrons, and muons.

Radiation safety systems (RSSs) are used to protect personnel from prompt radiation. The primary components of an RSS include

- Shielding, which attenuates radiation
- A *personnel protection system (PPS)*, which comprises an access control system that prevents personnel from entering areas in which dangerous levels of radiation may be present
- A *beam containment system (BCS)*, which prevents dangerous levels of radiation outside of the shielding enclosure

Other safety systems, such as *burn-through monitors (BTMs)* and interlocked radiation detectors, called *beam shutoff ion chambers (BSOICs)* at SLAC, may also be integrated into the RSS.

1.2 Policies

1.2.1 Shielding

During normal operations all beam lines and experimental facilities must be shielded to limit radiological dose to an individual not to exceed 1 rem in a year, for example, if continuously occupying an area (that is, 2000 h in a year), to an average normal dose rate of less than 0.5 mrem/h (5 μSv/h). The shielding design should aim at reducing the average normal dose rates to as low as is reasonably achievable (ALARA) levels.

Shielding must also be designed to protect individuals under the following defined two non-normal operating conditions:

1. If the accelerator beam is mis-steered, the dose rate outside the shield will not exceed 400 mrem/h (4 mSv/h).
2. If there is a complete failure of the protection systems,[2] the dose rate outside the shield will not exceed 25 rem/h (250 mSv/h).

1.2.2 Personnel Protection

To protect personnel from prompt radiation, personnel access to beam lines and experimental facilities will be controlled through the use of a PPS. The PPS will ensure that beam stoppers are in place to prevent personnel in beam enclosures from exposure to prompt radiation, prevent entry to beam enclosures while beams are operating, and turn off beams when a security violation is detected. Beam shutoff devices operating in response to signals from BTMs and BSOICs may also be integrated into the PPS. All PPSs must meet these requirements:

1. The PPS must be reliable, fail-safe, tamper-resistant, of high quality, and subject to configuration control and periodic certification and testing.
2. Before a new PPS is used for routine operation, the system must be documented with drawings and a written functional description and approved by the radiation safety officer (RSO).
3. PPS bypasses and system modifications must also be documented, reviewed, and approved by the RSO.
4. Each PPS must be certified, operated, and maintained following established written procedures.

1.2.3 Beam Containment

Beam containment means that all accelerator and experimental beams are transported within their designated beam channels to the designed termination point, such as a detector, beam dump, or injection into a storage ring. SLAC policy for containing beams requires all of the following to be met:

1. All beams (primary original accelerated beam and secondary beam produced by interaction of primary beam with matter or produced by primary beam deceleration [synchrotron radiation, FEL) must be prevented from escaping their designated beam channels to prevent exceeding allowable radiation levels outside the shielding enclosure and to prevent burn-through of the beam containment that could lead to acute radiation burns to personnel in occupied areas.
2. Beam **power** must be limited to prevent exceeding allowable radiation levels outside the shielding enclosure or in downstream occupied areas.
3. Beam **losses** must be limited to prevent exceeding allowable radiation levels outside the shielding enclosure or in downstream occupied areas.
4. Beams must be turned off if allowable radiation levels are exceeded outside the shielding enclosure (specifically in occupied areas downstream of the enclosure), or if the beam power striking a device that is designated to contain the beam exceeds the power limit of that device.

2 The failure of the credited control BCS devices that limit the beam power to maximum credible beam is not considered credible and is therefore not considered (see Section 2.3.3).

1.2.4 Other Safety Systems

Two other RSSs are BTMs, which prevent dangerous levels of radiation outside the shielding enclosure, and BSOICs, which terminate accelerator operation if excessive radiation is detected in potentially occupied areas.

BTMs are used to detect the onset of damage to traditional mechanical protection devices such as collimators, beam stoppers, and beam dumps. BTMs come in many sizes and shapes. They are either stand-alone devices or are incorporated into the traditional protection devices.

BSOICs are radiation detectors that are usually installed at specified locations, typically outside the beam housing. They are independent systems used to detect prompt radiation in potentially occupied areas, and are interlocked to turn off or reduce the accelerator beams, or other devices, if radiation levels exceed prescribed limits. Typically the limits are set to either 10 mrem/h or 100 mrem/h, depending on the location of the detector and the occupancy of the area. BSOICs may be integrated with the BCS or PPS. If the radiation limit detected by a BSOIC is exceeded, the beam is shut off by the PPS.

1.3 Credited and Defense-in-Depth Control

1.3.1 Reason for Classification

To satisfy the credited control requirements in DOE Order 420.2C, "Safety of Accelerator Facilities," the RSS controls (either passive or active) are classified as either *credited controls (CC)* or *defense-in-depth (DD)* controls, based on the risk levels of the hazards to people and the environment, as well as protection of the mechanical safety devices (i.e., stoppers, dumps and protection collimators).

The assignment of risk level is based on the radiation dose limits from 10 CFR 835 and on the shielding design criteria detailed in this document for normal beam losses, mis-steering, and *maximum credible incident (MCI)* scenarios. This method of evaluating hazards and assigning an appropriate risk level is consistent with the guidelines provided in *ESH Manual* Chapter 1, "General Policy and Responsibilities."

1.3.2 Classification of Credited and Defense-in-Depth Control

In general, credited controls are used to mitigate hazards with high or medium risk to people or environment from an unacceptable risk to an acceptable level, while defense-in-depth controls are used to mitigate hazards with low risk or to supplement/support credited controls (as an additional layer of defense) to further mitigate higher risk hazards. The credited control systems shall be fully operational for any section where the beam operates. Note the failure of a single component or of one chain in a credited system is not necessarily a failure of the credited control, provided the credited control faults safely.

Sections 2, "Shielding and Barriers," 3, "Personnel Protection Systems," and 4, "Beam Containment Systems," further detail the classification for the various aspects of the RSS controls.

1.3.3 Implementation of Credited and Defense-in-Depth Control

As is common for RSSs, for both credited and defense-in-depth controls, passive controls are preferred over active controls, and preventive controls are preferred over reactive controls.

Both credited and defense-in-depth controls are radiation safety controls and shall meet technical and management standards of rigorous design, fabrication, installation, operation, and maintenance (following the SLAC Conduct of Engineering Policy and *SLAC Conduct of Accelerator Facility Operations Policy*).

All RSSs must be designed to be reliable, tamper-resistant, and of high quality. Credited controls shall also be designed to be fail-safe, while defense-in-depth should be designed fail-safe (see Sections 3 and 4 for further details). The efficacy of the RSS controls shall be demonstrated, and additional controls may be required based on the specific hazard. This document specifies only the minimum requirements.

Both credited and defense-in-depth controls are required for accelerator operation and are be described in the safety assessment document (SAD) and listed in the operation authorization documents such as BAS and BLA. Both credited and defense-in-depth controls are subject to the same management requirements such as configuration management, testing and verification, and record-keeping.

