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Spallation Neutron Source Final Safety Assessment Document for Proton Facilities

July 2022

OAK RIDGE National Laboratory

ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

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SPALLATION NEUTRON SOURCE
FINAL SAFETY ASSESSMENT DOCUMENT FOR PROTON FACILITIES

July 2022

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
UT-BATTELLE, LLC
for the
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DOCUMENT APPROVAL RECORD

Spallation Neutron Source Final Safety Assessment Document
For Proton Facilities, SNS Document Number 102030103-ES0018-R03

This document describes the SNS proton facilities, identifies and analyzes associated hazards, and identifies appropriate controls to mitigate hazards in accordance with DOE Order 420.2C. This document is an update to the previous version (SNS 102030103-ES0018-R02, December 2010). The SNS *Final Safety Assessment Document for Neutron Facilities* (FSAD-NF), which serves as a companion document, is also being updated and will be approved and issued separately.

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ACRONYMS AND ABBREVIATIONS

ALARA	as low as reasonably achievable
APS	Advanced Photon Source
Argonne	Argonne National Laboratory
ASCE	American Society of Civil Engineers
ASE	accelerator safety envelope
BLMS	beam loss monitor system
BNL	Brookhaven National Laboratory
BTF	Beam Test Facility
CAA	Clean Air Act
CCL	coupled cavity linac
CD	Critical Decision
CEBAF	Continuous Electron Beam Accelerator Facility (at Thomas Jefferson National Accelerator Laboratory)
CEC	credited engineered control
CFD	computational fluid dynamics
CFR	Code of Federal Regulations
CHL	Central Helium Liquefier
CLO	Central Laboratory and Office
CTF	Cryogenic Test Facility
CUB	Central Utility Building
CVS	Concurrent Versions System
CWA	Clean Water Act
DI	deionized
DOE	US Department of Energy
DTL	drift tube linac
EPA	US Environmental Protection Agency
EPICS	Experimental Physics and Industrial Control System
ES&H	environment, safety, and health
ESH&Q	environment, safety, health, and quality
EVS	emergency ventilation system
ETTP	East Tennessee Technology Park (previously known as the K-25 site)
FACP	fire alarm control panel
FCT	fast current transformer
FELK	front end, linac, and klystron
FHA	fire hazards analysis
FODO	focus drift defocus drift
FPGA	field-programmable gate array
FSAD	final safety assessment document
FY	fiscal year
GHe	gaseous helium
HDL	hardware description language
HEBT	high-energy beam transport
HVCM	high-voltage converter modulator
ICS	integrated control system
Jefferson Lab	Thomas Jefferson National Accelerator Facility
JHA	job hazard analysis
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory

LEBT	low-energy beam transport
LHe	liquid helium
LLLW	liquid low-level waste
LTV	lock/tag/verify
MCNPX	Monte Carlo N-Particle Code
MEBT	medium-energy beam transport
MPS	machine protection system
NESHAP	National Emission Standards for Hazardous Air Pollution
NFPA	National Fire Protection Association
NPDES	National Pollutant Discharge Elimination System
ODH	oxygen deficiency hazard
OPM	operations procedures manual
ORNL	Oak Ridge National Laboratory
ORR	Oak Ridge Reservation
OSHA	Occupational Safety and Health Administration
PC	performance category
PLC	programmable logic controller
PPS	personnel protection system
PPU	Proton Power Upgrade
PSI	protective system interface
psia	pounds per square inch absolute
psig	pounds per square inch gauge
QA	quality assurance
QMS	quality management system
RAD	Research Accelerator Division
RCRA	Resource Conservation and Recovery Act
RCT	radiological control technician
RFQ	radio frequency quadrupole
RFTF	Radio Frequency Test Facility
RPMS	Radiological Protection Management System
RSO	radiation safety officer
RSS	Research Safety Summary
RTBT	ring-to-target beam transport
SAD	safety assessment document
SBMS	Standards-Based Management System
SBC	Standard Building Code
SCADA	supervisory control and data acquisition
SCL	superconducting linac
SIL	safety integrity level
SNS	Spallation Neutron Source
SPCC	Spill Prevention Control and Countermeasures
TDEC	Tennessee Department of Environment and Conservation
TLDs	thermoluminescent dosimeters
TPS	target protection system
USI	Unreviewed Safety Issue
VTA	vertical test-stand assembly
WSS	work smart standards

1. INTRODUCTION

1.1 BACKGROUND

The Spallation Neutron Source (SNS) is one of the world's foremost neutron scattering facilities. The facility provides important scientific capabilities for basic research in many fields, including material science, life sciences, chemistry, solid state and nuclear physics, earth and environmental sciences, and engineering sciences. A pulsed beam of negatively charged hydrogen ions (H^-) is generated and accelerated to an energy of more than one billion electron volts (1.3 GeV) using a linac. The H^- beam is transported to and injected into an accumulator ring by stripping the electrons as the protons are combined with the circulating pulse. In the ring, the protons are collected and bunched into short (<1 μs) pulses, which are directed onto the mercury target at a rate of 60 pulses per second. Neutrons are created via spallation reactions as the high-energy protons collide with mercury nuclei. Emerging neutrons are slowed, or moderated, and channeled through beam lines to instrumented experimental areas.

SNS is a US Department of Energy (DOE) Office of Science User Facility operated for DOE by Oak Ridge National Laboratory (ORNL). It was designed and constructed as a multi-laboratory partnership led by the SNS Project Office in Oak Ridge, Tennessee. The partner national laboratories included Argonne National Laboratory (Argonne), Brookhaven National Laboratory (BNL), Los Alamos National Laboratory (LANL), Lawrence Berkeley National Laboratory (LBNL), Thomas Jefferson National Accelerator Facility (Jefferson Lab), and ORNL. Figure 1.1 shows a schematic view of the facility and illustrates the national laboratories that participated in the initial design and construction. The collaborative approach took advantage of the best expertise available in different technical areas and made efficient use of resources. A commercial architect engineer–construction manager team (Knight-Jacobs) handled design and construction management of the conventional facilities under a task order contract.

The *Final Environmental Impact Statement*[1-1] for SNS was issued in April 1999; on June 18, 1999, the Secretary of Energy signed the Record of Decision to proceed with construction. A *Mitigation Action Plan* (MAP)[1-2] was issued that identified actions to avoid or to minimize environmental harm in building and operating the facility.

The SNS conceptual design was evaluated by a DOE review committee in June 1997. At the same time, a DOE independent cost estimate was performed. In response to recommendations from these reviews, the project schedule was extended from 6 to 7 years, and other adjustments were made that increased the total project cost from $1,226 million to $1,411 million (as spent).

The Secretary of Energy approved Critical Decision (CD) 1, "Approval of Mission Need," and CD-2, "Approval of Level 0 Project Baseline," for SNS in August 1996 and December 1997, respectively. The SNS Project Execution Plan,[1-3] which governed how the project was managed, was initially approved by the Secretary of Energy at the time of CD-2, with subsequent revisions approved in October 2005. The Level 0 cost and schedule baselines set at CD-2 comprised a total project cost of $1411.7 million and a 7 year design/construction schedule, with facility commissioning to occur in FY 2006. The project carried out advanced conceptual design and further research and development activities in anticipation of starting Title I design in FY 1999.

The project was formally complete after the CD-4 completion stage was achieved by demonstrating integrated operation of the accelerator to produce neutrons that met defined specifications. CD-4 was achieved in April 2006 as SNS transitioned into an operating facility that is managed for DOE by ORNL.

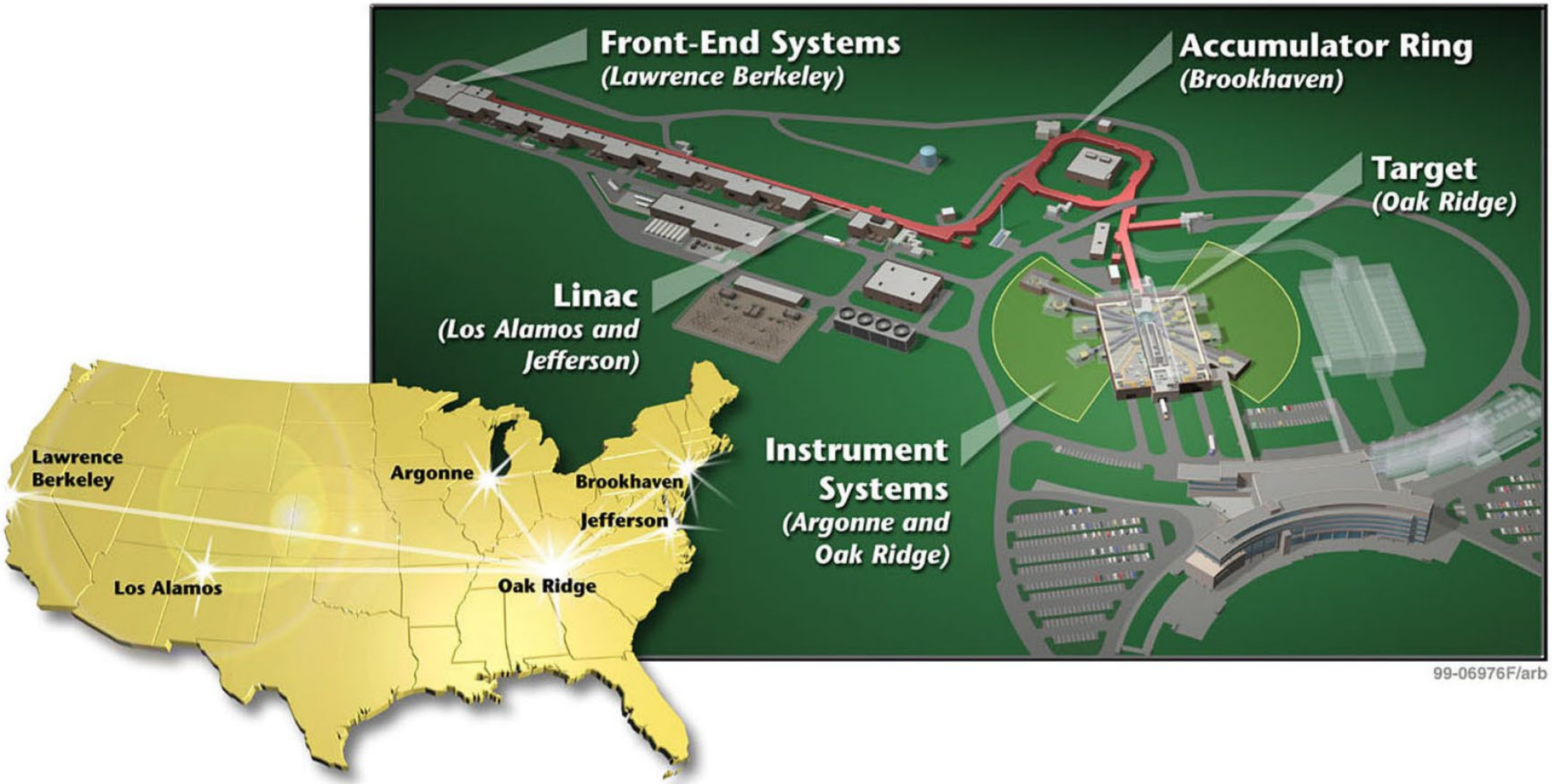

Figure 1.1. Schematic view of the SNS facility and the responsibilities of the partner national laboratories.

This revision to the SNS *Final Safety Assessment Document for Proton Facilities* (Revision 3) incorporates changes and updates that have occurred since the last revision (Revision 2, December 2010). It also includes relevant material from unreviewed safety issue evaluations, as well as miscellaneous updates and editorial improvements.

1.2 SNS APPROACH TO SAFETY

As an operating facility, SNS is fully integrated into the ORNL management systems. The ORNL institutional safety programs, as promulgated through the Standards Based Management System (SBMS), provide protection from standard industrial and laboratory hazards. The SNS management team is committed to ensuring a safe facility. Commitment to excellence in environmental safety and health (ES&H) is a constant goal at all levels at SNS, and improvements are sought on a continual basis. ORNL's Integrated Safety Management Program is implemented through the ORNL SBMS.

Projected radiation exposures from routine operations and the full spectrum of credible nonroutine events have been carefully analyzed, and controls are in place to ensure compliance with the requirements of DOE Order 420.2C[1-9] and 10 CFR (Code of Federal Regulations) 835.[1-5]

In accordance with the principles of integrated safety management, the SNS line management is responsible for safety at the SNS facilities. The SNS line organization includes an SNS operations manager and ES&H staff to provide direction and support to the line management. A system of internal review committees provides opportunities and processes for multidisciplinary peer review of safety questions in the design and operation of the facility.

SNS was designed and built in accordance with the SNS standards for design and construction.[1-6] These standards reflect UT-Battelle's commitments to DOE and the architect engineer–construction manager's contractual obligations to UT-Battelle. The standards were developed primarily to ensure that SNS would be safely designed, constructed, and operated. The SNS standards for design and construction incorporated the work smart standards for engineering design developed at ORNL.[1-7]

1.3 SCOPE

The *FSAD* [final safety assessment document] *for Proton Facilities* (FSAD-PF) addresses accelerator-specific hazards associated with the proton facilities, as well as SNS site-wide accelerator-specific hazards associated with the entire site. Accelerator-specific hazards associated with the SNS neutron facilities are addressed in a companion document entitled *SNS Final Safety Assessment Document for Neutron Facilities* (FSAD-NF).[1-8] Together, the FSAD-PF and FSAD-NF provide a comprehensive safety assessment for accelerator-specific hazards associated with SNS as required by DOE Order 420.2C.[1-9]

Accelerator-specific safety-related controls identified in the FSADs, combined with the applicable safety-related ORNL-wide institutional controls and management systems, serve to ensure comprehensive safety for all SNS activities.

Key components of the proton facilities include the front end, linac, klystron gallery, linac beam dump, high-energy beam transport (HEBT), ring injection dump, ring, ring extraction dump, and ring-to-target beam transport (RTBT), along with support facilities such as the HEBT-, RTBT-, and ring-support buildings, Central Helium Liquefier (CHL) facility, Central Utilities Building (CUB), and Central Laboratory and Office (CLO) Building. The neutron facilities are housed in the target building (Building 8700) and satellite buildings for instruments (e.g., Buildings 8702, 8705, 8707, 8711, 8713, 8714B). The neutron facilities include the target systems, neutron instrument systems, and associated support facilities.

The interface between the proton facilities and neutron facilities occurs within the target building where the proton beam enters the target core vessel, as detailed in Section 6.

Activities at the SNS site are expected to continue to evolve and expand. Additional structures and facilities will be planned and erected to support the scientific mission of the facility. Most such activities are expected to involve standard industrial and laboratory hazards that will be managed under the ORNL institutional safety programs promulgated through SBMS. Should future activities involve accelerator-specific hazards not fully addressed by the ORNL institutional safety programs, these hazards would be evaluated as part of the Unreviewed Safety Issue (USI) process and managed under DOE Order 420.2 as appropriate. For example, significant changes to the fundamental operating parameters of the facility, such as the Proton Power Upgrade (PPU) project to increase the beam energy from the baseline of 1 GeV to 1.3 GeV, are evaluated by using the USI process, and associated safety analysis is implemented as appropriate to evaluate potential hazards before implementation. This process is supported by the project management requirements of DOE O 413.3.[1-10]

1.4 REFERENCES

1-1 "Construction and Operation of the Spallation Neutron Source Facility," *Final Environmental Impact Statement,* DOE/EIS-0247, Office of Science, US Department of Energy, April 1999.

1-2 *Mitigation Action Plan for the Spallation Neutron Source*, DOE-0247-MAP-R0, US Department of Energy, October 1999.

1-3 The *Spallation Neutron Source Project Execution Plan*, Spallation Neutron Source, US Department of Energy, Oak Ridge National Laboratory, October 2005.

1-4 *Spallation Neutron Source Environment, Safety, and Health Plan*, 102030000-ES0001-R03, Spallation Neutron Source, Oak Ridge, TN, March 2006.

1-5 Title 10, *Energy*, Part 835, "Occupational Radiation Protection," 10 CFR 835, US Department of Energy, Washington, DC.

1-6 *Spallation Neutron Source Standards for Design and Construction,* 108030000-ST0001-R00, Spallation Neutron Source, Oak Ridge National Laboratory, September 1999.

1-7 *Oak Ridge National Laboratory Work Smart Standards,* "Other Industrial, Radiological, and Non-Radiological Hazard Facilities," Oak Ridge National Laboratory, July 1996, Revision Change No. 105, January 2018.

1-8 *Spallation Neutron Source Final Safety Assessment Document for Neutron Facilities*, SNS 102030102-ES0016-R03, Oak Ridge National Laboratory, September 2011.

1-9 *Safety of Accelerator Facilities*, DOE Order 420.2C, Office of Science, US Department of Energy, July 2011.

1-10 *Program and Project Management for the Acquisition of Capital Assets*, US Department of Energy, series.

2. SUMMARY AND CONCLUSIONS

Two significant accelerator-specific hazards associated with operation of the proton facilities have been identified: (1) prompt radiation associated with the accelerated beam and (2) oxygen deficiency hazards (ODHs) associated with the cryogenic systems that cool the superconducting linac (SCL) cavities. The safety analysis provided herein identifies appropriate controls to safely mitigate these hazards. The overall conclusion of the analysis is that the risks associated with the SNS proton facilities are low or extremely low with respect to on-site effects and are negligible with respect to off-site effects.

Credited controls, deemed essential for worker safety, have been established to mitigate the prompt beam radiation and ODHs. The personnel protection system (PPS) is an active credited control designed to protect personnel from prompt radiation hazards associated with beam operation. The ODH system and emergency ventilation system (EVS) are active credited controls designed to protect personnel from the potential for an oxygen-deficient environment associated with an inadvertent cryogenic cooling system leak. Finally, design features of the CHL facility that ensure natural convection flow serve as a passive credited control to protect workers from ODHs in portions of the CHL facility. Standard industrial and laboratory hazards are safely managed by the ORNL institutional safety program promulgated through SBMS.

The analyses clearly show that (1) the risks associated with operation of the SNS proton facilities are well understood and characterized and (2) effective controls have been implemented to mitigate risks to acceptable levels. This favorable outcome is the result of the following:

- The SNS Project formed partnerships for design, construction, and installation with national laboratories selected for proven expertise in specific areas.
- SNS has adopted the principles of integrated safety management. SNS has implemented the ORNL SBMS, which implements and promulgates codes and standards that the laboratory has agreed to follow, using the work smart standards process and best management practices adopted by the laboratory.
- SNS applied a standards-based approach for construction and fabrication of buildings, structures, systems, and components to ensure common industrial hazards are well controlled.
- The SNS design has provisions for unique hazards (i.e., those not considered standard industrial hazards) and design features that are at least the equivalent of those provided at other major DOE accelerators.

The SNS facilities and safety systems are described in Section 3 of this document. The SNS design is oriented toward safety of the worker, the environment, and the public.

The safety analyses discussed in Section 4 identify accelerator-specific hazards and appropriate controls. The analyses demonstrate the effectiveness of multiple layers of protection against an actual injury or death and identify instances in which credited engineered controls (CECs) are required to mitigate hazards associated with prompt radiation and oxygen deficiency.

Section 5, "Basis for the Accelerator Safety Envelope," addresses the safety function requirements for CECs and summarizes the basis for the accelerator safety envelope (ASE). The interface between the proton facilities and neutron facilities is discussed in Section 6 to highlight essential features and requirements. Quality assurance (QA) is addressed in Section 7.

3. SITE, FACILITY, AND OPERATIONS DESCRIPTION

This section describes the SNS site, facility, and operations, except for those associated with the neutron facilities portion of the site. The neutron facilities, housed in the target building (Building 8700), satellite buildings for instruments (e.g., Buildings 8702, 8705, 8707, 8711, 8713, 8714B), and ancillary support facilities, are described in the FSAD-NF [3-1] companion document.

3.1 SITE DESCRIPTION

The SNS site is located atop Chestnut Ridge, approximately 1.75 mi (2.8 km) northeast from the center of ORNL and is accessible by Chestnut Ridge Road across from the 7000 Area at ORNL. The SNS footprint extends on a long, wide, and gently sloping ridge top with a broad saddle area at its eastern end. The major buildings needed for the SNS linac, transport line, and ring tunnels are notched into the south side of the ridge using cut-and-fill techniques, providing economical construction and effective shielding.

Most of the information provided in this section is a summary of more detailed information contained in the *Final Environmental Impact Statement: Construction and Operation of the Spallation Neutron Source Facility,*[3-2] ORNL/ENG/TM-19, *Oak Ridge National Laboratory Site Data for Safety Analysis Reports,*[3-3] and ORNL-5870, *Environmental Analysis of the Operation of the Oak Ridge National Laboratory*.[3-4] The information taken from the reports has been reviewed and updated as necessary to reflect present conditions.

3.1.1 Geography

SNS is in Roane County, Tennessee, on the DOE Oak Ridge Reservation (ORR). The ORR lies within the Tennessee Valley between the Cumberland and Southern Appalachian mountain ranges in the eastern portion of the state of Tennessee and is within the corporate limits of the city of Oak Ridge. A road map of the Oak Ridge area is shown in Figure 3.1. The ORR consists of about 34,500 acres with three major industrial complexes located in separate but adjacent valleys: the East Tennessee Technology Park (ETTP, previously known as the K-25 site), the ORNL site, and the Y-12 National Security Complex site. SNS is about midway between the ORNL and Y-12 sites. The SNS site is about 4 mi southwest of the commercial and population center of the city of Oak Ridge and is about 22 mi west of the center (downtown) of the city of Knoxville.

A map of the ORR is shown in Figure 3.2. The closest ORR boundary to the SNS site is about 7,500 ft to the northwest on the south side of East Fork Ridge. Bethel Valley Road runs in an east-west direction approximately 1 mi to the south. Figure 3.3 is an aerial photograph of the area surrounding the SNS site.

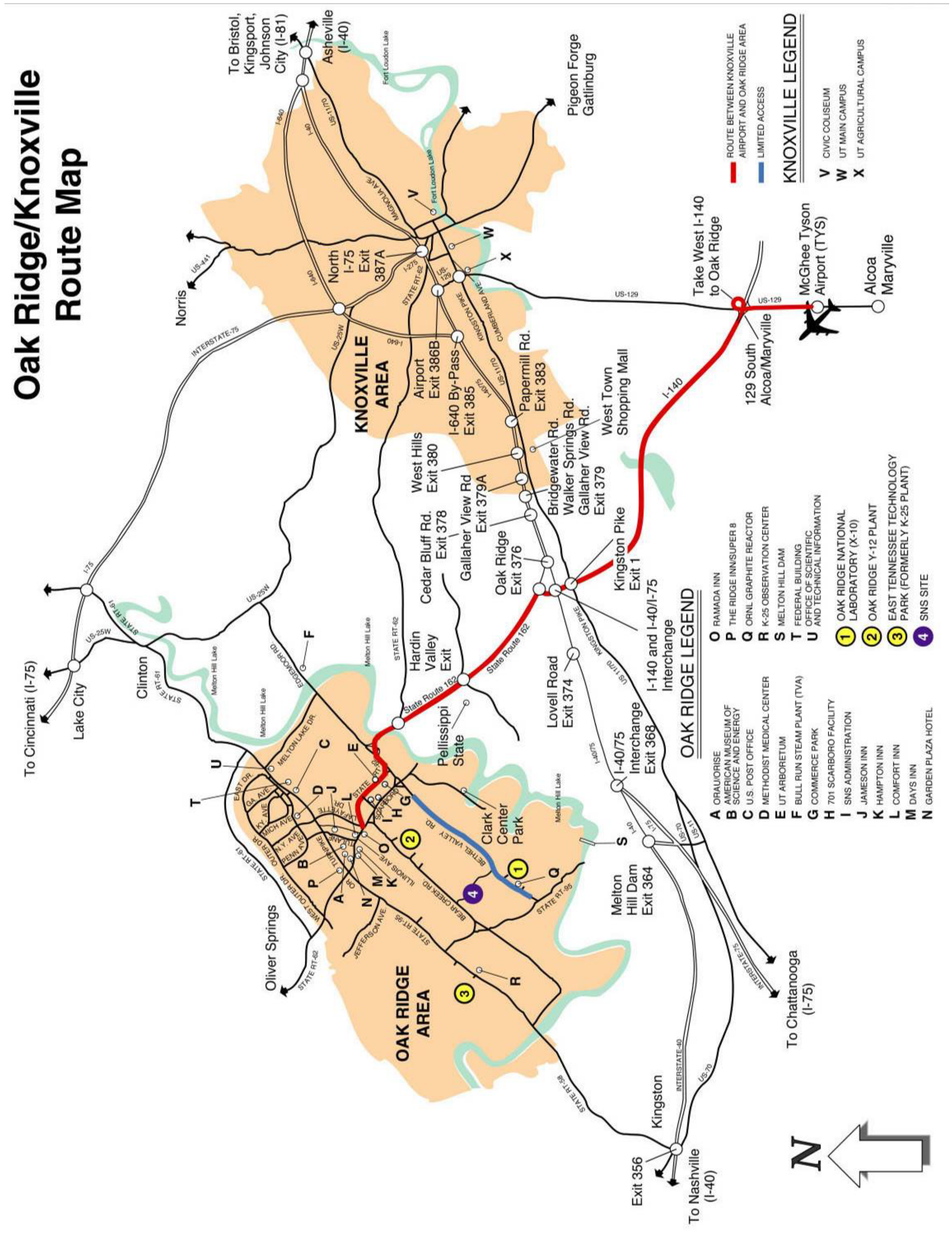

Figure 3.1. Oak Ridge/Knoxville route map.

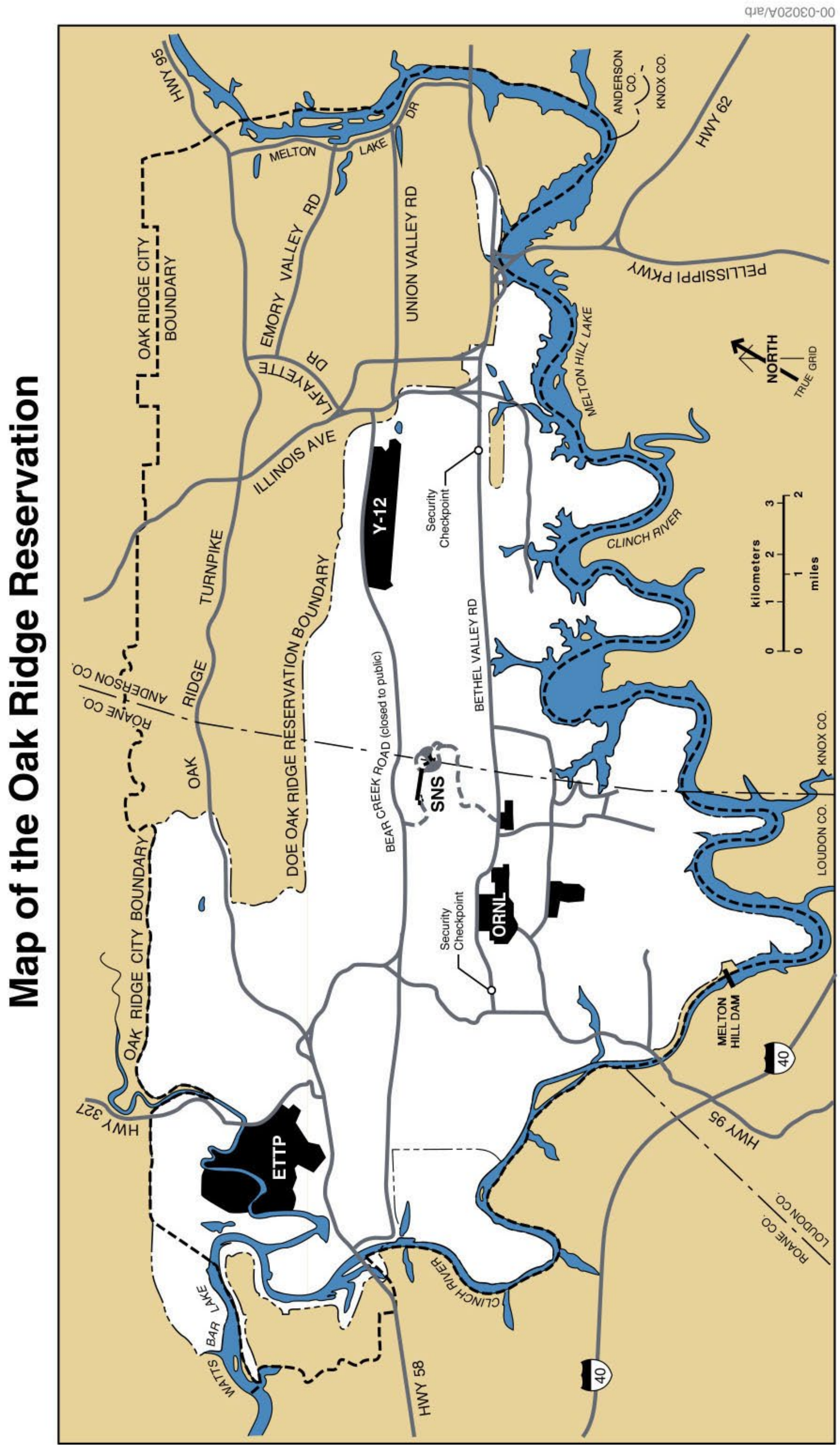

Figure 3.2. Map of the Oak Ridge Reservation.

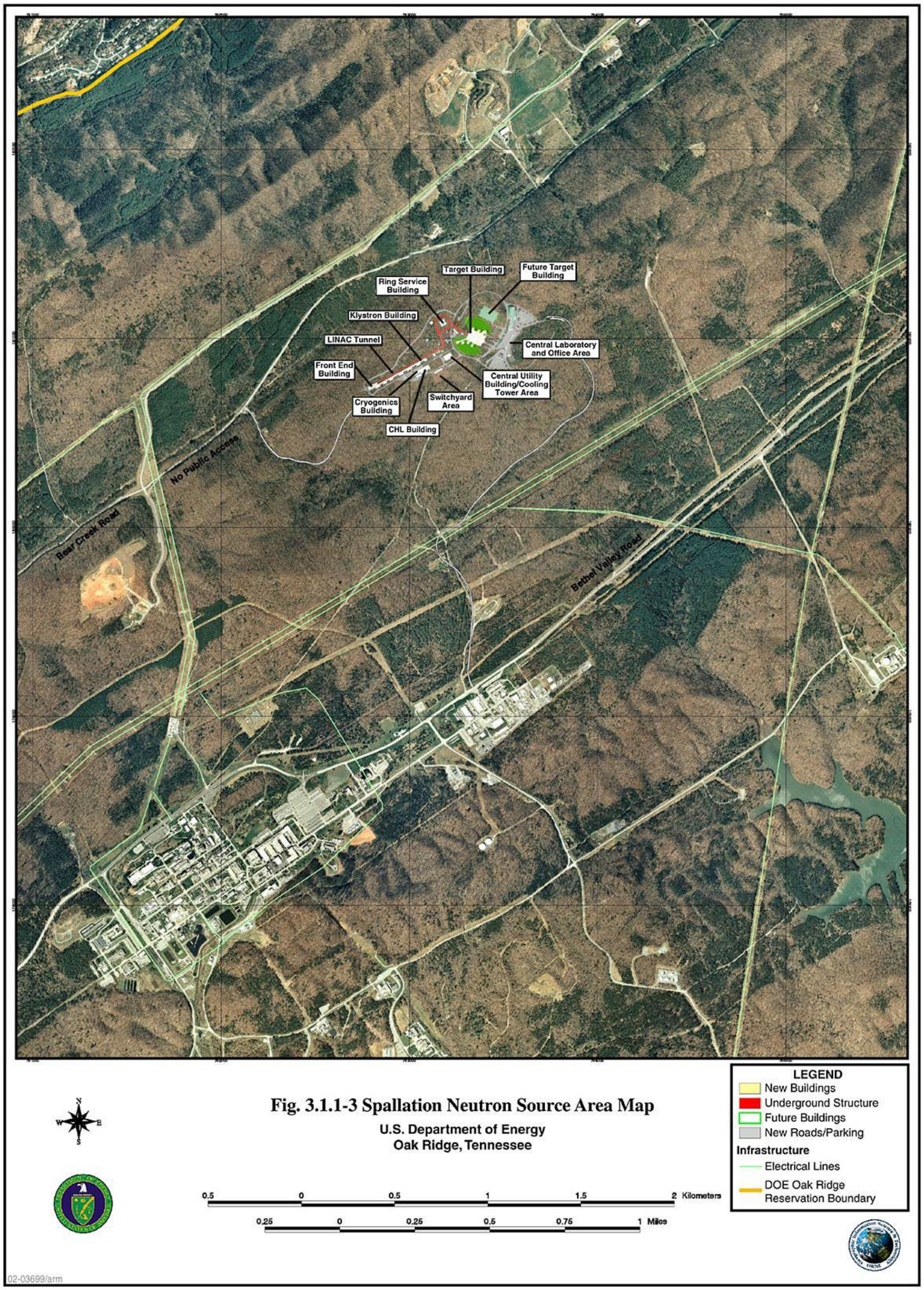

Figure 3.3. Spallation Neutron Source area map.

Access to ORNL is from Bethel Valley Road to the south and from Tennessee State Highway 95, which runs in a north-south direction west of ORNL. Bethel Valley Road is closed to the public thoroughfare by staffed gates located several miles to the east and west of the SNS site. The SNS buildings are sited on Chestnut Ridge about 1,030 to 1,050 ft above sea level. The overall SNS site development includes improved and rerouted Chestnut Ridge access roads that are closed to the general public. ORNL controls access on Bethel Valley Road and has the authority to control access on Tennessee State Highway 95 in the event of an emergency.

3.1.2 Demography

The ORR lies within the corporate limits of the city of Oak Ridge; however, no private residences are within the ORR. Except for the city of Oak Ridge, the major portion of the land adjoining the ORR is predominantly rural and is used largely for residences, small farms, and pastures. The city of Oak Ridge had a 2020 population estimate of about 31,400.[3-5] The Knoxville metropolitan statistical area (which includes the city of Oak Ridge) had a 2020 population estimate of about 879,700.[3-5] The demography of the area is not expected to change significantly.

