SLAC
NATIONAL ACCELERATOR LABORATORY

Radiation Safety Systems

Technical Basis Document

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Disclaimer

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Note *This latest revision (R004) is a minor substantive change to include SLAC's administrative control level (ACL) and dose-management ALARA level in the shield design objective (Section 2.2). To meet these levels, actual occupancy can be taken into account. In addition, the value for the effective dose rate for continual occupancy in Section 2.3.1, "Normal Operating Conditions", was corrected from 0.5 rem/h to 0.5 mrem/h to coincide with the correct value in Table 2.1.*

This document replaces (R003), in which dosimetry terminology was updated to conform to the 8 June 2007 amendment of 10 CFR 835.

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 are effective 15 December 2010.

Please send any comments to Sayed H. Rokni, rokni@slac.stanford.edu.

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Acronyms

ALARA	as low as reasonably achievable
BCS	beam containment system
BSOIC	beam shutoff ion chamber
BTM	burn-through monitor
HPS	hutch protection system
linac	linear accelerator
LION	long ion chamber
MCB	maximum credible beam
MPS	machine protection system
PIC	protection ion chamber
PLC	programmable logic controller
PPS	personnel protection system
RSC	Radiation Safety Committee
RSO	radiation safety officer
RSS	radiation safety system
RTD	resistance temperature detector
SSRL	Stanford Synchrotron Radiation Lightsource
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 containment shutoff system. This system utilizes two electronic summary modules that shut off the beam by three 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 engineer. The engineer responsible for the design 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 to put in beam stoppers (or turn off gun high voltage) if radiation is detected above a pre-set level

Burn-through monitor (BTM). A device wired into the personnel protection system (PPS) to turn off the variable voltage substations (VVSs) if the BTM mechanical beam containment device has melted. BTMs are presently limited to pressure or vacuum release. The BTM must turn off the VVSs in less than 1/10 of the calculated burn-through time of the beam containment device when the device is absorbing greater than the specified beam power.

Maximum credible beam. Highest beam power that the accelerator can deliver to a point assuming that the BCS devices that limit beam power have failed

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 and 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 criterion of 10 mSv/y (1 rem/y) inside secured areas when access is permitted.

Protection devices. Electronic circuits or modules connected to beam line transducers such as toroids, flow switches, or ion chambers that prevent the beam rate, beam power, temperature, or beam losses from exceeding specified values. When out-of-tolerance conditions are detected by these electronic modules, beams are shut off by the beam containment shutoff system.

Radiation safety system (RSS). A combination of active and passive systems designed to protect personnel from prompt radiation

Radiologically controlled area (RCA). Areas that may contain potential radiation hazards that may exceed 100 mrem per year. In these areas, a dosimeter must be worn at all times.

Responsible radiation physicist. That member of the Radiation Physics staff assigned to the design and operation of a specific beam line

Safety envelope. The administrative guideline for facility design 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 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

Year. The period of time beginning on or near January 1 and ending on or near December 31 of that same year used to determine compliance with the provisions of this part. The starting and ending date of the year used to determine compliance may be changed, provided that the change is made at the beginning of the year and that no day is omitted or duplicated in consecutive years.

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. Section 5 provides examples of safety system design and implementation at SLAC.

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 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 (RSS) are used to protect personnel from prompt radiation. The primary components of 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 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, 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 the 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]) must be prevented from escaping their designated beam channels to prevent exceeding allowable radiation levels outside the shielding enclosure.
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.

1.2.4 Other Safety Systems

Two other radiation safety systems 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. Refer to the examples in sections 5.1 and 5.2 for detailed descriptions of BSOICs and BTMs, respectively.

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 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 Personnel Protection System (PPS) Group and the Beam Containment System (BCS) Group of the Controls Department
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 start-up. 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 the facility, the **project manager** or **facility manager** should maintain as-built drawings of the RSS. All drawings and sketches should contain SLAC drawing numbers and all 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

DOE radiation protection standards are based on federal regulations for occupational exposure. The current applicable standards are regulations in Title 10, *Code of Federal Regulations*, Part 835, "Occupational Radiation Protection" (10 CFR 835)[1] and the SLAC *Radiological Control Manual.*[2]

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 sievert) in a year total effective dose (TED).

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

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[1] "Code of Federal Regulations: Main Page"

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

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 (TED) 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).

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 for 2000 h/y (5 µSv/h)	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 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 prior to reaching its 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 the *SLAC Environment, Safety, and Health Manual,* Chapter 9, “Radiological Safety”).[3] 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 is used to determine the required shielding and protection devices. It defines the highest beam power that the accelerator can deliver to a point assuming that the BCS devices that limit beam power have failed. In estimating the maximum credible beam, 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.

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.

Similarly, a failure of the PPS, if undetected, could allow personnel to be present inside a beam enclosure and 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 PPS and BCS is not considered to be a credible scenario.

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

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

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 facility 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 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)
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.

2.5 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. 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 significant exposed electrical hazards in tunnel areas through the use of interlock devices
7. Control access to certain areas outside the beam enclosures using physical barriers and controlled locks and keys

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. The following table provides a grading of required physical features (levels 1 to 3). The dose rate in Table 3-1 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.