A departure from the use of credited controls or an approved alternative must be reviewed through the USI process as described in *SLAC Conduct of Accelerator Facility Operations*.

Both credited and defense-in-depth controls are part of the RSS and as such are not part of the *machine protection system (MPS)*.

1.4 Radiation Safety System Design and Documentation

A **beam line engineer** or **physicist (designer)** will be assigned responsibility for the design of the beam line and its associated safety systems. The designer should be a SLAC employee or a user in residence at SLAC. In fulfilling this responsibility, the designer will

1. Seek advice and assistance from the Radiation Physics Group
2. Seek advice from the Protection Systems Group(s) responsible for PPS and BCS on the accelerator facility in question.
3. Use the beam containment system implementation guidelines (Section 4)
4. Submit the design for review by the Radiation Safety Committee (RSC), when requested by the RSO
5. Submit the design for approval by the RSO before operation starts

Design of a beam line includes an estimate of the beam losses and the specification of the locations of mechanical containment devices, with their power absorption capabilities. Ray traces that demonstrate the normal beam path and the consequences of incorrect beam steering should be included. Shielding calculations must be made for potential beam losses. The radiation levels in occupied areas must not exceed the dose rates specified in Table 2-1.

A **radiation physicist** will be assigned the responsibility to assist the designer with the design of the RSS. The proposal should include a written description of the PPS, shielding requirements, BCS specifications, requirements for BTMs, and locations of required BSOICs.

The **RSO** must approve all changes to the RSS. Minor modification to the RSS may be approved by the RSO upon recommendation of the *responsible radiation physicist*. No modifications to any RSS will be made without prior recommendation from the responsible radiation physicist and approval by the RSO. Beam time should be scheduled as requested by the radiation physicist to perform or supervise radiation surveys. Based on survey results, additional shielding, barriers, or controls may be required.

The RSO may seek review and advice from the **RSC**. Prior to RSC review of a proposed RSS, the designer will prepare a document describing each beam line and distribute it to the RSC members well in advance of startup. The RSC will review the proposed design and may recommend changes to the safety systems. The burden of proof for the safety of the beam line design lies solely with the designer.

After construction or modification of an accelerator facility element, the **project manager** or **facility manager** should maintain as-built drawings of the RSS. All RSS drawings shall follow the SLAC release/archive standards including utilizing a unique identifying number with version control. All RSS components should be clearly identified. It is the responsibility of the project manager or his/her designee to verify actual dimensions and materials used in the shielding configuration. The assigned radiation physicist is responsible for verifying the placement of BCS devices, BTMs and BSOICs, and performing a visual inspection of the shielding configuration. In situations where the shielding is not visible (for example shielding inside penetrations), the project manager or his/her designee is responsible for verifying that the shielding is in place.

The RSS documentation must include the following:

1. A general beam layout drawing showing all elements of the beam and the adjacent equipment
2. Ray traces of areas of interest
3. A list of all safety components and a quantitative description of their function
4. A statement of assumptions, including operating conditions and beam losses
5. A description of all accidents envisioned in the design
6. A list and description of routine inspections required to ensure integrity of the safety system
7. Description of tests or presentation of calculations that support performance claims of safety features or devices
8. Description of conditions and limitations of the design analysis, that is, which conditions were not considered in the analysis

2 Shielding and Barriers

2.1 Introduction

Radiation from accelerators and beam lines can be reduced to acceptable levels by locating accelerators and beam lines in enclosures that provide sufficient shielding between the radiation source and potentially exposed persons.

Different kinds of shielding materials are used for the various types of radiation. High atomic number materials such as lead and tungsten are very effective for shielding photons and x-rays. Hydrogen-containing materials such as concrete and polyethylene are very effective for shielding neutrons.

Because radiation decreases with distance from the source, barriers other than shielding may also be used to reduce personnel exposure to acceptable levels. These engineered safeguards are preferred over administrative controls. Administrative controls such as ropes and signs should be used only when it is impractical to add shielding or other barriers. All primary beams must be completely enclosed by shielding and barriers that cannot be circumvented.

The remainder of this section describes the shield design objective, the protocol for determining shielding requirements, and the shielding configuration. The shield design criteria will be applied for both modification of existing facilities and construction of new facilities.

2.2 Shield Design Objective

Department of Energy radiation protection standards are based on federal regulations for occupational exposure. The current applicable standards are regulations in 10 CFR 835 and the SLAC Radiological Control Manual.

According to 10 CFR 835.2:

> Radiological worker means a general employee whose job assignment involves operation of radiation producing devices or working with radioactive materials, or who is likely to be routinely occupationally exposed above 0.1 rem (0.001 Sv) in a year total effective dose.

10 CFR 835 sets an annual limit on the total effective dose for a radiological worker at 5 rem (50 mSv). The total effective dose sums the doses from radiation sources both internal and external to the body.

The personnel exposure limit at SLAC is lower than the limit set by 10 CFR 835. The SLAC *RadCon Manual* specifies the design objective for controlling personnel exposure from external sources of radiation in areas of continuous occupancy (2000 h/y), which is to maintain exposure levels below an average dose rate to an individual of 0.5 mrem (5 μSv) per hour and as far below this average as is reasonably achievable. Further, SLAC's adopted annual facility administrative control level (ACL) is 500 mrem, and a dose-management ALARA level of 360 mrem total effective dose per year.

Exposure rates for potential exposure to a radiological worker where the occupancy or duration of the exposure differs from the above will be ALARA and will not exceed 20 percent of the applicable standards given in 10 CFR 835.202 (see SLAC *RadCon Manual*, Table 2.1).

Affected areas outside the accelerator or beamline housing will be classified as accelerator area, controlled area, or radiological area according to the potential doses to individuals during operation, that are estimated based on the radiation levels, area dose monitoring results, and potential occupancy period.

Note that the effective dose quantity covers both broad-beam and narrow-beam exposure geometries. Therefore, for narrow beam (defined as a beam size with an equivalent diameter of no more than two inches) which involves only a small portion of body exposure (for example, a single tissue/organ such as an eye or hand), the equivalent dose to the exposed body part and the associated tissue weighting factor can be used to estimate the effective dose. To simplify the estimation of effective dose from narrow-beam exposures, a conservative tissue weighting factor of 0.20 can be used.

2.3 Radiation Design Levels

The design objectives in Section 2.2 are based on the potential exposure of the radiological worker under normal operating conditions. Shielding must also be designed to protect individuals under two defined non-normal operating conditions, namely mis-steering and safety system failure. Beam lines and experimental facilities must also be shielded to control exposure from external radiation under these two conditions.

Table 2-1 summarizes the maximum allowable radiation levels from any beam or experimental facility under the three conditions.