3.1.3 Environmental Description

3.1.3.1 Meteorology and Climatology

References 3-4 and 3-6 discuss Oak Ridge meteorology, including regional climatology and local meteorology.

Damaging winds are relatively uncommon, and peak gusts recorded in the Tennessee Valley are generally in the 60–70 mph range for the months of January through July and less during the other months. The Tennessee Valley is infrequently subjected to tornadoes and tropical storms (the remnants of hurricanes). The Oak Ridge–Clinch River area has one of the lowest probabilities of tornado occurrence in the state of Tennessee.[3-6]

3.1.3.2 Hydrology

Surface Water

Surface water at the Chestnut Ridge SNS site consists of a small perennial stream that acts as headwater to White Oak Creek. This unnamed tributary flows south from the valley below the SNS footprint on Chestnut Ridge into the ORNL main plant area. Two additional drainages northeast and southwest of the site dissect the scarp face of Chestnut Ridge and flow in a northwesterly direction into Bear Creek. Although these drainages may receive runoff from the footprint area, the site footprint does not overlay the actual stream channels. Site development provides a basin to retard runoff from the graded areas around the SNS site.

Subsurface Hydrology

Groundwater at the Chestnut Ridge site is observed at a depth of greater than 60 ft (18 m). Temporary water levels were recorded in open borings by Law Engineering at the site at 67 and 94 ft (20 and 29 m). Also, two groundwater monitoring wells located about 3,000 ft (914 m) east of the site (Oak Ridge Administrative Coordinates N27800, E44500) have water levels at depths of greater than 75 ft (23 m). Note that groundwater levels vary significantly depending on height above the valley floor and seasonal and climatic conditions.

The hydrology of the ORR is described by Moore.[3-7] Groundwater flow on the ORR closely parallels the contours of the surface topography, and the water emerges to contribute to local stream flow. Recharge is derived primarily from precipitation, and groundwater discharge is derived primarily from evapotranspiration, springs, and streams. The surface streams ultimately augment the water supply of the Clinch River, which is the hydraulic sink for the region. The riverbed lies at the base level of the zone of saturation, and all groundwater from both sides of the channel enters the river. Because the riverbed is a major topographic feature set down in bedrock, any groundwater is likely unable to flow beneath the Clinch River.

3.1.3.3 Geology

The ORNL site is located within the folded and faulted Valley and Ridge Physiographic Province of the Appalachians. Several major ridges, formed from resistant strata, dominate the topography of the ORR. Moving from southeast to northwest, prominent ridges are named Copper Ridge, Haw Ridge (south of the ORNL main plant), Chestnut Ridge (separating the ORNL and Y-12 sites), and Pine Ridge (between Y-12 and the city of Oak Ridge).

Law Engineering has completed soil borings at the SNS site on Chestnut Ridge to test subsurface conditions. Testing consisted of boreholes that obtained undisturbed samples at various horizons and continuous measurement of the penetration rate (as an indicator of soil strength, density, consolidation, and so on). The borings were taken to depths of approximately 150 ft (46 m) and encountered bedrock at several locations. A rotary drill hole was subsequently installed to determine actual depth to solid bedrock; details are documented in a series of reports. Initial conclusions were that a highly irregular and weathered bedrock surface exists at the site and that large slabs and fragments of chert may occur within the soil mass. Selected soil samples were analyzed for standard engineering characteristics such as grain size, consolidation rates, specific gravity, moisture content, and Atterberg limits. The soils tested ranged from clayey, sandy silt with gravel-sized chert[3-8] to highly plastic, clayey silt. Soil samples yielded unconfined compressive strengths between about 3.6 and 2.1 kg/ft^2 (8 and 4.7 lb/ft^2). These soils are typical of the ORR and are not susceptible to liquefaction or mass movement.

Historic seismic activity within 200 mi of the ORNL site has primarily occurred in the Valley and Ridge Physiographic Province, with some minor historical activity in the Appalachian Plateau province to the west and the Blue Ridge province to the east. The maximum historical ground accelerations at the ORNL site have resulted from earthquakes with epicenters located outside of the Valley and Ridge Physiographic Province, the Appalachian Plateau Province, the Blue Ridge Province, and further than 200 mi from the ORNL site.

3.1.4 Natural Phenomena Hazards

The SNS facilities were categorized as Performance Category (PC)-2 or PC-1, as listed in Table 3.1. Portions of the target facility were designated as PC-3 for seismic activity, as described in the FSAD-NF. SNS facilities have been evaluated for all applicable natural phenomena threats in accordance with DOE-STD-1020-94, *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities*.[3-9] DOE-STD-1020-94 required the evaluation of flooding, high winds and tornadoes, and earthquakes. Initial categorization of structures was governed by DOE-STD-1021-93.[3-10] These standards have since been updated as the approach to NPH evaluation in the DOE complex has been refined and developed. When existing analysis is revisited as part of an upgrade project or new analysis is required for new construction, current standards are applied, where practical.

3.1.4.1 Flooding

The site is atop Chestnut Ridge and thus not within a floodplain. Widespread flooding is not likely for a ridge-top site location several hundred feet above the valley floor.

3.1.4.2 Local Precipitation

In accordance with the applicable PC designation (Table 3.1), each structure's roof and building drainage is required to endure design-basis precipitation. The SNS site is graded to prevent undesired water accumulation, and a site retention basin is provided to control rainwater drainage from the SNS site.

DOE-STD-1020-94[3-9] specifies the evaluation of snow loads in accordance with applicable building codes and standards. Therefore, snow loads on the SNS roofs are evaluated in accordance with American Society of Civil Engineers (ASCE) 7-95, *Minimum Design Loads for Buildings and Other Structures*,[3-11] using an importance factor of 1.2. For the SNS site, the ground snow load from ASCE 7-95 is 10 lb/ft^2, which is not limiting compared with other design loads.

Table 3.1. Classification of structures.

Building/feature	Performance Category [a]	Code of record [b, c]
Front-End building	PC-2	Standard Building Code (SBC)[3-12]
Linac tunnel	PC-2 [d]	SBC
Klystron Gallery	PC-2	SBC
HEBT tunnel	PC-2	SBC
Ring tunnel	PC-2	SBC
RTBT tunnel	PC-2	SBC
Target building	PC-2 [g]	SBC
Ring service building	PC-1 [e]	SBC
RTBT service building	PC-1	SBC
Beam dumps	PC-2	SBC
Central Helium Liquefier facility	PC-1	SBC
RF cavity reconditioning and test buildings	PC-1	SBC
Central Utilities Building	PC-1	SBC
Central Laboratory and Office building	PC-1	SBC
Site[f]	PC-1	SBC

[a] PC designation based on requirements of DOE-STD-1021-93,[3-10] et al.
[b] Wind loads defined per ASCE 7-95.[3-11]
[c] Seismic accelerations determined per UBC-97.[3-13]
[d] PC-2 is based on cost and mission considerations; importance factor = 1.25. Peer review of design is required.
[e] PC-1 is essentially life safety; importance factor = 1.0.
[f] Site includes miscellaneous foundations (e.g., switchyards) and structures (e.g., conduit banks and piping tunnels).
[g] Portions of the target building are designated PC-3 as described in FSAD-NF[3-1].

3.1.4.3 Winds

Wind design and evaluation criteria for DOE facilities are specified in DOE-STD-1020-94[3-9] and ASCE 7-95.[3-11] The minimum wind design criteria for SNS are given in Table 3.2 (Table 3.1 lists building PC designations).

Table 3.2. Wind design criteria for SNS.

Performance category	1	2
Hazard annual probability of exceedance	2×10^{-2}	2×10^{-2}
Peak mph wind speed at 10 m height	90	90
Importance factor	1.0	1.07
Atmospheric pressure change	NA	NA
Missile criteria	NA	NA

3.1.4.4 Seismic Activity

Seismic design and evaluation criteria for DOE facilities are specified in DOE-STD-1020-94.[3-9] The seismic hazard levels and amplified response spectra have been determined for the SNS site in accordance with DOE-STD-1022-94, *Natural Phenomena Hazards Site Characterization Criteria.*[3-14]

3.1.5 External Anthropogenic Threats

No nearby industrial facilities or other anthropogenic threats present hazards to the SNS site. The Center for Nanophase Material Sciences facility is located adjacent to the SNS CLO Building, but it does not involve energetic processes or hazards that could threaten the SNS facilities. Major airports are more than 10 mi distant from the SNS site; for example, McGee Tyson Airport, the only major airport in the area, is located about 18 mi to the southeast, in Blount County, Tennessee.

3.1.6 Nearby Facilities

As mentioned previously (Section 3.1.1) and as illustrated by Figures 3.2 and 3. 3, three major installations are located within several miles of SNS: ETTP, Y-12, and ORNL.

3.1.7 Wildfires

Because the SNS site is in a forested area, an analysis was completed to evaluate the wildland fire potential/risk to the SNS accelerator facilities. This analysis is consistent with the requirements and guidelines of National Fire Protection Association (NFPA) 1144, *Protection of Life and Property from Wildfire*[3-15] (which supplanted NFPA 299) to determine the wildfire risk to the SNS site. The risk assessment was conducted in accordance with the Wildfire Hazard Severity Form checklist of NFPA 1144. The checklist is a summary of typical desirable characteristics found in various wildfire hazards analyses. Elements include emergency response ingress and egress, type of vegetation, topography, building construction and roofing materials, available fire protection, and utilities. The analysis is included as an attachment to the *Fire Hazard Analysis for Spallation Neutron Source Accelerator Facilities*.[3-16]

The risk and hazard ratings are the basis for the implementation of any mitigation measures needed relative to vegetation, other combustibles, and construction. Based on the analysis, the wildfire hazard for the SNS accelerator facilities is considered a slight to moderate hazard. Though these buildings have a slight to moderate threat from wildfire, the measures relative to vegetation and other combustibles, emergency response, and construction criteria lessen the potential hazard severity.

Based on the analysis, the hazard rating from wildfire for ORNL and the SNS site is "low." Refer to the specifics on the Wildfire Hazard Severity Analysis available in the *Fire Hazard Analysis for Spallation Neutron Source Accelerator Facilities*.[3-16]

3.1.8 Environmental Analyses

The environmental impact analyses for SNS are documented in the *Final Environmental Impact Statement.*[3-2] A supplemental analysis was filed to describe potential effects of the project change to an SCL early in calendar year 2000.

3.2 ACCELERATOR AND SUPPORT SYSTEMS

This section describes on-site accelerator-related facilities except for those associated with the neutron facilities, which are addressed in the FSAD-NF.[3-1] Figure 3.4 shows the SNS site with buildings labeled. It is a representative depiction of key SNS facilities. Below-grade accelerator structures, such as the tunnels, are depicted without their earthen berm for clarity. The anticipated future Second Target Station building is ghosted into the right of the present target building (i.e., the First Target Station Experiment Hall).

3.2.1 Accelerator Systems

Figures 3.5 through 3.11 show illustrations of accelerator facilities and systems and schematic illustrations of tunnel cross sections at various locations (i.e., not "as-built" drawings).

3.2.1.1 Front-End Systems

The SNS front end consists of a cesium-enhanced volume RF-discharge ion source with a nominal −65 kV potential to ground. H^- ions produced in the ion source are extracted by the −65 kV potential difference. The short low-energy beam transport (LEBT) section contains two electrostatic lenses that focus the beam into the RF quadrupole (RFQ). The second lens is split in four segments that steer and chop the beam. The 402.5 MHz RFQ bunches the H^- beam and accelerates the beam to about 2.5 MeV while periodically refocusing it in both transverse planes.

To match the transverse emittance properties of the beam exiting from the RFQ to the first accelerating tank of the drift tube linac (DTL), a medium-energy beam transport (MEBT) lies between these two structures. The MEBT includes the magnetic focusing elements and the RF bunching cavities to maintain the 402.5 MHz longitudinal beam structure. Scrapers are used to remove the beam halo.

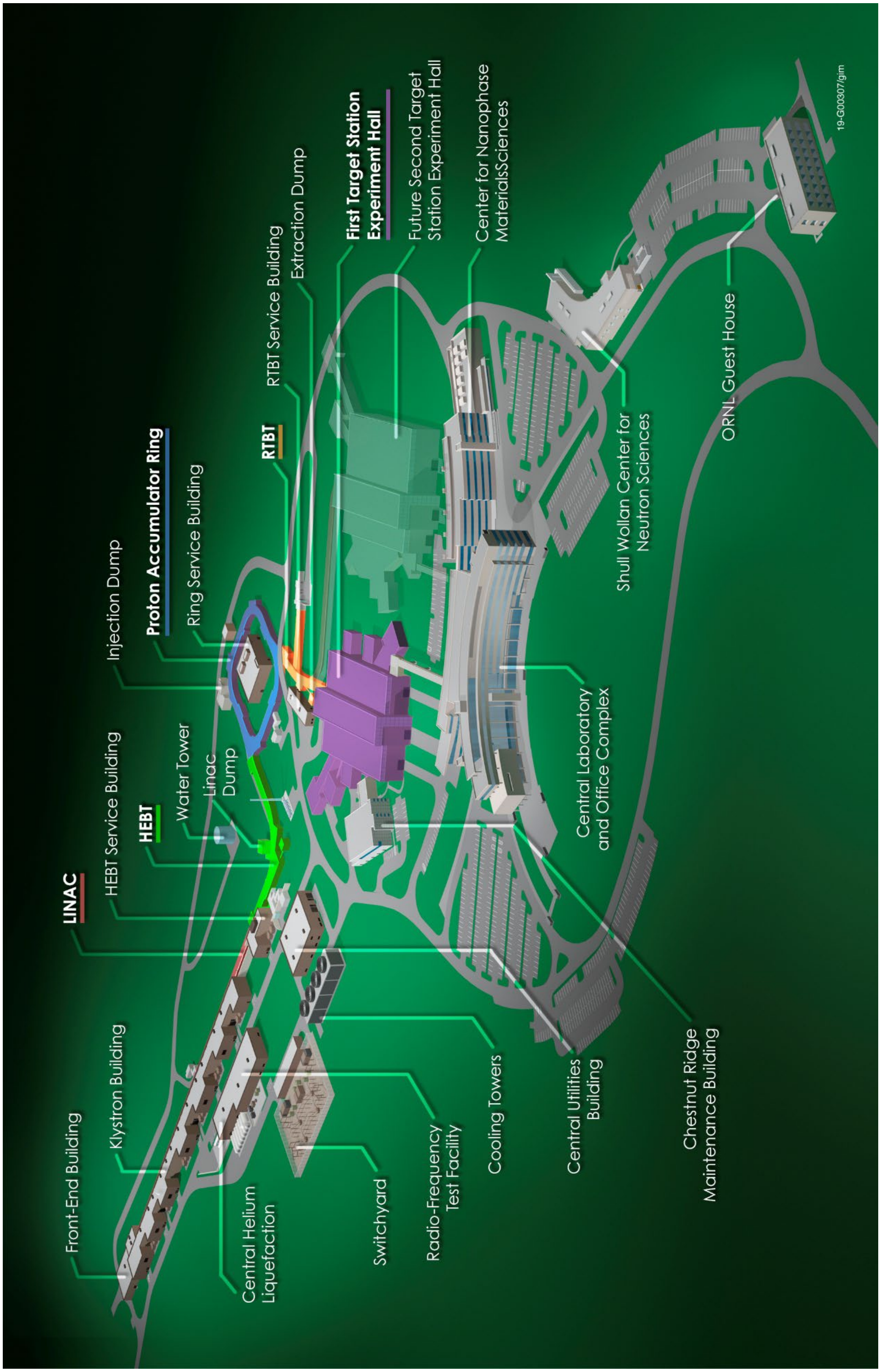

Figure 3.4. SNS site facilities.

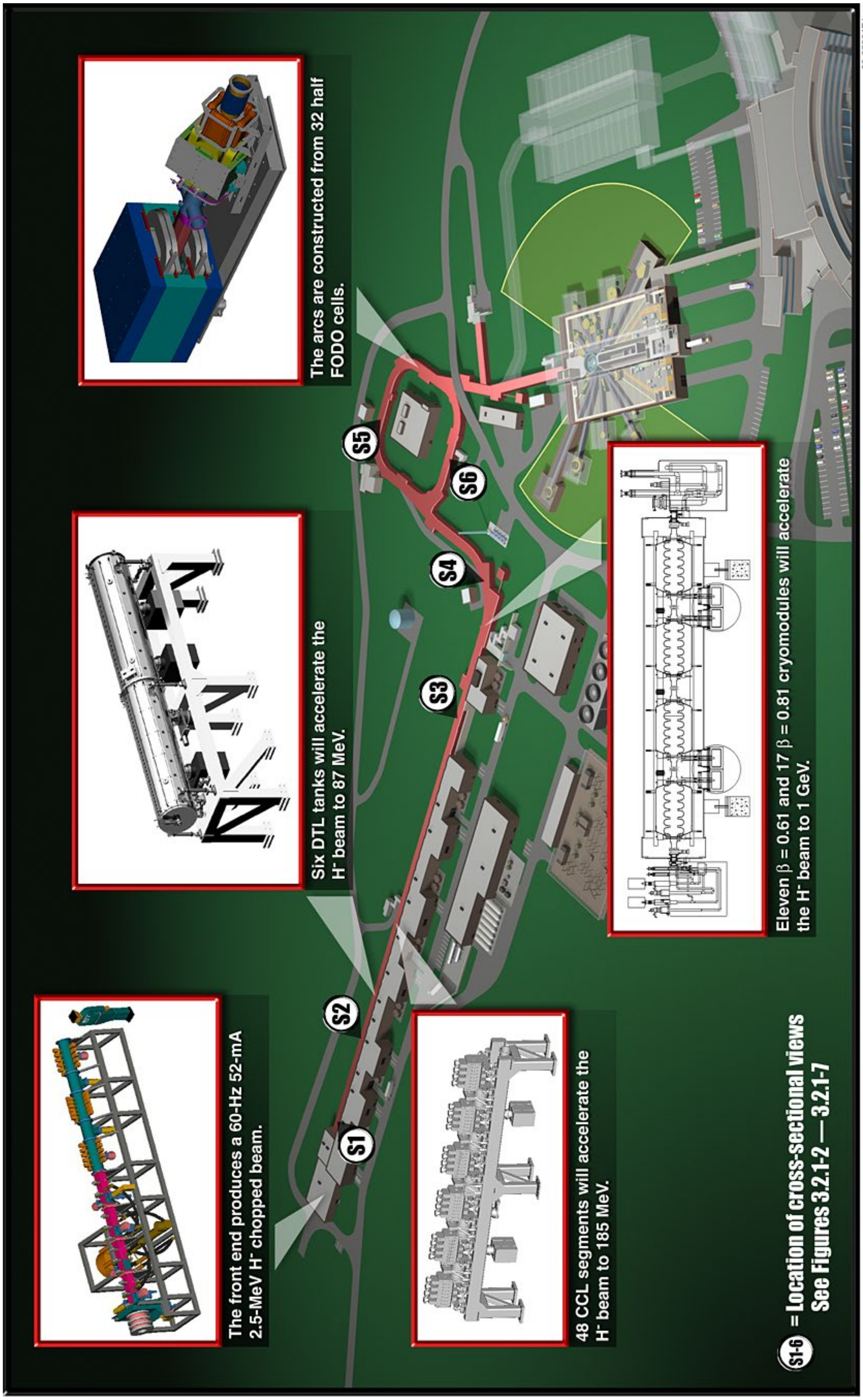

Figure 3.5. Accelerator systems technical equipment. Equipment configuration is representative of initial operations.
CCL: coupled cavity linac, FODO: focus drift defocus drift.

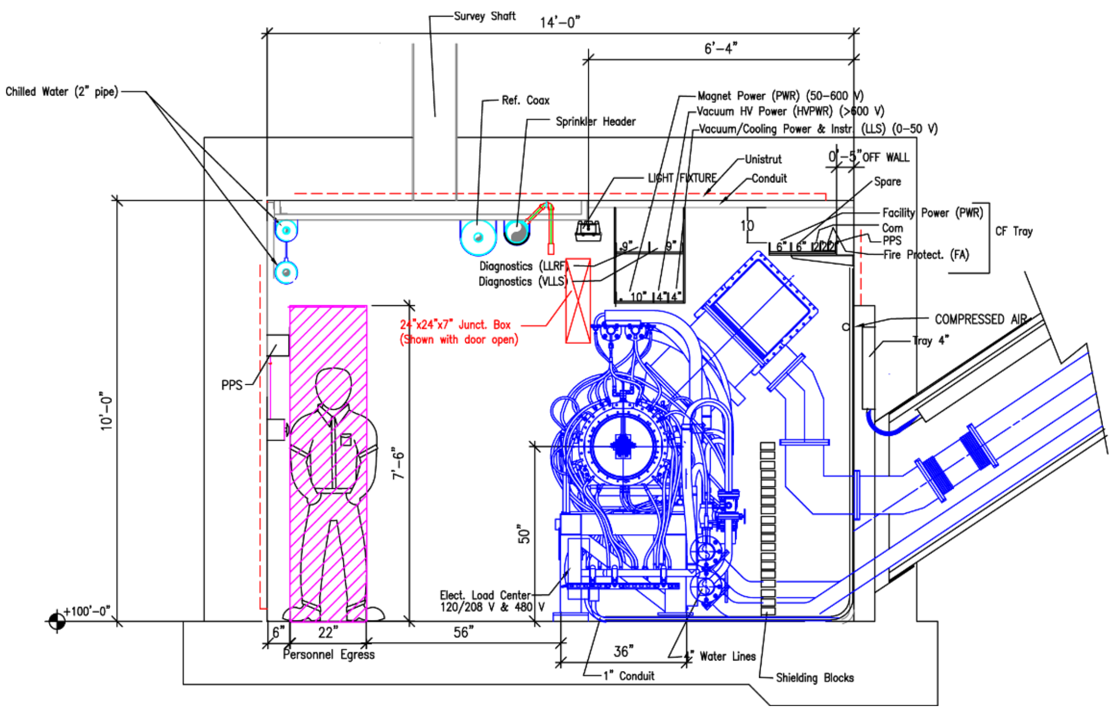

Figure 3.6. DTL tunnel cross section (schematic illustration).

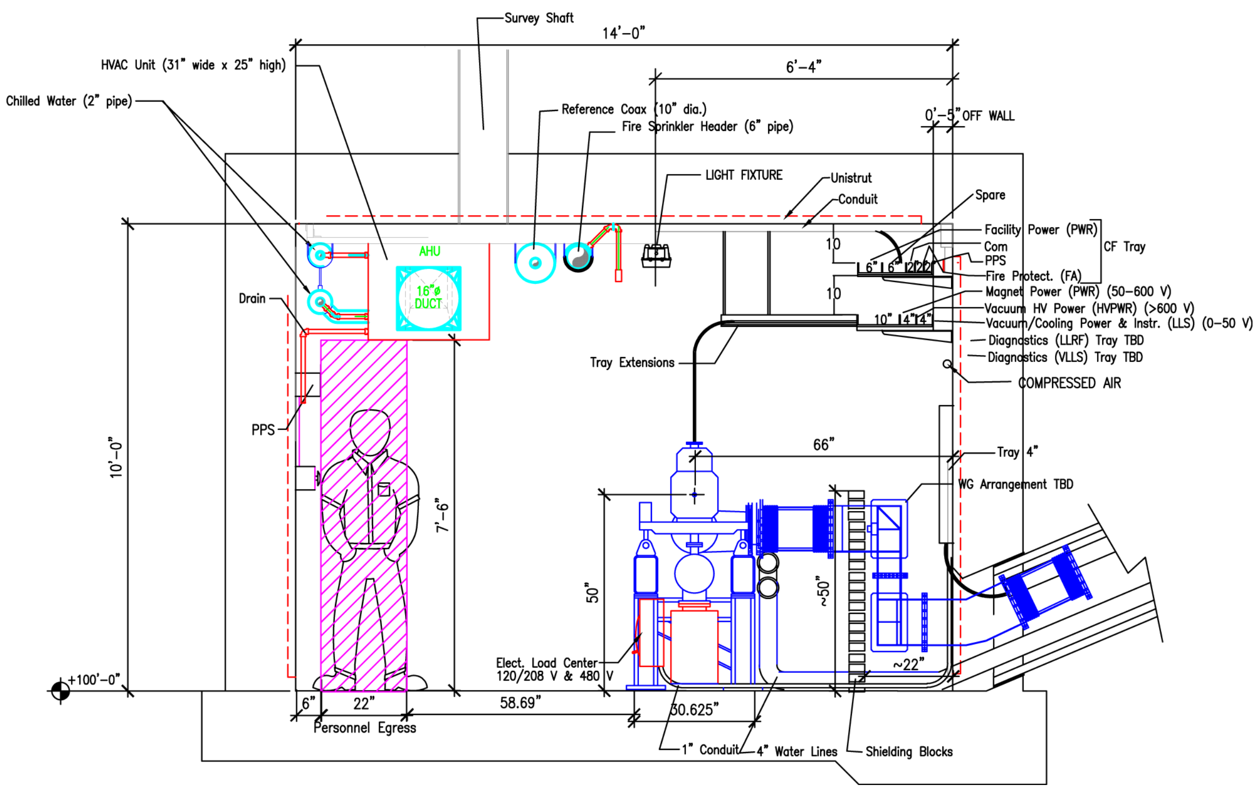

Figure 3.7. Coupled-cavity linac tunnel cross section (schematic illustration).

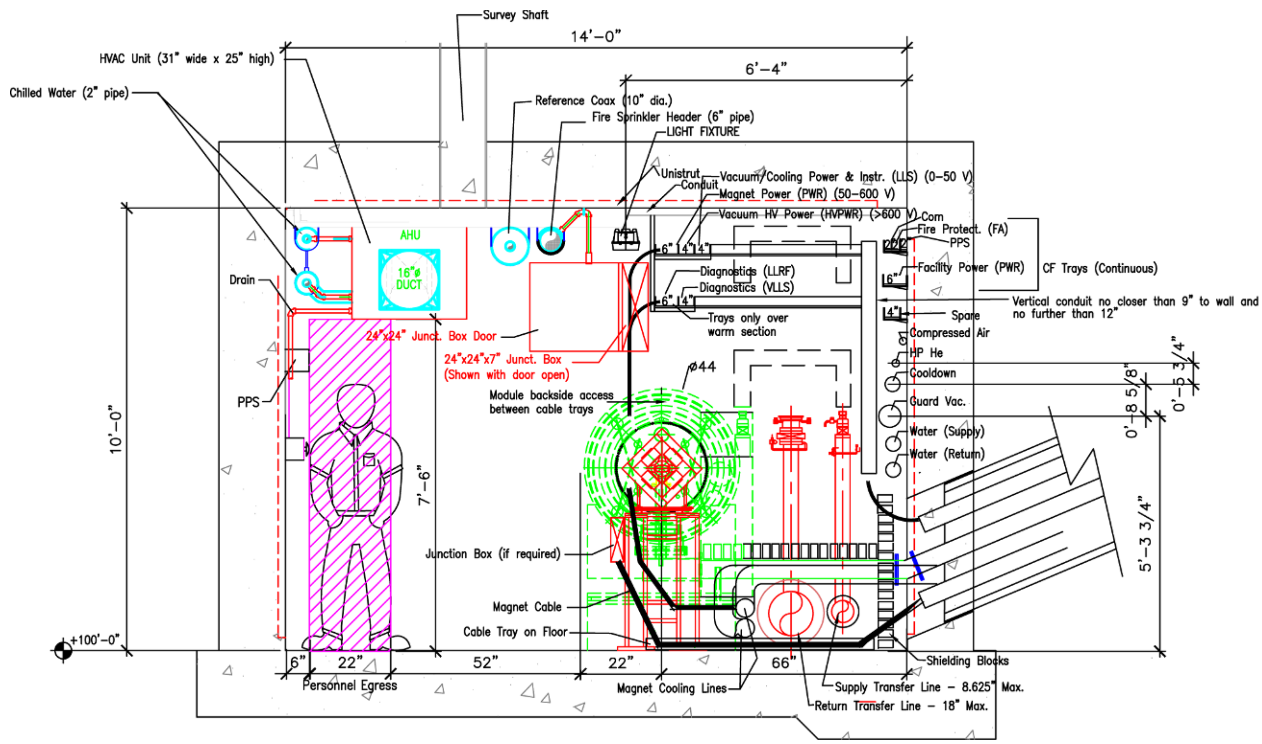

Figure 3.8. SCL tunnel cross section (schematic illustration).

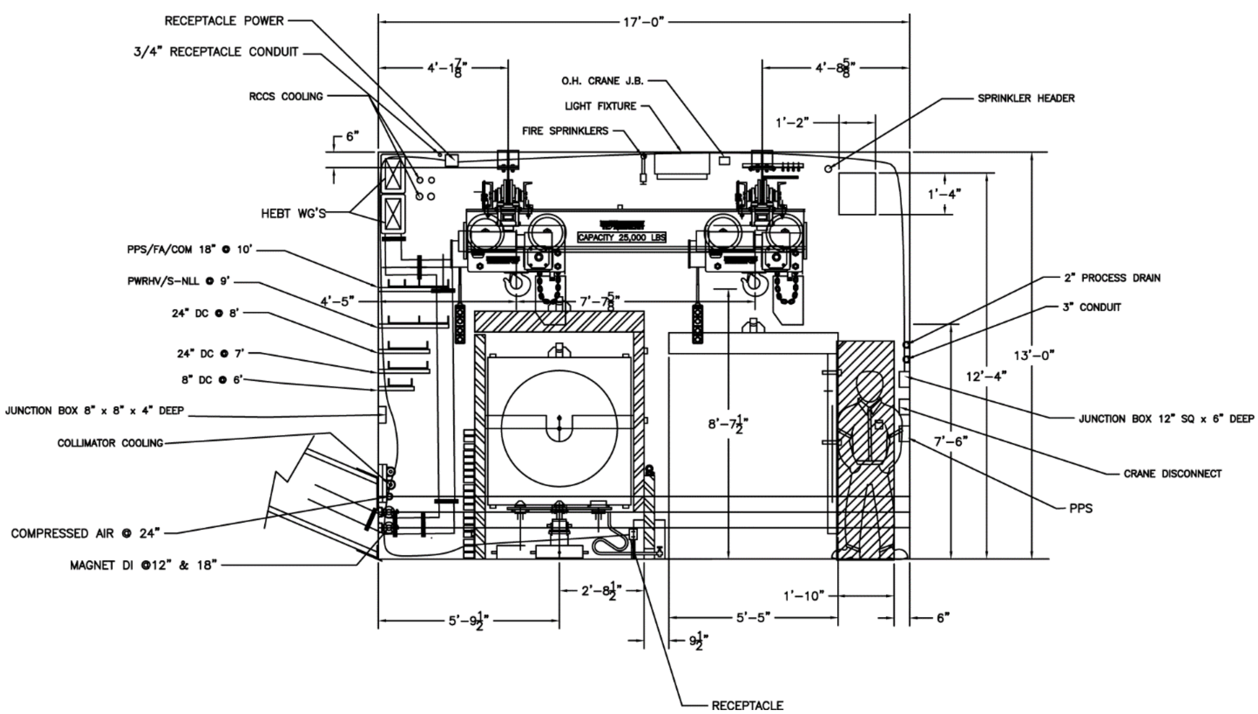

Figure 3.9. HEBT tunnel cross section (schematic illustration).

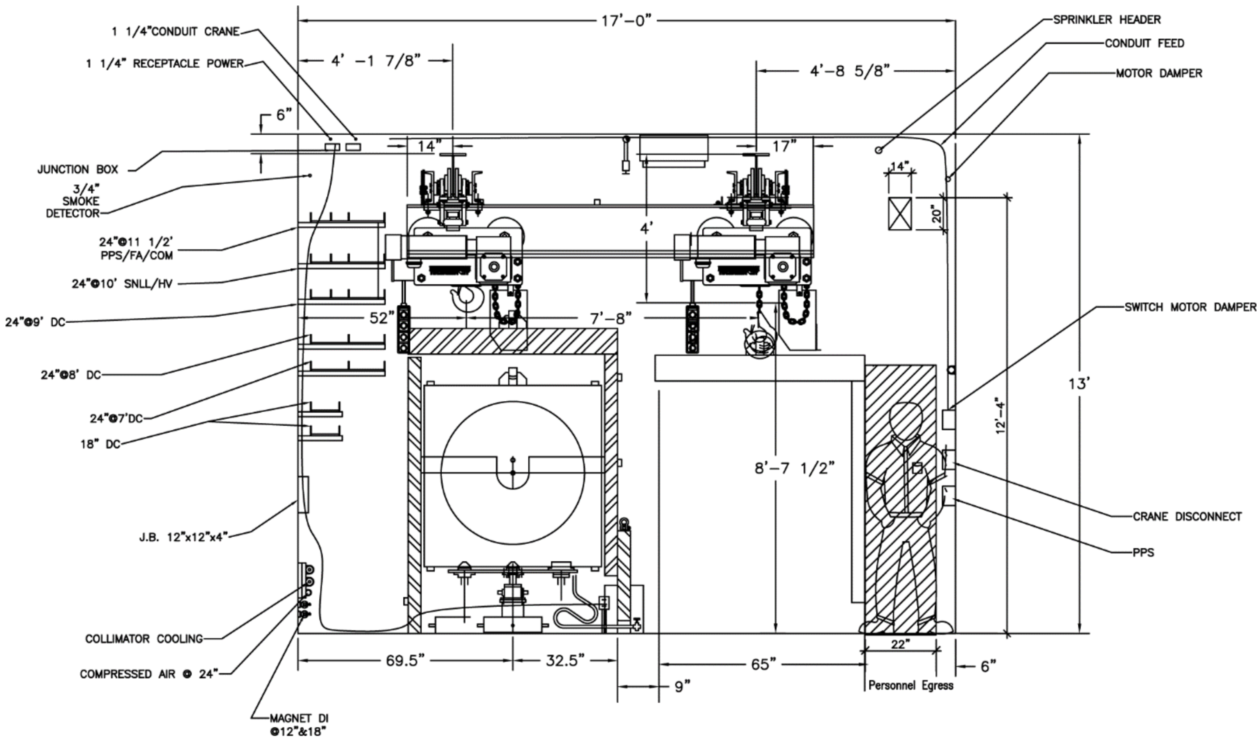

Figure 3.10. North ring tunnel cross section (schematic illustration).