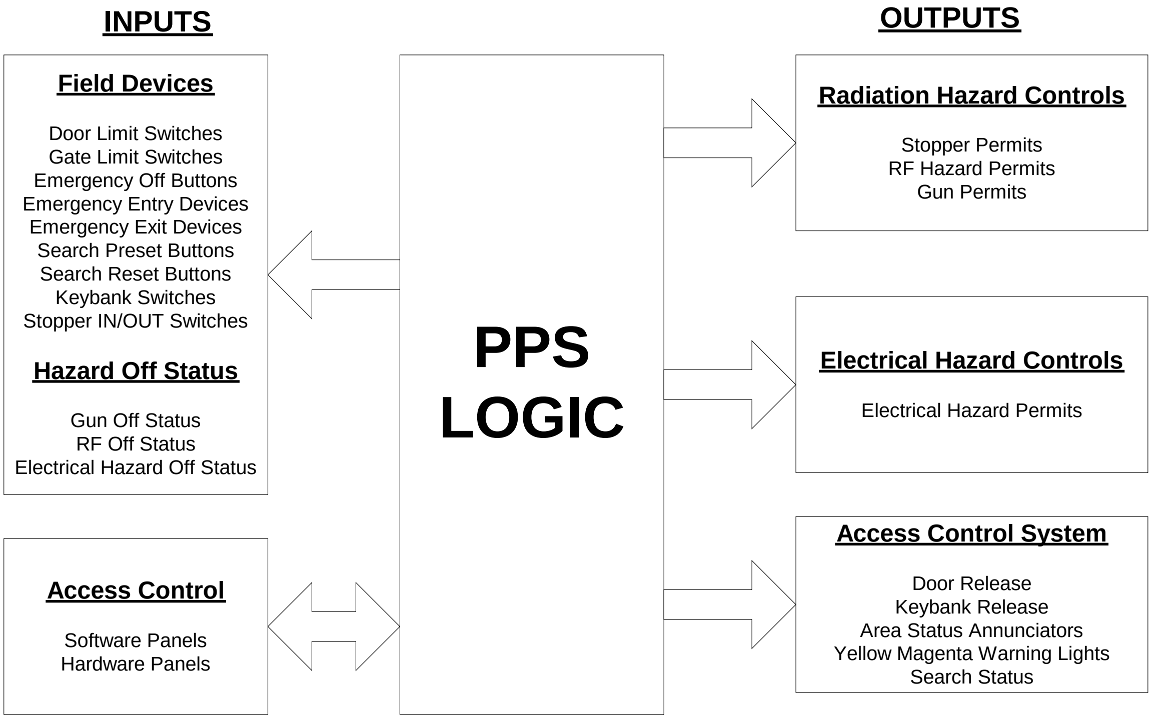

Figure 3-1 PPS System Information Flow

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 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, "PPS Stopper Design Requirements"). 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 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 and electrical hazards in the area. The 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, RF, and uncovered electrical hazards 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 uncovered electrical hazards to be on, but no beam. Searched status is required and no personnel are allowed in the area except with approval to perform a special administrative electrical test procedure called restricted access safety key (RASK). In the PEPII ring, RF is allowed to be on in Restricted Access without personnel access.

RASK is a special testing mode provided in some areas that permits personnel to occupy the beam enclosure with interlocked electrical hazards on and with beam and RF off. In this state, beam operation is prevented by the insertion of stoppers, housing lights are at full brightness, and key release at entrance door key banks is prevented once the test team has entered the enclosure.

Testing is done in strict conformance with approved test procedures (*SLAC Guidelines for Operations*, Guideline 27, "Testing of Personnel Protection Systems").[4] Procedures differ for each area, depending on the nature of the electrical hazards and the particular design of the PPS logic.

3.3.4.3 Controlled Access

The controlled access state means no beam, but RF and uncovered electrical hazards 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.

3.3.4.4 Permitted Access

Permitted access state means that the beam, RF and uncovered electrical hazards must be off. Personnel access can be made without restriction. Keys are not required. Before beams, RF, or uncovered electrical hazards 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 button 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

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[4] SLAC Guidelines for Operations (SLAC-I-010-00100-000)

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. At the end of two minutes, the lights are left in an off or dim condition.

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. A large red light is mounted on each switch assembly. These lights flash when hazards are permitted.

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, or a pull ring.

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. A circuit logic description of a typical PPS logic circuit system is provided in Section 5.3, “Personnel Protection System Logic and Enclosure Descriptions”.

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 was made to a restricted area.

These guidelines have been heavily influenced by publications such as the American National Standard N43.1[5] and the National Council on Radiation Protection and Measurements Report, NCRP 88.[6]

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 shut down 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.
3. Contain two independent and therefore redundant subsystems from the sensors through the logic to the hazard power sources. 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 environments 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, there 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 back-up for long-term retention of the program state. All parts of the PPS will 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 shut down 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.

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[5] American National Standards Institute, “American National Standard for Radiological Safety in the Design and Operation of Particle Accelerators” (ANSI N43.1 [currently under revision]). See the SLAC Library, QCD191:A43

[6] National Council on Radiation Protection and Measurements, Radiation Alarms and Access Control Systems (NCRP Report No. 88, December 1986)

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 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 system 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 must have a method to operate the stopper that is independent 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 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.

Examples of typical enclosures controlled by the PPS are given in Section 5.3, “Personnel Protection System Logic and Enclosure Descriptions”.

3.5 Administrative Procedures

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

3.5.1 Training

The ESH Division provides training in the use of the PPS in the Radiation Worker I Training course (RWT I).[7] Further guidance and reference material is provided in the SLAC *RadCon Manual* and the *SLAC Guidelines for Operations*, Guideline 19, "Use of Software-Based Control Systems".[8]

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.

3.5.2 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.

3.5.3 PPS Certification

Certification and validation of the PPS is done in accordance with the *SLAC Guidelines for Operations*, Guideline 27, "Testing of Personnel Protection Systems", 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 tests, electrical hazard tests and system logic tests.

3.5.4 Testing to Maintain System Integrity

Testing will be performed and documented at regular intervals, and must include sensors, relays, computers, and the shut down 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 Guidelines for Operations*, Guideline 27, "Testing of Personnel Protection Systems".

3.5.5 Configuration Control

Procedures that control the modification and retesting of PPS systems are described in the *SLAC Guidelines for Operations*, Guideline 14, "Configuration Control of Radiation Safety Systems". All changes must be carefully reviewed and approved, and retesting must be done in accordance with an approved procedure.

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[7] ESH Course 116PRA, Rad Worker Practical (ESH Course 116PRA)

[8] SLAC Guidelines for Operations (SLAC-I-010-00100-000)

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 ionization chambers) that ensure beam confinement within an approved beam channel at an approved allowed beam power and hence prevent the generation of excessive level of radiation within occupied areas.

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

- Mis-steering of beams during tune-up or because of magnet power supply
- Magnet wiring 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 three 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.

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

Examples given in Section 5.4.1, “Examples of BCS ”, illustrate the need for electronic BCS devices.

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 beam containment system.

4.4 BCS Devices and Design Requirements

4.4.1 General Design Requirements

The following general requirements guide the equipment design:

1. The beam power in a beam line must be limited to the allowed beam power by each of the three independent BCS devices if the allowed power is less than the maximum credible beam power.
2. Beam losses in radiation containment areas may need to be limited by two BCS devices to prevent radiation levels in occupied areas from exceeding those given in Section 2.2, “Shield Design Objective”, for normal beam operation.
3. Beams must be terminated in an appropriate BCS device, such as a dump designed to absorb the allowed beam power indefinitely.
4. Beam containment devices, such as magnets and mechanical and electronic protection devices, must be designed or implemented to fail in a safe manner.
5. No single-point failure should render the system unsafe.
6. 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.
7. Equipment and cabling should be protected in locked racks whenever possible.
8. All BCS circuits must be either self-checking or redundant.
9. When a fault is detected, all beams must be shut off by three 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 two additional electronic BCS devices. 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 (MCB) indefinitely.