Table 2-1 Maximum Allowable Radiation Levels

Operating Conditions	Effective Dose Rate	Integrated Effective Dose
Normal	0.5 mrem/h (5 µSv/h) for 2000 h/y	1 rem/y (10 mSv/y)
Mis-steering	400 mrem/h (4 mSv/h)	
System failure	25 rem/h (250 mSv/h)	3 rem/event (30 mSv/event)

2.3.1 Normal Operating Conditions

The shielding will be designed so that under normal operating conditions the annual effective dose in accessible areas at a distance of 1 foot (30.48 cm) from the shield or barrier will not exceed 1 rem (10 mSv). For areas that are continuously occupied the effective dose rate should not exceed 0.5 mrem/h (5 µSv/h). Continual occupancy is defined as 2000 h/y, but actual occupancy can be considered to meet SLAC ACL and ALARA levels.

If a general employee who is not a radiological worker but who works in the area is likely to be exposed to an annual effective dose greater than 100 mrem (1 mSv), taking exposure duration and occupancy into account, additional shielding may be required or the worker may be reclassified as a radiological worker.

2.3.1.1 Normal Beam Losses

The beam line physicist or engineer is required to specify the beam loss expected during normal operations. The specified beam loss should be a conservative estimate of the routine losses that will not cause BCS faults. It should consider additional beam loss that may occur during start-up, consider field emission and dark current from accelerator components, and allow for possible future changes in beam line operation. This normal loss is generally used to determine the shielding necessary to meet the maximum allowable radiation level.

2.3.2 Mis-steering Conditions

Mis-steering conditions are a result of equipment failure or operator error that causes the beam to be lost for a short time in a limited area other than the design termination point. The BCS will normally limit the beam power to its design or operational maximum and in many cases the BCS will turn off such errant beams. However, there may be situations in which the beam is impacting a device that is not protected by the BCS. Mis-steered beams are likely to produce radiation levels outside shielding barriers and in potentially occupied areas that exceed those present during normal operations, for which the barriers and protection systems were designed.

For the purposes of design, it is assumed that an attentive operator will recognize a mis-steering condition within a short period of time. Thus, a mis-steered beam will target a single area for less than an hour in a year. To avoid exceeding the SLAC individual effective dose control limit of 500 mrem/y (5 mSv/y) the maximum effective dose rate in accessible areas at 1 foot from the shielding or barrier should not exceed 400 mrem/h (4 mSv/h). (See *ESH Manual*, Chapter 9, “Radiological Safety”). The area should be also protected with an interlocked device such as a BSOIC.

2.3.3 Maximum Credible Beam

The concept of a *maximum credible beam (MCB)* is used to determine the required shielding and protection devices. It defines the highest beam power that the accelerator can deliver to a point. The maximum credible beam is the lower of (a) the maximum beam power that could be credibly created by machine capabilities and (b) the maximum beam power limited by BCS credited controls.

In estimating the machine capabilities, conservative, but reasonable, assumptions should be used. Assumptions will be reviewed by the RSO and RSC. For example, it is not necessary to assume that BCS device failure will coincide with a significant effort to retune the accelerator to deliver higher beam power than was approved for the facility.

If the maximum credible beam is limited by credited BCS, this credited BCS may reduce the power limited by hardware down to the power limited by this BCS only by a maximal factor of 20.

2.3.4 System Failure

In the event that a mis-steering condition coincides with a total failure of the BCS, a beam that may exceed the design allowable power may be lost at any point in the beam channel. This condition could result in very high radiation levels outside the shielded beam enclosures and in occupied areas. If undetected, this could result in unacceptable radiation exposures to personnel. Note that the failure of the credited control BCS device that limits the beam power to maximum credible beam is not considered credible and is therefore not considered here (see Section 2.3.3).

Similarly, a failure of the PPS, if undetected, could allow personnel to be present inside a beam enclosure at the same time a beam is present in the beam channel. This failure mode could produce very high radiation levels and unacceptable exposures to personnel.

The simultaneous failure of the BCS and PPS is not considered to be a credible scenario.

Under either a BCS or PPS failure condition, the following design criteria must be met:

1. The dose rate outside the shielding will not exceed 25 rem/h (250 mSv/h) for the maximum credible beam.
2. If the beam power is sufficient to burn through a BCS device or a shield, a BTM must be used to turn off the beam within a predictable time period such that the integrated effective dose will not exceed 3 rem (30 mSv). In this case the dose rate can exceed 25 rem/h (250 mSv/h) until the BTM turns off the beam. However, the shielding will be sufficient such that for beam powers just below the burn-through threshold, the dose rate outside the shield remains less than 25 rem/h (250 mSv/h).
3. Areas that are likely to be occupied during beam operation should be protected with one or more BSOICs, unless it can be demonstrated that the dose rate cannot exceed 5 mrem/h (0.05 mSv/h) under any circumstances. The BSOIC should be located at the place where the errant beam affecting the occupied area is likely to produce the highest dose rate.

2.3.5 Exceptions

In some cases radiation levels higher than those specified in Table 2-1 may be allowed. Examples include areas that are normally not occupied (beam enclosures, roofs, penetrations) where access is inhibited by engineered safeguards such as beam line enclosures and high fences with locked doors or gates and with warning signs. Access is usually controlled by a key release system or set of procedures. Exceptions should be handled on a case-by-case basis by the RSO. In any case, the directorate responsible for the relevant facility element should address the risk from abnormal operations satisfactorily by demonstrating the adequacy of the RSS, that is, higher levels of radiation hazards are mitigated by increasing layers of safety control (for example, thicker shielding, more interlock and/or operational controls on the beam and/or radiation, as well as occupancy control).

2.3.6 Boundary Dose

The maximum effective dose to the public off site from the operation of a single accelerator or experimental facility (due to direct and skyshine exposure) will be kept as low as is reasonably achievable and should not exceed 5 mrem in a year (50 μSv in a year). This design objective is established to ensure that the current SLAC performance criterion is met and that the annual dose to a member of the public off the SLAC site is well below 100 mrem (1 mSv).

2.4 Credited and Defense-in-Depth Control

Bulk shielding is credited control, because it is the primary control to mitigate high-risk hazards to personnel.

Local shielding may only be defense-in-depth control if it supplements the accelerator or beam line housing for an attenuation factor of not more than 10. Similarly, exclusion areas that increase distance and provide a dose reduction factor of not more than 10 may be defense-in-depth controls.

2.5 Protocol for Determining Shielding Requirements

The Radiation Physics Group is responsible for determining the shielding required for a facility and must be consulted prior to the construction of a new facility or the modification of an existing facility. It is the responsibility of the project manager or his/her designee to provide the following information in writing to the responsible radiation physicist:

1. Normal beam parameters
2. Duration of operation (use factors)
3. Operating conditions
4. Beam loss scenarios (normal, worst case and mis-steering, field emission, and dark current)
5. Beam ray traces
6. Occupancy factors
7. Maximum credible beam
8. Other pertinent information requested by RP

The radiation physicist will perform the analysis and calculations based on the above information and specify the shielding configuration (shielding thickness, type, and location). The beam line designer, with the assistance of the radiation physicist, will submit a proposal including a documented description of the beam line for review by the RSO, and the RSC as needed. The RSO has approval authority for the shield design.