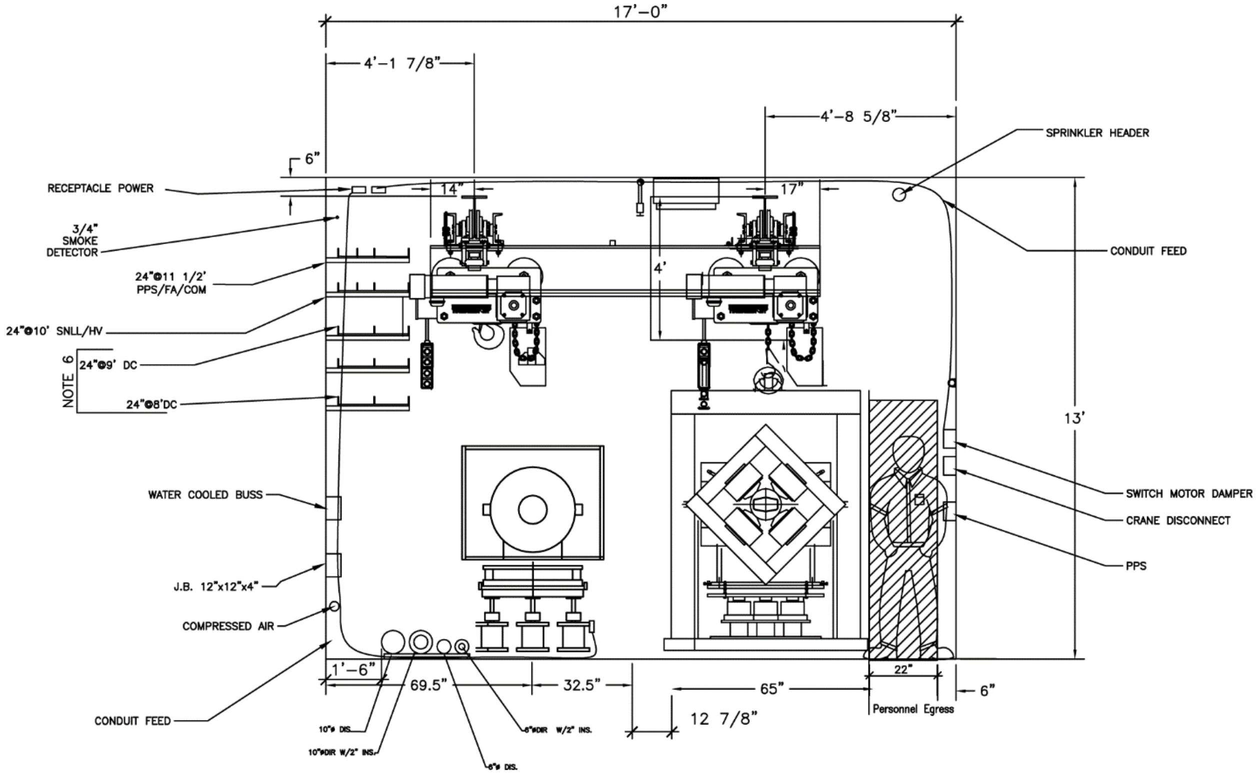

Figure 3.11. South ring tunnel cross section (schematic illustration).

The front-end facility includes space for two ion source test stands. One test stand has already been built and is being used to study design variations for ion source design improvement. The ion source test stand operates as a stand-alone entity (not connected to the linac) when in use. The test stand currently in use includes an ion source and an LEBT.

3.2.1.2 Linac Systems (Including Klystrons)

The SNS linac includes three separate accelerating technologies (the DTL, coupled-cavity linac or CCL, and SCL) in four distinct sections—two room-temperature sections and two superconducting sections. The H^- nominal beam in the linac is a 1 ms pulse every 16.67 ms (60 Hz).

1. The DTL accelerates the beam received from the MEBT from about 2.5 MeV ($\beta = 0.07$) to about 87 MeV ($\beta = 0.40$). It is operated at the same frequency as the RFQ and MEBT (402.5 MHz) and receives power from 2.5 MW klystrons. The beam is also transversely focused in the DTL via permanent magnet quadrupoles located within the cavity drift tubes.

2. The CCL then accelerates the H^- beam from about 87 MeV to about 186 MeV ($\beta = 0.55$). It receives power from 5 MW klystrons. As the H^- beam transitions into the CCL, it is captured by the CCL RF accelerating buckets (805 MHz), which operate at twice the DTL frequency.

3. Downstream of the CCL, the beam is injected into the SCL. The SCL consists of three-cavity medium-beta and four-cavity high-beta cryomodules (Figure 3.5). The first section is optimized for a velocity beta value of 0.61. The second SCL section is optimized for a beta value of 0.81. These cavities receive their power from 550 kW klystrons with the transverse focusing provided in room-temperature straight sections between cryomodules.

The 335 m Klystron Gallery originally contained 92 klystrons. Figure 3.12 shows a view of the superconducting Klystron Gallery that starts with the klystrons for cryomodule 18 and looks west (upstream) toward the normal conducting section. This photograph shows typical SCL klystrons and modulator sets as viewed from the maintenance aisle. High-voltage converter modulators (HVCMs) power these klystrons. Each HVCM provides 10 MW of peak power (1 MW average) at voltages ranging from 69 to 136 kV. Four water pump rooms (adjacent and to the south from the main Klystron Gallery) provide cooling water flows for the klystrons and for the normally conducting linac cavity (cavity resonance is sensitive to temperature). Controls and communications racks, magnet power supplies, and cavity field control (low-level RF) are also housed in the Klystron Gallery. The PPU project adds seven superconducting high-beta cryomodules and the additional infrastructure required to operate them, including klystrons, HVCMs, and cooling water capacity.

Figure 3.12. Klystron Gallery (from within the superconducting section, looking west).

3.2.1.3 HEBT, Ring, and RTBT Systems

The ring and transfer lines form three distinct areas: two single-pass beamlines and an approximately 248 m circumference ring into which nominally 1,000 turns of proton beam are injected and then extracted to the target station.

The HEBT is the beamline in which the H^- beam is transported from the linac to the ring. The H^- nominal beam that exists in the HEBT is a 1 ms pulse every 16.67 ms (60 Hz). Two locations in the HEBT have collimator systems that serve as controlled loss points for any beam halo that may develop. These systems control the effective transverse beam emittance of the HEBT to be within the acceptance of the ring injection system. Additionally, a similarly constructed air-cooled beam-stop structure in the HEBT is provided to remove off-momentum particles. This structure is designed to operate at 5 kW or less. This off-momentum beam stop accepts the portion of the beam with energy outside the desired ring acceptance criterion. The HEBT also has several quadrupoles in a focus drift defocus drift (FODO) configuration to define the required Twiss parameters at the injection foil. The HEBT beamline includes an arc of 90° to align the H^- beam as it approaches the ring.

An alternate destination for the HEBT beam is the linac beam dump located at 0° from the linac. The linac beam dump (discussed in Section 3.2.1.4) is intended to be used only for low-power beam-commissioning and accelerator studies. A shield wall and PPS gate are provided shortly after the HEBT arc to allow work activities to occur in the ring during linac studies and commissioning.

The ring is actually more of a "square" with gradual bends of the four arcs and a circumference of approximately 248 m. Several unique features and elements are within the ring:

- Injection is accomplished using DC septum magnets and a stripping foil to remove the two electrons from the H^- and yield protons that circulate in the ring. This stripping process should be nominally about 95% efficient (ranging from 90 to 99%, depending on the stripping foil material and thickness). The H^- particles that escape stripping accumulate in the injection dump, described in Section 3.2.1.4. In the ring injection region, eight pulsed/programmable kickers (four per plane) permit the circulating proton beam to be preferentially placed at specific locations in phase space as a function of turn number. This process is necessary to form the desired beam profile (density distribution) of the ultimate accumulated beam to be delivered to the target.

- The ring is designed using a "hybrid lattice" in which the arcs are composed of dipole magnets and quadrupoles in a FODO configuration, and the lattice functions in the straight sections are defined by quadrupole focus defocus doublet elements. This allows for more efficient use of the straight section space for other necessary equipment.

- A series of collimators in the north ring straight section (after injection) provide a localized area for controlled beam loss during accumulation. These water-cooled devices are each expected to operate at 2 kW or less.

- The south straight section is occupied primarily by the ring RF system. It consists of two RF cavities at about 1 MHz (fundamental) that provide the primary beam bunching, and two cavities operating at the second harmonic control the bunch shape.

- In the east straight section, the circulating beam is extracted from the ring to the RTBT beamline using a fast-rise ferrite kicker system (14 modules) and a magnetic septum. Extraction is accomplished by discharging a series of capacitor banks into their corresponding pulse-forming networks for the kickers (this process provides the proper field). These kickers then rise from zero to full field within the rotating beam bunch separation (between the tail and head) and extract the beam in one turn (<1 μs). If dipole magnet DH13 is energized, then the beam is deflected toward the target. If dipole DH13 is not energized, then the beam continues to the ring extraction dump.

At the exit of the ring is the RTBT beamline. The nominal beam pulse length in the RTBT is approximately 700 ns as it is transported from the ring to the First Target Station. Another set of collimators is included in this beamline to further control/localize any beam loss to one specific area. Transverse focusing of this proton beam is provided by a FODO lattice up to the end of the RTBT, where two quadrupole doublets are located to allow final shaping of the beam profile.

Beam diagnostics are used to quantify beam properties and to provide the operations staff with sufficient information to first define and then maintain the desired beam properties throughout the SNS accelerator facility.

3.2.1.4 Beam dumps

SNS has three beam dumps located outside the tunnels—one at 0° to the linac near the HEBT (linac dump), another downstream of the ring injection region adjacent to the ring (injection dump), and the third near the RTBT beamline (extraction dump). Each beam dump is located below grade at a short distance from the tunnel. The linac and extraction beam dumps are passive dumps designed for an average power of up to 7.5 kW. The passive dumps are intended for infrequent use (e.g., low-power commissioning and beam studies). However, the injection beam dump is designed for continuous use and accepts any portion of the HEBT beam not fully stripped at the foil (nominally 2%–10% of the injected beam). This beam dump is designed for an average power of up to 150 kW. Radiological hazards associated with the beam dumps are addressed in Section 4.3.3.

Table 3.2 gives selected representative values for major design parameters. The locations of these dump facilities, relative to the remainder of the accelerator, is shown on Figure 3.4.

Section 3.2.1.3 describes two sets of collimators and one beam stop (the off-momentum beam stop) located inside the HEBT. The expected thermal power level for each is smaller than the three beam dumps discussed in this section.

The general arrangement concept for the dumps provides a branch of the evacuated proton beam flight tube that extends horizontally through the berm and enters the beam dump shielded vault, as shown in Figure 3.13. The beam dump vault is filled with an array of multi-ton shielding blocks with sufficient thickness to minimize soil activation and reduce personnel radiation exposure consistent with 10 CFR 835 [3-17] (The soil berm around the beam dumps has the same water control features described in Section 3.2.7.3 for the accelerator tunnels.).

Table 3.3. Beam dump design parameters.

Beam characteristics at the beam dumps (representative values)			
Parameter	**Linac**	**Injection**	**Extraction**
Maximum average power (kW)	7.5	150	7.5
Beam energy (GeV)	1.0–1.3	1.0–1.3	1.0–1.3
Pulse length (ms)	~1.0	~1.0	~0.0006
Nominal pulse energy (kJ/pulse)	33	2.5	33
Frequency (Hz)	1	60	1
Duty cycle (%)[a]	10	100	10

[a] Note: Duty cycle is defined as the operating time in a 1 year period divided by 5,000 h.

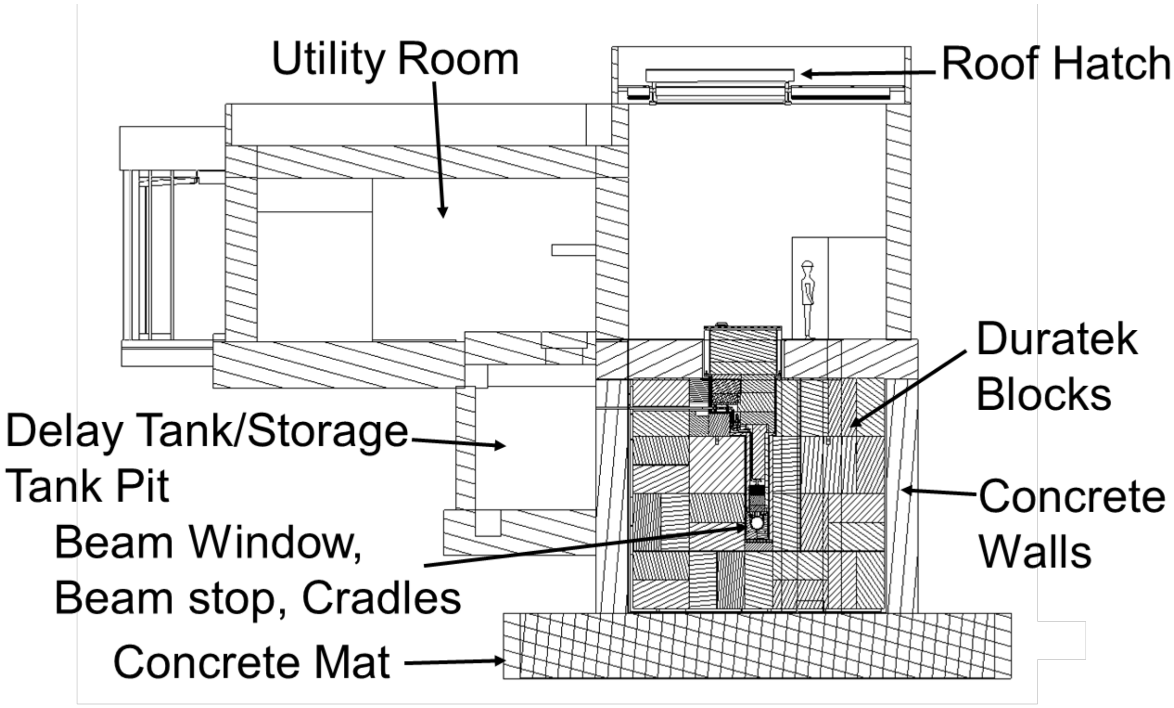

Figure 3.13. Vertical section of dump facility typical of ring injection dump. Linac and ring extraction dumps do not have mechanical/electrical or access rooms.

Linac and Ring Extraction Dump Description

The linac and ring extraction dumps have similar designs, and both passively dissipate the beam-induced heat.

For these two 7.5 kW passive dumps, the beam stop is a stack of carbon steel plates with variably thin center sections in the beam interaction region. The plates are firmly grouted and anchored at the bottom edges, so the heat is conducted through this connection to the surrounding shielding and eventually to the soil. Approximately 80% of the particle beam thermal energy equivalent is deposited directly in the stop, and the remainder is deposited in the surrounding array of multi-ton shielding blocks. The soil is the ultimate heat sink for these dumps.

The primary windows for the flight tubes leading to the linac and extraction dumps are in the HEBT and RTBT sectors of the beam tunnel. There is no planned access to the linac or extraction beam dump vaults, nor do these two dumps have above-ground buildings.

Ring Injection Dump Description

The injection dump is needed to accept unstripped and partially stripped H^- ions produced in the injection process from the HEBT to the ring. It is limited to an average power of 150 kW. This power limit was revisited during the PPU project to ensure that increasing beam energy did not adversely affect the thermal case.[3-28] This analysis confirmed that the 150 kW power limit would be sufficient for ring operations associated with the bounding anticipated case for the life of the facility (i.e., 2.8 MW and 1.3 GeV). It also demonstrated that 150 kW is an appropriate limit to ensure that all temperature design requirements are satisfied. Normal operating losses are less than the rated average power limit. The injection dump may also be used for HEBT tuning. An H^- intensity monitor after the injection foil is part of the injection system and is used to monitor the foil condition.

The beam stop for this dump is more sophisticated than that for the two 7.5 kW dumps. It is based on the successful beam stop at the Los Alamos Neutron Science Center facility. The SNS adaptation is illustrated in Figure 3.14. The beam stop is assembled into a beam-stop enclosure that is similar to the other dumps. It is shown in vertical section in Figure 3.15.

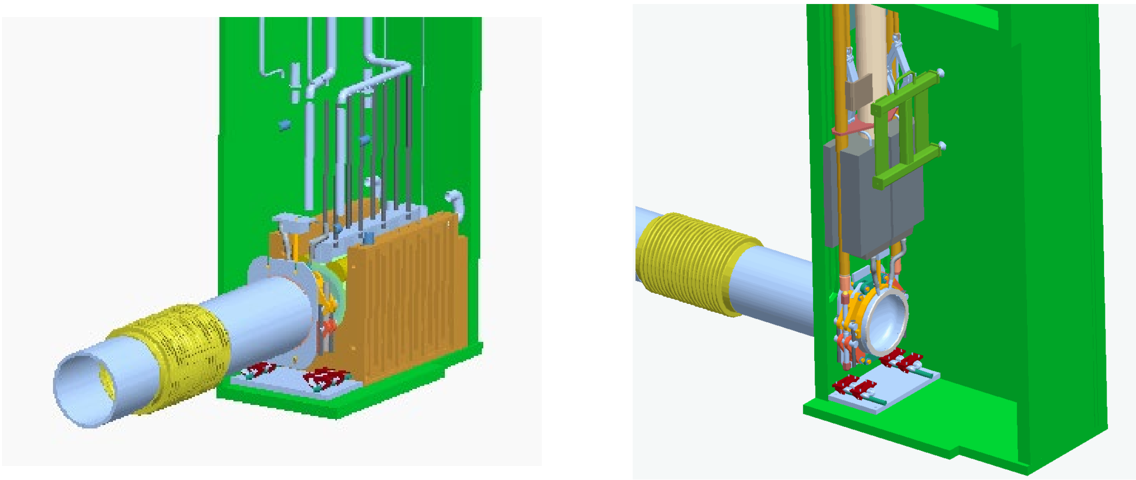

Figure 3.14. Injection beam stop.

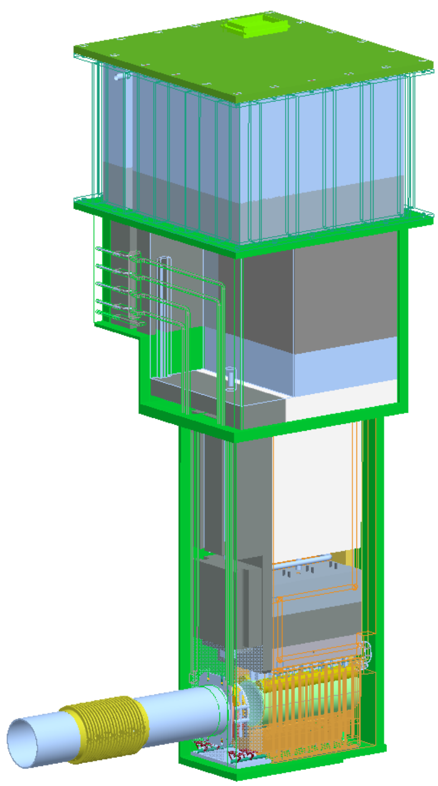

Figure 3.15. Vertical section of the injection beam stop and supporting/shielding structure.

This beam stop uses water-cooled copper disks enclosed in a stainless-steel vessel to absorb the proton beam energy and dissipate the energy to the water. The copper disks are sized (i.e., thickness increasing with beam penetration) to absorb about 5 kW in each disk, and a water flow path is machined into each disk. A heat exchanger, pumps, and ion-exchange units are located in the shielded utilities vault. The injection dump heat load is ultimately rejected to the SNS cooling tower through an intermediate cooling water loop. No direct connections are provided between tower water and radioactive beam-dump water. Design features are provided to minimize the probability of heat exchanger leaks causing inadvertent cross contamination. The primary heat exchanger is all welded plate-and-frame construction, and the secondary closed-loop deionized (DI) water system is at higher pressure than the primary system. The secondary system is cooled using another plate-and-frame heat exchanger that interfaces with the sitewide cooling tower water system.

The flight tube for the ring injection dump is capped with a water-cooled vacuum window immediately on the inside of the beam-stop enclosure. Criteria for periodic replacement of this vacuum window include applicable personnel radiation exposure considerations, including as-low-as-reasonably-achievable (ALARA) exposure goals. Failure of the window is an operational concern because of the potential that window failure could degrade the accelerator vacuum or spread contamination to the interior of the flight tube. The beam-stop enclosure contains the beam-stop assembly and miscellaneous shielding slabs.

Features of the ring injection dump building are described in Section 3.2.7.8.

Operation and Maintenance

Because the linac dump and ring extraction beam dump have no structures or buildings (other than the vault enclosing their shielding stack), no operation and maintenance activities are associated with them.

Maintenance activities at the ring injection beam dump occur in the three rooms above the beam-stop vault. These rooms are the mechanical/electrical equipment room, the utility services vault, and the beam-stop access room; they are depicted in Figure 3.16. The PPS controls access to the utility services room. Frequent access to the mechanical/electrical equipment room is anticipated. The equipment racks and utility equipment are in this room. When a beam-dump operation sequence is planned, personnel are expected to enter this room to turn on the pumps and prepare the dump for operation.

The beam-stop access room has very little equipment that requires routine personnel attention. It is primarily used when the beam stop is being removed through the hatch in the roof. Because the potential for increased radiation doses exists in this area, access to this room is controlled.

The utility services vault houses the water pumps, the heat exchangers, and the ion exchange columns used for injection dump cooling. This area has elevated radiation levels during operation and is equipped with 40 in. concrete walls and a labyrinth opening. Because some of the equipment contains activated material (especially the ion-exchange columns), access control is required even when the facility is not operating. Access to this area is controlled, and a PPS interlock is installed on the door so that the beam is tripped when unauthorized access is attempted.

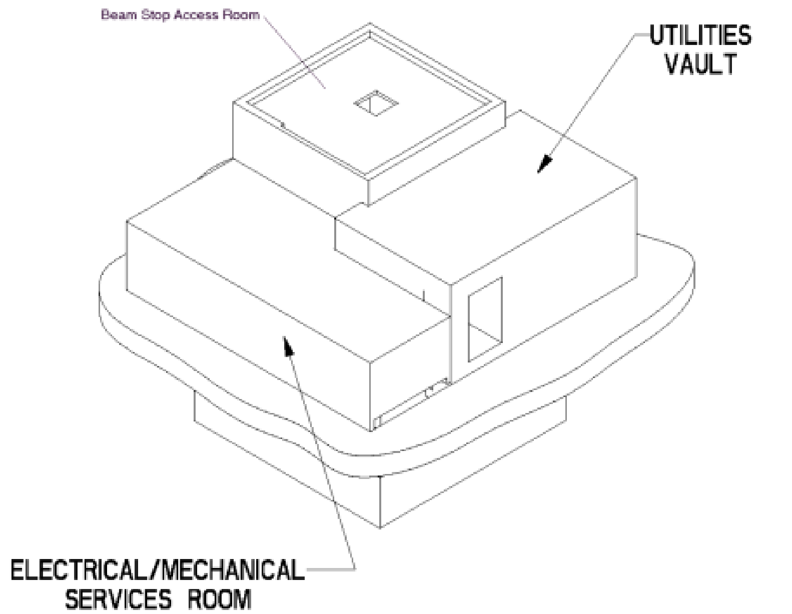

Figure 3.16. Isometric view of ring injection beam dump facility.

3.2.1.5 Support Facilities: CHL, RF Test, and Beam Test Facilities

Support facilities are in three adjacent buildings south of the linac, as shown in Figure 3.17. Building 8310 contains the CHL. Building 8330 contains the RF Test Facility (RFTF). Building 8320 contains the Beam Test Facility (BTF). The CHL and RFTF are fully separated by a steel wall. The RFTF and BTF have a roll-up door and personnel door to allow access between the two. Utilities are shared among the facilities. Because operation of the CHL is vital to the operation of the SCL, it is discussed in this section. The BTF is discussed in Section 3.2.7.5, and the RFTF is discussed in Section 3.2.7.6.

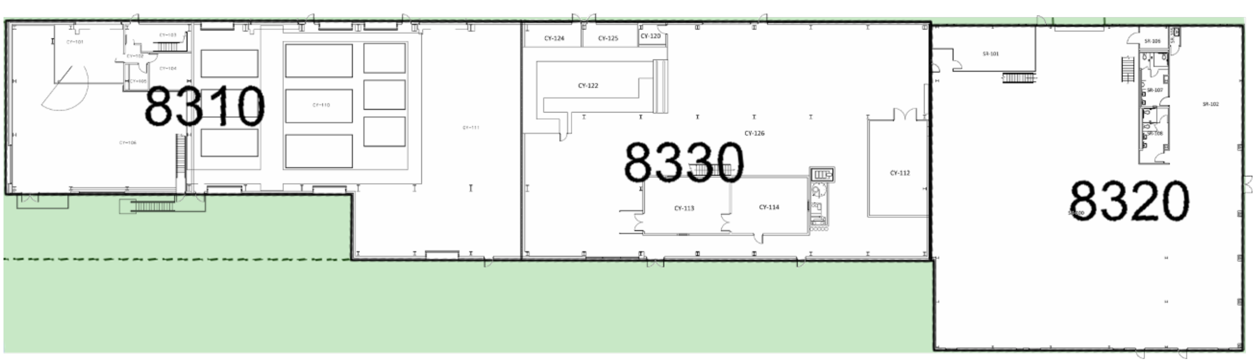

Figure 3.17. Overview of support facilities.

CHL facility. The CHL facility houses equipment that liquefies and circulates helium through the SCL. It contains compressors, pumps, cold boxes, vacuum equipment, oil removal equipment, and the controls and diagnostics necessary to allow smooth operation of the cryogenic systems. Gas and liquid storage areas are located outside the building, along with areas for tank and tube trucks to enter and make deliveries. The CHL facility is divided into two major rooms: (1) the warm compressor room on the west side houses the compressors, and (2) the cold box room on the east side houses the cold box and associated equipment (Figure 3.18). A mezzanine in the cold box room contains the CHL control room.

Underground cryogenic transfer lines transport supercritical helium from the CHL to the linac tunnel. Electrical power is essential for routine operation of the CHL equipment. An emergency diesel generator (not credited for safety purposes) is provided to minimize the probability that an extended AC power loss could lead to safe, but financially costly, venting of helium inventory to the outdoor air. A system of oxygen deficiency alarms (described in Section 3.2.5) is maintained to warn workers in the CHL in the event of a potentially hazardous inadvertent release of inert gas. ODHs associated with the CHL are addressed in Section 4.3.4.

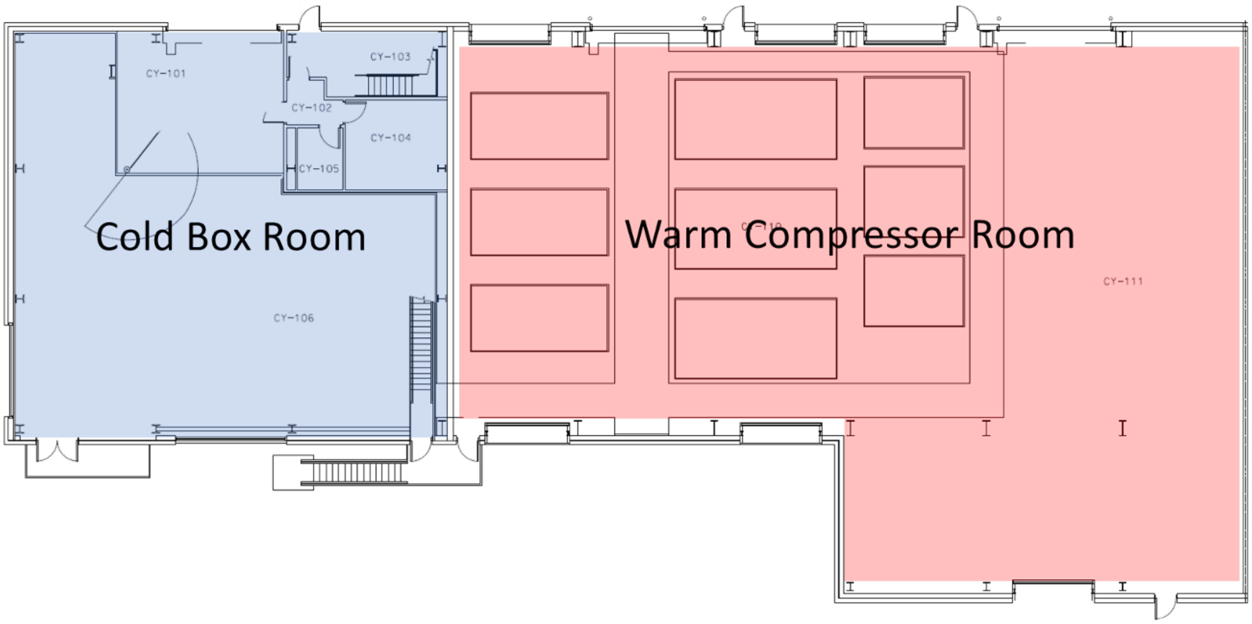

Figure 3.18. Overview of the CHL facility (Building 8310).

The outside walls of the warm compressor room have sound-suppressing vents. The helium compressors operate continuously and lose considerable heat to the air of the compressor room, so the warm compressor room is provided with ventilation features that help maintain habitable temperatures. Side vent panels with an area in excess of about 300 ft^2 are built into the compressor room north and south walls to allow relatively cool outdoor air to enter the building. Ceiling vents with an area of about 40 ft^2 provide a passive path to exhaust warm air to the outdoors. The ceiling vents are equipped with fans to increase flow rate as desired. The passive side and ceiling vents are safety credited with providing a natural convection pathway to remove helium in the event of inadvertent release of non-cryogenic helium into the compressor room. An analysis of ODHs presented in Section 4.3.4 determined the need to designate the side and ceiling vents as a passive CEC as described in Section 5.2.4.

The cold box room ceiling is equipped with two ceiling exhaust fans, each rated at 9,500 cfm.[1,2] The ceiling exhaust fan vents do not have dampers and thus provide a passive natural convection pathway to the outside environment. A free-standing expansion unit provides air conditioning only for the CHL control room and office area.

[1] Drawing H8.91.61, Rev 1, CHL/RF Miscellaneous Control Diagrams CHL/RF Systems, 7/31/2001.
[2] Drawing H9.10.60, Rev 1, CHL/RF Mechanical Equipment Schedules, 7/31/2001.

Outside and immediately adjacent to the building are eight 30,000 gal gaseous helium storage tanks with purifier systems, a 20,000 gal liquid nitrogen dewar, a 9,200 gal liquid nitrogen dewar, and parking and unloading areas for helium and liquid nitrogen trailers.

Figure 3.19 provides a block diagram of the cryogenic system that supports cryogenic operation of the SCL. This system comprises eight major subsystems: gas storage, compressor system, main cold box, 2.1 K cold box, purification system, 7,000 L liquid helium dewar, linac distribution system, and cryomodules. It spans from just outside the CHL facility through the CHL and into the tunnel. The gas storage system uses the eight 30,000 gal vessels adjacent to the building to store helium at approximately 250 psig. Helium gas flows from these tanks to/from the compressor system and to/from the purification system. The compressor system (located in the compressor room of the CHL facility) consists of three dual-stage compressors; two are in constant operation and the third is a standby. The compressed helium flows to the main cold box (cold box room on the east side of the CHL facility) where it is precooled with liquid nitrogen. It is further cooled to 4.5 K within the cold box through a series of turbo expanders and countercurrent flow heat exchangers. The main cold box supplies the liquid helium dewar and the tunnel distribution system. The cold boxes are confined spaces that are not routinely occupied. They may, however, be entered under carefully defined conditions that may require a confined space permit as defined per the ORNL SBMS.

The liquid helium dewar was designed to support the commissioning of the refrigeration system before the commissioning of the transfer lines and of the cryomodules. During normal operation, the liquid helium dewar is used to manage the refrigeration system capacity. The tunnel distribution system uses approximately 950 ft of both supply and return transfer line. These lines connect the refrigeration system to the cryomodules. The cryomodules are the last part of the cryogenic system. It is within these components that the cryogenic and accelerator systems are intertwined. Helium is liquefied across a Joule-Thompson valve in the cryomodule. The 2.1 K cold box pumps the liquid inventories into all the cryomodules, thereby lowering the temperature of the liquid to 2.1 K. This 2.1 K liquid (a superfluid) provides cooling to the superconducting cavities that propel the H^- beam.

A separate Cryogenic Test Facility (CTF) helium dewar system is installed in the east side of the warm compressor room. It provides a supply of liquid helium through the east wall to the RFTF test cave and vertical test-stand assembly (VTA) facilities located in Building 8330. The CTF helium system is independent from the cryogenic system that supports the linac.