Mechanical BCS devices that are designed to absorb the MCB 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 (RTDs) 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 beam containment system 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.

The various electrical and electronic BCS devices are described in the Section 5.4.2, “Electrical and Electronic BCS Devices”.

4.5 Administrative Requirements

The beam containment system 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 Accelerator Department Safety Office, or the Stanford Synchrotron Radiation Laboratory (SSRL) Safety Office. To ensure that this time is allocated, line items may be included on the Beam Authorization Sheet.
- All protection devices must be protected against unauthorized modification or bypassing.
- Operation of the BCS equipment will be checked either daily, or weekly, using formal procedures.

The RSC should review new protection devices.

5 Examples of RSS Components

5.1 Beam Shutoff Ion Chamber System

5.1.1 Introduction

There are currently two types of BSOICs at SLAC, the SLAC-made BSOIC and the commercially available NRC model.

5.1.2 SLAC-made BSOIC Description

5.1.2.1 Ionization Chamber

The ionization chamber and associated electronics are housed in a cylindrical can, 25.4 cm (10 inches) in diameter and 71.1 cm (28 inches) high. The ionization detector is a 10-liter aluminum chamber filled with P-10 gas (90 percent ethane, 10 percent argon) at one atmosphere. Aluminum and ethane are approximately tissue-equivalent for photons in the energy range from 200 keV to 10 MeV. Ethane was selected to enhance the response to fast neutrons. The chamber response to neutrons is about 20 percent of its response to the same dose of photons. The chamber is designed to produce 1 pA/mrad.hr with a collecting potential of 500 V and retains a linear response in photon fields up to 100 rem/h.

5.1.3 Electronics

The unit is AC-powered and the electronic processing is all solid-state with a circuit design that is temperature independent. The collecting potential is provided by a 500 V internal power supply.

5.1.4 Fail-safe Design

To provide fail-safe operation, a ~ 0.1 μCi ^{9O}Sr source is incorporated within the chamber. The source produces a current corresponding to about 2 mrem/h. This “housekeeping” current generates a continuous analog voltage at the output of the integrator. When the output signal drops below a pre-set level (low-trip point), indicating either a deterioration of the source, loss of chamber pressure, or a reduction of high voltage or electrometer output, a non-resettable trip is generated. At this point the BSOIC must be replaced or repaired. The electrometer has other potential failure modes that may not be detected (for example, a shorted output signal).

5.1.5 Power/Signal Cable Disconnection

A trip is generated if the AC power cable or the signal cable is disconnected.

5.1.6 Output Signals

5.1.6.1 Trip Status

There are two varieties of BSOIC trips. A *high trip* occurs when the BSOIC signal exceeds its high-trip point (typically 10 mrem/h or 100 mrem/h) indicating excessive radiation levels. A *low trip* is generated when the BSOIC signal falls below its low-trip point (approximately 1.5 mrem/h) indicating hardware failure. Both trip points are set locally at the BSOIC.

For example in the SLAC main Linac, two signals are generated by a BSOIC when it trips. One signal notifies the PPS directly (via hardwire) of the radiation event and the PPS responds in the appropriate way. This trip signal also reports status via hardwire to a primary annunciator panel in the control room, signaling the operations staff audibly and visually. The other signal is monitored by the control system and can be displayed at all remote terminals.

5.1.6.2 Warning Signal

This signal is derived in software by the control system. A *high warning* is generated if the BSOIC output analog reports an elevated radiation level (for example, above 5 mrem/h for BSOICs set to trip at 10 mrem/h, and 10 mrem/h for BSOICs set to trip at100 mrem/h). A *low warning* is generated if the BSOIC output analog reports a reduced reading (below 1.7 mrem/h) indicating a possible future failure of the BSOIC. A high or low warning may trigger an audible and visual alarm on a primary annunciator panel in the control room.

5.1.6.3 Local Status

There is a red light on the front of the BSOIC to indicate the unit has tripped.

5.1.7 NRC BSOIC Description

A radiation detection system made by NRC (Nuclear Research Corporation) is used as a BSOIC at some locations such as PEP II. This system consists of a neutron detector, a photon detector, and an alarm and readout unit.

5.1.8 NP-100 Neutron Detector

The NRC model NP-100 neutron detector used at SLAC is based on the well-known Anderson-Braun remmeter design. It has a BF_3 gas tube at 60 cm Hg pressure inside a polyethylene cylinder 29.2 cm (11.5 inches) long and 24.4 cm (9.6 inches) diameter, which gives an effective dose response that is nearly energy independent between 0.025 eV and 15 MeV. The response decreases rapidly as the neutron energy increases above 20 MeV. The response to neutrons at about 100 MeV is a few percent of its response at 1 MeV.

The operating high voltage for the BF_3 proportional counter tube is 1,750–2,000 V, which gives a neutron sensitivity of 7,000 counts per mrem. The neutron detector has been tested for linearity with isotopic neutron sources in fields up to 100 mrem/h. The response is linear in pulsed fields to 50 mrem/h neutron dose rate. The neutron detector has no response to a continuous photon field up to 200 rem/h.

5.1.9 IP-100 Photon Detector

The NRC model IP-100 photon detector used at SLAC is an ionization chamber. The ion chamber sensor tube, 8.9 cm (3.5 inches) long, is enclosed inside a moisture-proof aluminum cylinder 30.5 cm (12 inches) long and 6.4 cm (2.5 inches) in diameter. The measured current is converted into a pulse train the frequency of which is proportional to the photon field intensity. The photon response is nearly energy-independent between 50 keV and 2 MeV. The photon detector has no response to neutrons.

The operating high voltage for the ion chamber is 1,600–1650 V, which gives a photon sensitivity of 1,000 counts/mrem. The response is linear over a dose rate range from a few mrem/h to a few rem/h in pulsed fields.