2.6 Shielding Configuration

The shielding configuration is determined by the responsible radiation physicist and should be verified by the responsible project manager. A knowledgeable radiation physicist, assigned by the head of RP, will review all shielding design calculations performed by the responsible radiation physicist. Shielding calculations are performed using the information provided by the project manager. Semi-empirical and analytical methods and codes (for example, SHIELD11, PHOTON, and STAC8 for synchrotron radiation) may be used in simple cases and radiation transport codes (for example, EGS, FLUKA, MORSE, MCNPX, HETC, MUCARLO, MARS, MUON89) may be used in more specialized cases. The responsible radiation physicist will issue a written memo or report specifying the final shielding configuration.

3 Personnel Protection Systems

3.1 Introduction

Personnel protection systems (PPS) consist of electrical interlocks and mechanical barriers and locks that prevent personnel from entering beam enclosures and other areas in which the potential for high radiation exposure exists so that they are protected against prompt radiation. The interlocks also serve to shut off the radiation source if any of the interlocked barriers into beam enclosures are breached. Hutch protection systems (HPS) are a sub-category of PPS employed in photon beam enclosures. It should be noted that the PPS is not designed to protect people against residual radiation when the beam is off, although it can be used to control access to areas in which high levels of residual activation exist. The interlock system must be operated, maintained, and tested in accordance with a set of administrative procedures. Administrative procedures ensure that activities such as setting access states, searching the beam enclosures, and testing the interlocks are carried out safely and thoroughly.

At SLAC, the PPS serves primarily as an access control system. It prevents exposure by prompt radiation of persons inside the beam enclosures by ensuring that beam-blocking stoppers remain in place and radiation generating devices are disabled. The PPS also prevents entry to beam enclosures when beams are operating, and turns off the beams when a security violation is detected. PPS will not be used as the normal means to turn off the beam. The important functions that the PPS must accomplish are

1. Terminate or remove the hazard in PPS areas through the use of interlock devices
2. Ensure orderly searching of an area before beam turn-on through the use of appropriate interlocks
3. Establish the various entry states, such as Controlled and Restricted Access, using appropriate interlocks
4. Provide emergency shutoff
5. Operate annunciator signs and audio warning systems
6. Control access to certain areas outside the beam enclosures using physical barriers and controlled locks and keys

The control of non-radiological hazards is not in the scope of the RSS (though in some cases PPS is employed in electrical hazard mitigation). Therefore lock-out/tag-out (LOTO) of non-radiological hazards may be required for access. PPSs also provide the logic and the hardwired connections to beam shutoff devices that operate in response to signals from BSOICs and BTMs and may provide other safety functions.

3.2 Application Criteria

If an access control system is warranted, the controls required depend on the radiation dose potential. Table 3-1 provides a grading of required physical features (levels 1 to 3). The dose rate refers to the level of effective dose in one hour for which the area was designed or is expected to receive during beam operation. For example, an area with the Level 3 category has a dose rate higher than 5 rem in one hour and will need the locked and interlocked access control system. The requirements for the Level 3 system are given in Section 3.4, “Level 3 PPS Design Requirements.”

Table 3-1 Physical Features Required for Access Control

Category	Effective Dose Rate	Minimum Requirements
Level 1	5–100 mrem/h (0.05–1 mSv/h)	Administrative procedures (ropes and signs)
Level 2	0.1-5 rem/h (1–50 mSv/h)	Locked or interlocked PPS barriers and signs
Level 3	> 5 rem/h (> 50 mSv/h)	Locked and interlocked shielding barriers, signs, visual and audible warning

3.3 Level 3 System Description

The PPS physically consists of an instrumented enclosure that provides information concerning the status of the enclosure to a PPS logic system. This PPS logic system then determines if it is safe to send permits to devices that allow hazards to be present in the enclosure or to devices that allow access to the enclosure. The flow of information in a PPS system is illustrated in Figure 3-1. Devices and methods that are used to determine the status of a PPS enclosure and to control the hazards, including planned and unplanned entry and access states of the enclosure, are described in detail below.

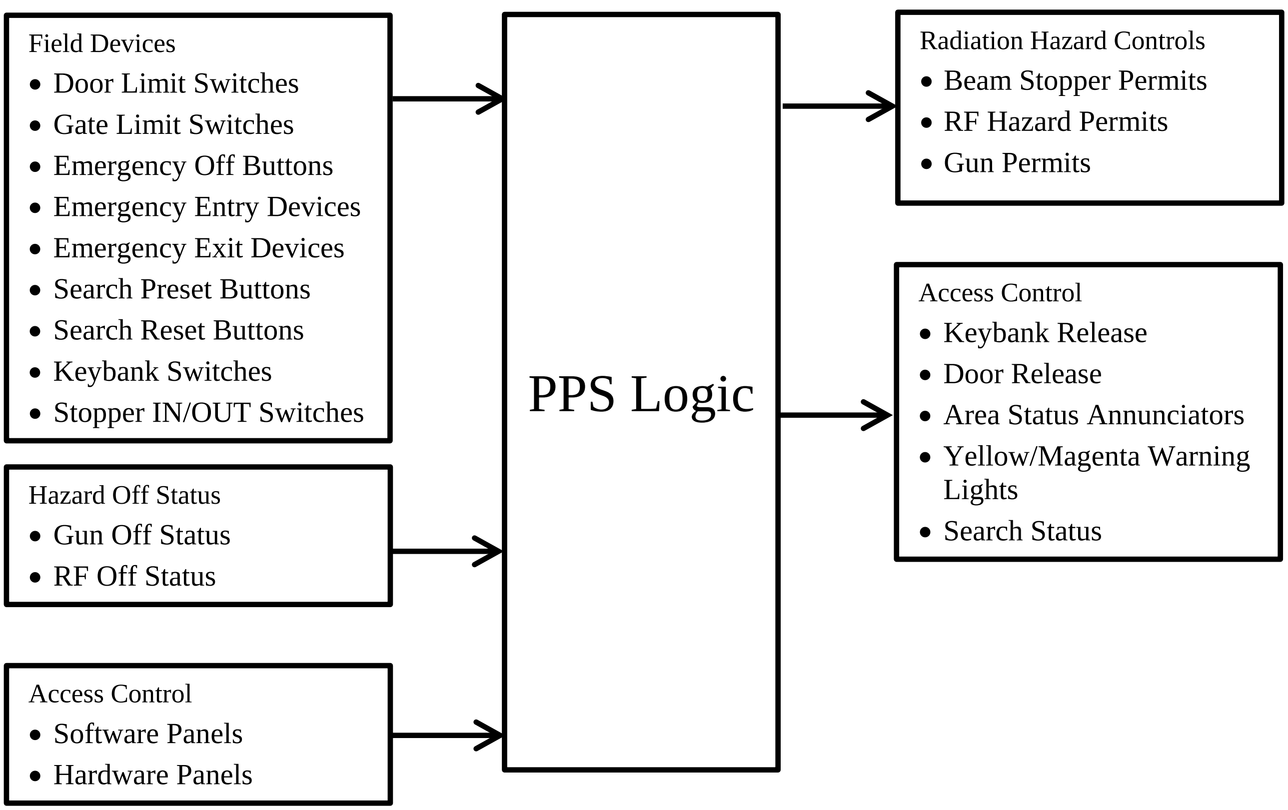

Figure 3-1 PPS System Information Flow

The operator interface to the PPS may be achieved through hardware or software control panels. Frequently, both types of panels are provided – a hardware panel near the entrance to the enclosure and a computer touch screen in a main control room area. The PPS logic system can be either electro-mechanical or a programmable logic control system.