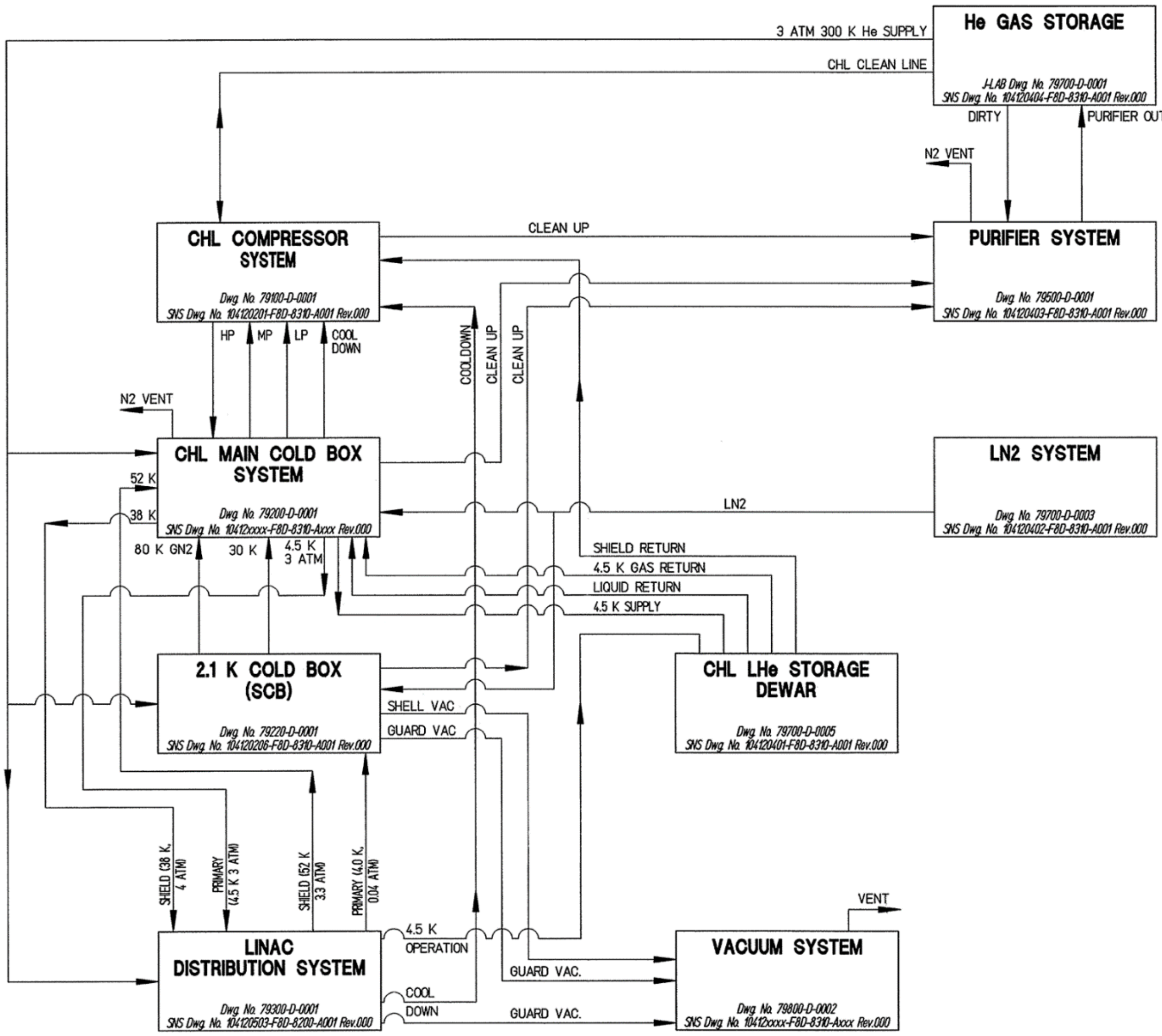

Figure 3.19. Cryogenic system block diagram.

3.2.2 Integrated Control System

3.2.2.1 Introduction

The integrated controls system (ICS) provides both high- and low-level machine control and cutoff functions. It includes both the machine protection system (MPS) and the PPS. An approved security plan[3-18] is implemented to protect the controls network from intrusion. Operator console access is controlled by passwords. Other means are used, as appropriate, to minimize the probability of unauthorized actions.

The ICS provides the following:

- Supervisory control and data acquisition (SCADA) for accelerator, conventional, and target subsystems
- The MPS for protecting equipment from beam-related damage

- The timing system for synchronization of accelerator subsystems
- The PPS for protecting workers against prompt radiation.

SNS supervisory controls are implemented using the Experimental Physics and Industrial Control System (EPICS) software tools. EPICS follows the “standard model” for a distributed control system. The architecture of this model is characterized by distributed controllers, operator interface workstations, and file servers, all of which are linked via an Ethernet TCP/IP local area network. EPICS is in use at several major accelerator facilities, including the Advanced Photon Source (APS) at Argonne and the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab. All SNS technical systems (front end, linac, ring, target, and CHL, as well as the conventional facilities) are controlled via EPICS-based supervisory controls. The entire Ethernet TCP/IP network is isolated from the SNS public network (e.g., office computers) by a commercial firewall, and the SNS network is in turn isolated from the ORNL enterprise network by another commercial firewall layer. This security is regularly probed for vulnerabilities by the ORNL cyber security group.

Proper operation of SNS requires synchronization of equipment for generation, acceleration, transport, storage, and extraction of beam. For example, beam chopping in the front end must be timed to maintain the gap in the beam circulating in the ring. The ICS includes a timing and synchronization system to fulfill this function. This system is modeled after a system in use at the Relativistic Heavy Ion Collider at BNL. For this purpose, it uses two dedicated fiber communication links: a “real-time data link” and an “event link” for synchronization.

The ICS includes the MPS for the protection of SNS equipment from beam-related damage. This system inhibits beam when equipment is not configured to accept it, whether due to equipment failure or operational error. Examples of events that prevent beam include (1) detection of significant beam loss, (2) magnet failures, and (3) target system not configured to receive beam. Configuration of the MPS is dependent on the operational mode of the SNS facility, which is distributed redundantly by the timing and synchronization system links.

Figure 3.20 is a schematic of these major ICS subsystems and their interfaces with other systems and subsystems. The elements of the distributed control system are shown in yellow. The PPS is in yellow, the MPS is in blue, the Timing System is in olive, and the various systems being controlled are shown in green.

3.2.2.2 Layered Protection

ICS subsystems are structured in a manner that provides layered protection against threats to both equipment and personnel. Figure 3.21 shows this layering of subsystems schematically. The PPS ensures protection of workers against prompt radiation; as discussed below, other controls provide layers of protection against potential operational problems before they require PPS actuation.

The supervisory control system provides the first layer of defense by enforcing system configuration rules, annunciating abnormal conditions, and responding when conditions approach unacceptable boundaries. While the supervisory control system acts to prevent challenges to other ICS systems, it is not considered to be either a safety system or a protection system.

The MPS provides the second layer of defense, responding to out-of-bound operating conditions by shutting off the beam. The MPS is a high-reliability system but is not a safety system. However, it does contribute to layered protection because it prevents challenges to the PPS radiation monitoring function by cutting off beam quickly when beam losses occur.

Thus, both the EPICS-based supervisory control system and the MPS contribute to overall assurance of safety by limiting challenges to the PPS, as described in Section 3.2.4. Control, protection, and safety functions are layered such that the quality level of the responsible system increases as the consequences of a failure increase.

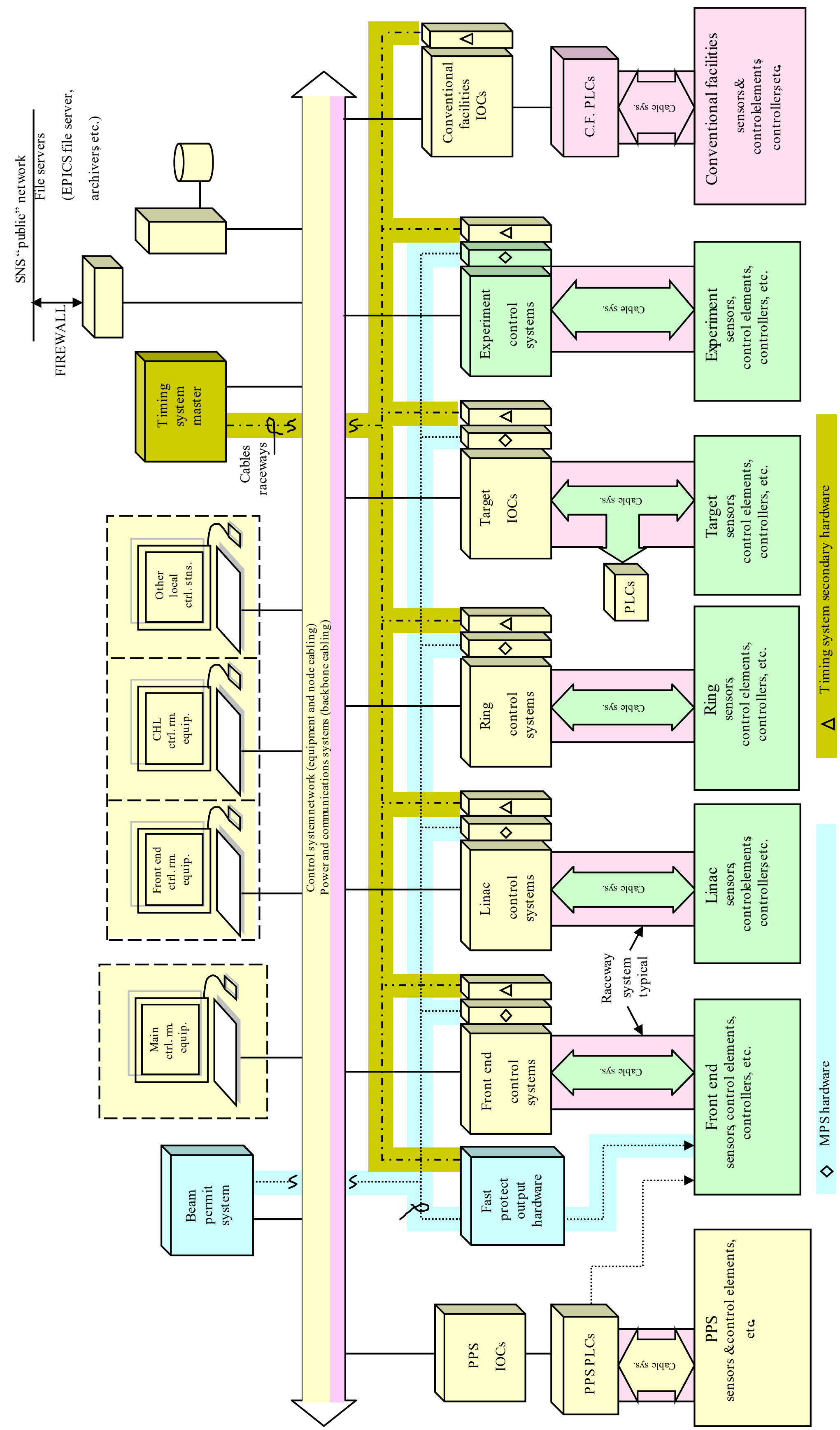

Figure 3.20. Integrated Control System block diagram.

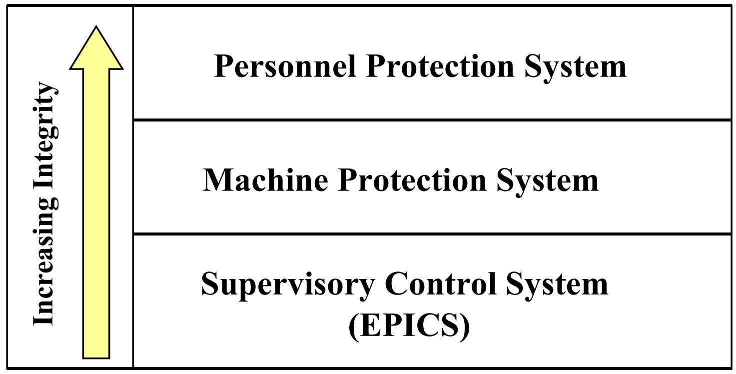

Figure 3.21. Integrated Control System "Layers of Defense."

3.2.2.3 Machine Protection System

The MPS is used to shut off the beam if equipment malfunctions are detected that could result in equipment damage. It is made up of the following three subsystems listed in decreasing order of criticality and QA requirements:

1. A "fast protect–auto reset" subsystem rapidly terminates the beam pulse creation (20 µs response design goal) upon detection of an anomalous beam-related condition (e.g., high losses) but allows the next pulse to be accelerated. This hardware system has an independent fiber link to the front end for beam turnoff. It makes a significant contribution to ALARA principles by minimizing structure activation.

2. A "fast protect–latched" subsystem rapidly terminates the beam pulse creation (20 µs response design goal) upon detection of an anomalous equipment status (e.g., power supply trip) that requires operator intervention to reset. This hardware system has an independent fiber link to the front end for beam turnoff.

3. A "beam permit" system verifies that selected aspects of the facility are configured to conform to the requirements of the operator-selected (or program-selected) mode before allowing beam pulse creation. This software system indicates equipment status to the operator, including the two fast-protect systems and the PPS, and alerts when equipment is not configured correctly.

These subsystems collectively provide the following functions:

- Protect SNS equipment from beam-induced damage. If a mis-steered beam (e.g., caused by a magnet failure) is not quickly terminated, then equipment damage may result. Similarly, if the target or the ring injection dump is not ready to receive beam (e.g., because of a cooling system failure), then the beam must be terminated, or else damage may result. The MPS monitors beam-related equipment and beam parameters and terminates the beam if failures are detected.

- Reduce activation of equipment by cutting off the beam when beam loss is detected. The MPS is designed to terminate beam in tens of microseconds when excessive beam loss is detected. This action also serves to reduce prompt radiation levels.

- Facilitate beam tuning by regulating the beam pulse duration when the beam tuning is less than ideal. After a beam loss is detected and the beam pulse is terminated, the system automatically resets so the next pulse can occur. This pulse width modulation automatically minimizes the repercussions of the beam loss while allowing tuning to continue.

- Guard against equipment configuration errors. When an operator requests a new operating mode, the MPS allows the mode change only if related equipment is configured properly. The operator is informed of any conditions that are preventing the mode change.

The beam loss monitor system (BLMS), part of the MPS, consists of approximately 260 ion chambers distributed around the linac, ring, and beam transport lines. These ion chambers detect beam loss by detecting the secondary particles from lost beam interactions. Predetermined and experimentally measured loss limits are used to set the maximum acceptable losses allowed by the BLMS. The MPS is designed to prevent the beam from damaging equipment and is designed to detect faults and to interrupt the beam very quickly, in many cases within 20 µs. The BLMS is designed to truncate the beam pulse train in midpulse and reduce the repetition rate of the accelerator or turn it off, depending on the severity of the beam loss. The MPS system is also used to detect current failure in several critical beam isolation magnets via programmable logic controller (PLC) analog input modules.

The MPS protects against some events that could otherwise result in a significant loss of capital and/or operating time. Those portions of the MPS for which a failure could result in a significant loss are assigned quality control measures commensurate with the institutional risk while the remainder of the system is assigned quality control measures using a graded approach. MPS trip features may be bypassed (e.g., during maintenance or testing activities) but only in accordance with specified SNS operating procedures. Access to MPS inputs and bypasses is restricted to qualified personnel. Bypasses are only applied as prescribed in the *Spallation Neutron Source Operations Procedures Manual* (SNS OPM). [3-21]

Because of the potential effect of the MPS on the availability of SNS, steps are taken to ensure its reliability. The steps include the following:

- Design the system to operate reliably.
- Design the system to fail to a safe state (i.e., a power outage, open circuit, or out-of-range signal should cause SNS to revert to the protected state).
- Design the system to facilitate fast and efficient periodic testing (e.g., by automated configuration testing and verification).
- Apply configuration control commensurate with the consequences of a failure.

3.2.3 Accelerator Safety System Overview

Active accelerator safety systems are used to protect workers from significant hazards associated with the proton facilities: (1) the PPS, (2) the ODH system, and (3) the tunnel EVS. The hazard analysis presented in Section 4.3 designates these safety systems as CECs. These systems protect workers from accelerator-specific hazards, namely prompt radiation associated with the H^- or proton beam and inert gases associated with the SCL, that could cause worker injury.

3.2.3.1 General Scope of the PPS, EVS, and ODH Systems

The primary function of the PPS is to protect workers from potentially injurious prompt radiation produced by accelerator operations. The PPS provides protection in the Front-End building, accelerator tunnels, ring injection dump, and target building. The areas protected by the PPS are partitioned into five major segments—linac, HEBT, ring (including the injection dump), RTBT, and target—as shown coded by color in Figure 3.22. All portions of the PPS, except for the target segment, are associated with the proton facility and are addressed here. The target segment of the PPS, addressed in the FSAD-NF, covers areas associated with mercury target systems and the neutron instruments.

The PPS is patterned after other successful radiation protection systems at the CEBAF and the APS. The PPS controls access to hazardous areas (e.g., accelerator tunnels, equipment rooms) during accelerator operation. If the potential exists for personnel to access a PPS-protected area during operation, the accelerator is not allowed to operate or is shut down to prevent injury. The PPS monitors the power being sent to the target and trips the beam before exceeding the power limits required by the ASE. The PPS supports administrative actions to clear PPS-protected areas of personnel before operation (sweeps) and provides other protective features, as described in Section 3.2.4.

Cryogenic systems are used in the linac and the CHL to support the SCL cavities. These systems circulate helium in the linac and helium and nitrogen in the CHL facility. A breach of a cryogenic system could release cryogens, leading to an ODH. The ODH system provides protections against ODHs in the accelerator tunnels and in the CHL facility. A system composed of oxygen transmitters linked to warning lights and horns is installed to protect workers in the event of a release of inert gas. ODH warning horns are designed to make a different sound from the PPS warning horns, so workers know which hazard they are being warned about. Upon detecting low oxygen levels in the linac tunnel, the ODH system initiates forced venting via the EVS fans. The EVS protects the atmosphere in the Front-End building and ring/RTBT tunnels by confining (and ventilating) an accidental cryogenic release within the accelerator tunnel.

The PPS and ODH/EVS systems are designed to operate independently from each other and are maintained as separate systems. Operation of the EVS is dependent on the ODH system functionality because the ODH system provides the signal to initiate EVS operation.

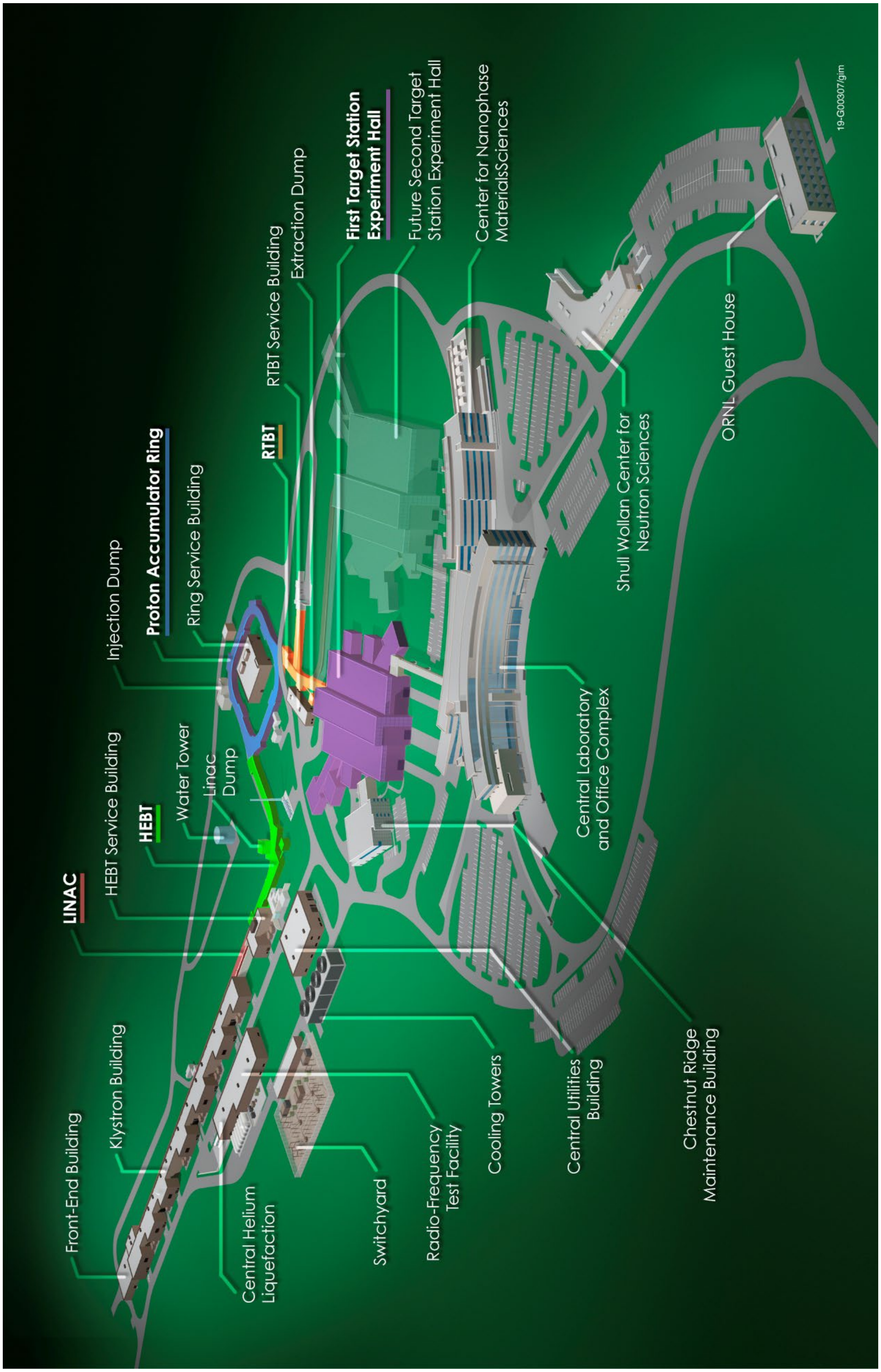

Figure 3.22. SNS site facilities; the major PPS segments are color coded (linac, HEBT, ring, RTBT, and target).

3.2.3.2 Safety Life Cycle

The PPS, EVS, and ODH systems are implemented in accordance with a safety life cycle, which contains the elements required to ensure proper performance of those systems throughout the life of the facility. The safety-life cycle for the PPS and the ODH systems was developed using as guidance the requirements outlined in ANSI/ISA-84.00.01, *Functional Safety: Safety Instrumented Systems for the Process Industry Sector* and IEC 61508-2010, *Functional Safety of Electrical/Electronic/Programmable Electronic Safety-related Systems*, which has since been replaced by IEC 61511-2016 *Safety Instrumented Systems for the Process Industry Sector*.[3-19]

The safety life cycle begins with a hazard analysis to discern the hazards presented by the system, and then the appropriate methods to mitigate these hazards are determined. The analysis includes a determination of the safety functions and the required level of risk reduction for each safety function. The required level of risk reduction, defined in the standard[3-19] as the safety integrity level (SIL), defines the minimum reliability requirements commensurate with risk documented in hazard evaluations.

The PPS, EVS, and ODH system are designated to receive the highest degree of quality rigor in accordance with the *Spallation Neutron Source Quality Manual*.[3-20] These systems are maintained in accordance with rigorous standards and procedures to provide a high level of system performance. The PPS, EVS, and ODH system are configuration controlled in accordance with SNS procedures. These requirements include activities such as (1) independent design reviews, (2) thorough documentation, (3) vendor qualifications, (4) configuration control, (5) formally trained operations and maintenance workers, and (6) formal testing and certifications. The SNS Radiation Safety Committee provides independent review of proposed substantive changes to the PPS as appropriate.

3.2.4 Personnel Protection System

The primary mission of the PPS is to protect individuals from prompt radiation hazards associated with accelerator operations. The PPS spans the entire SNS facility, including proton facilities and neutron facilities. The PPS functionality associated with the SNS neutron facilities (i.e., the target segment) is addressed in the FSAD-NF.[3-1]

During beam operation, excessive radiation levels can be created within the accelerator tunnels and the ring injection dump utility vault. During off-normal beam spills, radiation levels could be high enough to pose a risk to workers outside the tunnel (e.g., adjacent to an unshielded penetration). The PPS controls access into the accelerator tunnels (and injection dump), trips the beam upon access violations, and uses a series of interlocked radiation detectors to trip the beam if excessive radiation levels are detected outside the tunnel.

The PPS provides other safety-related functionalities (e.g., controlling gamma blockers), as described in the subsections below. Certain PPS safety functions are credited for preventing/mitigating credible postulated accidents as determined in the hazard analysis presented in Section 4.3. Credited safety functions of the PPS are further addressed in Section 5.2.1.

For the purposes of access control, SNS is partitioned into discrete segments, as described in Section 3.2.4.3. Each segment includes hardware that monitors and controls access to one or more exclusion areas, including accelerator tunnels, utility vaults, or other hazardous areas. Beam delivery is prohibited to a segment if its associated exclusion areas are accessible using critical devices described in Section 3.2.4.4. PPS access control features are described in Section 3.2.4.5. The PPS function to automatically cut off the beam based on excessive radiation levels detected by interlocked radiation monitors is described in Section 3.2.4.6. The Beam Power Limiting System (BPLS), a subsystem of the PPS, is described in Section 3.2.4.7. Other features of the PPS are addressed in Section 3.2.4.8.

3.2.4.1 Safety Functions

The PPS is responsible for the following credited safety functions:

- Prevent beam operation in a segment unless its associated exclusion areas are cleared of personnel (beam containment).
- Shut off beam if personnel enter an exclusion area associated with a segment where beam is permitted (access violation).
- Shut off beam if radiation levels set by the SNS radiation safety officer (RSO) are reached at PPS-interlocked area radiation monitor locations.
- Shut off beam to prevent beam directed to the target from exceeding the beam power limit defined in the SNS ASE.
- Prohibit beam to the target when the target cart is not in the “cart inserted” position (this function is also addressed in the FSAD-NF).

The PPS also provides for the following auxiliary safety assurance features:

- Enforce administrative access control requirements by controlling electromagnetic locks on personnel access doors.
- Support administrative actions to clear personnel from exclusion areas before beam operation (sweeps).
- Drop the sweep if personnel enter a cleared exclusion area.
- Activate audible and visual warning devices to alert personnel of beam conditions and status changes.
- Prohibit beam to a PPS-interlocked area upon activation of a PPS beam shutdown station emergency stop device.
- Prevent operation of RF klystrons associated with exclusion areas not cleared of personnel and shut off RF klystrons if personnel enter an exclusion area where RF klystron operation is permitted.
- Insert gamma blockers to reduce back-streaming radiation from activated components.

3.2.4.2 System Architecture

The PPS is structured to provide reliable performance of its safety functions while supporting flexible operations. The design principles of redundancy and fail-safe are integrated throughout the system, especially in those portions that provide a credited safety function. This section describes the types of components and programming practices that support the design principles of the PPS. The safety functions of the PPS are fundamentally accomplished through a network of sensors that inform the execution of logic designed to prevent unsafe operations by controlling critical devices.

Programmable Logic Controller Hardware

The computational core of the PPS is a network of PLCs that monitor the status of remote sensors, execute logic, and send control signals to operate critical devices based upon the outcomes of the executed logic. PLCs are more reliable than software-based solutions because the logic is executed by flexibly configured hardware, which has fewer failure modes. The logic functions for the PPS were originally performed by standard PLCs. An initiative to transition to safety-rated PLCs has begun, and several standard PLCs have been upgraded to safety-rated PLCs. The PLCs are applied redundantly to increase the system reliability (e.g., implementing two independent channels, typically referred to as A and B, to execute safety logic). The PLCs are applied in a one-out-of-two architecture or equivalent for the SIL-2 safety functions. In some cases, SIL-1 safety functions are performed by a single designated channel. In one-out-of-two architecture, if either channel detects the designated potential hazard under the predetermined condition(s), then the source of the hazard (e.g., beam production) is eliminated. I/O to the PLCs are scattered throughout the facility. For this reason, a dedicated standard industrial control network is provided for each PPS channel, connecting the remote PLC I/O modules to the associated PLC processor. The PPS PLCs have the following features:

- All I/O circuits are designed to be fail-safe. In the event of a power loss, broken wire, or out-of-range signal, the equipment goes to a safe condition (e.g., beam production stopped, klystrons shut down).
- Each redundant PLC in a one-out-of-two configuration is maintained as a separate system to minimize common mode failures.
- PLC network and I/O cable are routed separately from other facility cabling.
- Equipment that interfaces to the PPS, but that is not under the control of the PPS group, is isolated from the PPS. Isolation of external equipment prevents damage to the PPS in the event of a fault in the external equipment (e.g., short circuit, over-voltage).

Programmable Logic Controller Programming

The PLC logic programming is based on a rigorously prepared and reviewed logic specification. Separate programmers develop the PLC programming independently for each redundant PLC. The certified programs are never temporarily modified to bypass an input or force an output from the PLC. PLC programs are copied to a secure revision-controlled storage location before certification. The project files are maintained in accordance with procedure by the PPS System Engineer. During operation, the PLC programming computer is removed from the control room and the network connection is disconnected inside the PPS rack. Installation and use of the programming computer during troubleshooting is controlled by procedure. Only authorized personnel are allowed to modify the PLC programs in accordance with the configuration control procedure.

Field Programmable Gate Array Hardware

The BPLS is a subsystem of the PPS designed to monitor total beam power being delivered to the first target station and shut off beam if the total delivered power exceeds a threshold chosen to ensure integrated beam power does not exceed ASE limitations. Due to the timescales associated with the delivered proton beam pulse (<1 μs length), PLC hardware alone was determined to be inappropriate for the application of measuring and integrating the beam power. As part of the Proton Power Upgrade project, the BPLS was designed using field-programmable gate array (FPGA) hardware with a μTCA framework. This approach is well suited to the power measurement and is typical of similar systems already implemented in non-credited beam instrumentation deployed in SNS and other accelerators in the DOE complex.

The FPGA hardware provides a way to collect and evaluate the signal produced by fast current transformers (FCTs) installed in the RTBT beam pipe. Because of the short, intense beam pulses being measured, PLC-based analog inputs are not able to accurately monitor the FCT outputs, so FPGA based hardware was designed to perform the required "fast" functions and provide outputs to a PPS PLC that executes the safety logic and interfaces with the PPS.

Field Programmable Gate Array Configuration

FPGA hardware is configured using hardware description language (HDL). HDL provides an interface and functional language similar to a software programming language to facilitate configuration of the FPGA hardware by the end user. However, there are key differences between HDL and software programming. The configured FPGA is not constrained to execute functions in a strict sequential fashion such that the outcomes of a particular hardware configuration are not as deterministically predictable as software. Therefore, HDL code must be simulated using proprietary models provided by the manufacturer in a mathematic environment such as MATLAB. As a result, even apparently simple changes to the configuration can require an iterative process of modification and simulation before the desired outcome is achieved. Moreover, writing and checking/verifying HDL both require a specialized skill set separate from what is required for PLC logic.

As a result, the design of the FPGA hardware that performs the safety functions was developed to minimize the potential need to modify the configuration and use the PLC part of the system wherever possible to perform slow calculations, store safety related parameters, and interface with outside systems. The safety portion of the FPGA hardware is generally referred to as the digital processing unit (DPU). Another piece of FPGA hardware, the protective system interface (PSI), was developed in parallel with the DPU. PSI performs the same basic functions as the DPU while also providing additional information and tools to operators to aid in assessment of system performance. It also provides an output to the MPS to provide an additional layer of defense. PSI improves overall operational reliability by reducing challenges to the safety system and interrupting the beam in a way that allows rapid return to operation compared with a PPS trip of critical devices (Sections 3.2.2.3 and 3.2.4.4).

Personnel Protection System Computer Displays

PPS PLCs are connected to EPICS workstations in the Central Control Room. These workstations are used to display the status of the PPS. The workstations allow the operator to rapidly obtain information on the status of each segment in terms of operating mode and status of critical devices. Most of the inputs monitored by the PPS are logged by the main archive engine. This allows EPICS workstations to display historical data, such as radiation levels recorded by the radiation detectors. The PPS PLCs are connected to a controller using a private network system separate from the network used for accelerator controls. The PPS EPICS controller has two network connections, one for the PPS private network and one for the controls network. The controller has provisions to prevent transmission of information from the controls network to the private network. This feature, along with the firewall installed between the controls network and the external laboratory networks, precludes the possibility that someone could access the PPS PLC equipment from a remote location. The EPICS workstations are provided as operator aids. The proper execution of safety functions by the PPS is not dependent on the operation of the workstations.

Interface with Machine Protection System

The PPS interface with the MPS is designed to ensure that the PPS and MPS agree that beam generation is permitted. The MPS does not affect any safety function of the PPS, and a malfunction of the MPS would not affect the ability of the PPS to perform its safety functions. A minimum number of connections have been provided between the PPS and the MPS to enhance the mission reliability of each.

The PPS provides a status signal from the A and B PLCs for each segment to inform the MPS PLC when beam is allowed in the segment (the A and B PLCs must both be in beam permit mode before the MPS allows beam operation in that segment). When the machine mode key switch requests beam for a machine segment, MPS disables beam if the PPS indicates the required segments are not in beam permit mode. The PPS inputs are provided to the MPS PLC system and are not maskable by the MPS system except through a hardwired jumper or a software change to the MPS PLC program. If the PPS detects an internal fault in one of the interlocked area radiation monitors, then it sends a signal to the MPS calling for beam cutoff prior to a PPS trip.

If the MPS detects a beam shutoff fault (MPS attempts to shut off beam, but the beam does not shut down), then the MPS provides an input signal to the PPS. When the PPS receives this signal, the PPS shuts down the beam using the PPS critical devices described in Section 3.2.4.4.

3.2.4.3 Segmentation

The design of the PPS segments the facility for ease of monitoring and operational organization. Each segment is a division of hardware, treated as a unit, that monitors and controls accelerator access and operations in a defined area of the facility. Each segment monitors and controls access to one or more exclusion areas. Access control and beam containment functions of the PPS treat each segment, including its associated exclusion area(s), as a single unit. A segment is accessible if it is in an operating mode (Section 3.2.4.5) that allows personnel to enter an exclusion area monitored by that segment. The facility is divided into the following five major segments with their associated areas and components (Figure 3.22).

1. Linac segment— linac tunnel and front-end critical devices

2. HEBT segment—HEBT tunnel and HEBT dipoles

3. Ring segment—ring tunnel, ring injection dump, and ring extraction septum

4. RTBT segment—RTBT tunnel and RTBT dipole

5. Target segment—target system areas and neutron instrument enclosures (the target segment is addressed in the FSAD-NF[3-1])

Each segment is associated with one or more exclusion areas. An exclusion area is a defined portion of the accelerator tunnel or another access-controlled space that has been identified as potentially hazardous due to prompt radiation produced by the accelerated beam.