5.1.10 ADM-610 Alarm and Readout Unit

The NRC ADM-610 Area Dose Monitor is a dual channel microprocessor controlled alarm and readout unit. Each channel can be configured to accept either photon or neutron detectors. Nominal sensitivities (counts/mrem) used for all detectors are stored in the ADM-610. A scaling factor that accounts for the variation in sensitivity for each detector is stored in the detector and can be adjusted during calibration. When a detector is present, the ADM-610 will read in the type and scaling factor information from the detector. Data are buffered for both photon and neutron detectors in the ADM-610 for later retrieval. The previous 30 values for one-minute data, hourly data, and daily data are available.

The *high-level alarm* and *high-level warning* set points are compared with the average dose rate over a pre-set time. This time period is typically one minute, but can be adjusted in the PROM. If the average dose rate from either neutron or photon detector exceeds the alarm set point, the alarm is turned on. With an alarm set at an average dose rate of 10 mrem/h, an integrated dose of 0.17 mrem will generate a trip.

The average dose rate is not the dose rate indicated on the local display; instead, an exponential filtering algorithm is used. This display is updated every 2 seconds. Even if the display indicates an instantaneous dose rate greater that 10 mrem/h, the ADM will not generate a trip unless a dose of 0.17 mrem is integrated within one minute. It is the displayed reading that is sent to the SCP control system.

The ADM-610 provides local and remote visual trip indicators. Battery backup is provided for the ADM-610 in the event of AC power failure when normal operation functions are required.

5.1.11 Output Signals

5.1.11.1 Trip Status

A high trip occurs when the BSOIC signal exceeds its high-level alarm set point (typically 10 mrem/h or 100 mrem/h) indicating excessive radiation levels. The high-trip point is set locally at the BSOIC.

5.1.11.2 Warning Signal

This signal is derived in software by the control system. A high-level warning is generated if the BSOIC output analog reports an elevated radiation level (above 5 mrem/h for BSOICs set to trip at 10 mrem/h, and 10 mrem/h for BSOICs set to trip at100 mrem/h). For the photon detector only a low-level warning is generated if the BSOIC output analog reports a reduced reading (below 1.7 mrem/h) indicating a possible future failure of the BSOIC.When this condition is reached, an audible and visual alarm is triggered on a primary annunciator panel warning the operators.

5.1.11.3 Equipment Failure

In order to guarantee proper operation this instrument performs many internal checks while operating. Whenever any of these internal checks fail, an equipment failure signal is generated and causes the instrument to report a Trip Status. The equipment failure signal reports directly to the SCP control system and can be monitored at any time.

5.1.11.4 Local Status

Under normal operating conditions, a steady green beacon is lit on the ADM. Under a warning condition, the green light goes off and a small “alert” indicator light is illuminated. After a BSOIC trip, a red beacon on the ADM begins flashing. There is also a “fail” indicator light, which is illuminated when there is an equipment failure.

5.1.12 Fail-safe Design

The signal from cosmic neutrons is used over a pre-set time period to ensure that the neutron detector is working continuously. If zero count is observed over the integration period, a no-count failure occurs and an equipment failure is generated. The integration time for a no-count failure is set at 6 hours. The operating high voltage is set at approximately 1950 V, which generates a signal of two to three counts per hour from cosmic neutrons.

A small, 10 μCi ^{137}Cs source is attached to each ionization chamber detector, generating a housekeeping signal of 2 mrem/h (>30 counts/min) to ensure that the detector is working in a continuous mode. The integration time for a no-count failure is set at 2 minutes.

5.1.13 Power/Signal Cable Disconnection

A trip is generated if the signal cable is disconnected, or if the AC power is disconnected and the battery has failed.

5.1.14 Use of BSOICs at Storage Rings

The instantaneous dose rate for sudden loss of stored beam from a storage ring can be quite high, but persists for very short periods of time (for example, microseconds). When averaged over a longer time period, the dose rate is reasonably low. BSOICs are generally used to detect errant beam loss during injection. At storage rings, BSOICs are allowed to integrate over longer time periods to avoid trips from stored beam loss. This does not cause a significant difference in dose to personnel.

5.2 Burn-through Monitors

5.2.1 Introduction

The motivation to incorporate burn-through monitors (BTMs) as protection devices resulted from analysis of the consequences of the destructive capability of the beams generated in the SLAC linac. A series of destructive tests were performed in the Beam Switchyard in the early 1970s[9] to examine typical beam-line power absorption devices such as beam stoppers, collimators, and beam dumps and evaluate their worthiness as safety devices to achieve and maintain high standards of personnel protection. It was recognized early that safe containment of the primary $e^-/e^+/\gamma$ beams had to be an essential feature of any personnel protection system.

Consequently, any review of the probable operational safety of a beam line or experiment poses questions about failure modes and beam burn-through times. We define *burn-through* as the time interval from the beginning of beam exposure to a power absorber or other beam transport component to the time when the beam emerges substantially unattenuated from the downbeam face of such a component, that is, when the beam has destructively created a passage thereby allowing its further propagation to points beyond.

A typical BTM consists of three in-line subsystems and two remotely located support systems:

- The in-line systems are
  - Cascade shower builder or “amplifier”
  - Pressure vessel
  - Remaining beam power absorber
- The remotely located support systems are
  - Gas supply or reservoir
  - Electro-mechanical pressure switch

5.2.2 Design Description

5.2.2.1 Shower Builder

BTMs are pressure vessels, usually located near shower maximum, that are designed to rupture when the device being protected absorbs greater than its allowed beam power. The shower builder is typically a slab of carbon steel of appropriate transverse size to adequately cover all possible errant beam conditions. It is a few radiation lengths (X_o) long in the direction of beam propagation to let the cascade develop to a range where the highest per unit volume energy deposition takes place. Note this shower is short of allowable shower maximum since at some depth the increase in transverse beam size starts to dominate the still increasing shower multiplicity thereby reducing per unit volume energy deposition from peak values.

5.2.2.2 Pressure Vessel

The pressure vessel is the “active” element and consists of an austenitic stainless steel container, which is thin-walled and thin in direction of beam propagation, sandwiched between the shower builder and remaining beam absorber. It has the same appropriate transverse size as the shower builder. Stainless steel was chosen because of its very low thermal conductivity and thermal diffusivity. In a real beam exposure this property results in heat pile-up and eventual earlier perforation due to melting than would be possible with a material of higher thermal conductivity. A beam with power of 1 kW would likely rupture the pressure vessel in times of the order of tens of minutes, while a 5 kW beam would rupture the vessel within seconds.