3.3.1 Stoppers

The term *stopper* refers to any device used to block the beam or prevent it from reaching areas controlled by the PPS. A stopper could be a mechanical assembly, a deflecting magnet, a gun, or radio frequency (RF) device. Specific requirements for stoppers are described in Section 3.4.3, “PPS Stopper Design Requirements.”

3.3.2 Entry Requirements

A planned entry into an area controlled by the PPS may be made in the permitted access state or in the controlled access state (Section 3.4.3). Stoppers must be inserted in a beam line before entry is allowed into a down-beam area. The PPS logic requires two status signals from each stopper confirming the IN status before the area can be set to an entry state (controlled access or permitted access) and generates permissives to release keys and open doors. In the case of mechanical stoppers such as slits, collimators, dumps, or scatterers, two microswitches are used to determine the IN position. When magnets are used as stoppers, the magnet power supply provides two independent status signals to the PPS logic to confirm that the power supply is off.

In the case of the linac, the variable voltage substations (VVSs) that power the klystron modulators are shut off, eliminating the hazard. Each VVS provides two OFF status signals to the PPS logic.

In addition to the requirement that stoppers are inserted, all other interlocked hazards in the area must be turned off before door latch and key permissives are given.

3.3.3 Security Violation

A security violation (such as an unplanned entry) of any zone must immediately shut off all machine-produced radiation in the area.

For example, at the LCLS copper beam linac, internal PPS logic circuits respond within about 10 to 100 milliseconds to the opening of any gate or the pushing of an EMERGENCY OFF button. This delay is due to the propagation delay inherent in the logic elements that make up the PPS. Beyond this internal delay, there is an additional delay due to the time taken for the stopper to reach the IN position in the beam line or for large electromechanical contactors on power supplies or VVSs to release. This second delay could add as much as seven seconds to the internal delay of 10 to 100 milliseconds.

Note that the logic circuits generate two permissives for each stopper. The removal of either permissive will render the system safe; however, both permissives are removed when there is a security violation.

3.3.4 PPS Access States

The PPS design provides for up to four access states – No Access, Restricted Access, Controlled Access, and Permitted Access. In some locations, such as the linac, only two states are available.

3.3.4.1 No Access

The no access state allows the operation of beam and RF in the area controlled by the PPS. Searched status is required, and no personnel are allowed in the area.

3.3.4.2 Restricted Access

The Restricted Access state allows residual dose and oxygen deficiency hazards to be on, but no beam. Searched status is required and no personnel are allowed in the area except with approval via special administrative procedure. LOTO of other non-radiological hazards may be required.

Testing is done in strict conformance with approved test procedures (see *SLAC Conduct of Accelerator Facility Operations*). Procedures differ for each area, depending on the particular design of the PPS logic.

3.3.4.3 Controlled Access

The Controlled Access state means beam and RF must be off. Personnel access is allowed by contacting the control room. Each person entering must be logged in by an operator, take a key from a key bank, and be in possession of the key at all times while in the area controlled by the PPS. The key bank must be complete before the access state can be transferred to no access; searching the area is not required before establishing the no access state and resuming beam operation unless searched status is lost. LOTO of non-radiological hazards may be required.

3.3.4.4 Permitted Access

The Permitted Access state means that the beam and RF must be off. Personnel access can be made without radiologically related restriction, but LOTO of non-radiological hazards may be required. Keys are not required. Before beams or RF can be turned on, operators must search the area controlled by the PPS.

3.3.5 Other Design Features

3.3.5.1 Search and Warning Provisions

Interlocks have been provided to ensure complete and effective searching of an enclosure. Interlocks consist of push buttons or key switches for

- Search preset
- Search complete

The interlock circuits prevent beams from being turned on until the search has been completed and the audio and visual warnings have run their cycle. The no access/restricted access audio warning is a voice recording that instructs persons who may have been overlooked in the search that they must push the nearest EMERGENCY OFF button and exit immediately. In some areas a siren provides the audible warning. The visual warning is given by the flashing of the overhead lights.

3.3.5.2 EMERGENCY OFF Switches

Emergency shutoff switches have been installed in all beam enclosures. The switches are large, clearly labeled, and easily accessible. They are provided to shut the beam off in emergency conditions.

3.3.5.3 Emergency Entry / Exit Provisions

Most doors have exit and entry mechanisms for use only under emergency purposes. These may consist of a crash-bar, door release button, a pull ring, or equivalent.

3.3.5.4 Radiation Warning Lights and Signs

A typical entry point to an area controlled by a PPS has radiation warning lights and an annunciator. In most areas, each entry point has a large annunciator that indicates the access state for that area (no access, restricted access, controlled access, permitted access) and a yellow and magenta radiation light pair. The klystron gallery contains radiation warning lights mounted only above the manway doors. When the yellow light is on continuously, the linac is off, but there may be residual radiation in the tunnel. A steady magenta light indicates that the area has been searched and is ready for beam (RF may be on). A flashing magenta light indicates that the beam is on.

3.3.5.5 Door Micro-switches and Door Locks

All doors and gates to areas controlled by the PPS have two mechanical or magnetic switches that monitor the closed status of the door. If the door is opened when it is not safe to enter the enclosure, the accelerator is shut off. In addition, the outer doors of the area remain locked in the no access and restricted access states. Many of these door locks are remotely releasable by a PPS operator for controlled access entry.

3.3.6 Circuit Logic Description

The PPS logic circuits receive information from the accelerator about the status of doors, key banks, EMERGENCY OFF switches, and other devices. Depending on the state of these components, permissive or enable signals are generated or withdrawn to activate safety devices such as beam stoppers or to allow the turn-on of hazards.

3.4 Level 3 PPS Design Requirements

3.4.1 Interlock and Control System

The PPS will be designed in accordance with guidelines commonly used in other accelerators and at similar facilities where a life-threatening situation might arise if inadvertent entry is made to a restricted area.