The PPS segments associated with the proton facilities are the linac, HEBT, ring, and RTBT segments. A system of access control features (Section 3.2.4.5) allows the control room operator to rigorously control access to exclusion areas in each segment without requiring the exclusion areas in other segments to be reswept. Each PPS segment is independent of the other segments, so modifications or repairs to one segment do not affect the other segments.

A redundant pair of PLCs serves each segment. Using this architecture, testing or maintenance can be conducted on the PPS equipment in one segment without affecting the PPS equipment in other segments.

3.2.4.4 Critical Devices

Designated critical devices are listed in Table 3.4. They are used to stop beam production at the front end, or to prevent beam transport into an accessible segment, depending on the operational configuration. Critical devices are selected for the reliability, determinism, and verifiability of the desired beam-control state. PPS control of critical devices is implemented in accordance with fail-safe principles: credible failure modes, such as loss of PPS power or continuity, result in removal of power to the device, causing the device to return to or remain in the desired safe state.

Beam Shutoff

The primary method the PPS uses to eliminate prompt radiation hazards associated with accelerator operation is to shut off the beam at the front end. Three critical devices are normally used to stop beam production: (1) the −65 kV extraction power supply associated with the ion source, (2) the RF supply to the RFQ, and (3) the RF power supply for the ion source plasma antenna. Eliminating any one of these three energy sources completely terminates beam production by the front-end system. The PPS is operable if any two of the three are operable; thus, the PPS logic allows the power supply for the ion source plasma antenna to be used instead of the −65 KV power supply before beam operation to allow conditioning of the high-voltage section of the front end, described below as the operational configuration called ion source conditioning. In the event the PPS detects a fault condition with either of the first two beam production critical devices, the plasma RF is automatically shut off. These devices, together being used to shut off the beam, are referred to as the front-end critical devices.

Beam Containment (Downstream Access Mode)

The PPS uses critical devices to contain beam to portions of the accelerator to allow limited accelerator operation while downstream segments are accessible.

Table 3.4 lists the various operational configurations, or beam containment modes, and the critical devices used to contain beam to the exclusion areas. For beam to be produced and transported in one of the listed operational configurations, all associated exclusion areas must have been verified clear of personnel, and the PPS must be aligned such that any potential access to an exclusion area trips the front-end critical devices, stopping beam production. Although the name of an operational configuration describes the type of operations typically performed in that mode (e.g., linac tuning, ring tuning), other operations may be performed if they remain within the acceptable bounds of the operational configuration of the machine. For example, in linac tuning mode, the Faraday cup at the end of the CCL might be inserted for testing or development work, terminating the beam well before it reaches the linac dump. This work could similarly be performed with the machine configured for full operation if maintaining the downstream segments cleared of personnel and ready for neutron production is desired. The operational configuration controls personnel access in areas where the beam could be delivered.

Table 3.4. Operational configurations and associated segments, critical devices, and exclusion areas.

Operational configuration	Operating segments	Critical devices	Exclusion areas	Access allowed areas
Ion source conditioning mode *No beam*	Linac segment (front end critical devices)	RF to RFQ *and* −65 KV power supply *or* RF power to ion source plasma	None	All
Front-end-only mode *Beam to MEBT beam stop*	Linac segment up to MEBT beam stop	– MEBT beam stop [a] – RF waveguide shutters (DTL1 and 2) [b]	None	All
Linac tuning mode *Beam to linac dump*	Linac segment HEBT segment	–First HEBT dipole magnet –Second through eighth HEBT dipole magnets	– Linac tunnel – HEBT tunnel	Ring tunnel, ring injection dump, RTBT tunnel, target areas [c]
Ring tuning mode *Beam to extraction dump*	Linac segment HEBT segment Ring Segment RTBT Segment	– RTBT dipole magnet [d] – Extraction septum dipole magnet [d]	– Linac tunnel – HEBT tunnel – Ring tunnel – Ring injection dump – RTBT tunnel	Target areas [c]
Full operation *Beam to target*	Linac segment HEBT segment Ring segment RTBT segment Target Segment	NA[e]	– Linac tunnel – HEBT tunnel – Ring tunnel – Ring injection dump – RTBT tunnel – PPS protected areas associated with mercury target system portion of the target segment [c]	Neutron instrument beamline enclosure portion of the target segment [f]

[a] PPS detects MEBT beam-stop position and monitors for burn-through, tripping the beam if either indicates a fault.
[b] Shutters prevent RF transmission to DTLs in front-end-only mode.
[c] Described in FSAD-NF (Reference 3-1).
[d] When target cart assembly not in position, the extraction septum is disabled along with the RTBT dipole magnet (RTBT.DH13). In this case, beam cannot be extracted from the ring.
[e] The beam terminates into the mercury target; the PPS ensures no beam to target unless target cart is in place (details in FSAD-NF).
[f] When primary and/or secondary shutter closed as addressed in the FSAD-NF.

Control of Critical Devices

Front-End Power Supplies. The −65 kV power supply and the RF power to the ion source plasma are controlled by redundant PPS AC contactors that remove power from the power supplies. Each redundant contactor is controlled by both PLCs for the linac segment. During the ion source high-voltage conditioning phase of prebeam startup preparations, the PPS can allow use of the −65 kV power supply by shutting off power to the plasma RF (Table 3.4).

RF to RFQ. The PPS controls the output of the RF to the RFQ using two diverse methods:

1. The PPS controls the 2,100 V AC power supply to the high-voltage modulator using the input line contactor contained in the SCR controller cabinet. The control signal to the contactor is routed through interposing relays controlled by the PPS. When the PPS removes power from the interposing relays, the control signal is removed and the contactor drops out, removing high voltage from the klystron tube and thereby stopping RF production.

2. The PPS controls the AC power to the RF drive amplifier using interposing relays controlling the AC power to the amplifier. When the PPS removes power from the power relays, AC power is removed from the RF drive amplifier, stopping RF production.

MEBT Beam Stop and RF Wave Guide Shutters for DTL 1 and DTL 2. During routine operation, the front end feeds the H^- beam to the linac for acceleration. By contrast, during operation in "front-end-only" mode, the beam ends at the PPS-controlled MEBT beam stop. This mode enables coordinated operation of the front end while preventing beam transport into the linac, allowing safe worker access to the linac tunnel exclusion area. The MEBT beam stop is a carbon block with a reentrant shape that does not require active cooling at the intended beam power (~45 W). The PPS does not allow front-end-only mode unless the MEBT beam stop is in place.

The MEBT beam stop is a movable beam instrumentation device installed in the MEBT. When the beam stop is in the inserted position, beam from the front end can be tuned into the beam stop. In the front-end-only operational configurations, the PPS allows operation of the front end (−65 kV power supply, plasma RF and RF to RFQ) with the linac or HEBT tunnels accessible. The PPS monitors the status of the MEBT beam stop when the PPS is in the MEBT beam-stop mode. While the PPS is in front-end-only mode, the following conditions ensure the critical devices are properly aligned:

- MEBT beam stop is fully inserted into the beam path
- MEBT beam stop is intact
- MEBT beam stop is locked in position
- DTL 1 and DTL 2 waveguides shutters are closed
- RF monitors downstream of the waveguide shutters indicate no RF leakage

The PPS monitors the MEBT beam-stop position when front-end-only mode is active to ensure that the beam stop is fully inserted in the beam path. The beam stop has a pressurized cavity. The pressure is monitored by the PPS to ensure that the beam stop is intact (beam has not burned through the beam stop). Motor power to the beam-stop drive motor is controlled by the PPS. In front-end-only mode, power to the motor is disabled to prevent retraction of the beam stop. Operation of the RFQ RF requires that the RF to DTL 1 and DTL 2 be enabled. Because the linac tunnel can be accessed during front-end-only mode, no RF can be transmitted to the DTL cavities. Preventing RF to DTL 1 and 2 prevents beam transport. Before operation, waveguide shutters (also known as "shorting" plates) are switched (closed) to short the DTL 1 and DTL 2 waveguides. These shutters are monitored by the PPS to ensure they are configured before front-end-only mode is enabled. Additionally, the waveguide shutters have RF pickups installed upstream and downstream to validate that RF power is being blocked by the shutter. Disabling the beam-stop motor power and configuring the waveguide shutters is also enforced via trapped keys. A key exchange unit in the front end releases the front-end-only mode operating key used in the front end only after the waveguide shutters have been configured and the beam-stop motor power has been disabled.

HEBT Dipole Magnets. The HEBT arc dipole power is deenergized by the PPS when ring or RTBT access is required during linac operation. Two power supplies feed the eight dipole magnets (one for the first magnet and one for the remaining seven). Either critical device sufficiently mitigates any prompt radiation hazard in the ring.

These power supplies are controlled by the PPS using two devices. A dedicated PPS AC contactor is used to remove power from the power supply. This contactor is controlled by both PLCs for the HEBT segment. Both PLCs also control the power supply via the standard PPS interface. The PPS interfaces with each power supply via a dedicated unique electrical connector. The PPS provides a control signal that enables or disables power supply operation. Two readback contacts are provided from the power contactor(s) in the power supply to indicate the contactor status (open/closed).

RTBT Dipole Magnet. The RTBT dipole magnet (RTBT.DH13) is used by the PPS and target protection system (TPS) to prevent beam transport to the target. Equipment provided by the TPS controls both the AC power (AC contactor) to the RTBT.DH13 magnet power supply and the DC power (DC disconnect) to the magnet. These devices are controlled and monitored by the PPS and are monitored by the TPS. When power is removed from this magnet, beam is contained to the RTBT (i.e., directed to the ring extraction dump).

The power to the RTBT.DH13 dipole is controlled by the PPS using three devices. The RTBT segment PLCs supply a control signal to the TPS AC contactor. Both PPS PLCs also control the dipole's power supply via the standard PPS interface (details in HEBT Dipole Magnets subsection). The PPS actuates the DC disconnect, but only after the AC power has been shut off.

Extraction Septum Dipole Magnet. If beam were to be transported to the target building without the target cart assembly in place, then extremely high radiation levels could occur in occupied areas, as described in the FSAD-NF. For this reason, a second critical device is used (in addition to the RTBT dipole magnet) to ensure the beam cannot be transported to the target building when the target cart is not in place. This second device, the extraction septum magnet, is interlocked, preventing extraction of beam from the ring. When the target cart assembly is not in the "cart inserted" position, the PPS interlocks power to the extraction septum power supply. This action, in conjunction with the RTBT dipole magnet, prevents beam transport to the target building while allowing beam operation in the linac, HEBT, and ring. However, with the extraction septum dipole magnet disabled, operations in the ring are limited because the beam cannot be extracted to the extraction dump and instead is lost only by gradual dissipation into ring components.

The extraction septum power supply is controlled by the PPS using two devices. A dedicated PPS contactor is used to remove power from the power supply. This contactor is controlled by both PLCs for the ring segment. Both PLCs also control the power supply via the standard PPS interface (HEBT Dipole Magnets subsection).

3.2.4.5 Access Control Features

To prevent beam operation in exclusion areas not cleared of personnel (beam containment), rigorous control of access to exclusion areas, also called beam enclosures, is enforced. The accelerator tunnels are designed with a limited number of access points, and each access point is monitored by the PPS. The access points (doors and gates) are described in the subsections below. The exclusion area is verified clear of personnel using SNS procedures and supporting features of the PPS (Section 3.2.4.8), a process generally referred to as a *sweep*. A completed sweep is one of the requirements in the PPS logic to elevate the operating mode of a segment for beam operations. The PPS monitors each access point; if an access violation is detected while the segment is operating, then it shuts off the beam (Section 3.2.4.4). Once this happens, a sweep is required to return to operation. Access monitoring is typically provided by redundant door position switches connected to both independent PPS channels.

As an additional layer of protection, the PPS controls power to the electromagnetic locks on tunnel entrance doors. These locks enforce administrative access controls designed to ensure that personnel entering access-controlled areas are properly trained, comply with ORNL SBMS Radiological Controls requirements such as dosimetry, and have a specific need to be in the area. The PPS also supports administrative accountability processes to allow limited, controlled access to a secured segment without requiring the segment to be swept. The specific training, qualification and record-keeping requirements are detailed in the SNS OPM. [3-21]

The PPS is designed to allow each of the PPS segments to be in one of five PPS operating modes. The PPS requires an orderly progression from one mode to the next before the accelerator can be operated. The operating modes are listed in Table 3.5.

Acting within the administrative controls of the SNS OPM,[3-21] the operator selects the appropriate mode for each segment using key switches located in the control room. If the operator selects the controlled access mode or higher, the PPS will not transition to that mode unless a correct sweep of the tunnel has been performed.

Table 3.5. PPS operating modes and features

PPS operating mode	Features
Restricted access	Personnel access to exclusion areas in segment is controlled by ORNL proximity card with the option to require control room operator concurrence. Access limited to trained or escorted personnel. Hazardous operations[a] in segment not permitted.
Sweep	Personnel access to exclusion areas in segment controlled by operator and ORNL proximity card. Only search personnel allowed in exclusion area. Personnel required to carry an exchange key while in the exclusion area. Hazardous operations[a] in segment not permitted.
Controlled access	Personnel access to exclusion areas in segment controlled by operator and ORNL proximity card. Access limited to specially trained personnel only (no escorting). Personnel required to carry an exchange key while in the exclusion area. Hazardous operations[a] in segment not permitted.
Power permit	No personnel access permitted. RF klystron operation allowed. No beam operation in segment.
Beam permit	No personnel access permitted. Full operation allowed.

[a] Hazardous operations include RF klystron operation or beam acceleration.

Double Entrance Doors to Tunnel

Normal personnel entrances to accelerator tunnels have a small alcove with two doors—an inner and outer door in series. The doors are locked with electric locks controlled by the PPS. These locks are controlled differently depending on the operating mode of the segment that controls the exclusion area being entered.

When the exclusion area being entered is in the restricted access mode, the outer door is unlocked. The locked inner door controls access. Entry into the accelerator tunnel is controlled by the PPS and the ORNL proximity card reader. Trained personnel can use their ORNL proximity cards to access the tunnel. The operator can monitor the door remotely via network-based video camera and can place the PPS in a mode in which both operator action and the proximity card reader are required to open the door.

During a sweep, both the inner and outer doors are locked and must be opened by the control room operator to allow sweep teams to enter the accelerator tunnel. Each person on the sweep team must take an exchange key when entering the tunnel.

When the sweep is complete and the segment is placed in controlled access, both the inner and outer doors are locked. The control room operator controls both doors. To prevent piggybacking (unauthorized persons attempting entry along with authorized persons), only one door can be opened at a time. If both doors open at the same time, the sweep is dropped and must be repeated to get back to controlled access mode. To gain entry, a worker contacts the control room. The operator unlocks the outer door, the worker enters the alcove, and the outer door locks (provisions are made for emergency exit from each personnel door). The operator supervises the entry procedure via network video camera. Before entry, each worker going into the accelerator tunnel must take an exchange key. These keys are trapped in a key release box located in the alcove. To release the keys, a master key must be removed from an interlock switch and be inserted into the key exchange box (this master key is released by the control room operator). The master key is electrically interlocked to the PPS, so that when the key is removed, hazardous operations are not allowed by the associated segment. Personnel entering during this mode use a separate proximity card reader to verify that each person has special training. The operator opens the inner door, and the workers can proceed into the accelerator tunnel. Upon exiting the accelerator tunnel, the workers replace the exchange keys.

Warning light and status display are mounted at the outer doors. These devices are used to inform workers of the segment's operating mode.

Double entrance doors have a provision for emergency entry. A device located at the outer door is available to unlock both doors in an emergency. This device requires deliberate action to operate (i.e., breaking the glass). This action also disables hazardous operation in the exclusion area (associated segment drops to restricted access mode).

Single Entrance Doors to Injection Dump Room

A single entrance door is used to control access to the utilities vault associated with the injection beam dump. This area does not have a controlled access mode (a search is performed after each entry) and therefore does not require a second door. The method to control access is similar to that used for a double entrance door. Warning and status devices located at the door inform workers of the room's status. Provisions are made for emergency entry.

Tunnel Equipment and Emergency Exit Doors

Equipment and emergency exit doors are monitored, but not remotely unlocked, by the PPS. The emergency exit doors have standard emergency door features that allow crash-bar opening from the inside but prevent opening from the outside. Equipment doors include the truck doors adjacent to the double entrance doors at the RTBT and HEBT. The equipment doors are locked using conventional locks; the keys to these locks are controlled administratively by the operations team. A warning device is located at each door to alert workers to hazardous conditions inside the accelerator tunnel.

Accelerator Tunnel Gates

Gates located inside the accelerator tunnel separate adjacent tunnel segments using a wire mesh structure, except for the HEBT/ring interface gate, which consists of a personnel door installed in the shielding labyrinth at that location. These gates are monitored by the PPS and locked using magnetic locks controlled by the PPS. PPS gates are used to separate one segment from another. PPS PLCs for the upstream and the downstream segment both monitor the gate position. Warning devices are located on both sides of the gate to alert personnel of potentially hazardous operations on the other side of the gate. Push buttons are located on both sides of the gate to allow personnel to unlock the gate in the event of an emergency.

Wire mesh gates are of a prefabricated double swing-type. One side of the gate is locked with a conventional lock; the other side is locked using a magnetic lock controlled by the PPS. Both doors are monitored by the PPS. The doors swing open toward the closest tunnel exit. A wire mesh fence is installed across the tunnel at each gate to prevent personnel entry past the gate when the gate is locked. The HEBT/ring gate is a personnel door located in the shield wall installed at this location. The door is locked with a magnetic lock and has the same features (e.g., warning devices and push buttons) as described in this subsection for all segmentation gates.

Front-End Shield Door

The front-end shield door is a movable shield between the front end and the linac. The shield door opens to provide access for movement of large equipment into and out of the tunnel, such as a cryomodule. The door is constructed of borated polyethylene encased in steel, providing both gamma and neutron shielding. The door position is monitored by the PPS to ensure that the door is shut before beam operation, and an access fault is initiated if the door is opened during beam operation. A magnetic lock interlocked to the PPS status is provided to prevent inadvertent opening of the shield door during beam operation.

Target and Instrument PPS Access Control Areas

The target PPS segment is described in the FSAD-NF.[3-1] Whenever it senses a need for beam cutoff, the PPS cuts off the beam at the front end. Instrument PPSs for individual beamlines provide signals to the target PPS, as described in the FSAD-NF.

3.2.4.6 Interlocked Area Radiation Monitors

PPS interlocked area radiation monitors (Fermilab-style "Chipmunks" or approved equivalent) are provided to monitor radiation levels and to shut off beam if setpoints are reached. Interlocked area radiation monitors are hard-wired fail-safe monitors generally located in occupied areas adjacent to potential high-loss areas along the beam path. For example, they are installed around the accelerator and target building in areas where higher-than-expected prompt radiation levels may occur (because of beam loss, insufficient shielding, and/or tunnel penetrations). Interlocked area radiation monitors may also be placed in unoccupied beam areas and correlated with measured levels in adjacent occupied areas. This function is preventive and is distinct from personal dosimetry. Interlocked area radiation monitors are used to automatically shut off the beam if significantly elevated radiation levels that are inconsistent with the area classification are detected. Interlocked area radiation monitors are part of the PPS and therefore are subject to the strict configuration-control and other administrative procedures that govern the implementation and maintenance of the PPS.

Each interlocked area radiation monitor is associated with the PPS segment where a beam spill could potentially result in excessive radiation levels outside the beam enclosures.

Each interlocked area radiation monitor provides an output of the detected radiation level to the PPS and may also provide a digital alarm trip signal. The PPS will then trip the beam based upon adjustable dose rate limits or digital alarm trips. Additionally, internal alarm setpoints of the interlocked area radiation monitor may be used to actuate a local and remote alarm below the PPS trip threshold. Interlocked area radiation monitors are designed with fail-safe features and self-diagnostic functions that together ensure that an instrument malfunction results in a beam trip soon after occurrence. The radiation level is also displayed locally and is transmitted to EPICS via network connection to support radiation protection activities such as posting, operational monitoring, and ALARA measures.

When the Fermilab Chipmunk is serving as an interlocked area radiation monitor, it sends a pulsed frequency to the PPS that correlates to the detected radiation level; these pulses form the principal input from this instrument to the PPS. The ion chamber of the Fermilab Chipmunk is designed to detect both neutrons and gammas and has a quality factor setting that can be adjusted to account for differences in neutron energy and gamma/neutron dose ratio. The PPS totals the number of pulses over time to determine the dose rate. Adjustable dose rate limits are used to activate area alarms and stop beam production. Limits are provided based on a rolling average and on the prompt level. These trip levels are set by the RSO.

The radiation levels are recorded by the main archive engine to allow personnel to retrieve historical data and to study trending radiation levels in monitored areas.

The RSO, subject to review by the Radiation Safety Committee, determines the location and the number of interlocked area radiation monitors. Factors considered in optimizing coverage include routine periodic radiation surveys, beam fault studies, shielding calculations, and potential personnel occupancy or use. The RSO determines the appropriate quality factor setting for each instrument location, and the PPS group is responsible for ensuring the appropriate setting is implemented. Quality factors used to adjust the instrument sensitivity are determined based on predicted and measured neutron/gamma ratios and, where available, neutron energies. For each radiation detection instrument connected to the PPS, justification of the instrument location, the effective quality factor, and any changes are documented by the RSO. Instruments connected to the PPS are subject to the same level of configuration control as the rest of the PPS. These instruments are calibrated periodically against National Institute of Standards and Technology standards in accordance with ORNL procedures.

Because the SNS layout and operational approach have remained essentially unchanged throughout the life of the facility, the approach to distributing monitors throughout the facility has not been significantly modified since the original evaluation and placement. In general, monitors are installed in the Klystron Gallery and other service buildings near the outlet side of utility penetrations into the shielded tunnels, particularly in sections where the beam has reached high energy such as the SCL, HEBT, Ring, and RTBT. One chipmunk is designed to be installed intermittently as required in the HEBT tunnel to monitor for potential dose to personnel occupying the ring during linac tuning operations. A selection of positions outside the earthen berm have also been maintained to validate expectations for exterior dose rates. In the target facility, monitors are installed above the final section of the RTBT and in a perimeter around the monolith in the instrument hall. Monitors were also added to the front-end area due to concerns about potential backscatter down the tunnel into the occupied Front-End building.

3.2.4.7 Beam Power Limiting System

The BPLS was developed as part of the Proton Power Upgrade (PPU) project to ensure that delivered beam power to the target does not exceed the power limitations of the ASE. Its inclusion as a subsystem of the PPS minimizes the potential for adverse effects on facility operation by using existing infrastructure where possible and only implementing new functionality when necessary. The BPLS design is consistent with the design approach for the PPS described in Section 3.2.4.2, including a two-chain architecture with redundant components where appropriate and a fail-safe design.

The BPLS supports the safety function “Shut off beam before the delivered beam power to the target exceeds the beam power limit defined in the SNS ASE.” There are two major components to this process, measurement of beam parameters to determine delivered power and the calculation of integral delivered power over time.

Two types of sensors are deployed to measure beam parameters, fast current transformers (FCTs) and DC current transformers. Two FCTs are installed in the beam tube in the RTBT segment to measure beam current. Accurate interpretation of the FCT signal is what led to the need for FPGA architecture. The DC current transformers measure the current being supplied to the RTBT.DH13 bending magnet, which can be directly correlated to beam energy through a proportionality. To successfully deliver the beam to the target, the field strength of the magnet (determined by the current) must closely match the actual beam energy. Thus, if the two are unmatched, the beam will be lost in or shortly after the dipole magnet. This allows the simple measurement of DC current supplied to the magnet to be used to directly infer the beam energy. Because the DC magnet current is stable and changes slowly, the DC current transformers are connected to the BPLS PLC via analog I/O modules. The BPLS PLC then combines the beam-energy values and the power threshold values to produce a charge threshold, which is sent to the DPU for comparison against the integrated charge measured by the FCT.

The DPU performs the fast processing functions required to integrate beam current. The DPU receives data from the FCTs via an analog front end and analog-to-digital converter. This digital signal is evaluated using a moving window integrator that identifies individual pulses and integrates the charge within a window surrounding the charge (e.g., a 5 μs window around a 700 ns pulse). The DPU is designed to use information from the timing system to aid in identifying pulses but can perform its function without timing information. The integrated charge from pulses is combined using a rolling summation which is then compared to the charge threshold provided by the BPLS PLC. If the summed charge exceeds the charge threshold, the DPU issues a trip signal to the BPLS PLC. The BPLS PLC sends a trip request to the RTBT PLC, and the trip request then passes through the normal pathways to the linac segment where the front-end critical devices are tripped.

3.2.4.8 Auxiliary Safety Assurance Features

Warning Lights and Horns

Various types of warning devices are used to alert workers before hazardous operations commence inside the accelerator tunnels. Warning lights are installed at each entry point to the exclusion area of an accelerator tunnel (personnel, emergency exit, or equipment door). These lights are on any time hazardous operations are permitted inside the tunnel. Each beam shutdown station inside the tunnel, equipment room, or instrument enclosure has a warning light and horn to alert workers inside the area before hazardous operations are allowed. Accelerator tunnel lighting is automatically dimmed before hazardous operations.

Beam Shutdown Stations

Beam shutdown stations are located throughout the accelerator tunnels and inside PPS-interlocked radiation areas such as vaults and instrument enclosures. These devices perform multiple functions:

- Inform workers of the status of the segment associated with the accelerator tunnel
- Provide an emergency stop capability
- Provide a visual and audible warning before permitting hazardous operations
- Support the search function

Stations located in tunnels are installed so that they are visible to workers in the normal personnel walkway from anywhere in the tunnel. A person located anywhere in the tunnel, walking at a normal pace, can reach a beam shutdown station within 30 s. A minimum 60 s delay between the time that an operator requests power permit or beam permit mode and the time when the PPS-controlled equipment is enabled allows workers in the tunnel sufficient time to exit the tunnel or press the emergency stop button on the nearest beam shutdown station.

PPS Control of RF Sources

The PPS controls additional devices associated with the accelerator to protect workers from non-beam–related x-rays that could be generated by RF during access to the tunnel. Although PPS control of these devices is beneficial to worker safety, they are not credited because the x-rays are not associated with accelerated beam and are at a lower level of radiation than that associated with the accelerated beam.

RF Supplies for Accelerating Cavities

The PPS shuts off the RF supplies for the normal and superconducting cavities in the linac whenever access is allowed to the linac or HEBT segments or when there has been an access violation in either segment. These RF supplies are controlled in the same manner as the RF to the RFQ (Section 3.2.4.4). Each channel of the PPS controls the 2,100 V power supply to the HVCM and the power to each RF amplifier.

RF Supplies for the MEBT Rebuncher Cavities

The PPS also controls the RF to the MEBT rebuncher cavities because these cavities can create ionizing radiation in occupied areas. An interlocked area radiation monitor is located near the MEBT rebuncher cavities at the front end. Excessive radiation from these cavities shuts off the MEBT RF source, the −65 kV power supply, and the RF source to the RFQ. The RF source to the RFQ is controlled to prevent beam production (Section 3.2.4.4).

The PPS controls the AC power to the MEBT RF drive amplifiers using interposing relays in the supply. When the PPS removes power from the power relays, AC power is removed from the RF drive amplifier, stopping RF production.

Gamma Blockers

Components inside the injection dump and the target become activated during normal operation. Gamma radiation from these activated components can shine back down the flight tube when the accelerator is shut down. To minimize gamma dose rates for workers in the applicable tunnel segments, gamma blockers have been installed as an ALARA measure in the vacuum pipe near the injection dump in the ring tunnel and at the end of the RTBT.

Each gamma blocker consists of a vacuum chamber containing a metal cylinder that is rolled in and out of the beam path via pneumatic cylinders. These actuators are controlled by the PPS. When the tunnel is accessible, the respective gamma blocker is rolled into the beam path. When personnel are excluded from the tunnel, the PPS rolls the gamma blocker out of the way, allowing beam operation. The design of the gamma blocker results in a “fail-as-is” design. Upon loss of air or power, the gamma blocker remains in the last position.

The inserted and retracted position of the gamma blocker is monitored by the PPS and MPS using redundant position switches. If the gamma blocker should remain in the beam path when commanded to open, then the MPS and PPS would both prevent beam operation. If the gamma blocker fails to close when the tunnel is accessible, then the PPS requires operator intervention to open the PPS access doors to the tunnel (personnel cannot enter via the badge reader–only mode). The position of each gamma blocker is indicated in the central control room via status lights and on the EPICS displays.

3.2.5 Oxygen Deficiency Hazard System

The ODH analysis presented in Section 4.3.4 determined the need for a credited ODH system to warn workers to evacuate (or not to enter) the CHL and linac/HEBT should hazardous oxygen levels be present. The analysis further determined the need to credit the ODH system for initiating the EVS to confine a cryogenic release within the linac tunnel area, as described in Section 3.2.6.

The ODH system detectors continuously monitor the oxygen levels and initiate alarms whenever the detected oxygen level drops to 19.5% or less. The oxygen sensors are connected to electronic transmitters that provide digital and analog outputs to a PLC-based system. Separate ODH systems are installed in the CHL and linac/HEBT tunnel as described below.

Other non-credited ODH monitoring systems and alarms may be installed at various locations across the SNS site as needed to provide protection against oxygen deficiency consistent with ORNL-wide SBMS requirements (e.g., the RFTF) for standard industrial hazards.

CHL ODH System. The CHL is divided into three zones: the warm compressor room, the cold box area, and the CHL control room. The ODH system monitors the oxygen level in each zone and can independently provide audible and visual evacuation alarms in each zone. Oxygen sensors are installed in each zone and tied to a central system installed in the CHL control room. Warning beacons are installed at each entry door to the CHL to alert personnel of an ODH condition before they enter the building. An alert is provided in the CHL control room when the oxygen levels are abnormal (either high or low). A graphical display is provided in the CHL control room to indicate the oxygen levels at each detector location and the status of each zone (normal, alert or evacuation). The ODH system monitors fault signals from the oxygen transmitters and alerts the CHL operator if a fault condition is detected. The oxygen levels are recorded by the main archiver.

The cold box area has multiple sensors sampling elevated locations to detect helium leaks and near the equipment floor to detect nitrogen leaks and cryogenic helium releases. The ODH system provides audible and visual alarms upon detection of low oxygen levels to warn individuals inside the cold box room to evacuate. Warning beacons are installed at each entry door to the cold box room to alert personnel seeking entry. ODH systems are installed in the CHL cold box area (one system at each entry door to the cold box area) which function independently from the ODH system PLC logic to provide a measure of redundancy. These stand-alone systems consist of an oxygen sensor/transmitter, warning beacon, and electronic horn. The output of oxygen transmitters is fed to the main ODH system and activates the main system's warning lights and horns if oxygen levels of 19.5% or less are detected.

As described in Section 3.2.1.5, the CHL cold box room is equipped with ceiling ventilation fans. A non-credited function of the ODH system is to provide a signal to start the ceiling fans upon detection of low oxygen levels.

In the warm compressor room, oxygen sensors are placed in an elevated location to detect warm gaseous helium leaks. The ODH system provides audible and visual alarms upon detection of low oxygen levels to warn individuals inside the warm compressor room to evacuate. Warning beacons are installed at each entry door to the warm compressor room to alert personnel seeking entry. Flashing lights and warning horns are installed in the warm compressor room and cold box section of the CHL to warn personnel of low oxygen levels; flashing lights are also installed at each entry point to the CHL.

Linac ODH System. The linac ODH system monitors oxygen levels via oxygen sensors mounted on the ceiling of the SCL section of the tunnel and tunnel sections directly adjacent to the SCL. Flashing lights and warning horns are installed in the linac and HEBT tunnels to warn personnel of low oxygen levels; flashing lights are also installed at each entry point into the SCL section of the linac tunnel. Warning lights are provided at the entrance to the HEBT. The linac ODH system initiates the EVS (Sections 3.2.6 and 5.2.3), which exhausts accidentally released helium directly from the linac to the outdoor air, protecting workers by confining the helium release to the linac. Cryogenic helium is supplied to the cryomodules via transfer lines running the length of the SCL. Each cryomodule maintains an inventory of liquid helium during operation. The ODH system protects workers from a leak of gaseous helium from the transfer lines or the release of the liquid inventory inside a cryomodule.

An alert is provided in the central control room when the oxygen levels are abnormal (either high or low). These alert alarms are adjustable. A graphical display is provided in the central control room to indicate the oxygen levels at each detector location and the status of the tunnel (normal, alert, or evacuation). The ODH system monitors fault signals from the oxygen transmitters and alerts the operator if a fault condition is detected. The oxygen levels are recorded by the main and backup archivers. The area is treated as a single zone by the ODH system. Warning lights and horns are installed throughout the length of the linac tunnel, the north linac fire escape tunnel, and the HEBT tunnel. Warning beacons are installed at each possible entrance to the SCL to alert personnel of an ODH condition before they enter the linac tunnel. The linac ODH system actuates regardless of the beam-on or beam-off status.

3.2.6 Emergency Ventilation System

The EVS is a portion of the tunnel ventilation system originally intended to provide smoke removal capability in the case of a fire in the linac tunnel. These components are designated to perform the safety function to prevent an ODH in the linac tunnel from propagating into adjacent areas such as the Front-End building. This is accomplished by operating exhaust fans mounted to the ceiling of the SCL portion of the linac tunnel to draw fresh air into the linac tunnel and exhaust the oxygen-deficient atmosphere. An ODH analysis presented in Section 4.3.4 determined the need to designate the EVS system as a CEC.

The EVS consists of two grade-mounted exhaust blowers located atop the linac berm, ductwork connecting these blowers to the SCL portion of the linac tunnel, dampers that normally isolate the tunnel atmosphere, and associated infrastructure and instrumentation. The linac ODH system automatically initiates EVS operation based upon indications of oxygen deficiency in the linac tunnel. When the EVS initiates, a damper in the entrance labyrinth between the front end and linac opens to admit air directly from the outdoors into the linac tunnel. Dampers at the inlet to the two blowers also open and the blowers start, exhausting the atmosphere from the linac tunnel and drawing fresh air into the tunnel from the damper near the front end.