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[9] D. Walz, et al., “Tests and Description of Beam Containment Devices and Instrumentation – A New Dimension in Safety Problems” (SLAC-PUB-1223, March 1973)

5.2.2.3 Gas Supply

The pressure vessel is connected to the inert gas (for example, dry nitrogen) bottle(s) or reservoir with a very small diameter tube (usually copper). There is a valve at the reservoir, which is always open when in service. There is also a pressure regulator next to it, set at ~20 psig (~1.4 atm) above ambient pressure. This arrangement prevents false pressure switch responses due to possible small leaks in the gas plumbing. Yet, at the same time it does not have enough gas flow delivery capacity to compete with the loss of gas from the BTM pressure vessel due to a real, beam-caused, perforation.

5.2.2.4 Pressure Switch

The BTM pressure vessel is also connected to a remotely located electro-mechanical pressure switch with a metallic tube (usually copper) of large enough flow diameter to guarantee quick response (a few seconds) when the beam has perforated the vessel. The signal from the pressure switch goes into a circuit that terminates beam. The switch acts through energized relays that de-energize on a BTM fault, the loss of power, or a short or open circuit on any connecting cable. The BTMs do not act through the electronic shutoff circuits of the BCS. They operate directly through the Personnel Protection System to terminate beam delivery by removing the gun permissive and tripping the VVS.

5.2.2.5 Power Absorber

Downbeam of the BTM pressure vessel there is another steel block of appropriate transverse size and sufficiently long enough in the beam direction (20 to 30 radiation length) to attenuate the cascade shower to safe residual levels. Its heat capacity and heat rejection capability allow time for other safety systems to respond in case of real beam exposure.

5.3 Personnel Protection System Logic and Enclosure Descriptions

5.3.1 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. A block diagram of a typical personnel protection system is shown below in Figure 5-1.

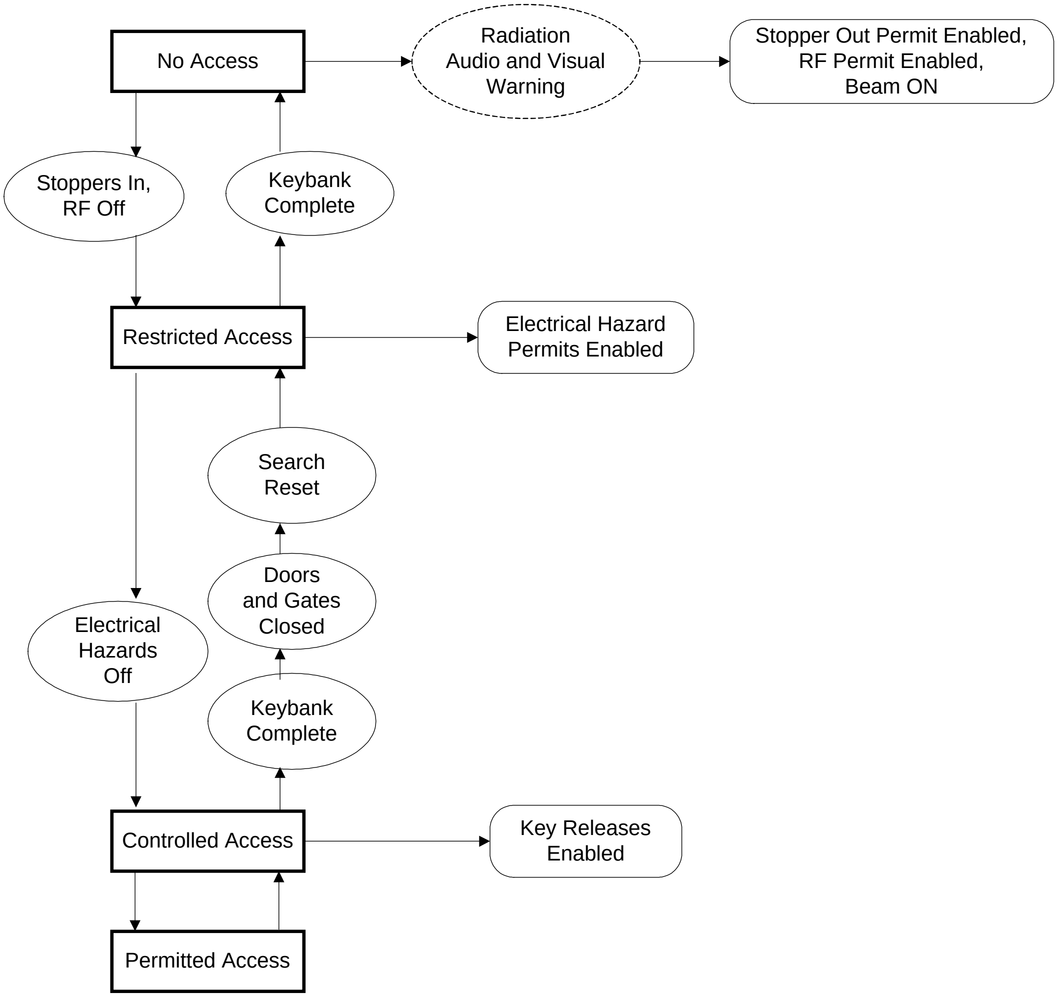

Figure 5-1 PPS System Overview

The logic also issues control signals to release keys at doors controlled by the PPS and to operate warning systems at entrance doors and in accelerator tunnels. There are several major logic blocks that make up a typical personnel interlock system. These may include the following:

- Search and secure logic
- Stopper permissive logic
- Electrical radiation hazard logic
- Access state change logic
- Key and door release logic
- Annunciator and warning system logic
- Logic electrical test

An example of such a logic block is shown in Figure 5-2.