These guidelines have been heavily influenced by publications such as ANSI N43.1 and the NCRP Report No. 88.

At SLAC, the PPS can be implemented using relay-based logic or computer-based programmable logic controller (PLC) systems that include fail-safe circuits. Dual or redundant signal paths or interlock chains are used in critical circuits to improve reliability and to eliminate unsafe single-point failures that can completely disable the protection system. The redundancy is carried from the input devices, such as door switches or sensors, through duplicate wiring to the dual chains in the logic through logic output to typically redundant shutoff devices. At least two independent paths are used to ensure positive shutdown of beams.

The PPS will meet the following design requirements:

1. Use fail-safe devices and interlock logic circuit designs. Failure mode analyses need to be performed for hardware and software.
2. Use field devices capable of handling two independent circuits or have dual independent devices at a single location, except if the field device belongs only to a defense-in-depth control.
3. Contain two independent and therefore redundant subsystems from the sensors through the logic to the hazard power sources, except if the field device belongs only to a defense-in-depth control. The two subsystems may share a common power source.
4. Each subsystem will operate as a stand-alone protection system, except for state transition circuits in relay-based systems.
5. The hardware components must be capable of maintaining high reliability in the environment in which they operate.
6. The subsystems must be protected from inadvertent tampering or modification. Computers used for PPS interlocks must be dedicated and isolated from external links that can corrupt the system.
7. If a computer-based system is used and is part of credited control, it will be redundant and independent, each with its own independently written logic and control software. If volatile memory is used, it should have error detection and correction features and it should have sufficient battery backup for long-term retention of the program state. All parts of the PPS must be under strict configuration control. All changes in hardware or software must be thoroughly tested for intended function and for effects on other parts of the system.
8. There will be an independent operator-actuated shutoff override that permits manual shutdown of the radiation hazard.

3.4.2 PPS Physical Barrier

All PPS access module barriers could consist of doors, gates, steel mesh, iron bars, radiation shielding, concrete, and padlocks (on physical devices). The PPS barriers will have the following design requirements to prevent inadvertent access during beam running:

1. Movable barriers must be interlocked to the PPS by an engineered method.
2. Stationary barriers must be prevented from moving by means of padlocks, cables, chains, bolts, or other administrative means.
3. Barriers must have no hole with a size that exceeds 8 inches by 8 inches.

3.4.3 PPS Stopper Design Requirements

Mechanical or magnetic PPS stoppers may be considered beam containment devices in that their function is to “contain” the beam upstream of an area controlled by the PPS when access is permitted. The required redundancy of PPS stoppers depends on the beam line design.

If the beam line is designed to permit the primary beam to be incident on the first stopper when access is permitted to the beam line downstream of the stoppers, two additional PPS stoppers are required. If fewer stoppers are used, the design must be justified on the basis of adequate safety.

If the beam line is designed so that the primary beam cannot be incident on the first PPS stopper unless a prior failure occurs, then at least two PPS stoppers are required. If fewer stoppers are used, the design must be justified on the basis of adequate safety.

For primary beam stoppers, each mechanical stopper must be designed so that in the case of a PPS failure that permits the maximum allowable beam power to be incident on a single remaining stopper, the maximum effective dose rate in the downstream area controlled by the PPS will not exceed 25 rem/h. The maximum integrated effective dose to an individual will not exceed 3 rem per event.

One or more magnets may replace one of the stoppers. If three stoppers are used, at least two stoppers must be mechanical devices. If only two stoppers are used, both stoppers must be mechanical devices.

Stoppers should have a method to put the stoppers to the IN (safe) position independently of the stopper permissives from the PPS. All stoppers are required to redundantly report IN/OFF status to the PPS.

These stoppers must meet the criteria for beam containment devices specified in Section 4.4.2.2, “Beam Dumps and Beam Stoppers.”

For synchrotron radiation/FEL beam lines, only two stoppers are required (hutch stoppers).

It is not necessary to consider multiple system failures of both the BCS and PPS in the design.

3.5 Credited and Defense-in-Depth Controls

The three safety functions performed or supported by PPS/HPS are

1. Radiation hazards off during access: ensure hazards are removed while personnel may access an accelerator housing
2. Clearing of area: ensure no person is left in an accelerator housing before radiation hazards return
3. Keeping personnel away from radiation hazards: ensure personnel is kept outside an accelerator housing while radiation hazards are on inside

These safety functions of PPS/HPS have to be achieved through a combination of credited controls and defense-in-depth controls. The engineered PPS devices are classified into credited and defense-in-depth controls as follows:

- The engineered systems that enforce the removal of hazards during access (safety function 1) and that keeps personnel away from the beam (safety function 3) are credited control, with exceptions of devices that are supplemental to locks and interlocks in that they prevent challenges to the system. Those devices are considered defense-in-depth.

  Examples may be:

  - Stopper (hardware, IN sensors, BTM); door limit switches; associated logic and shutoff systems are credited control.
  - Annunciator lights are defense-in-depth.

- The clearing of the area (safety function 2) depends on human actions such as search by operators and users. The engineered systems that support the clearing may be defense-in-depth.

  Examples may be:

  - Search buttons with logic for order and timing of pressing search buttons; audio and visual warnings are all defense-in-depth.

3.6 Administrative Procedures

In addition to engineered interlock systems there are administrative rules and procedures covering PPS operation, testing, and modification. These tools are summarized below.

3.6.1 Training

The ESH Division provides training in the use of the PPS in ESH Course 116, Radiological Worker I (RWT I) (ESH Course 116). Further guidance and reference material is provided in the SLAC *RadCon Manual* and the SLAC *Conduct of Accelerator Facility Operations*.

Operators receive additional training in the use of the PPS by qualified personnel, and the progress and status of their training is carefully monitored and recorded in PPS workbooks written for each area.

Photon system users are trained in the use of HPS as part of their light source utilization training.

3.6.2 Entry/Exit and Search / Secure Procedures

Entry and exit procedures, and searching and securing procedures for an area controlled by the PPS are fully documented by the responsible safety officer for each of the SLAC facilities. These are formal documents that must be rigidly followed. All unusual or unsafe conditions must be reported to the responsible safety officer and these must be corrected or mitigated before beam operation.

3.6.3 PPS Certification

Certification and validation of the PPS is done in accordance with the SLAC Conduct of Accelerator Facility Operations, following detailed procedures and checklists prepared by the group having responsibility for the facility PPS and approved by the responsible safety office. These procedures include radiation interlock and system logic tests.

3.6.4 Testing to Maintain System Integrity

Testing will be performed and documented at regular intervals, and must include sensors, relays, computers, and the shutdown mechanisms. Specific tests are performed by members of the search team on door switches and EMERGENCY OFF buttons following a prolonged period of permitted access. These tests are described in the *SLAC Conduct of Accelerator Facility Operations*.