The ducts of the EVS have bubble-tight dampers that remain closed when the tunnel is closed for normal beam operation. The dampers are automatically opened when the tunnel is accessible (i.e., not in beam-permit mode). The EVS is automatically actuated by the ODH system, but operation for smoke removal associated with a fire would be initiated manually. Operation of the EVS causes ventilation units in the linac tunnel to shut down.

Each of the EVS blowers is rated at 10,000 cfm. Passive partial barriers, 2.5 ft deep lintels projecting downward from the ceiling at each end of the SCL, help channel the relatively buoyant helium from an inadvertent release into the EVS ceiling louvers that lead to the EVS.

3.2.7 General Description of Structures

Unless otherwise noted, buildings at or above grade are steel frame structures. The exterior skins of the above-grade buildings are made of insulated metal panels consistent with the overall site design. The roofs are made of composite built-up roofing. Personnel access doors are provided as required by code. Air conditioning is typically provided by central air-handling units using water from the chilled water system and the hot water heating system. Support buildings and other facilities with no significant potential for airborne contamination typically run at a slight positive pressure or a neutral pressure. Facilities with potential for airborne contamination (e.g., injection beam dump vault) are maintained at a slight negative pressure with respect to ambient.

3.2.7.1 Building 8100—Front-End Building

The Front-End building houses the accelerator ion source, RFQ, LEBT line, MEBT line, ion source test stand(s), first 30 ft of the DTL, and related support equipment. The first 30 ft of the DTL is behind the shield wall that separates the linac tunnel from the Front-End building. The ground floor elevation is at the same level as the linac tunnel with the beam centerline elevation at 50 in. above the floor. There is a mezzanine level in the Front-End building. The HVAC units for the building are housed in the mezzanine. The building HVAC normally runs continuously to circulate air throughout the building (~19,000 cfm) with a small amount (~800 cfm) of fresh air intake.[1] Circulating air is pulled into the mezzanine level through a floor grate and exhausted throughout the building. The approximate free volume of the Front-End building main level is estimated at approximately 192,605 ft^3, and the mezzanine area is estimated at approximately 36,762 ft^3.

Personnel access to the linac tunnel from the Front-End building is normally controlled via a series of two doors in the labyrinth that separates the two spaces. As with all tunnel access points, this entrance is PPS controlled and interlocked (Section 3.2.4.5). Access is also possible through a PPS-interlocked large equipment shield door that is opened as needed during maintenance periods to allow passage of large equipment items. The building has two independent chilled water systems for the RFQ. The following systems support operation of the Front-End building: DTL DI water, compressed air, chilled water, building heating water, potable water, sanitary waste, and process waste.

Radiation hazards in the Front-End building are addressed in Section 4.2.1.

3.2.7.2 Building 8300—Klystron Gallery

The Klystron Gallery houses the power supplies, cooling systems, and controls supporting the linac. It is 18 ft 10 in. from the linac tunnel (interior wall to interior wall) and parallel to it. The rear (north) wall is designed as a concrete retaining wall to support the earth shielding that surrounds the linac tunnel. The building has an interior clear height of approximately 26 ft. Utility chases for routing mechanical system piping, electrical cabling, and RF wave guides are provided between the Klystron Gallery and linac tunnel. The penetrations are mostly sealed for fire protection purposes. The Klystron Gallery floor elevation is 9 ft above the floor elevation of the Front-End building and linac tunnel.

Air conditioning is provided throughout the building except for the DI water equipment rooms. The building was originally provided with four DI water systems, a glycol water system that supports the RF equipment in the gallery, and 11 smaller DI systems for cooling linac equipment in the tunnel. Additional utilities are being added as necessary to support equipment installed to support the PPU project. It is

[1] *SNS FELK Air Balance Report*, SNS 108030100-VS0027-R00.

serviced by the following systems: tower water, chilled water, compressed air, potable water, sanitary waste, and process waste.

3.2.7.3 Building 8200—Accelerator Tunnels

Unless otherwise noted, the below-grade tunnels are constructed of reinforced concrete. Tunnel floors are flat and have a gutter along the aisle way wall to help clean up any water leakage from beamline equipment. Necessary utilities and other equipment are routed overhead or along the wall. Consistent with the need to prevent worker access to the tunnel during beam operation, the entrance ways are controlled and/or monitored by the PPS (Section 3.2.4).

Shielding for the tunnels and access passageways is provided by an earthen berm. The berm is nominally 17 ft thick around the tunnels and, when combined with the concrete walls and roofs of the tunnels, is sufficient to protect the surrounding buildings and their occupants. The berm is vegetated with grasses to prevent erosion without requiring frequent cutting. A waterproof membrane is provided over the tunnels to further mitigate water intrusion from the earth shielding. A system of perforated drain line is provided along the tunnel foundation on the klystron side to allow monitoring of water that does exit the berm. A typical cross section of the linac tunnel showing the berm, the membrane, and the groundwater interceptor drain is shown in Figure 3.23. This membrane runs along the linac, HEBT, ring, and RTBT tunnel segments, as well as out to the beam dumps (i.e., above the proton beam tubes that extend to the dumps).

Air conditioning in the linac tunnel is provided by four ceiling-mounted air-conditioning units positioned at intervals along the length of the tunnel. These units provide local air recirculation. Air conditioning in the HEBT, ring, and RTBT tunnels is provided by two surface HVAC units with supply distribution ducts in the tunnel and common wall returns in the injection and extraction areas of the ring. Cooling is accomplished using water from the chilled water system. Heat is provided by duct-mounted electric coils in the linac and by the building hot water system for the ring units. A separate exhaust that uses grade-mounted exhaust fans also exhausts the tunnel. The exhaust system was originally designed to facilitate the removal of smoke in response to a fire. Portions of the exhaust system function as the EVS, as described in Section 3.2.6.

Tunnel ventilation is described in Section 3.2.8.2. During normal accelerator operation with beam, the tunnel is not occupied, and bulk supply and exhaust flows are not provided. Positive ventilation (including fresh air intake) may be provided any time workers are present in the tunnel. The Front-End, Klystron, and ring service buildings have connection paths to the tunnel. Penetrations between the tunnel and service buildings (e.g., HEBT service building, ring service building, RTBT service building) are provided to route utilities. The penetrations are largely sealed for fire protection purposes, impeding potential tunnel air leakage into these areas. Air in the potentially occupied spaces connected to the tunnel is periodically monitored to ensure that radioactive air does not exceed allowable levels where workers may be present or contribute unnecessarily to worker exposure.

Potable water is not supplied to the tunnel. Cooling water supplied to the tunnel may become activated by normal beam loss. Design features are provided to prevent this water from cross-contaminating nonradioactive streams and to ensure its proper routing for disposal. Closed-loop piping with higher pressure on the nonradioactive side of the heat exchanger is the typical design approach. HVAC condensate from the tunnel is potentially activated, so it is collected for sampling and disposal. Its disposal is based on water quality measurements according to the ORNL SBMS (Section 3.2.8.4).

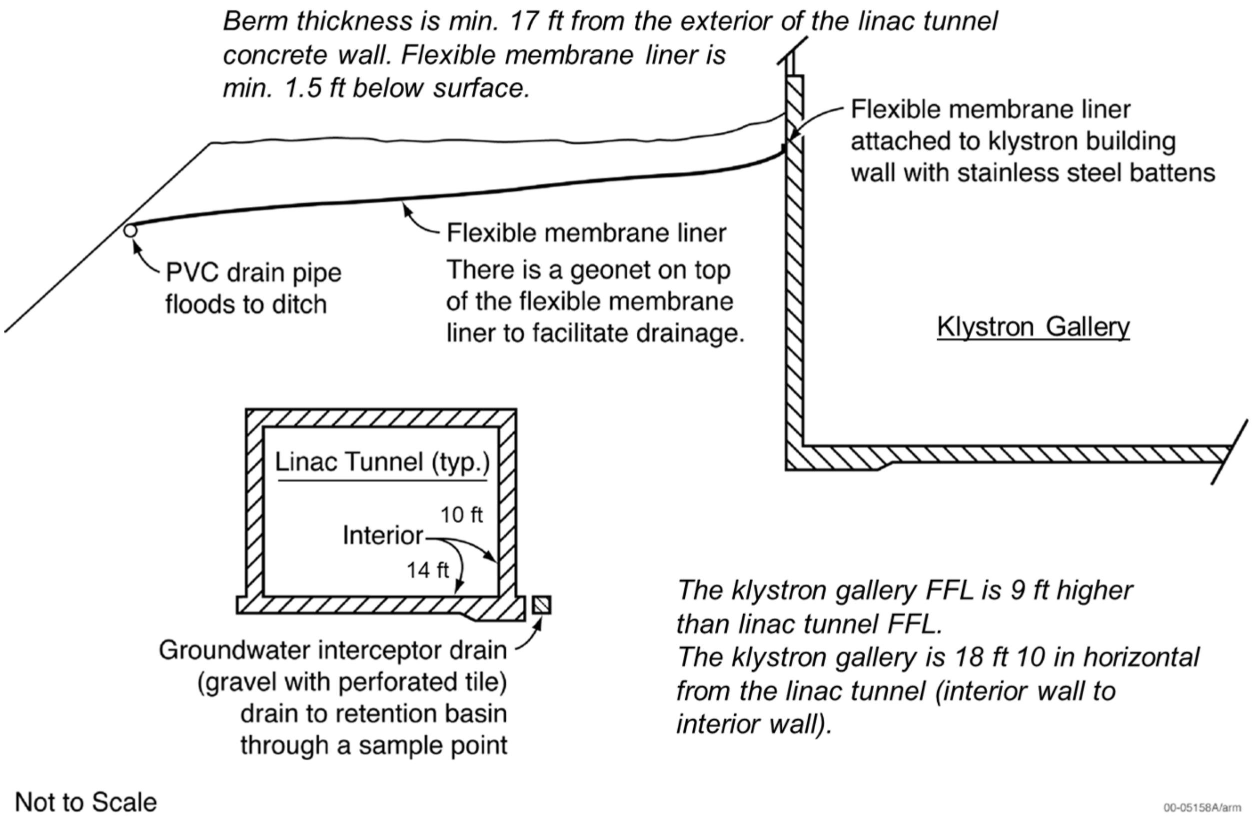

Figure 3.23. Typical berm cross section.

Building 8200—Linac Tunnel

The linac tunnel houses the majority of the linac components. These components consist of the DTL, the CCL, and the SCL (low- and high-beta cryomodules). The tunnel floor elevation is the same as in the Front-End building. The linac tunnel is approximately 10 ft high and 14 ft wide, as shown in Figures 3.6 through 3.8.

Access to the tunnel for personnel and heavy equipment is through the Front-End building on the west and through a large equipment plug and nearby personnel door located to the east of the HEBT service building. The tunnel is serviced by the chilled water system, the compressed air system, and the process waste system. Structures and magnets in the linac tunnel are cooled by gallery-mounted closed-loop DI water systems that are, in turn, cooled by chilled water. The cryogenic section of the tunnel has design features to facilitate helium venting in response to an ODH evacuation alarm (Section 3.2.5). This function is provided by automatic initiation of the EVS fans upon detection of low oxygen. Lintels are placed across the top 2.5 ft of the tunnel near either end of the superconducting section to channel helium releases to the EVS ceiling vents and minimize propagation to the non-superconducting areas of the tunnel (Section 3.2.6).

Building 8200—High-Energy Beam Transport Tunnel

The HEBT tunnel houses the HEBT equipment, including the proton beam tube, magnets, and collimators, used to transport the proton beam from the linac to either the ring or the linac dump. Included in the equipment is an overhead crane to be used throughout the ring tunnels to maintain and remove equipment. The crane has remote controls to minimize exposure to the workers.

Access to the tunnel is through the linac tunnel, the ring tunnel, a large equipment plug door, and personnel access ways. A stacked shield wall separates the ring from the HEBT. The shield wall is equipped with a personnel door and a set of dampers located above the personnel door. The HEBT tunnel is approximately 17 ft wide by 13 ft tall (Figure 3.9). The tunnel is serviced by the instrument air system, the magnet DI water loop, two collimator cooling loops, and the process waste system.

A shielding labyrinth equipped with a personnel door serves as a partition between the HEBT and the Ring tunnels.

Building 8200—Ring Tunnel

The ring tunnel (Figures 3.10 and 3.11) houses the ring injection dump beamline, proton beam tube, magnets, RF cavities, and collimators. The ring accumulates beam pulses received from the linac via the HEBT, bunches them into intense short pulses, and delivers them to the target by way of the RTBT tunnel. The required beam height is approximately 50 in. above the floor. Included in the equipment are two overhead cranes to be used throughout the tunnel to maintain and remove equipment. The cranes have remote controls to minimize exposure to the workers.

Access to the ring tunnel is through the HEBT tunnel, the RTBT tunnel, and the south personnel access way. The tunnel is serviced by the chilled water system, the instrument air system, magnet DI water loop, collimator cooling water system, RF cooling loops, and process waste system.

Building 8200—Ring-to-Target Beam Transport Tunnel and Stub

The RTBT tunnel houses the beam tube, magnets, and collimators that transport the short proton bursts from the ring to the target or to the ring extraction dump. The required beam height is approximately 41 in. above the floor. Included in the equipment is an overhead crane to be used throughout the tunnel to maintain and remove equipment. The crane has remote controls to minimize exposure to the workers. RTBT facilities are illustrated in Figure 3.24.

Access to this section of the tunnel is through the ring tunnel and a large equipment plug door and personnel access way. The tunnel is serviced by the instrument air system, magnet DI cooling system, and collimator cooling loops.

As part of the PPU project, an additional section of tunnel is being added that will ultimately provide the connection between the existing accelerator facility and the anticipated Second Target Station. This portion of tunnel is referred to as the RTBT stub. It connects at the corner the RTBT beam tunnel and the truck tunnel. While awaiting equipment installation as a part of the future Second Target Station project, a stacked shield wall will be installed in the RTBT stub, completely separating the beam tunnel from the exterior access door at the end of the RTBT stub. The space accessible from the exterior is provided with HVAC and lighting. Access to the opposite side of the shield wall is provided from the RTBT tunnel interior by a personnel door installed in the tunnel wall.

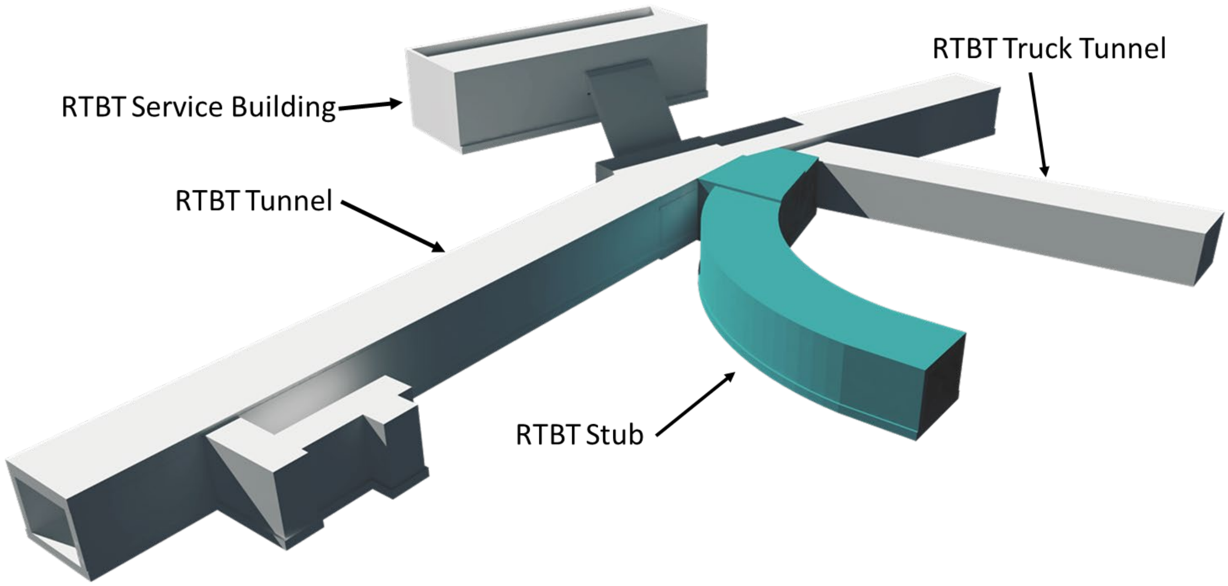

Figure 3.24. RTBT facilities.

3.2.7.4 Building 8310—Central Helium Liquefier Facility

The CHL facility is located across the street from the Klystron Gallery immediately adjacent to the RFTF on the west side. Its intended use is to provide superfluid helium for use in the SCL cryogenic systems (details are provided in Section 3.2.1.5).

The building has its own helium and nitrogen systems and is serviced by the following systems: DI water, compressed air, potable water, sanitary waste, and process waste.

3.2.7.5 Building 8320—RF Annex and Beam Test Facility

The RF Annex, Building 8320, was added to the RFTF, Building 8330. It houses RF equipment, the RF Annex modulator, and the BTF. The RF Annex modulator can be configured to provide RF power to the BTF, RF test stand, or RF test cave (discussion in Section 3.2.1.5).

The BTF, housed in Building 8320, contains equipment similar to the front-end portion of the SNS accelerator, including an ion source, LEBT, RFQ, and MEBT. This equipment, coupled with a high-energy beam stop after the MEBT, was used to test and validate beam parameters for the installed RFQ. The setup is also used to perform accelerator physics experiments. Figure 3.25 provides an overview of the layout of Buildings 8320 and 8330.

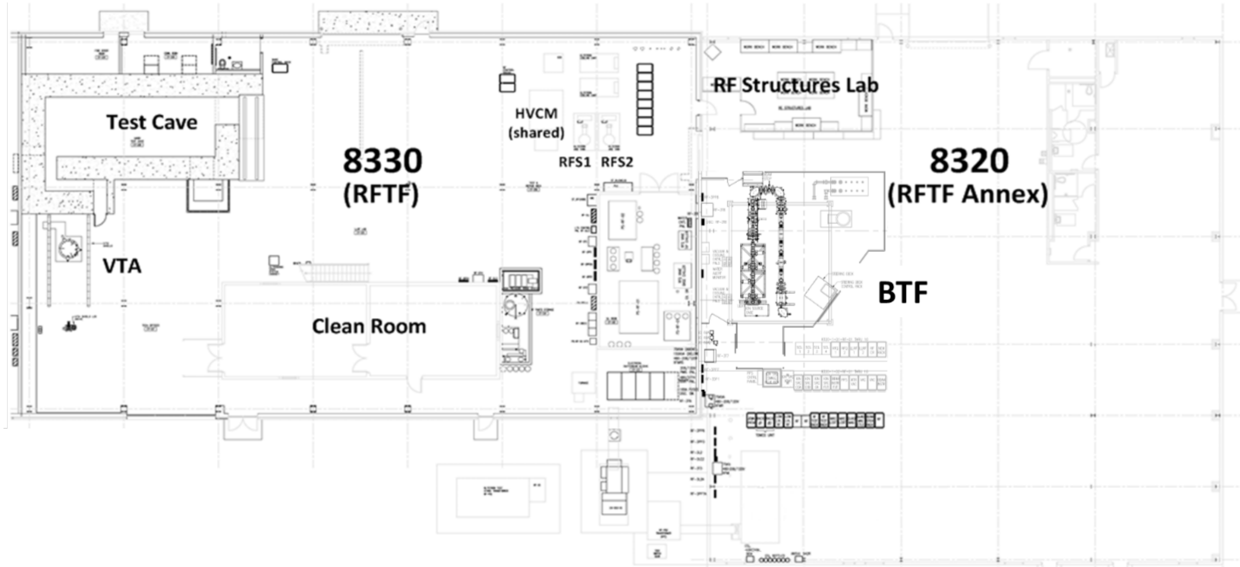

Figure 3.25. Overview of RFTF and BTF.

The BTF has boundaries in place to control and limit access to the area adjacent to the beam accelerating and transporting devices during beam operations. This area is normally posted as a radiation area during operation. An independent safety system is provided to ensure personnel safety using access control and area radiation monitors in a manner similar to the SNS PPS. Depending on its configuration, the BTF may be operated under an exemption from DOE O 420.2C or as an accelerator facility as determined by line management with the concurrence or approval of DOE, as necessary.

3.2.7.6 Building 8330—RF Test Facility

The RFTF is located to the east of the CHL facility. Its intended use is to test 402.5 MHz and 805 MHz klystrons, RF power components, and superconducting accelerating structures, and to repair cryomodules. Major modulator repair can be performed in this area, along with low-level RF testing and development and conditioning of couplers. To accomplish this mission, the building has 805 MHz test areas, a 402.5 MHz test area, an RF test lab, a cleanroom, a cryomodule repair area, a shielded test cave, the VTA, and a cave support equipment area. There is a transition area with a separate entrance where radiation confirmation surveys can be performed on components from the linac tunnel.

Inside the RF building are the high-power RF stations that provide RF power at 402.5 and 805 MHz to all RF test stations, along with a small area to store spare klystrons. RF power at 805 MHz is transported via waveguides to the superconducting cavity shielded test cave or to the VTA. The VTA allows additional testing of superconducting cavities oriented vertically. Liquid helium is provided to the test cave and VTA by transfer lines connected to the CTF helium dewar system in the CHL warm compressor room (Section 3.2.1.5). RF power at 402.5 MHz is also available to test DTL modules in the RFTF. RF power at 402.5 MHz can also be provided to the BTF in the adjacent Building 8320.

The building is serviced by the following systems: DI water, glycol water, tower water, chilled water, building heating water, compressed air, potable water, sanitary waste, and process waste. Liquid helium is supplied from the CHL.

3.2.7.7 Building 8340—HEBT Service Building

The HEBT service building is located east of the Klystron gallery. It houses the power supplies, instrument racks, vacuum racks, and control cabinets for the HEBT technical equipment. The building contains electrical cabinets and the necessary equipment for a DI water cooling system for the power supplies. Air conditioning is provided throughout the building except in the DI water equipment room. The building has a DI water system and is serviced by compressed air, potable water, sanitary waste, and the process waste systems.

The HEBT service building contains a test stand for testing of modulator units. Hazards associated with the modulator test stand are safely managed under the provisions of the ORNL SBMS.

3.2.7.8 Building 8350 – Accelerator Support Office Complex

The Accelerator Support Office Complex provides office space and conference rooms for personnel who support accelerator operations and benefit from proximity to the accelerator facilities and support buildings. The building construction and provided utilities are consistent with commercially available office structures.

3.2.7.9 Building 8520—Ring Injection dump

The ring injection dump houses the beam stop, the shielding vault, and all associated electrical, control, cooling, waste, supply, and heating and ventilation systems in an appropriate, serviceable environment. The ring injection dump service areas are located on grade level, adjacent to the below-grade dump. Design features of the beam dump systems are described in Section 3.2.1.4.

The dumps are below-grade vaults constructed of reinforced cast-in-place concrete surrounding the metal shielding of the dump. The dumps extend approximately 21 ft below finished grade.

The injection dump utility vault, adjacent to the mechanical/electrical rooms, is enclosed with concrete shield walls. The concrete floor is covered with a stainless-steel liner that turns up 8 in. onto the base of the wall. A 5 ft wide overhead service door provides access from the exterior of the dump vault. A deep tank sump with a stainless-steel lining below the utility vault floor level is accessed through a hatch.

Injection dump building heating is provided by units using water from the water heating system. The building is serviced by the tower water, chilled water, compressed air, and potable water systems. The central ventilation system maintains the utility vault and the beam-stop access room under a negative pressure and provides HEPA filtering of the exhaust air from these two rooms.

3.2.7.10 Building 8540—Ring Service Building

The ring service building houses the power supplies (including RF), electrical systems, cooling systems, vacuum control systems, and air systems to serve the ring equipment.

The basement of the ring service building contains the pumping and heat exchange equipment for the three separate cooling systems: HEBT/ring/RTBT magnets, ring RF, and ring service building power supply cooling water systems. The basement walls, floor, and floor/ceiling assembly are concrete.

Air conditioning is provided throughout the building (except for the pulse forming network area and basement) by a roof-mounted air-conditioning unit. The building contains equipment for the DI water system(s) and is serviced by the compressed air, potable water, sanitary waste, and process waste systems.

3.2.7.11 Building 8550—RTBT Service Building

The RTBT service building houses the power supplies, instrument racks, vacuum racks, and control cabinets for the RTBT technical equipment. The building contains electrical cabinets and the necessary equipment for a DI water-cooling system for the power supplies.

Air conditioning is provided throughout the building except for the DI water equipment room. The building contains a DI water system and is serviced by the compressed air system and the process waste system.

3.2.7.12 Building 8600—Central Laboratory and Office Building

The CLO Building is a mixed-use facility providing the office, laboratory, conference, cafeteria, and shop space necessary to operate the SNS facility. The building combines a five-story, curved office “bar” connected to a four-story shop and lab “block.” The CLO Building is adjacent to the Center for Nanophase Materials Sciences, which is not part of the SNS complex.

The main CLO Building entry plaza is on the west side, on Level 1. Other entrances are provided on all sides of Level G. The CLO Building service access, a triple-bay truck dock, is located on Level G at the north side of the shop and lab block. A freight elevator links the dock area with the three lab floors and mechanical penthouse.

The accelerator control room located on Level 1 has direct access to a small service vehicle parking area. The control room features a mezzanine overlook at Level 2 for public tour viewing. User offices are located along the perimeter for access to the target building. All heavy-duty technical support shops and the material handling area—which require truck access, forklift use, and a minimum ceiling height of 12 ft—are located on Level G, the ground floor, of the shop and lab portion of the building. Other building service spaces requiring ground-level access, such as the plant shop, are located on Level B1. The sub-basement, Level SB, provides space for electrical, mechanical, and telecommunications functions.

The large technical support labs are located primarily above the shops on Level 1. The CLO Building labs on Level 1 conduct small-scale measurements, analyses, and studies in support of accelerator operation and development. For example, the foil research facility includes equipment such as the foil evaluation diagnostic scanner. Labs located on Level 2 are devoted to measurements, analyses, and studies that support SNS development and science activities. For example, the x-ray lab is one of the labs located on the second floor. The activities conducted in the CLO Building labs are authorized through the RSS system and are compliant with applicable ORNL SBMS safety requirements.

3.2.7.13 Building 8700—Target Building

The target building and activities conducted in it and its connected satellite buildings and ancillary support buildings are described in the FSAD-NF.[3-1]

3.2.7.14 Activated Equipment Maintenance Shop

An activated equipment shop (hot shop) has been envisioned for eventual inclusion in the SNS facilities. Possible features may include facilities for handling/maintaining radiologically activated accelerator equipment and instrument choppers, and a target equipment shop, including a waste staging area. The types of facilities could include a machine shop, a vacuum shop, an instrument repair shop, a magnet repair area, a negative air hood area, a storage area, and a receiving/packaging area. The building would be serviced by the compressed air system, the potable water system, the sanitary waste system, and the process waste system. Portions of the building would be maintained at a slight negative pressure relative to ambient if warranted by a potential for airborne contamination.

3.2.7.15 Building 8910—Central Utilities Building

The CUB houses the chilled water system, the tower water pumps, and the compressed air system serving the site. The building also has a boiler room containing two gas-fired, water tube boilers that provide hot water for heating the following buildings: 8910, Front-End, Klystron, RFTF, CHL, HEBT, ring and RTBT service, ring HVAC, ring injection dump, and target.

The building has a multiple-zone refrigerant monitor to detect refrigerant leakage from the chillers, with at least one zone per monitor or refrigerant storage vessel. The monitor has audible and visible alarms both inside and outside the building. The building also has an automatic refrigerant spill exhaust system designed with opposing intake(s) and exhaust outlet(s) to sweep air across the potential spill zone at floor level. The monitor automatically initiates operation of the refrigerant spill exhaust system and simultaneously deactivates other ventilation equipment in the event of a refrigerant spill. Hazards associated with the refrigerant are standard industrial-type hazards and are safely managed under the provisions of the ORNL SBMS.

Air conditioning is provided in the offices and restrooms. The building is serviced by the potable water system and the sanitary waste system. Power is supplied from the site 13.8 kV distribution system, including transformers that provide 4.16 kV to the chillers and 480 Vac to the motor control centers.

3.2.7.16 Building 8920—Receiving, Acceptance, Testing, and Storage II

Receiving, Acceptance, Testing and Storage II, located west of the Front-End building, provides warehouse-type storage for various materials, including activated components. It also serves as a central shipping and receiving facility for the Chestnut Ridge complex. Radiological hazards associated with this building are safely managed under SBMS.

3.2.7.17 Building 8930—Chestnut Ridge Maintenance Shop

The Chestnut Ridge Maintenance Shop, located southwest of the target building, houses workspace and tools to support the repair and maintenance of SNS components. It also contains office spaces.

3.2.7.18 In-Process Storage of Activated Components

On-site areas are used, as needed and as authorized by management, for storage of accelerator-related activated components and equipment items. For example, designated Sea-Land trailers, a fenced area, and a concrete pad to the west of the Front-End building have been designated as areas for storage of bulk accelerator-related activated/contaminated items that do not require indoor storage. Indoor storage of activated components is provided by the RATS-II building. Precautions and procedures commensurate with potential hazard are in place, in keeping with ORNL SBMS radiological safety requirements. For example, administrative control and surveillance is maintained, the objects are properly labeled, and the areas are properly posted.

3.2.8 Services and Utilities

Services and utilities include (1) electrical site services, (2) tunnel exhaust systems, (3) mechanical/piping utility systems, (4) waste systems, (5) maintenance and general-purpose equipment, (6) fire protection system, and (7) conventional facilities instrumentation system.

3.2.8.1 Electrical Site Services

The electrical site services network has a nominal 50 MW capacity and includes (1) the SNS primary substation, (2) the site electrical distribution system, (3) the telecommunications/alarm systems, and (4) the miscellaneous electrical utility systems.

SNS Primary Substation

The SNS primary substation receives electrical power from two off-site 161 kV supply sources via the primary plant service transformers and supplies 13.8 kV for on-site distribution. The substation has a SCADA subsystem that provides the capability of remote monitoring and control. It also has overhead passive lightning protection equipment for the primary substation and provides lightning and surge protection at the 161 kV level.

Site Electrical Distribution System

The site electrical distribution system routes electrical power via underground feeders from the SNS primary substation to the various facilities that constitute SNS. It is divided into A and B systems to provide a degree of isolation between the large RF power supply loads and other loads. The system provides protective relaying and equipment to minimize equipment damage by isolating faults and is designed and coordinated so that an electrical fault is isolated by the source-side circuit protective device nearest the fault. The site electrical distribution system follows National Electrical Code criteria by using methods such as ensuring that conduits containing instrumentation, communication, and alarm circuits are isolated from conduits containing power circuits (i.e., circuits 120 V and higher). The site electrical distribution system includes the SNS site-grounding mat, which is buried beneath buildings.

Telecommunications/Fire Alarm System

The telecommunications system provides high-speed data communications systems, interplant data and voice communications, and the SCADA system to the various facilities that constitute SNS. The system terminates off-site telecommunications and alarm services at a site main distribution frame and provides at least two redundant means of communication between SNS and other ORNL facilities during normal and emergency plant operation. The system is integrated with the Oak Ridge Federal-Integrated Communications network, the ORNL intraplant fiber-optic network, the ORNL portable radio system, and various other ORNL communication services (e.g., fire alarm, security).

The SNS site fire alarm system is a protected premises fire alarm system that provides alarm, supervision, and monitoring functions for fire protection, fire detection, and manual alarms to the SNS site and at a constantly monitored alarm station. The system consists of EST 3 fire alarm control panels (FACPs) located in key facilities, which are connected via the EST FireWorks system to report alarms to the fire department at Building 7130 and to the Laboratory Shift Superintendent (LSS) in Building 4512. A remote FireWorks Client monitor has been provided in the SNS CCR to allow CCR personnel to observe all alarms initiated on the Chestnut Ridge site. The accelerator facilities are served by three EST 3 FACPs located at the Front-End building riser room, CHL/RF riser room, and ring service building riser room. They function to receive alarm, supervisory, and monitoring information and annunciate or interface with other systems as needed.

Miscellaneous Electrical Utility Systems

Miscellaneous electrical utility systems include the cathodic protection system and exterior area lighting. Exterior area lighting provides exterior lighting systems with sufficient illumination to accomplish operations and maintenance functions under normal operating conditions and provides areas requiring continuous lighting for safety or security reasons with an emergency power source for such lighting.

3.2.8.2 Tunnel Exhaust Systems

The accelerator tunnels were designed so that they could be exhausted through the central exhaust stack or by local exhaust fans. Exhaust via the central exhaust stack is one portion of the Central Exhaust System. The local exhaust fans were originally included to serve as smoke removal fans, as discussed below. Certain features of the smoke removal system are incorporated into the EVS, as described in Section 3.2.6.

Central Exhaust System

The central exhaust facility, Building 8915, is the outdoor area containing the blowers that discharge to the central exhaust stack. The central exhaust facility is illustrated in Figure 3.26. Confinement exhaust systems located remotely from buildings and tying into the centralized exhaust stack include the tunnel exhaust system, confinement exhaust systems from the target building, and injection dump building exhaust. The centralized exhaust stack is a prefabricated, free standing, all welded, steel construction with ladder and platform to provide access to isokinetic monitoring equipment, mounted a minimum of five diameters above any duct connection. The platform is wide enough to provide room for personnel and adequate clearance for maintenance of monitoring equipment. The stack is sized to handle the maximum simultaneous exhaust airflow from the tunnel, injection dump building, and target hot off-gas and target building primary and secondary confinement systems up to a maximum discharge velocity of 4,000 ft/min. The stack is 80 ft tall and is located to minimize the length of duct runs and the number of runs that traverse the berm.