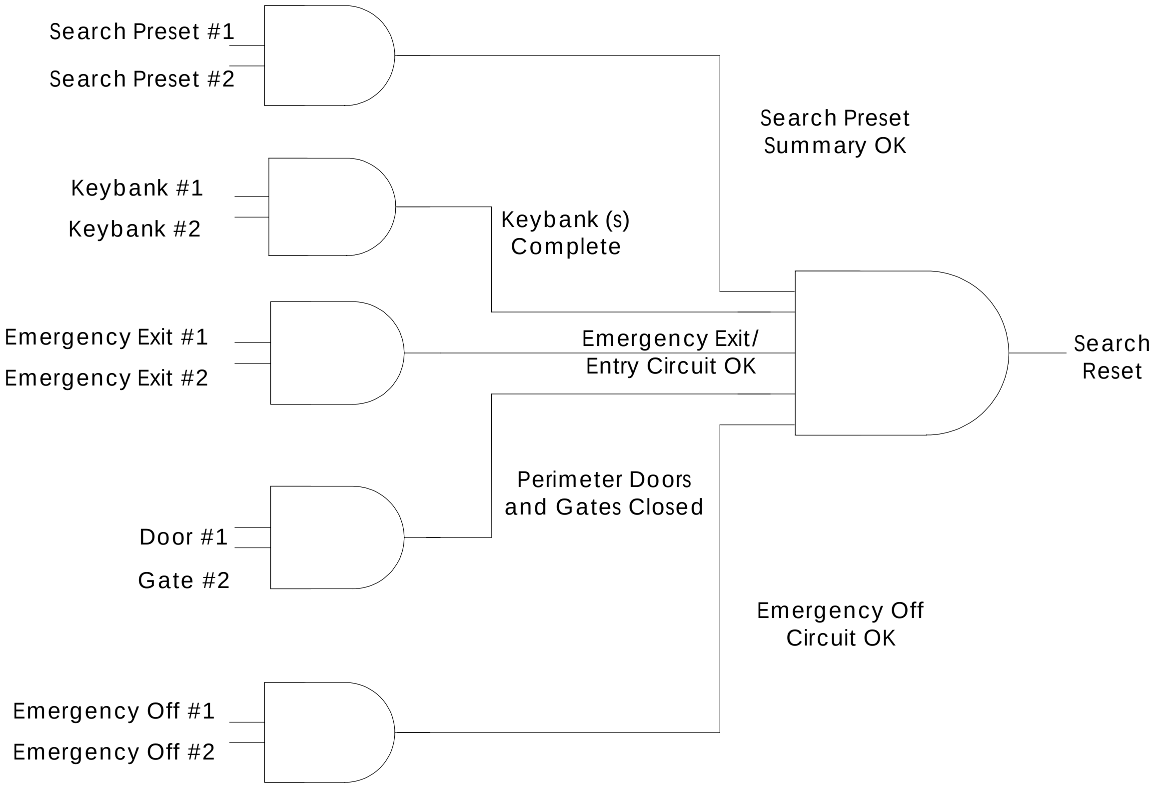

Figure 5-2 PPS Logic Circuit

5.3.2 Typical SLAC Enclosure Controlled by the PPS

Figure 5-3 shows an enclosure that is controlled by the PPS at SLAC. It consists of an area with a main entrance module and another gate leading to an adjacent area also controlled by the PPS.

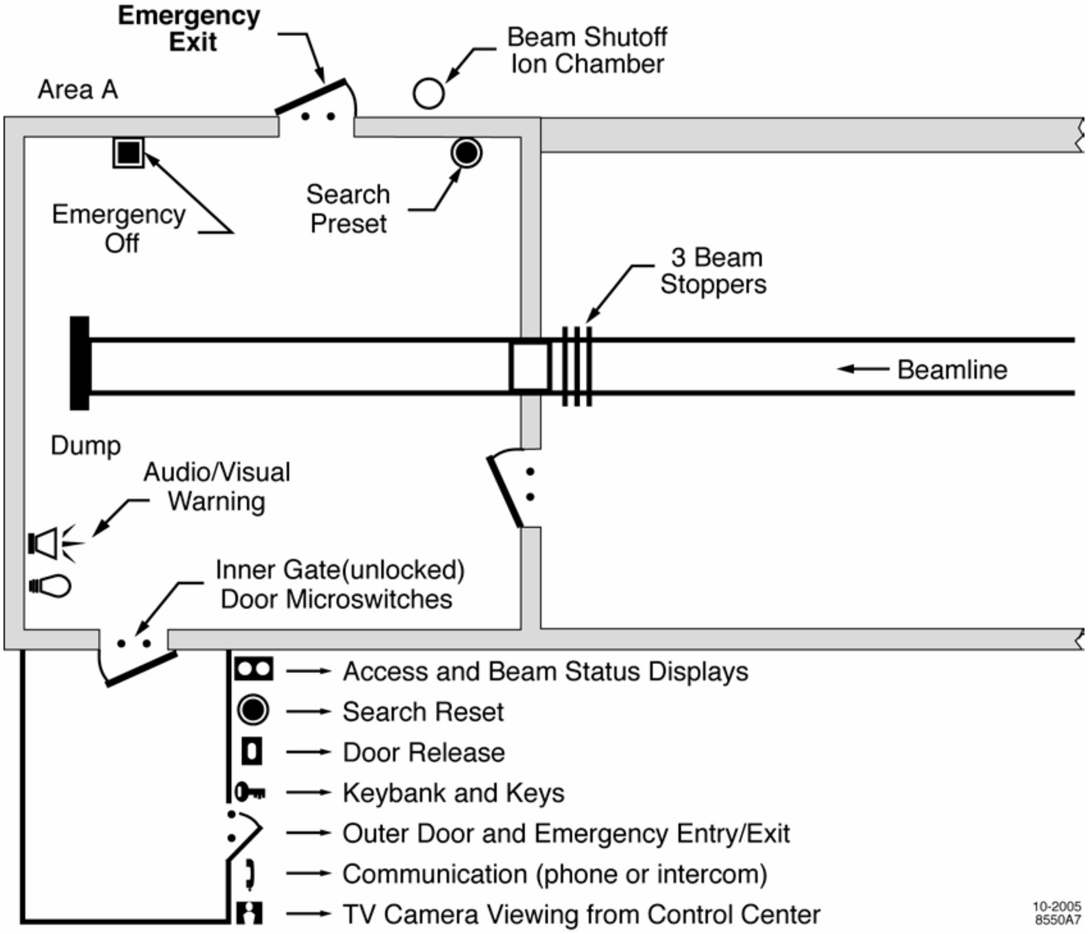

Figure 5-3 Typical PPS Enclosure at SLAC

The features of main entrance modules should include

- An interlocked door and an interlocked gate; the outside door must be locked
- Emergency entry/exit mechanism
- Key banks
- Door release key switch and/or push button
- Search pre-set buttons
- Search reset button
- Emergency-off buttons with indicator lamps
- Video camera
- Intercom or telephone
- PPS annunciator sign for area status and hazard status
- Audio-visual warnings

- Yellow/magenta lights

5.3.3 Typical SSRL Hutch Enclosure

Following is a description of an experimental enclosure (hutch) that is controlled by the PPS, for a synchrotron radiation beam line at SSRL. It consists of lead- or steel-shielded housing with one or more access doors. The PPS for hutches is called a hutch protection system (HPS) at SSRL and it is operated by authorized experimenters.