3.6.5 Configuration Control

Procedures that control the modification and retesting of PPSs are described in the *SLAC Conduct of Accelerator Facility Operations*. All changes must be carefully reviewed and approved, and retesting must be done in accordance with an approved procedure.

4 Beam Containment Systems

4.1 Introduction

Radiation safety at an accelerator requires that beams deposit their energy in or at devices capable of absorbing the planned maximum beam power. If the devices are incapable of absorbing the maximum beam power or if beams diverge from their proper channels, the resulting beam loss may create high radiation levels in unprotected areas. Certain components of the beam line, such as collimators, are designed to contain the beam if it should deviate from the designed beam channel. Other components, such as beam dumps, are designed to terminate the beam in a well-shielded area. These components are part of a *beam containment system (BCS)*. A BCS also is made up of devices that detect when accelerated beams diverge from the desired channel, and when excessive beam intensity that could cause unacceptable radiation levels in occupied areas exists. When this happens, the beam delivery system is shut down.

A BCS is a combination of mechanical devices (such as collimators and beam dumps) and associated electronic protection devices (such as current toroids, meter relays, or radiation detectors) that ensure beam confinement within an approved beam channel at an approved allowed beam power and hence prevent the generation of an excessive level of radiation within occupied areas.

Factors that contribute to the beam not being contained, which could result in the production of unacceptable levels of radiation in occupied areas, include

- Mis-steering of beams during tune-up or because of magnet power supply mis-settings
- Magnet wiring errors that result in misdirected beams
- Photon optics errors that result in misdirected beams
- Damage to beam line components because of excessive beam power

Given the potential destructive power of SLAC beams and the possibility of excessive radiation in occupied areas, formal guidelines and procedures have been adopted to ensure that appropriate protective devices are installed to contain beams. These guidelines, and the devices that are used to provide protection, are described in the following sections.

It should be noted that a BCS is distinct and separate from a machine protection system (MPS). The BCS protects personnel against elevated radiation levels in occupied areas. One of the means by which this protection is achieved is to prevent damage to beam line devices that have been designated as having a safety function. The MPS also protects beam line components from damage due to high power beams, but in this case, the components being protected do not have a personnel safety function. Thus, even if there were to be significant damage to an MPS device, there would be no notable increase in radiation levels in occupied areas.

The MPS uses many of the same protection techniques and instruments as the BCS, but there is less redundancy and less rigid administrative control compared with the BCS. In addition, BCS and MPS systems differ in the manner in which a fault impacts beam delivery: BCS faults prevent delivery of all beams by two independent methods; MPS faults could also prevent beam delivery, or rate limit beam delivery to lower average beam power.

4.2 Beam Containment

A properly contained beam is one that terminates on a mechanical BCS device that can absorb either the maximum credible beam indefinitely or the allowed beam power indefinitely if the device is protected by appropriate measures (see Section 4.4, “BCS Devices and Design Requirements”).

In addition to the mechanical BCS devices, there are also electronic systems that serve four basic functions:

1. To monitor and limit the beam power in a beam line to the allowed value
2. To limit the losses along a beam line that is operating at its allowed power
3. To protect safety-related beam line components from damage
4. To shut off the beam if excessive radiation levels can be produced in occupied areas

4.3 Beam Containment Policy

The fundamental requirements for containing primary and secondary beams are

- Primary beams must be prevented from escaping containment
- Secondary beams must be contained if they are of sufficient power such that they are capable of producing radiation levels that exceed SLAC radiation design limits
- Primary and secondary beams must be prevented from striking beam line components or the shielding enclosing the beam line if this results in radiation levels in occupied areas that exceed SLAC design limits
- Primary and secondary beams must be turned off if excessive radiation levels occur in occupied areas or if the beam power striking a device, which is designated to contain the beam, exceeds the power limit of the device

In addition, primary beams must be prevented from entering *secondary beam channels* unless the secondary beams are also completely contained. This may be accomplished by one or more of the following:

1. All bends in the primary beam line must be in different planes than the secondary beam channels for charged particles.
2. Failure of magnets or the most radical steering, at all energies, must not send the primary beam into the secondary beam channels.
3. Secondary beam channels must be plugged or shadowed with a beam containment device meeting the design requirements in sections 4.4.2, “Mechanical Devices,” and 4.4.3, “Electrical and Electronic Devices.”
4. A system of permanent magnets must prevent the primary beam from entering the secondary beam channels. The permanent magnets must be protected from beam-related damage.
5. Charged particle secondary beams can be controlled by proper secondary transport magnet polarity and/or transport energy. The polarity must be properly controlled and/or interlocked into the BCS.

4.4 BCS Devices and Design Requirements

4.4.1 General Design Requirements

The following general requirements guide the equipment design:

1. Maximum credible beam must be limited by machine capabilities or by credited controls consisting of two independent BCS devices (sensor/electronics).
2. The beam power in a beam line must be further limited to the allowed beam power by a BCS device if the allowed power is less than the maximum credible beam power.
3. Beam losses in radiation containment areas may need to be limited by at least one BCS devices to prevent radiation levels in occupied areas from exceeding those given in Section 2.2, "Shield Design Objective," for normal beam operation.
4. Beams must be terminated in an appropriate BCS device, such as a dump designed to absorb the allowed beam power indefinitely.
5. Beam containment devices, such as magnets and mechanical and electronic protection devices, must be designed or implemented to fail in a safe manner.
6. No single-point failure should render the system unsafe.
7. The protection devices in each beam line should be independent of each other and different whenever possible. For example, one protection device might monitor the average beam current while another, such as an ion chamber, monitors the radiation level. Type diversity such as this reduces the chances that a common mode failure would disable both channels simultaneously.
8. Equipment and cabling should be protected in locked racks whenever possible.
9. All BCS circuits must be either self-checking or redundant.
10. When a fault is detected, all beams must be shut off by two independent methods.

4.4.2 Mechanical Devices

Mechanical devices that are used to contain beams are subject to damage or destruction from either loss of coolant or when design specifications are exceeded. Almost all SLAC power absorption devices that are designed to dissipate more than a few hundred watts of beam power on a regular basis are water-cooled. Their safe operation depends heavily on the proper functioning of the cooling system. Malfunctions in this system, such as loss of coolant due to a leak, loss of flow due to pump failure, or excessive inlet water temperature due to loss of heat exchanger capacity, can have disastrous consequences for the heat dissipating areas of the power absorption device. This potential outcome could be realized even if the beam power is within the rating of the device. Failure is generally due to melting in the areas of high beam power deposition, but other mechanisms, such as plastic deformation and/or fracture due to thermal stresses exceeding the yield and tensile properties of the material, may also contribute to the failure. The latter may occur in combination with thermal fatigue due to the pulsed nature of the beam. In such cases, BCS protection devices are required to prevent damage to the mechanical devices. Some considerations for device protection are as follows:

1. If water flow is considered in the power limit of a mechanical BCS device, then the cooling system for the device must be interlocked to the BCS.