The tunnel exhaust system conveys tunnel exhaust air underground to the central exhaust stack. The system is intended to function only after the beam has been cut off, but it is generally not employed for short outages. Measurements of airborne radioactivity in the tunnel air have indicated that tunnel exhaust is not required for radiological protection of workers entering the tunnel when the beam is off. During beam operation, the makeup and exhaust ducts, as well as the smoke removal ducts, are closed off from the tunnel by isolation dampers. This prevents the discharge of potentially activated tunnel air during beam operation. The air within the tunnel is maintained under temperature and humidity control by local heating and cooling units inside the tunnel that utilize local recirculation and do not involve discharge of air outside the tunnel. The tunnel exhaust fans are located near the central exhaust stack. Exhaust fans and makeup air units are sized to ventilate the tunnel complex at a flow rate that provides acceptable air quality (nominal exhaust capacity is about one air-change per hour).

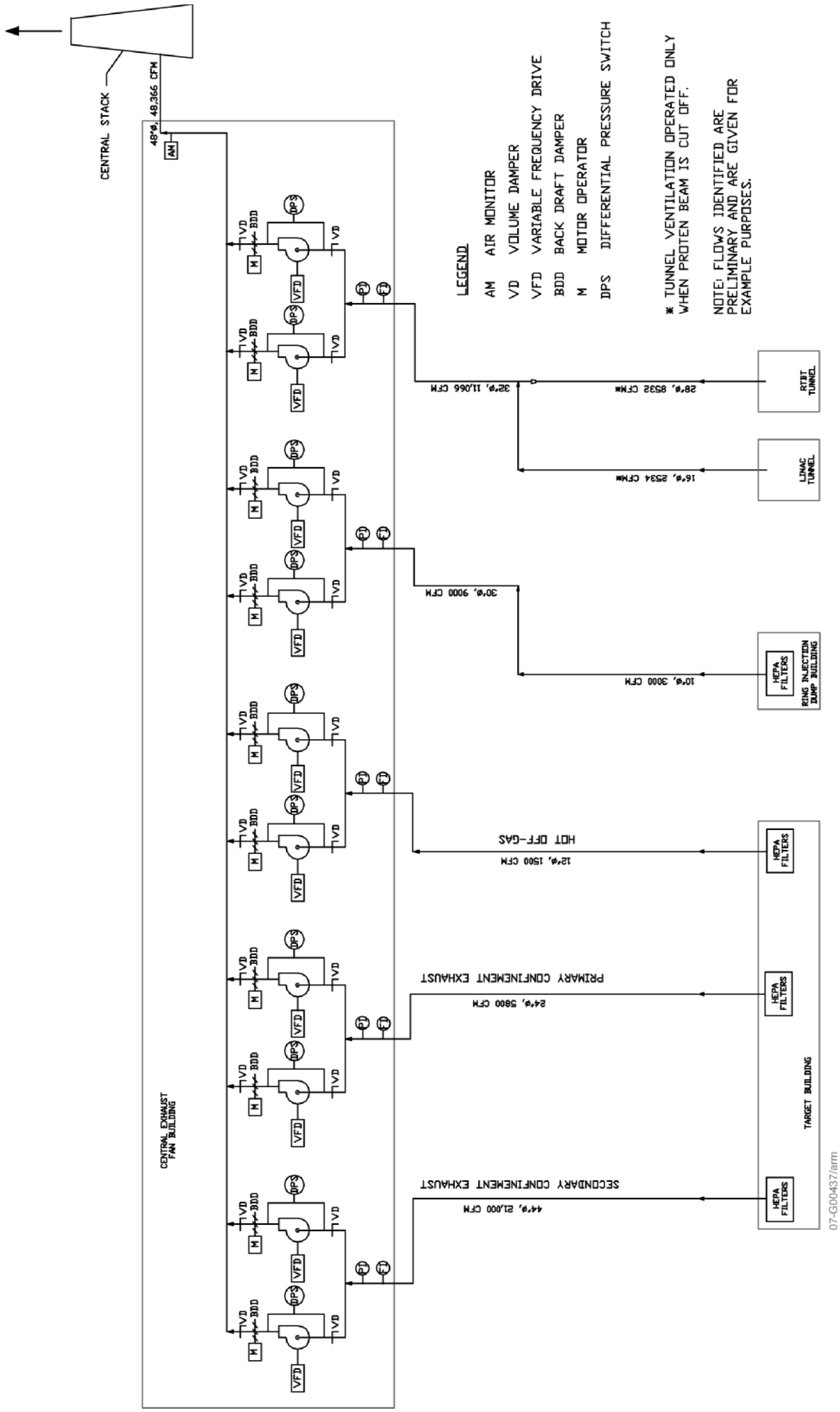

Figure 3.26. Schematic diagram of the central exhaust facility.

The exhaust duct connections to the tunnel complex are coordinated with the location of makeup air inlets to affect a sweep of air through the tunnel progressing from the area of least radioactive activation (the Front-End building has no activation) toward the area of greatest potential activation (high-energy end of the linac, ring, and transport tunnels). The number of exhaust and supply connections to the tunnel were minimized because of the requirement for shielding at each penetration—each connection incorporates at least two 90º changes of direction near the tunnel to minimize radiation streaming. The effect of intermediate shield walls on airflow in tunnels was taken into account in the determination of the number of exhaust and makeup points necessary for complete coverage of the tunnel.

The exhaust systems from the target and injection dump buildings convey exhaust air from the injection dump and target building confinement systems via underground ducting to the central exhaust stack. The injection dump building has its own confinement exhaust. The target building confinement systems that vent to this system are the hot off-gas, the primary confinement exhaust, and the secondary containment exhaust systems (details in FSAD-NF). Each of these exhausts is HEPA filtered. The use of HEPA filters for target or dump exhaust filtration is not a requirement but is a good ALARA practice that minimizes the potential for routine spread of radioactive contamination. Where ducts are manifolded together for common routing to the stack, backflow prevention is provided to prevent the possibility of reverse flow and to isolate branches when they are inactive (no flow). Dedicated ducts are provided for the exhaust from the target building up to the point of connection to the stack. Air measuring stations and isolation dampers are provided for each exhaust system.

Smoke Removal System

A tunnel exhaust system was included in the accelerator tunnel design to provide smoke removal capability in the case of a fire. However, smoke removal capability was not determined to be necessary for fire protection services, so the system was never certified according to NFPA requirements[3-22]. The components are still generally referenced as "smoke removal" in software and drawings, so the moniker "smoke removal system" is retained. Certain features of the system are incorporated into the EVS as described in Section 3.2.6. As discussed in Section 2.3.1 of the *Fire Hazard Analysis for Spallation Neutron Source Accelerator Facilities*,[3-16] these systems are not credited as part of the overall fire safety envelope but could still provide utility support for manual firefighting. Components include the grade-mounted fans in the SCL, a makeup air fan in the HEBT, and the two ventilation units serving the ring and RTBT. A more detailed description of the smoke removal systems is provided in the *Fire Hazard Analysis for Spallation Neutron Source Accelerator Facilities*.[3-16]

3.2.8.3 Mechanical/Piping Utility Systems

Mechanical/piping utility systems include (1) the tower cooling water system, (2) the chilled water system, (3) the building heating water system, (4) the process water system, (5) the sanitary waste system, (6) the potable water system, (7) the compressed air system, and (8) the natural gas system. The mechanical/piping utility systems are designed to last 40 years; to provide for ease of inspection, testing, and maintenance activities; and to permit routine testing without causing a change in plant operating status. They were designed, constructed, and procured in accordance with appropriate codes and standards.

Tower Cooling Water System

The tower cooling water system provides adequate coolant flow and pressure to remove heat from the chilled water and DI cooling water systems and other water-cooled equipment throughout the facility. The system has a maximum coolant temperature of 82°F at design atmosphere conditions of 77°F WB (wet bulb) and 94°F DB (dry bulb). It maintains cooling water quality so that fouling, corrosion, and blockage of heat exchangers, as well as other detrimental effects, are prevented; it also has a means of adding environmentally acceptable biocides and corrosion protection materials to the open cycle cooling water system. The evaporative cooling towers are located with respect to prevailing winds to minimize fogging, icing, noise intrusion, deposition of drift, and other issues, on and to adjacent plant structures. Special consideration is given to high-voltage equipment. Cooling tower blowdown is routed to the conventional liquid waste collection system (Section 3.2.8.4). The tower cooling water system operates at a higher pressure than the components served where the components can become activated.

Chilled Water System

The chilled water system provides adequate chilled water flow, temperature, and pressure to remove heat from the HVAC air handling units, the activated and inactivated DI chilled water systems, and other chilled water users. The system can operate all water chillers at between 20% and 100% of full chiller capacity to meet varying chilled water demands and reject heat generated by the chillers to the tower cooling water system. It operates at a higher pressure than the components served where the components can become activated, such as the 10 resonance control cooling systems, quadrupole magnet cooling system, and ring RF cooling system.

Building Heating Water System

The building heating water system supplies adequate water flow, temperature, and pressure to water heating coils in air handling units and unit heaters throughout the facility. The system provides the exterior underground piping to distribute and return hot water at a suitable temperature for space heating for identified buildings.

Process Water System

The process water system supplies nonpotable water to various systems requiring a clean source of makeup or process water. The system provides the exterior underground piping to distribute process water throughout the site. It is supplied by the potable water system, with all direct connections between the two systems having reduced-pressure backflow preventers to prevent contamination of the potable water system.

Sanitary Waste System

The sanitary waste system collects sanitary waste from fixtures served by the potable water system and from floor drains in restrooms and change rooms. The sanitary sewage is collected at sewage transfer station(s) for pumping to the ORNL sewage plant for treatment and disposal.

Potable Water System

The potable water system provides clean water to the combined fire and domestic water supply system. The system provides water to the storage tank and distributes potable water for domestic and firewater usage throughout the SNS facility. Reduced-pressure backflow preventers isolate all nonpotable water tie-ins to the system, including fire protection headers. A water supply system is provided for safety showers and eyewash stations using only key lock valves in the piping. The system provides hot and cold potable water to all fountains, lunchrooms, showers, and restrooms located in office buildings, support buildings, and the main control room.

Water is provided from the site utilities water system. The system includes a 300,000 gal elevated, combined, fire-process-potable water storage tank; a combined, looped water distribution system; fire hydrant connections; control valves; and building fire suppression system tie-ins. Nine sprinkler system tie-ins and one standpipe tie-in are provided on the water distribution system.

The design basis for the elevated water storage tank capacity considered maximum potable and process water demands concurrent with firewater demands and required a minimum 259,400 gal supply to meet those demands for 2 h. Approximately 195,000 gal in the elevated gravity tank are reserved for fire-suppression purposes. This reserve capacity is designed to provide approximately 2 h of firewater flow at the maximum anticipated demand. The combined water service distribution mains are designed to meet the general requirements discussed in the ORNL Utilities Division's Water Distribution System Description.[3-23] In addition, two equivalency analysis documents have been written to determine sufficient design features of the SNS water supply system. Discussions related to the requirement to heat the water tank are discussed in the equivalency analysis document for the Heating of the Water Tank.[3-24] Discussions related to the requirement to hydrostatically test the water main piping are covered in the *Equivalency Analysis Document for the Hydrostatic Test Pressure of the SNS Water Mains* .[3-25]

The elevated tank is filled by three 550 GPM booster pumps, which draw water from either the existing 16 in. or 24 in. city water main. The booster pumps can be manually reconfigured to supply water directly to the looped water distribution system if the water tower is out of service.

Compressed Air System

The compressed air system provides pressurized clean air to instruments, pneumatic devices such as air-operated valves, and service air outlets throughout the facility. The system has two compressor packages located in the CUB that provide a continuous supply of oil-free, clean, dry air.

Natural Gas System

The natural gas system provides a source of fuel for heating the building heating water system and various water heaters. The system receives natural gas from a line tying into the ORNL gas transmission line downstream of the pressure reducing and metering station at 100 psig and supplies it to building heating boilers and natural gas-fired water heaters at less than 5 psig. Natural gas is not supplied to the target building.

3.2.8.4 Waste Systems

Waste systems include the central functions that collect and process all generated wastes and discharge them to appropriate repositories. These include portions of the process waste system and the sanitary liquid waste system.

Process Waste Collection System

The process waste system collects wastewater from normal operations and from any anticipated abnormal occurrences. As guided by the ORNL SBMS requirements for wastewater management, sampling is used to ensure that process waste with nonnegligible radioactivity is diverted to liquid low-level waste (LLLW) treatment.

Included in the system are diversion tanks within buildings and underground piping and manholes to the sanitary sewer system. The piping layout is designed for gravity flow from collection manholes in the SNS area into the sanitary sewer system. Any LLLW originating because of accelerator operations is directed into a tank truck for transport to the ORNL LLLW treatment system.

Conventional Liquid Waste System

The conventional liquid waste system transfers cooling tower blowdown to the storm water retention basin for retention and stabilization prior to release to White Oak Creek. The system ensures water discharged to the storm water retention basin does not have excessive chlorine and is cooled to ambient temperature before it is discharged to the creek through a National Pollutant Discharge Elimination System (NPDES)-permitted outfall that measures flow and temperature and facilitates periodic sampling to verify permit compliance. Instrumentation and controls are compatible with the plant operating systems.

Conventional Solid Waste

Conventional solid waste handling uses a series of dumpsters for sanitary waste, paper/cardboard, white and miscellaneous paper, glass, and metal. The collection method facilitates materials recycling.

Hazardous and Mixed Waste

Hazardous and mixed wastes collected as necessary from the SNS site include oils, solvents, and reactive metals for off-site disposal. The procedures and equipment comply with the ORNL SBMS for hazardous and mixed waste, including transportation and facility acceptance, and have the capability to temporarily store remotely handled mixed wastes at the SNS site.

SNS operates as a scientific user facility in which a wide variety of samples are brought in for neutron scattering measurements. Some of these samples are, or may become, hazardous, but they are all subject to SNS and ORNL procedures. The following means are used to ensure appropriate handling and disposal:

- The SNS tracking system for experiments tracks location and disposal of all used experiments; ORNL procedures for shipping ensure DOE- and DOT-compliant shipping.
- Experimenters are required to undergo training to ensure they follow ORNL requirements regarding the introduction of materials to the SNS site, as well as requirements for taking materials away from the SNS site.
- SNS employs a full complement of radiation control technicians and procedures to perform radiological evaluations of all samples before release.

3.2.8.5 Maintenance and General-Purpose Equipment

Maintenance and general-purpose equipment provide the maintenance and shop equipment needed to support normal operations, achieve plant availability and predictability, and support user experiments. This equipment includes (1) handling and transportation equipment, (2) technical laboratories and shop equipment, (3) yards and grounds maintenance facilities equipment, and (4) material control and storage facilities equipment.

Handling and transportation equipment provides mobile handling and transportation equipment as necessary for the repair, removal, relocation, and installation of complete or partially disassembled items of equipment that cannot be serviced by installed equipment. Included are mobile cranes, forklifts, mobile platforms, dollies, air pads, and other equipment necessary to transport material, equipment, and supplies from one area of the plant to another. Mobile platforms and scaffolds are used for access to and maintenance of installed equipment only in areas where permanent platforms are not practical and where access is infrequent. Only electrical and/or manual transportation equipment is used in areas where fueled equipment is not practical or safe.

Technical laboratories and shop equipment provide the equipment needed for plant maintenance workers (e.g., pipe fitters, millwrights, carpenters, refrigeration mechanics) to perform routine maintenance of nonradioactive and uncontaminated mechanical, electrical, and instrument equipment, as well as radioactive and contaminated equipment.

Cabinets meeting Occupational Safety and Health Administration (OSHA)[3-26] requirements are provided in each area for the storage, control, and disposal of hazardous chemicals that are used in each area. Electrical tools, equipment, and workbenches have nonconductive surfaces for troubleshooting, testing, repairing, and calibrating plant electrical systems and components. Portable welding machines, equipment, tools, and accessories are provided to perform the following welding processes: shielded metal arc, tungsten inert gas, metal inert gas, oxyacetylene, and plasma cutting. A welding fume exhaust system is used for welding operations separate from the building HVAC system.

3.2.8.6 Fire Protection System

The fire protection system provides the water supply necessary for potential firefighting efforts throughout the SNS site. Included are an elevated, combined, fire-process-potable elevated water storage tank described in Section 3.2.8.3, fire hydrants, and building fire suppression system tie-ins. Associated pumps and valving are included in the potable system. Features of the fire alarm system are described in Section 3.2.8.1.

The system, in accordance with NFPA and DOE standards, has a minimum capacity of 2 h of firewater flow at the maximum anticipated water demand at peak domestic demand. Hydrants are positioned, and firewater supplied, within the guidance of NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances*.[3-27] No hydrant is closer than 50 ft to a building. Pressure at any hydrant is at least 20 psig at the maximum anticipated fire demand. Each hydrant has an isolation water-control valve.

3.2.8.7 Conventional Facilities Instrumentation

Conventional facilities instrumentation provides control and system status of all conventional facilities systems and associated components, which include the support and utility systems that are needed for accelerator operation but are not part of the technical systems involved in the production of the proton beam. Both local control/monitoring functions, located near each system or component, and remote control/monitoring functions, located at a control center in the CUB, are provided. Remote control functions for all conventional facilities equipment are provided via one stand-alone human–machine interface database system with a multi-screen display for accessing the various systems for control and status information. The SNS conventional facilities instrumentation is divided into the following subsystems: (1) the electric power monitoring system, (2) the HVAC control system, (3) the mechanical systems control system, (4) the waste systems control system, and (5) the plant security system.

In addition to the capabilities listed in the previous paragraph, the following capabilities are provided in the main accelerator control room located in the CLO Building: (1) EPICS-based view-only monitoring capability is provided for all utilities, and (2) control capability is provided for the skid-mounted cooling water systems that serve accelerator components.

3.2.8.8 Emergency Power Systems

The site is served by two separate 161 kV power supplies to provide redundant power to SNS. In addition, SNS has emergency on-site AC power supplies and uninterruptible power supplies (UPSs) to ensure the site has adequate, reliable electrical power to support equipment protection and mission continuity.

3.2.8.9 Emergency Onsite AC Power Supply

The emergency on-site AC power supply consists of multiple diesel engine generator units installed at various locations at the SNS site. Emergency power is supplied at 480 Vac to normal/emergency distribution equipment serving the essential loads described in the following list. In general, UPS loads requiring power beyond the maximum backup period provided by the UPS also can be supplied from the emergency on-site AC power supply system. The following are the essential loads supplied:

- Safety interlock system (a mission continuity feature only, because these systems fail to a safe state on loss of power)
- Vacuum system instrumentation and controls and control PLCs for the SCL cryogenic systems
- Main control room servers and hardware
- Selected telecommunications equipment
- Selected alarm systems, including fire alarms
- Access control system
- Standby ventilation fans for target cells and tunnels
- Emergency lighting systems for tunnels
- Standby lighting systems

The emergency on-site AC power supply system is capable of automatically supplying the connected loads upon loss of the plant primary power supply.

The system's power supplies and associated distribution systems are provided with instrumentation to monitor variables and components so facility operations personnel can evaluate whether these systems are performing the intended functions to support SNS loads.

3.2.8.10 Uninterruptible Power Supply System

The UPS systems employed at SNS consist of that portion of the facility electrical power system that inverts DC power to AC power and distributes this power to loads requiring a continuous source of power. Such loads are considered essential to providing for the general operational safety of facility personnel and/or preventing severe economic loss in the event of primary power supply failure. Loads requiring UPS systems include the following:

- Safety interlock system (a mission continuity feature only, since these systems fail to a safe state on loss of power)
- Vacuum system instrumentation and controls
- Critical power supply controls and protection
- Main control room servers and network hardware
- Selected telecommunications equipment
- Selected alarm systems (e.g., PPS radiation, fire alarm)

The UPS systems provide 120 V AC, nominal, single-phase, two-wire, 60 Hz and 120/208 Vac nominal, three-phase, four-wire, 60 Hz uninterruptible power to essential loads.

3.3 OPERATIONS

SNS's operational goal is to provide safe, efficient, and responsive operations in support of the world-class neutron research user facility. Organizations are focused on achieving and maintaining rated design conditions for the accelerator and emphasize an integrated approach to operations.

The operations organization is expected to continue to evolve as needed to best meet safety and operational goals, incorporate lessons learned, and effectively interface with the rest of the directorate. The description here reflects the organization at the time of this revision.

The responsibility for safety rests with line management, flowing through the ORNL associate laboratory director for the Neutron Sciences Directorate. The SNS operations manager, who reports to the associate laboratory director, is responsible for providing safety support, information, and oversight. The SNS operations manager is the ultimate authority on environment, safety, health, and quality (ESH&Q) issues within the SNS complex.

The Research Accelerator Division (RAD) is responsible for operating the entire SNS facility except the neutron instruments. SNS is operated by members of both the Accelerator Operations Group and the Target Operations Team. This operational integration provides smooth coordination between proton and neutron facility operational activities, with unambiguous lines of authority and responsibility to ensure prompt and appropriate response to operational off-normal conditions up to and including site emergency response.

3.3.1 Organization for Operations

The division director for RAD has line responsibility for operational activities of the proton facilities and the neutron facilities with the exception of the neutron instruments, which operate under the authority of the Neutron Scattering Division director. The RAD director also fulfills the responsibilities of the SNS operations manager. The SNS operations manager is the agent for the Neutron Sciences Directorate associate laboratory director responsible for

- Ensuring compliance with the accelerator regulatory requirements
- Ensuring safe, efficient, reliable operation of the accelerator, target building, test facilities, and related SNS support systems.

3.3.2 Environment, Safety, Health, and Quality Organization and Interface with Operations

SNS is operated as part of NScD. The ESH&Q group reports to the SNS operations manager. Policies for the safe and environmentally sound operation of SNS are developed and approved by the operations manager. The ESH&Q staff are responsible for providing direction and support to SNS line organizations.

Where it is cost effective to do so, ESH&Q services such as health physics support, environmental permit development, and radiation shielding calculations are purchased by SNS from ORNL support organizations or subcontractors.

To ensure uniform and effective implementation of key ESH&Q issues throughout SNS, committees to evaluate and develop ESH&Q policies are established as needed. For example, the Accelerator Safety Review Committee, Radiation Safety Committee, Cryogenic Safety Committee, and Instrument Systems Safety Committee have been chartered. Committees are multidisciplinary, as necessary, to ensure comprehensive reviews.

3.3.3 Description of Operations

3.3.3.1 Proton Facilities

The SNS proton facilities are operated and maintained by RAD personnel. Within RAD, the specific responsibility for operations is assigned to the Operations, Integration, and Maintenance Section. The operations team consists of an accelerator operations manager (section head of OIM), the Accelerator Operations Group leader, control room shift supervisors, and control room accelerator specialists. The accelerator operations manager has the overall responsibility for operation of the SNS accelerator, with responsibilities that include the following:

- Direct the preparation of tracking and reporting of operational and maintenance statistics for the purpose of maximizing the scientific throughput of the facility. Participate in the planning for, and execution of, acceptance and installation tests of accelerator systems.

- Assist in the review of planning and preparation of documents with an eye to the operability and maintainability of accelerator systems, including budgeting for long-term operation.
- Direct and assist in the development and maintenance of operational tools for the accelerator systems, including computer screen interfaces.
- Supervise the preparation of training and certification documentation for personnel in collaboration with other RAD team leaders.
- Be involved with the design and implementation of personnel and equipment safety systems including (1) beam and accelerator subsystem interlock and (2) access and testing modes.
- Ensure team, group, and individual compliance with ES&H requirements, including the Integrated Safety Management System.

The current plan calls for rotating shifts staffed by three RAD personnel: a control room shift supervisor and two control room accelerator specialists. A control room shift supervisor may function as an accelerator specialist when on shift. System specialists are not on shift 24 h/day but are called in as needed using an organized call-in structure.

The CCR has enough centrally located and compact multifunction workstation screens simultaneously accessible to the operations personnel and other support personnel as necessary.

The design goal of SNS accelerator operations is to provide 5,000 h of beam to the target per year with 90% availability during beam-on-target operation. This includes beam time for scheduled scientific users, additional user time, accelerator physics, and start-up/transition/post-maintenance operation. It also accounts for weekly maintenance periods, routine target changes, and semiannual shutdown periods. These numerical goals should not be regarded as commitments or requirements because the information is only intended (in this context) to provide an approximate picture of normal operations.

Maintenance days are normally routinely scheduled as determined by management to allow for maintenance activities that require the beam to be off. Other routinely scheduled maintenance periods are scheduled for tasks that require more than 1 day to complete. Extended maintenance shutdowns lasting several days are routinely scheduled as needed to support operations. Unscheduled maintenance days occur based on a variety of factors and are taken as needed with the goal to minimize unscheduled maintenance.

Operations Procedures

Operations and maintenance activities are both performed in accordance with approved written procedures. Maintenance is conducted using a work authorization process that ensures configuration control of facility CECs. This process interfaces with the ORNL institutional work control system, allowing SNS to gain the advantages of a well-developed and established work control process while maintaining sufficient independence to ensure that all work performed at SNS is appropriately reviewed and approved by personnel familiar with the unique aspects of performing work at the complex accelerator facility that is SNS.

Several facilities have well-established, proven operations procedures that SNS reviewed for use as a guideline in the development of the SNS OPM.[3-21] Of these facilities, the one with the most comprehensive set of documentation similar in application to that required for SNS was the

Collider-Accelerator Department at BNL. SNS has taken a similarly comprehensive approach in the development of the SNS OPM.

Technical procedures specific to SNS are provided to operations by the senior team leaders and group leaders, primarily in RAD. These procedures are incorporated into the SNS OPM. The Neutron Scattering Division also uses the SNS OPM for procedures regarding the neutron instruments. The SNS OPM procedures address normal and off-normal, as well as non-physics, operations. The level of detail devoted to off-normal operations, events, or alarms is commensurate with the potential safety or environmental consequences. The SNS OPM is accessible at https://ns-staff.ornl.gov/operations/SNS-OPM_Folder_Tree/index.html.

3.3.3.2 Neutron Facilities

Operations specific to the SNS neutron facilities are described in the FSAD-NF.[3-1]

3.3.4 Radiological Protection Program

The lab-wide radiological protection program is a mature and effective program. A wide range of radiological activities are accommodated at ORNL through the SBMS Radiological Protection Management System (RPMS). RPMS subject areas such as Radiological Area Controls, Radiological Dosimetry, and Radiological Work implement the requirements of 10 CFR 835 to maintain exposure to radiation ALARA, protect facilities and equipment from radioactive contamination, and promote compliance with regulatory and contractual requirements. SNS uses matrixed support staff from the Nuclear and Radiological Protection Division, which owns the RPMS, to serve in radiological protection functions such as radiological control technician (RCT), RSO, and program health physicist. This approach allows SNS to benefit from the robust institutional radiation safety practices at ORNL.

The ALARA principle has been integrated into the design, construction, and operation of SNS throughout its lifetime. ALARA considerations were a key factor in the original design of facility shielding, and the Radiation Safety Committee continues to review design changes using the ALARA principle. The ORNL ALARA program, as supplemented by SNS policy, is integrated into the RPMS to ensure ALARA principles are incorporated into the various aspects of radiological protection, such as design and work planning. Finally, SNS periodically performs ALARA reviews that holistically evaluate the implementation of ALARA principles at the facility to verify that existing policies and practices have been effective and to identify opportunities for further improvement.

3.3.4.1 Radiation Monitors

SNS uses radiation monitors to accomplish a variety of goals. Many of these uses are according to SBMS processes such as routine radiation surveys and personnel frisking. Personnel dosimetry services at SNS are provided by the ORNL Nuclear and Radiological Protection Division. SNS also uses radiation monitors to evaluate accelerator performance and identify abnormal conditions near accelerator components or target systems. These uses ultimately serve to monitor, control, and reduce personnel exposure to radiation and radioactive materials.

Retrospective Radiation Dose Measurements

The long-term integrated radiation dose in areas accessible to the public and to other individuals not wearing personnel dosimeters is measured to establish the background in these areas and to confirm that the doses are acceptable. Thermoluminescent dosimeters (TLDs) identical to those worn by radiation workers are mounted in locations specified by the RSO for this purpose. The dose recorded by these TLDs is indicative of the exposure of a person spending full time at that location. Neutron albedo dosimeters, if their use is indicated for this purpose, are attached to phantoms or other suitable moderators to simulate use by personnel.

Real-Time Radiation Monitors

Various types of real time radiation monitors are also provided at various locations within the target building as determined by the RSO. Fixed-location area radiation monitors provide real-time dose information for two purposes: (1) dose rate information is provided to the PPS so that it can turn the beam off in case of elevated radiation levels in potentially occupied areas, and (2) local radiation monitors warn workers of unexpected elevated dose rates. General locations have been selected for the real-time monitors based on radiation modeling under operating and accident conditions; exact locations may be refined based on beam-loss tests (normal and/or fault conditions, as needed) conducted during commissioning activities and on radiation surveys during operations. The RSO determines area radiation monitoring instrument locations and subsequent relocations. Some monitors selected for this application are sensitive to both gamma and neutrons, whereas gamma-only monitors are more appropriate in other applications.

PPS-interlocked area radiation monitors are located outside the protective shielding at points adjacent to possible high-loss areas along the beam path. For additional protection and monitoring purposes, interlocked area radiation monitors may also be placed in unoccupied beam areas and correlated with measured levels in adjacent occupied areas. These monitors are interlocked to the beam and trigger a shutdown if radiation levels become significantly greater than expected. This technique is currently standard practice at other accelerator facilities around the country; the intent is to maintain personnel safety and area classification compliance by providing a robust and rapid beam-inhibit if any monitor exceeds a preset interlock limit. PPS-interlocked area radiation monitors are described in more detail in Section 3.2.4.6.

Portable Radiation Monitors

Portable radiation detection instruments are an essential part of any robust radiological control program and are used by RCTs at SNS. ORNL requirements and procedures relating to portable radiation monitors are included in the SBMS Radiological Control Subject Area.

Frisking Instruments

Instruments are used to frisk personnel who are exiting posted areas that might contain removable contamination. Instruments are selected as appropriate for the expected types and energies of the contamination. ORNL requirements and procedures relating to frisking and frisking instruments are included in the SBMS Radiological Control Subject Area.

Personnel Dosimetry

All radiation workers wear TLDs while working in areas posted for actual radiation hazards (i.e., posted radiation areas designate an actual hazard). Other workers are issued appropriate dosimetry for their work assignments, including consideration of potential accident scenarios. In addition to the standard ORNL dosimeter that measures beta, gamma, and gross neutron radiation exposures, workers who are likely to be exposed to measurable levels of neutron radiation are issued special neutron dosimeters that provide a more accurate assessment of neutron dose. Selection of appropriate neutron dosimetry is based on predicted neutron dose rate, integrated dose, and energy spectrum.

ORNL requirements and procedures relating to personnel dosimetry are included in the SBMS Radiological Control Subject Area.

3.3.5 Other Administrative Controls Supporting Safe Operations

3.3.5.1 Work Control

All workers at ORNL have a responsibility for identifying and understanding the hazards they may encounter in the workplace. This responsibility is embedded in the SBMS "Work Control" subject area, which implements the Integrated Safety Management System and applies to all work performed at SNS. For example, this subject area implements safety standards for research and development activities through the RSS process and for operations and maintenance through the Job Hazard Evaluation process.

3.3.5.2 Electrical Safeguards

Adherence to the ORNL SBMS Electrical Safety subject area is the primary method used by SNS to ensure electrical safety. This subject area covers several topics:

- Acquiring or fabricating new electrical equipment
- Using or working adjacent to electrical equipment
- Training requirements for electrical workers
- Performing electrical work
- Verifying absence of electrical energy for lock/tag/verify (LTV)

SNS practice is to guard exposed electrical connections on accelerator technical components in accelerator technical areas to minimize any electrical hazards. However, a deviation from this practice was necessary in the HEBT, ring, and RTBT tunnels. The electrical connections for the HEBT, ring, and RTBT tunnel magnets are exposed. These buss connections are not guarded for the following reasons:

- ALARA: The use of Lexan bus covers would require removal of these covers during maintenance, which would increase worker time in the radiation field.

- ALARA and waste minimization: The radiation field in the vicinity of the magnets would likely cause the covers to decay, thereby creating a waste stream and requiring additional worker time in a radiation field.

Remedial actions for the exposed electrical conductors in the HEBT, ring, and RTBT tunnels include marking the tunnel floors with a red paint barrier that workers must not cross unless the magnet power supplies are under LTV control. The red paint barrier is located 30 in. from any exposed electrical conductors and is labeled "APPROACH BOUNDARY LOTO REQUIRED." Furthermore, the current routine operating practice at SNS is to de-energize and LTV these tunnel magnets for any activity that requires personnel to cross the red approach boundary during a maintenance period.

The use of Lexan guarding for the front-end and linac magnets and the administrative controls described previously for the HEBT, ring, and RTBT tunnels is covered in "Accelerator Access Training," which is required for any person to access the accelerator tunnels unescorted.

Under rare circumstances, personnel may need to enter one of the accelerator tunnels with the magnets energized for technical measurements. Access to accelerator tunnels during such an activity is tightly controlled. Entry requires job-specific work planning and approval before entry is allowed. The planning must include training requirements, radiation concerns, magnetic hazard considerations, PPE needed to mitigate electrical hazards, and enforcement of the two-worker rule, which designates one of the workers as a safety observer.

3.3.5.3 Lockout/Tagout

SNS follows the requirements and procedures of the ORNL SBMS Lock/Tag/Verify subject area.

3.3.5.4 Safety Reviews and Committees

As discussed in Section 3.3.2, standing safety committees have been chartered and are used to focus project expertise on safety and to help maintain configuration control.

3.3.5.5 Training

Personnel training and qualification are important components of safety in operations at SNS. The SNS *Training and Qualification Plan* published in the SNS OPM[3-21] outlines core requirements for training and qualification functions and processes for conducting work at SNS. The *Training and Qualification Plan* implements requirements established through the ORNL SBMS by the Training and Qualification Management System. The ORNL enterprise learning management system is used to manage staff training requirements, facilitate delivery of course offerings, track completion of training, and monitor qualification status for performance of work.