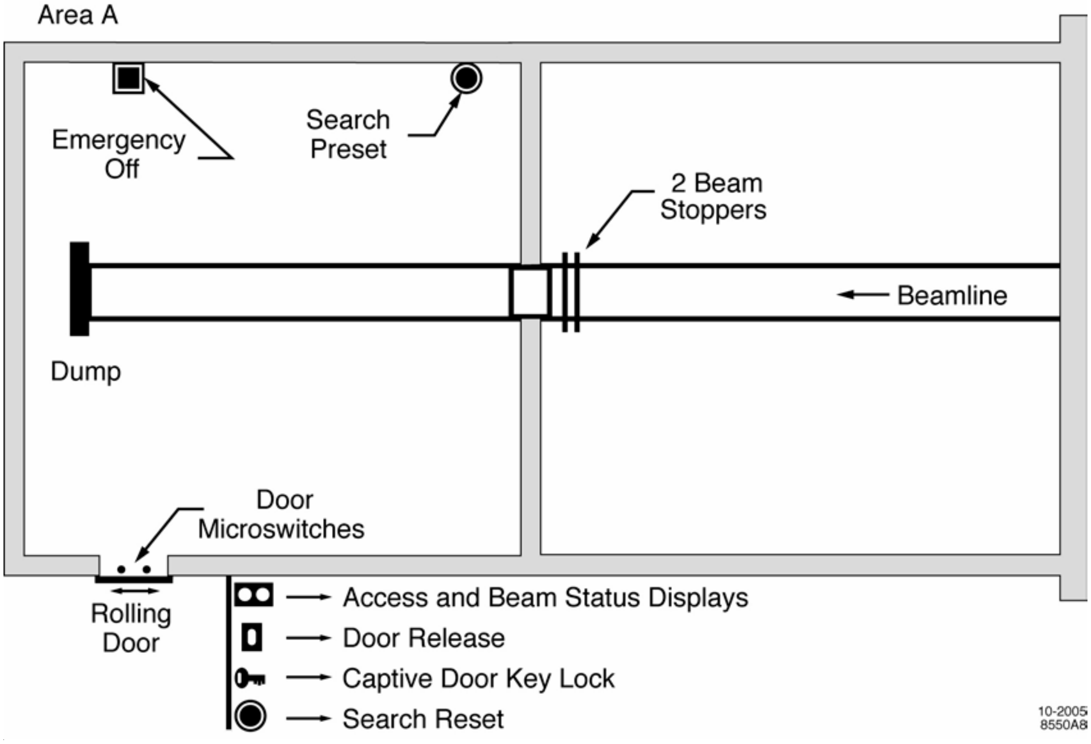

Figure 5-4 Typical Hutch Enclosure

Its features should include

- A door that is interlocked and locked
- Emergency entry/exit mechanism
- On-line and off-line key and green/red status lights (controlled by the SPEAR operator)
- One or more search reset keys or buttons (with timer) inside hutch
- Hutch Kirklock door key
- Emergency-off buttons
- Audio (tone) and visual (red) radiation warnings prior to beam on

5.4 Beam Containment System Examples and Device Descriptions

5.4.1 Examples of BCS Applications

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.

5.4.1.1 Example 1

The maximum credible beam that could be delivered to a particular beam line might be as high as 100 kW if all the beam power-limiting interlocks failed. If the dump at the end of the line could absorb 100 kW indefinitely, then the beam would be safely contained at the dump. If, however, the dump had a rating of 50 kW, then it would have to be protected by electronic BCS devices such as ion chambers or current toroids that would shut off the beam when the power exceeded 50 kW. The dump may also have to be equipped with a BTM to protect it in the event of a failure of the electronic BCS devices.

5.4.1.2 Example 2

A 50 kW beam is targeted on a 50 kW dump, and the beam is diverted from its proper trajectory in the beam line by either mis-steering or magnet failure. If the beam hits a BCS collimator that is rated for 50 kW, no additional protection is needed. If the collimator is rated for less than 50 kW, electronic BCS devices must be installed to protect it in a manner similar to the aforementioned dump. The collimator may also have to be equipped with a BTM to protect it in the event of a failure of the electronic BCS devices.

5.4.1.3 Example 3

If a beam can be diverted from its proper trajectory and strike a component that is not a mechanical BCS device, electronic BCS devices such as ionization chambers should be installed to detect and shut off such an errant beam. BSOICs may have to be placed in the region outside the shield surrounding the area where this could occur.

5.4.2 Electrical and Electronic BCS Devices

Examples of various electrical and electronic Beam Containment Devices are described in detail below:

5.4.2.1 Average Current Monitor

An average current monitor is a gated device that is used to limit the average beam current in a specific beam line to a pre-set value. The input transducer is a toroid. The monitor consists of a 100 ms auto-resetting integrator, a sample-and-hold circuit, meter, and a hi-trip comparator. Self-check is accomplished by generating a 360 Hz test pulse, equivalent to 100 nA at 1 ms before beam time, and sensing the sample and hold output with a low-trip comparator. A 20 nA to 50 µA range switched meter is included on the front panel. The use of zero suppression of the test-pulse signal provides direct reading of average beam current.

5.4.2.2 BCS Bypass and Summary

A bypass and summary unit is an eight channel input chassis with two summary outputs. Each input channel can be independently bypassed, either locally or remotely. The input circuit is optically isolated and is used to detect fault interrupts from BCS devices. The summary output circuits are the dry contacts of two redundant relays and can be used as the inputs to another BCS bypass and summary chassis unit.

5.4.2.3 BCS High-charge Monitor

A high-charge monitor measures the instantaneous charge on a pulse-by-pulse basis from a beam line toroid.

5.4.2.4 BCS Trigger Distribution

A trigger distribution unit provides triggers to the average current monitors and the Pulse-to-pulse comparators. The purpose of the triggers is to allow the devices to generate beam time gates to suppress noise. These devices are the only BCS devices that require triggers. The triggers are derived from the fiducial generator, which is a fixed source and is the main accelerator-timing source.