2. Mechanical BCS devices (such as dumps and collimators) and PPS stoppers must be capable of absorbing the allowed beam power indefinitely or must be protected by additional electronic BCS devices (see Table 4-3). These must turn off the beam to prevent exceeding the power limit of the mechanical device.
3. Such a device should also be equipped with a BTM over as large an area as the beam can be steered if not capable of absorbing the maximum credible beam indefinitely.

Mechanical BCS devices that are designed to absorb the maximum credible beam indefinitely need no further protection.

The specific mechanical devices used for beam containment are discussed in the following sections.

4.4.2.1 Protection Collimators

Protection collimators are placed in strategic locations to intercept a mis-steered beam and prevent it from entering another beam port or from striking a shielding barrier. These devices are either cooled or not cooled, depending on whether they intercept the beam on a regular basis. They are typically at least 20 radiation lengths long and offer good protection, except where a high-power beam impinges at grazing angles along the aperture. Typically they are not designed to absorb the maximum credible beam indefinitely and are protected by devices such as ionization chambers and flow switches and a BTM. In addition, temperature sensors such as resistance temperature detectors and thermocouples are used in the MPS. If the electronic protective devices fail to shut off the beam collimator burn-through could occur. In this event, the BTM would turn the beam off within short time, for example, one to two seconds after the detection of damage to the collimator.

4.4.2.2 Beam Dumps and Beam Stoppers

Beam dumps and stoppers are designed to absorb a beam of specific power for an indefinite period and must be protected in the same manner as protection collimators. If they are designed to absorb the maximum credible beam, no protection devices are needed.

4.4.3 Electrical and Electronic Devices

If mechanical containment devices could be designed to absorb the maximum credible beam power, there would be no need for additional electronic protection. However, cost and physical space limitations preclude such an approach in most beam line designs. The alternative is to provide fast electronic protection for devices and beam lines. The electronic devices in the BCS provide this protection.

Also, bending magnets are frequently used as protective devices in the BCS and can only be monitored and interlocked electronically. Typically the magnet polarity, the magnet current, and the on/off status of the power supply are monitored and interlocked, such that when an out-of-tolerance condition is detected, the beam is deflected into a safe location, or is prevented from entering a beam line that has an inadequate power rating.

Electronic protection systems, from the sensor (toroid, ion chamber, flow switch and so) to the processing electronics, are designed to be as fail-safe as possible and are either redundant or utilize self-checking signals that confirm the correct operation of the sensor and electronic module.

4.5 Credited and Defense-in-Depth Controls

BCS controls mitigate a wide range of hazards, such that the classification of BCS requires more differentiation than for shielding or PPS. For active BCS (i.e., interlocked-type controls), specific criteria and requirements are established based on a graded approach, and details like the numbers of credited controls and/or defense-in-depth controls required to mitigate different hazard levels are prescribed.

4.5.1 Classification

The tables below describe the classification of the BCS devices into credited and defense-in-depth controls. The description is for the minimum implementation. Additional controls, and additional CCs, may be implemented, and trip limits shall not only be set to meet the minimum requirements, but, per ALARA, should be lower if practical.

Table 4-1 Classification Criteria and Minimum Requirements for BCS Devices That Protect People (criteria 1 and 2 for limiting beam power and beam losses)

Criteria for Classification	Risk Level	Required Minimum Controls
1) BCS devices that limit the MCB to meet the MCI shielding design limit of 25 rem/h or 3 rem per event	High	2 CC
2a) BCS devices that limit abnormal beam losses to reduce radiation levels in accessible areas to meet the shielding design limit of 400 mrem/h for mis-steered beam conditions	Medium	1 CC + 1 DD
2b) BCS devices that limit abnormal beam losses to reduce radiation levels in accessible areas to meet 10 CFR 835 Radiation Area (≤ 5 mrem in 1 hour) posting compliance	Medium	1 CC
2c) BCS devices that mitigate long-term dose hazards (e.g., hourly or daily dose controls)	Low	1 DD

Table 4-2 Classification Criteria and Minimum Requirements for BCS Devices That Protect People by Containing Beam to the Beam Channels

Criteria for Classification	Risk Level	Required Minimum Controls
3a) BCS devices that serve as primary layer to define beam channel to protect people	Medium	1 CC + 1 DD
3b) BCS devices that supplement the shielding enclosure and beam loss controls to contain the beam channels, and serve to further reduce the risk that has been lowered with the first layers of defense	Low	1 DD

Table 4-3 Classification Criteria and Minimum Requirements for BCS Devices That Protect Mechanical Safety Devices

Criteria for Classification	Risk Level	Required Minimum Controls
4a) BCS devices to ensure thermal performance of mechanical safety devices	Low	2 DDs for a CC mechanical safety device 1 DD for a DD mechanical safety device
4b) BCS devices to protect mechanical safety devices when beam power exceeds power limit of the device	Low	1 DD

4.5.2 Implementation of Credited versus Defense-in-Depth BCS Controls

The technical requirements include that both credited and defense-in-depth controls shall be highly reliable and tamper proof. The difference for credited and defense-in-depth controls (interlocked sensor/electronics) is in the fail-safe requirement. A fail-safe design is defined here as one that avoids single-point failure. A fail-safe design should employ self-checking. If this is not practical, redundancy should be used. A Type A device or sub-system defined in IEC 61508 (with well-defined failure modes and with demonstrated low unsafe failure rates) also meets the fail-safe requirement.

- For credited controls, the sensors and accompanying electronics shall be designed to be fail-safe. This is a minimum requirement for an acceptable level of performance. This means that all credited control circuits and sensor/electronics must be either self-checking or redundant.
- For defense-in-depth, the sensors and accompanying electronics should be fail-safe. They should be implemented per best management practices, unless otherwise justified. Therefore, the sensor/electronics of a BCS defense-in-depth control needs not be redundant, but self-checking may be required to achieve the high standard required for RSSs.
- The shutoff path for both credited and defense-in-depth controls shall be redundant to ensure no single point failure.

4.6 Administrative Requirements

The BCS must be administered effectively to ensure reliable operation. This requires that the devices be certified, tested, and protected against unauthorized modification:

- All protection devices must be certified to function properly before a beam line is operated.
- A BCS system and integrity check must be performed during start-up following a major downtime or annually.
- Sufficient scheduled accelerator time must be provided for adequate beam containment checkout as prescribed by the responsible radiation physicist and the safety office responsible for the accelerator facility element. To ensure that this time is allocated, line items may be included on the BAS.
- All protection devices must be protected against unauthorized modification or bypassing.

- Operation of BCS equipment needs to be checked using formal procedures or automated tests daily, weekly, or at other approved intervals as appropriate for the given failure modes, hazards they protect against, and existing self-checks.

The RSC should review new protection devices.