5.4.2.5 BCS Trigger Timing Watchdog

A trigger timing watchdog unit is used to ensure that the BCS trigger distribution has not drifted from synchronization with the main accelerator-timing source

5.4.2.6 BCS Shutoff Chassis

This device has two independent summary inputs that inhibit or permit the transmission of four isolated shut off circuits. These in turn provide permits to three accelerator shutoff systems, which when present enable beam.

5.4.2.7 Bipolar Preamplifier

This amplifier is used to detect the presence of electrons or and positrons passing through the same toroid. Its function is to rectify the bipolar pulses from a beam line toroid so that the existing average current monitors can be used to limit beam power of both electrons and positrons in the same beam line.

5.4.2.8 Fan-in Amplifier

A fan-in module is used as a part of the self-checking scheme developed for the pulsed systems. It allows time multiplexed test pulses from more than one signal processor to be buffered and sent out to the calibrate inputs of each beam line toroid. It is a 6-input summing amplifier with adjustable gain from 0.5 to 1.8.

5.4.2.9 Fan-out Amplifier

A fan-out module is used to distribute buffered beam signal outputs to more than one signal processor from a single beam line sensor. It provides a means for normalization of signal levels (system gain adjustment) to each processor input. It has a balanced input differential amplifier with switchable gain of from one to 25, and six isolated output stages, each independently adjustable in gain from 0.5 to 2.

5.4.2.10 Long Ion Chamber

A long ion chamber (LION) is a gas-filled coaxial cable that functions as an ion chamber. It is used in lieu of many discrete ion chambers when a number of devices in a beam line are to be protected or when a long section of a beam line requires protection. Radiation from a beam loss intercepts a portion of the cable and induces a pulsed current that is proportional to the ionizing charge. If the radiation level exceeds pre-set levels, all beams are shut down. The detection and shutoff circuit is similar to that used for the *protection ion chamber (PIC)*, described in Section 5.4.2.12, "Protection Ion Chamber Processing Electronics".

5.4.2.11 Meter Relay

The meter relay is used to monitor magnet shunts and power supply voltages, and to require that they be inside or outside the meter relay set points. The inside or outside window is switch selectable. This unit is used as a module in a crate and as a chassis.

5.4.2.12 Protection Ion Chamber Processing Electronics

The sensor of protection ion chamber (PIC) is a gas-filled cylindrical ion chamber situated on or near the mechanical device that is to be protected. When beam loss at the ion chamber exceeds pre-set levels, all beams are shut down. The ion chamber processing consists of 10 PIC cards in a chassis, which provides two independent summary output signals. For self-test, the chamber high voltage is fed from the high voltage power supply to a resistor network at the chamber. This injects a small housekeeping current back along the signal cable to produce a voltage at the output of an operational amplifier integrator on a printed circuit card. The integrator output is fed to a low-trip comparator for self-test, and to a high-trip comparator which responds to beam loss signals. A cable or chamber disconnection causes a fault trip via the low-trip comparator. When beam loss radiation at an Ion chamber exceeds pre-set levels, excessive radiation causes the high trip comparator generates a fault signal that shuts off all beams. The integrator has a 100 millisecond (ms) time constant for most applications. There are 10 PIC cards per chassis, which provides two independent summary output signals.

5.4.2.13 Pulse-to-Pulse Comparator

A comparator functions to compare beam derived signals from an upstream toroid sensor and a downstream toroid sensor on a pulse-to-pulse basis. It generates a fault output if the downstream signal is less than a pre-set percentage of the upstream signal, indicating excessive beam loss along the line. This module incorporates two self-check schemes. The first, called "auto-test" simulates beam losses to ensure that the electronics is wired properly. The interpulse test is designed to check external signal path integrity and overall gain whether beams are on or off.

5.4.2.14 Repetition Rate Monitor

The repetition rate monitor is used to limit the beam pulse rate, thereby limiting maximum attainable beam power. It counts beam pulses within a second that are above a typical electron/positron intensity of about 10^9 electrons/pulse. Self-checking circuitry transmits test pulse at 1 Hz and, if detected, turns on an internal 1 MHz pulse train that steps two redundant counters to the fault condition. During the self-check period the fault condition is suppressed.

5.4.2.15 BCS Summary Interlock and Shutoff Chassis

This device has two sets of 16 Summary input channels, completely isolated from one another. The +24V source voltage for these inputs is internally generated from within the chassis. Each set of 16 summary inputs drive two independent optically isolated shut off circuits. These in turn provide permits to three accelerator shutoff systems, which when present enable beam.

5.4.2.16 Unipolar Preamplifier

A preamplifier with nominal gain of 25 is located as close to the beam-line toroid as radiation levels will permit. It raises the toroid signal strength and thereby improves the signal-to-noise ratio. It is a fixed-gain amplifier with differential input and output circuits.

5.4.2.17 Beam-line Transducers

Electronic beam containment devices are designed to turn off the beam in the event that an out-of-tolerance condition is detected. These devices depend on transducers to monitor the beam and detect any such condition. Beam line transducers are described in the following sections.

5.4.2.18 Flow Switch

Flow switches are installed in cooling water systems for dumps, collimators, stoppers and slits. They provide on/off signals indicating normal or low flow. The signal is transmitted on a wire pair to a detector device module.

5.4.2.19 Ionization Chambers

Ion chambers, referred to as PICs (protection ion chambers) are typically gas-filled (argon, air) cylinders about 15 inches long and four inches in diameter. High voltage is applied to one of the internal electrodes. The output signal developed on the other electrode is transmitted on coaxial cable to an electronic processing module. A long ion chamber is a gas-filled coaxial cable. The signal is transmitted on an extension of this cable to the processing electronics.

5.4.2.20 Magnet Shunt and Transductor

Magnet shunts and transductors are used to monitor magnet current. Typically they are installed inside the power supply cabinet, in series with the magnet lead. The voltage signal developed across the shunt, or from the output of the transductor electronics, is transmitted on a wire pair to a meter relay.

5.4.2.21 Microswitch

The signals from microswitches on stoppers are transmitted over a wire pair through the PPS logic circuit system to the BCS detector module.

5.4.2.22 Toroid

A toroid is used as a current transformer that produces an output proportional to beam current. Typically there are at least five turns on the signal pick-up winding. A separate, single turn winding is used for calibration and self-checking. The output signal is amplified locally and transmitted on balanced Twinax cable to the processing electronics.