All SNS personnel, including nonemployees, facility users, and support service staff, are required to have an appropriate level of training to ensure awareness of potential hazards and emergency conditions that may be encountered as they perform their work. Objectives of this training focus on controls to mitigate hazards, measures for personnel protection, and appropriate emergency response actions. Training requirements established for implementation by multiple ORNL organizations (institutional requirements) are defined in ORNL SBMS subject area procedures. SNS-specific training requirements having broad applicability to SNS personnel are defined by SNS plans, policies, or operating procedures. These local requirements are largely focused on facility or area access and may be used in access control. An established process is used to assign personnel training requirements based on potential hazard exposure, job/task assignments, functional roles, or access needs. Completing a combination of institutional and local training requirements imparts knowledge and skills appropriate to work performance in such areas as radiological safety, hazardous energy control, electrical safety, fall protection, hoisting and rigging, cryogenic safety, and emergency response.

Training on system components, job duties/tasks, operating procedures, and work processes also supports safety in operations. Positions that require staff qualification to address requirements of DOE O 420.2C, *Safety of Accelerator Facilities*, have been identified based on analysis of responsibilities defined by the SNS ASE and the SNS operations envelope. These positions are listed in the SNS *Training and Qualification Plan* which, in turn, references training plans in the SNS OPM that have been approved for qualification of operators and technicians based on operating procedures. Training and qualification requirements are defined for such positions as

- Accelerator specialists and supervisors
- Technicians performing target systems operations
- Engineers with responsibility for CECs
- Preparers/reviewers executing the USI process

Training in the process and requirements for work control in operations, maintenance, and services is also required for workers and those in roles of screeners, planners, task leaders, and managers.

3.3.5.6 Personal Protective Equipment

SNS use of PPE is governed by ORNL SBMS requirements.

3.4 REFERENCES

3-1 *Spallation Neutron Source Final Safety Assessment Document for Neutron Facilities*, SNS 102030-102-ES0016, Oak Ridge National Laboratory.

3-2 *Construction and Operation of the Spallation Neutron Source Facility*, *Final Environmental Impact Statement,* DOE/EIS-0247, Office of Science, US Department of Energy, Washington, DC, April 1999.

3-3 F. C. Fitzpatrick, *Oak Ridge National Laboratory Site Data for Safety Analysis Reports*, ORNL/ENG/TM-19, Union Carbide Corporation Nuclear Division, Oak Ridge National Laboratory, December 1982.

3-4 J. W. Boyle et al., *Environmental Analysis of the Operation of Oak Ridge National Laboratory (X-10 Site)*, ORNL-5870, Union Carbide Corporation Nuclear Division, Oak Ridge National Laboratory, November 1982.

3-5 US Census Bureau, 2020 Census of Population and Housing, obtained from www.census.gov, accessed March 4, 2022.

3-6 *1997 Local Climatological Data Annual Summary with Comparative Data, Oak Ridge, Tennessee*, US Department of Commerce, National Climatic Data Center, Asheville, North Carolina, 1997.

3-7 G. K. Moore, *Groundwater Parameters and Flow Systems Near Oak Ridge National Laboratory*, ORNL/TM-11386, Publication Number 3403, Environmental Sciences Division, Oak Ridge National Laboratory, September 1989.

3-8 *D2487-00 Standard Classification of Soils for Engineering Purposes (Unified Soil Classification System),* ASTM International, West Conshohocken, PA, 2002.

3-9 *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities*, DOE-STD-1020-94, US Department of Energy, Washington, DC, April 1994, Change Notice No. 1, January 1996.

3-10 *Natural Phenomena Hazards Performance Categorization Guidelines for Structures, Systems, and Components*, DOE-STD-1021-93, US Department of Energy, Washington, DC, Change Notice No. 1, January 1996, reaffirmed with Errata April 2002.

3-11 *Minimum Design Loads for Buildings and Other Structures*, ASCE 7-95, American Society of Civil Engineers, New York, 1996.

3-12 *Standard Building Code, 1997,* Southern Building Code Congress International, Inc., Birmingham, AL, 1997.

3-13 *Uniform Building Code,* International Conference of Building Officials, Whittier, California, 1997.

3-14 *Natural Phenomena Hazards Site Characterization Criteria*, DOE-STD-1022-94, US Department of Energy, Washington, DC, March 1994, Change Notice No. 1, January 1996, reaffirmed with Errata, April 2002.

3-15 *Standard for Reducing Structure Ignition Hazards from Wildland Fire*, NFPA 1144, National Fire Protection Association, Quincy, MA, current edition, 2013.

3-16 *Fire Hazard Analysis for Spallation Neutron Source Accelerator Facilities,* Rev. 7, 108000000-FP0004-R07, Spallation Neutron Source, Oak Ridge National Laboratory, October 2017.

3-17 Title 10, *Energy*, Part 835, "Occupational Radiation Protection," 10 CFR 835, US Department of Energy, Washington, DC.

3-18 *Cyber Security Plan, Spallation Neutron Source Integrated Control System Network*, OCIO-CSP-010 Spallation Neutron Source, Oak Ridge National Laboratory, June 2017.

3-19 *Application of Safety Instrumented Systems for the Process Industries,* ISA-S84.01-1996, Instrument Society of America, February 1996.

3-20 *Spallation Neutron Source Quality Manual,* SNS-QA-P01, Rev. 6, 102040000-QA0001-R06, Spallation Neutron Source, Oak Ridge National Laboratory, September 2011.

3-21 *Spallation Neutron Source Operations Procedures Manual*, Spallation Neutron Source, Oak Ridge National Laboratory, . http://ns-staff.ornl.gov/operations/SNS-OPM_Folder_Tree/index.html

3-22 *Recommended Practice for Smoke-Control Systems*, NFPA 92A, National Fire Protection Association, Quincy, MA, current edition, 2000.

3-23 *Water Distribution System Description*, ORNL UT-MECH-ADM-002, Rev. 2, IDMS #16540, March 2016.

3-24 *Equivalency Analysis Document for the Heating of the SNS Water Tower*, SNS 108040000-ES0001-R01, Rev. 1, Spallation Neutron Source, Oak Ridge National Laboratory, August 2007.

3-25 *Equivalency Analysis Document for the Hydrostatic Test Pressure of the SNS Water Mains*, SNS 108040000-ES0002-R00, Spallation Neutron Source, Oak Ridge National Laboratory, June 2007.

3-26 *Oak Ridge National Laboratory Work Smart Standards,* "Other Industrial, Radiological, and Non-Radiological Hazard Facilities," Oak Ridge National Laboratory, July 1996, Revision Change No. 105, January 2018.

3-27 *Standard for the Installation of Private Service Mains and Their Appurtenances*, NFPA 24, National Fire Protection Association, Quincy, MA, current edition, 2016.

3-28 *Ring Injection Dump (RID) Thermal Analysis Review and Benchmarking*, SNS 106090200-TR0001-R00, Spallation Neutron Source, Oak Ridge National Laboratory, October 2020.

4. SAFETY ANALYSIS

This section provides evaluations necessary to achieve two major objectives of the FSAD:

1. Evaluate hazards posed by SNS operation that are unique to accelerators and make sure they are adequately controlled/mitigated. As discussed below, standard industrial and laboratory hazards are not covered in detail because they are safely managed through the ORNL SBMS.

2. Identify controls that are essential to safety, so that they may be given close attention throughout operational and maintenance activities in accordance with the *SNS Quality Manual*[4-1] (Section 7). Controls that fall into this category are referred to as credited controls.

The basic approach followed in this section is to complete a hazard analysis for accelerator-unique hazards in each major segment of the proton facility. Hazard analysis is the standard method for applying the DOE graded approach for minimizing risk to workers, the public and the environment. It is well suited to identifying and understanding risk because it requires facility designers and operations personnel to consider the likelihood and the potential consequences of hazards. The product of likelihood and consequence constitutes risk. To conduct a hazard analysis, the approach is to evaluate the risk and to identify controls—preventive and mitigative features—that ensure risk is maintained at low or extremely low levels. Controls that provide essential primary protection are designated as credited controls. Controls that work to reinforce the primary controls by contributing to the layers of overall safety assurance are typically not designated as credited controls. Criteria and guidance applied by SNS in designating credited controls are described in Section 4.1.2.

Standard industrial and laboratory hazards do not require credited controls because they are safely managed as part of ORNL's established institutional safety programs. ORNL implements institutional safety through the ORNL SBMS. Promulgation of the SBMS is a key part of ORNL application of the principles of integrated safety management.

Section 4.1 explains the SNS implementation of the DOE graded approach to risk minimization. Section 4.2 identifies the hazards present in the major segments of SNS and its support facilities, excluding the neutron facilities. Section 4.3 provides hazard analysis summaries for each major segment of SNS, except for the neutron facilities, the safety of which is addressed in the FSAD-NF.[4-2] Section 4.3.6 summarizes the safety analysis results, including the controls that have been identified as credited. Section 4.4 identifies potential hazards to the environment, the regulatory framework under which those hazards are managed, and the controls in place to manage the identified hazards.

4.1 HAZARD ANALYSIS METHODOLOGY

Hazard analysis includes the following steps: (1) identification and screening of hazards, (2) assessment of the frequency and potential consequences of unmitigated risk, (3) identification of relevant and effective mitigation/preventive measures, and (4) assessment of mitigated risk. Hazard analysis is a process whereby it is possible to understand the risk and make informed risk mitigation or acceptance decisions. It is desirable to identify and apply safety measures that make accelerator specific risks fall into the "extremely low" category (Figure 4.1).

Consequence level

High	**Low risk—acceptable**	Medium risk—unacceptable	High risk—unacceptable	High risk—unacceptable
Medium	Extremely low **desirable**	**Low risk—acceptable**	Medium risk—unacceptable	High risk—unacceptable
Low	Extremely low **desirable**	Extremely low **desirable**	**Low risk—acceptable**	Medium risk—unacceptable
Extremely low	Extremely low **desirable**	Extremely low **desirable**	Extremely low **desirable**	**Low risk—acceptable**
	Extremely unlikely ($<10^{-4}$/y)	**Unlikely (between 10^{-4}/y and 10^{-2}/y)**	**Anticipated—medium (between 10^{-2}/y and 10^{-1}/y)**	**Anticipated—high (above 10^{-1}/y)**

Probability level

NOTE: 10 CFR 835[4-4] ALARA may require more stringent limits for anticipated events.

Definition of consequence levels	
Level	**Definition**
Extremely low	Will not result in a significant injury or occupational illness or significantly impact the environment.
Low	Minor on-site impact with negligible off-site impact. May cause minor injury, minor occupational illness, or minor environmental impact.
Medium	Major on-site or off-site impact. May cause severe injuries or occupational illness to personnel, a single accidental death, major damage to a facility or operation, or minor environmental impact.
High	Serious on-site or off-site impact. May cause deaths or loss of the facility/operation. Possible significant environmental impact.

Figure 4.1. The risk matrix.

4.1.1 General Approach to Risk Minimization

The steps in the hazard analysis process and general decision criteria are discussed in the following paragraphs.

Hazard identification produces a comprehensive list of the hazards present in a process or facility, and the screening phase removes all hazards below a threshold of concern or that are covered by recognized industrial codes and standards. The standard industrial hazards that are screened out do not need to be studied in a hazard analysis because their risks are already well understood and mitigated by standard means.

For each hazard retained for hazard analysis, the unmitigated risk is first evaluated in terms of frequency and consequence. This places it on the risk matrix, illustrated by Figure 4.1. An adaptation of the Figure 4.1 risk matrix developed specifically for evaluating ODH risk is provided in Appendix F. The following assumptions govern the determinations of unmitigated risk:

- The unmitigated risk does not include active safety or control systems or administrative controls.
- Assigned frequencies (labeled "Probability level" on Figure 4.1) are qualitative and are typically based on engineering judgment. For the unmitigated evaluation, the frequency is that of the unmitigated initiating event. Examples are discussed in Appendix A.
- Assigned consequence can be qualitative but must be conservative.
- The hazard analysis is not carried further if the unmitigated risk is extremely low.

At this point, the risk is reevaluated, considering the mitigating factors in place that would either reduce the consequence or make the challenge less frequent. This analysis should move the location on the risk matrix based on assumed conditional probabilities of failure for the mitigating systems (Appendix A).

The mitigated risk should be either low or extremely low. For low risk, the evaluation should be reviewed to determine whether preventive or mitigative features could be added to bring the risk to extremely low. The risk of serious consequences should be made extremely low if that is reasonably achievable.

Credited controls are established for unmitigated hazards that fall into the unacceptable risk category (Section 4.1.2). A credited control is one determined via hazard evaluation to be essential for safe operation directly related to the protection of personnel or the environment. The number of credited controls should be a limited subset of the total number of controls employed for overall facility operation. Credited controls should be assigned a higher degree of operational assurance than other controls.

4.1.1.1 Risk Minimization for Radiation Hazards

Prompt radiation hazards associated with operation of the SNS proton facilities are minimized by using passive shielding and the PPS. As described in Section 3.2.4, the PPS uses a system of automatic interlocks and beam cutoffs to render the beam enclosures inaccessible during beam operation and to help ensure that beam enclosures are cleared of personnel before beam operation. In addition, the PPS helps to protect personnel and area radiation designations outside beam enclosures by using a system of interlocked area radiation monitors. The *SNS Shielding Policy*[4-3] establishes policy expectations for preventing exposure to ionizing and nonionizing radiation, the performance and configuration control of shielding, and the control of access to radiological areas. Comprehensive radiological risk minimization is ensured through application of the ORNL SBMS Radiological Protection subject areas, which promulgate procedures and requirements applied throughout ORNL, including SNS, for full implementation of 10 CFR 835.[4-4]

Area designations (e.g., radiation areas as defined in 10 CFR 835) are established to control the flow and behavior of workers in each area so that workers receive the minimum radiation exposure coincident with operating the facility to achieve its authorized research mission. Area boundaries are set with the expectation and verification that radiation levels will not exceed certain specified maxima depending on the type of posting. SNS management expect the area radiation limits to be met considering both the base level of residual radiation fields and the integrated effect of the short bursts typical of beam faults. The different area radiological postings used at SNS for minimizing worker and visitor exposures to external radiation are governed by the ORNL SBMS Radiological Protection subject areas. The PPS, by using a system of interlocked area radiation monitors, helps ensure the integrity of area designations by alarming or tripping the proton beam when specified thresholds are exceeded.

4.1.1.2 Risk Minimization for Oxygen Deficiency Hazards

The risks associated with ODH hazards are assessed in a manner consistent with that described above, in which the consequences are ranked based on the severity of potential health effects to a person being exposed to low oxygen concentrations in occupiable areas as the result of an accidental release of helium or nitrogen. These scenarios are addressed in more detail in Section 4.3.4.

4.1.1.3 Risk Minimization for Fire Hazards

Fire is a standard industrial hazard that is mitigated at SNS through the ORNL SBMS Fire Protection, Prevention, and Control subject area, which implements the DOE fire-related directives and NFPA standards. Although workers are not present in the accelerator beam enclosures during routine operation, the tunnel-like geometry of the beam enclosures, combined with the existence of combustible materials in the tunnel, require life safety evaluation. The general approach to ensure an acceptable level of fire risk is through SBMS provisions that require compliance with applicable codes and standards. The original design of the SNS facilities complied with NFPA 101, *Life Safety* Code 1997 edition,[4-5] and the *Standard Building Code* (SBC) 1997 edition.[4-6] Assessments as required by SBMS are performed to ensure compliance with current editions of these codes.

4.1.2 Selection of Credited Controls

A control is credited if it is determined through hazard evaluation to be essential for safe operation directly related to the protection of workers, the public, or the environment. As described in DOE Guide 420.2-1,[4-7] the number of credited controls should be a limited subset of the total number of controls employed for overall facility operation. Credited controls are assigned a higher degree of operational assurance than other controls.

A credited level of control is needed to control a radiation hazard when that hazard, unmitigated, poses *unacceptable risk*, as presented in Figure 4.1. For an ODH, quantitative thresholds for oxygen concentration are used to evaluate consequence as described in Section 4.3.4. The risk matrix for ODH is provided in Appendix F. A credited level of control is needed to control an ODH if a credible, unmitigated accident could result in a worker breathing an atmosphere with an oxygen concentration of 12.5% or less and for which existing SBMS standards do not provide adequate design or operational requirements to ensure worker safety.

As used above, the term "level of control" refers to one or more credited controls that are sufficient to prevent or mitigate the identified accelerator hazard. For neutron facilities, selection criteria were developed to accommodate additional hazards as described in the FSAD-NF.[4-2]

Guidelines for selecting credited controls include the following:

- When either an active or passive device can be credited to ensure the safety function, the passive device is preferred because passive devices are inherently more reliable than active devices.

- If either an engineered control(s) or administrative control(s) could perform the needed safety function, then the engineered control is preferred because engineered controls are generally more reliable than human actions.

- When a choice exists between controls that would prevent an event and controls that could mitigate the consequences of the event, the preventive controls are preferred.

4.2 HAZARD IDENTIFICATION

This section describes the hazard identification performed for each of the major structures of the SNS proton facilities. Hazard identification associated with the neutron facilities in the target building are addressed in the FSAD-NF.[4-2]

The focus in this section is on accelerator-specific hazards. Standard industrial and laboratory hazards, which may exist throughout SNS facilities, are not addressed because they are safely managed by using the ORNL institutional safety program as promulgated through the SBMS, summarized in Section 4. This program includes, for example, modulator testing and coupler conditioning in the RFTF building and RF Annex managed according to SBMS procedures that cover the applicable hazards. The SNS work control policy ensures that evaluations (described in Section 3.3.5.1) are performed, as needed, to identify the standard industrial and laboratory hazards and to match them to control measures to be applied by workers in the field.

Two significant accelerator-specific hazards have been identified: (1) prompt radiation associated with operation of the proton beam and (2) ODHs associated with the cryoplant and SCL. Radiation hazards are discussed in Section 4.2.1, and ODHs are discussed in Section 4.2.2. Section 4.2.3 identifies other hazards associated with the proton facilities.

4.2.1 Radiation Hazards and Shielding

Radiation is a primary hazard associated with the SNS accelerated beam. The most significant radiation hazard is prompt radiation associated with operation of the proton beam. Residual radiation hazards resulting from radioactivity induced by proton beam operation are also present. During the design of the SNS facility, predictive models were used to evaluate potential radiation fields in each area, which then informed shielding design. Shielding is addressed in Section 4.2.1.1, and radiation hazards associated with the various portions of the accelerator are addressed in Section 4.2.1.2.

4.2.1.1 Radiation Shielding

The *SNS Shielding Policy*[4-3] signifies the commitment of SNS management to ensure acceptable shielding is provided for radiation protection and that worker radiation exposures are ALARA. In evaluating radiation hazards at SNS, the shielding design is considered a passive robust design feature managed by rigorous configuration control processes.

Permanent shielding is designed to mitigate the prompt and residual radiation hazard that may be present at SNS. In locations where beam losses may be greater (e.g., collimators), physical barriers may be required; and depending on the area classification, these may be engineered barriers (e.g., locked gates) or simply posted. Because SNS is a production proton accelerator, the proton beam path has not been significantly modified since commissioning was completed, and beam losses produce disperse distributions of gamma and neutron radiation. Therefore, the shielding design relies on massive shielding that surrounds beam areas combined with access control so that radiation levels in accessible areas are ALARA during routine beam operation.

With the intense beam of the SNS facility, relatively high residual activity is possible in several locations (e.g., collimators, ring injection region, ring extraction region). Radiological hazards associated with work in the vicinity of high residual activity are safely managed with the ORNL SBMS Radiological Protection

SBMS subject areas. To work near these locations, ALARA procedures are applied as needed. Local and customized temporary shielding may be brought into place as needed. This process greatly minimizes the potential collective dose for shutdown work performed within the beam enclosures. Furthermore, a cool-down period after shutdown of the accelerator systems may be implemented as needed before entering these areas to reduce the background residual dose.

Shielding Design Guidelines

Shielding design analyses have been integrated into the overall facility design. The permanent shielding and access control areas are configured to support the ORNL SBMS Radiological Protection requirements, which implement the 10 CFR 835[4-4] requirements, including ALARA considerations. Extensive radiation surveys of normal operations, as well as low-intensity simulated beam faults, have been conducted during commissioning and initial operations. Radiation surveys are conducted periodically during routine operations. Shielding surveillance includes periodic inspections of the condition of the berm shielding. These visual and radiation measurement surveys provide assurance and verification of the adequacy of the shielding. In addition, shielding is configuration controlled by procedure in the SNS OPM.[4-8]

Early in design, the SNS Project adopted the following guideline for shielding: the shielding should be designed so that, during normal operations, the dose rate on accessible outside surfaces of the shield should be less than 0.25 mrem/h in areas with no occupancy restriction for workers. This is a guideline rather than a requirement because it is derived from an extremely conservative postulate: 100% occupancy at the shield face outer surface (i.e., so that 2,000 h/year residence time at 0.25 mrem/h would yield an annual exposure of 500 mrem). Adopting a shielding goal below the 0.5 mrem/h objective of 10 CFR 835.1002(b)[4-4] was desired as a means of ensuring that shielding design meets ALARA requirements. Where mission and/or cost considerations make meeting the goal impracticable, the shield is optimized using ALARA principles. Access and residence time can be controlled in many ways, including by area designations, training, and signage. Furthermore, physical factors dictate the decrease of dose rate with distance from the shield surface. Therefore, significantly higher dose rates are often acceptable. The following subsections present shield evaluations in terms of the 0.25 mrem/h guideline value, but instances in which higher values are acceptable are mentioned to indicate examples for which area designations or other factors play a major role in minimizing radiation exposures.

Shielding Analysis Methodology

A strategy using coupled Monte Carlo and multidimensional discrete ordinates calculations has been implemented[4-9] to perform radiation transport analyses when pure Monte Carlo analyses cannot give statistically satisfactory answers. The methodologies are explained in Appendix B, "Shielding Analysis Methodology."

Permanent Shielding Materials

The permanent shielding materials for SNS are primarily the types of materials typically found at large accelerator facilities. For example, concrete and earth provide protection for personnel outside the tunnel for the proton beam transport system (linac, HEBT, ring, and RTBT external to the target building). The concrete for the structural walls is ordinary concrete (~2.34 g/cm^3), and the earthen material (indigenous to the SNS site) has an approximate density range of 1.76 to 1.99 g/cm^3 and an equilibrium moisture content between 20% and 22%.

The primary shielding material for the RTBT inside the target building, the target shielding monolith, the target service bay, and the neutron beamlines is steel and/or concrete. The types of steel used in the shielding include low-carbon steel easily machined into the complex shapes required in many areas of the SNS shield design, recycled steel shield blocks (some of which contain low levels of nonremovable bulk radioactive contamination) of fixed specific sizes, and inexpensive off-specification steel obtained from the end of a steel mill run. (The off-specification steel is generated as the mill transitions from one grade of steel to another and does not generally contain elements that could cause activation problems; the content of the off-specification steel is known and is considered in purchasing.). The different types of concrete used for SNS include ordinary structural concrete, high-density concrete (~3.93 g/cm^3) specifically designed for shielding, and borated concrete (boron content typically on the order of 0.5 to 0.75 wt %). In the design of the permanent shielding for SNS, the concrete used for structural design was integrated into the shield design. In addition to these materials, paraffin, borated paraffin, polyethylene, borated polyethylene, cadmium, boron carbide, and lead are used for local shielding and in special circumstances.

Shielding during Transportation and Storage

Adequate shielding is provided to protect the personnel and the public from the transportation and storage of radioactive materials. Interfaces for the shipping casks and transfer areas (e.g., target service bay, beam dump vault room) are designed to mitigate radiation streaming. SNS has an on-site storage facility for in-process storage of used components (e.g., magnets, shutters), as described in Section 3.2.7.17. Adequate shielding is provided [4-10] to protect site personnel, the public, and the environment from these sources of radiation in accordance with 10 CFR 835 [4-4] and the *SNS Shielding Policy*.[4-3]

Movable Shielding

Movable shielding is permanent shielding designed to be moved to allow access. Significant radiological hazard to facility workers and researchers is possible if movable shielding is displaced without proper care and oversight. The threat involves both prompt (beam-on) and residual (beam-off) radiation. Two simplifying assumptions are reasonable: (1) any shielding blocking a significant hazard is too heavy to be moved by an unaided individual, and (2) under almost all circumstances, the radiation at a given location is higher when the beam is on than when the beam is off. Therefore, safety involving movable shielding is based on configuration control and independent confirmation of acceptable radiation levels under operational conditions.

Shielding that protects workers from a significant hazard typically either weighs at least on the order of a ton or consists of hundreds of concrete blocks; this shielding is either too heavy or unwieldy to be moved by a single, unaided worker in a reasonable time without detection. Operational procedures require a proper review and approval of any planned reduction or change in shielding. The basic approach is tailored to the hazard, considering how radiation levels could change with changes in the shielding. Shielding important to worker safety either is installed in such a way that removal requires special equipment and planning or is designated and labeled as configuration-controlled shielding. Routine inspections by operations staff and periodic area radiological surveys by qualified RCTs confirm the adequacy and integrity of installed shielding. Start-up and periodic radiological area surveys provide independent confirmation that shielding modifications have not compromised safety and that radiological postings remain appropriate. This process provides reasonable assurance that shielding changes do not affect worker safety.

Ensuring radiation safety when shielding has been removed may require that beam operation be prevented or be restricted from reaching the area with decreased shielding. The "Hold for Radiation Safety (RS Hold)" administrative system of locking and tagging of equipment or beamlines has been developed and is used for such cases. A written procedure specifies requirements for establishing and removing radiation safety locks and tags.

PPS interlocks may be used for movable shielding in certain cases to augment the administrative controls. For example, PPS trap-key interlocks provide assurance that steel shield blocks are in place at the HEBT and RTBT truck locks, and PPS monitors the position of the shield door between the front-end and linac sections.

4.2.1.2 Radiation Hazards in Accelerator Structures

The following sections describe the radiation hazards that have been identified for each accelerator structure. These hazards are considered within the context of routine operations and designed shielding for that structure. Analysis of the radiation hazards associated with accident beam spill scenarios requires further evaluation as provided in Section 4.3. One of the primary objectives of the PPU project was to increase the machine capability to enable normal operations at a beam energy of 1.3 GeV. Because the beam energy has the potential to significantly affect the character of radiation hazards (e.g., geometry of radiation fields resulting from beam losses, activation of beam line components), a significant effort was undertaken to revisit the conclusions of existing radiation hazard evaluation and determine whether operations at 1.3 GeV would require new or different controls to ensure the safety of workers, the public, or the environment. The results of these evaluations indicate that the activation of beam line components could increase moderately compared with existing estimates, by about a factor of two.[4-50] The effect on prompt radiation fields caused by beam loss was determined to require no modifications primarily because the increased beam energy tends to shift the radiation fields in the forward direction.[4-51] The worst-case shielding thickness is typically for radiation emitted perpendicular to the beam direction, which is reduced when beam energy is increased to 1.3 GeV and proton current is accordingly reduced to obtain an equivalent power. Thus, dose rates outside of beam enclosures during accident scenarios are not expected to increase because of increased beam energy of 1.3 GeV.

Front-End Building

The principal beamline components inside the Front-End building are the ion source, the LEBT line, the RFQ, and the MEBT line, including the first two DTL tanks. The DTL tanks are behind the shield wall that separates the linac tunnel from the Front-End building. The primary sources of radiation in this area are due to (a) neutron and gamma production by the interaction of proton beam losses with the DTL structural elements (copper), (b) x-ray production by RF in the front end and DTL, and (c) back-streaming radiation from the linac operation. Calculations based on expected beam losses and measurements of dose buildup owing to dark current effects have provided the basis for concrete and steel shielding around the DTL tanks to yield the desired dose rates in the Front-End building and other areas outside of the tunnel[4-47]. An optimized shielding configuration addresses the back-streaming radiation component.[4-11] Shielding features of the production front end components are reproduced in the ion test stand as needed to ensure that test-stand activities have a similarly low radiation profile.

Most of the electrons extracted, together with the negative ions, are steered toward and intercepted by the e-dump, which is kept at a positive voltage in the range of 2 to 7 kV with respect to the source body. Depending on this voltage, the extractor voltage, and the state of cesiation, a fraction of the electrons miss the e-dump; most of them impact on the e-target mounted on the extractor. A few appear to miss the extractor and impact on the vacuum enclosure. The impact energies between 65 and 85 kV can cause a radiation field in excess of about 1 mrem/h. This hazard is not significant, but it is mitigated, as needed, with lead shielding to minimize worker exposure in accordance with ALARA principles.

With a maximum beam energy of approximately 2.5 MeV in the MEBT, a measurable dose rate (e.g., from the p–^{65}Cu and p–Ti interactions) may occur if the beam is mis-steered onto any copper structure. Furthermore, beam loss may require prompt radiation controls and/or local shielding in the area. A measurable neutron dose rate has been observed near the MEBT rebuncher in an occupied area owing to (p,n) reactions in copper at 2.5 MeV. Localized gamma dose rates of up to 80 mrem/h have also been found in the MEBT rebuncher area. Radiological surveys are performed regularly to document conditions, and the area is posted appropriately for the measured conditions.

Radiation hazards associated with test stand(s) that may be operated in the Front-End building are similar to or less than those posed by the operational ion-source equipment, and the test stands are operated in accordance with the same radiation safety and ALARA requirements.

Linac

The principal linac components include the DTL, CCL, and SCL sections that accelerate the H^- beam to the required energy (~1.3 GeV energy range). The permanent shielding for the linac is designed to protect personnel from anticipated normal operational beam losses[4-12] as defined by the SNS/Accelerator Physics Technical Note 07.[4-13]

The normal conducting (warm) linac structures are composed of a DTL, which accelerates the beam to about 87 MeV, followed immediately by a CCL, which further accelerates the H^- beam to around 186 MeV. In both types of linac structures, the primary loss points of concern are those located adjacent to penetrations in the bulk shielding for RF waveguides and utilities. For each penetration, the packing factors (e.g., cables, water lines) have been properly estimated, and the attenuation factors for prompt radiation have been calculated (as a function of beam energy).

The two SCL structures have geometric beta (i.e., relative-phase velocity) design fixed at $\beta = 0.61$ (accelerating the beam to ~330 MeV) and $\beta = 0.81$, producing a final beam energy at the end of the linac of about 1.3 GeV. Transverse focusing of the beam is provided in normal (warm) conducting straight sections throughout the SCL; these locations are where beam loss (if any) is most likely to occur. The same concerns noted for the warm linac structures also apply in these cases. The penetrations have been carefully evaluated and potentially occupied areas adjacent to these beam enclosures appropriately classified.

The permanent shielding for the linac consists of the 1.5 ft thick concrete linac tunnel structural walls and a 17 ft thick earth berm made of earthen material indigenous to the SNS site (a typical berm cross section is illustrated in Figure 3.23). Between the linac tunnel and Klystron Gallery, the permanent shielding consists of the 1.5 ft thick concrete linac tunnel structural walls, an earthen berm 15 ft and 10 in. thick, and a 1.5 ft thick concrete Klystron gallery structural wall. The dose rate on top of the berm and inside the Klystron building due to normal operational beam losses in the linac is measured as less than about 1 mrem/h.[4-14] The klystrons emit a field of x-rays, yielding a localized dose rate in the Klystron building of about 0.3 mrem/h (without external shielding) at floor level.

Several penetrations through the earth berm require additional consideration with respect to the shield design—in particular, the personnel and equipment egresses,[4-43] klystron waveguides, survey pipes, and ventilation exhaust and intake ducts.[4-44] Near the chase penetrations on the Klystron Gallery north wall, dose rates depend on the details of the loss pattern but are generally below 1 mrem/h. DTL tanks are equipped with Faraday cups that can be inserted into the beam for diagnostics. A tuning beam stop located downstream of the CCL creates a loss point that has been modeled in detail. The resulting localized radiation is reduced by shadow shielding in the beam tunnel and/or by block walls in the Klystron Gallery, as appropriate. In the Klystron Gallery, radiation buffer areas may be created near penetrations in klystron housings—these radiation fields are appropriately shielded and/or posted. Detailed analyses (including streaming) have been performed for penetrations connecting the Klystron Gallery to the beam tunnel.[4-15,4-16,4-17] Various shielding types (e.g., polymer bead fill material, stacked concrete blocks, etc.) and other appropriate countermeasures have been evaluated and installed as needed to protect workers in the Klystron Gallery from radiation produced by operations in the beam tunnel.

HEBT, Ring, and RTBT

The remainder of the proton beam transport system includes the HEBT tunnel, the ring, and the RTBT tunnel. The HEBT transports the H^- beam exiting the SCL for injection into the ring, and the RTBT transports the proton beam from the ring extraction point to the target. The HEBT consists of a straight section of the linac tunnel, a 90° arc, and another straight section leading into the ring. After being accelerated to the full energy of 1.3 GeV, the H^- beam is passed through two transverse collimators before being transported into the bend section of the HEBT. The maximum losses at the transverse collimators are assumed by calculation to be 10^{-5} of proton beam current.

The ring accumulates the protons from the linac in pulses. It includes four major straight sections: (1) injection, (2) collimation, (3) extraction, and (4) RF, linked by 90° arcs. The permanent shielding for the HEBT, ring, and RTBT is designed to protect personnel from normal uncontrolled operational beam losses of a maximum of 1 W/m. The maximum controlled losses for a collimator in the collimator section are assumed to be about 10^{-3} of the total proton beam current.[4-46]

The dose rates on top of the berm owing to normal operational beam losses in the HEBT, ring, and RTBT are calculated to range up to about 1 mrem/h for the HEBT and RTBT. The injection, RF, and extraction sections of the ring have dose rates of less than 0.25 mrem/h[4-18,4-19] at approximately 1 MW beam power. Dose rates on the order of 1 mrem/h on the top of the berm would be acceptable because the berm is occupied only a small fraction of the time.

As is the case with the linac, several penetrations through the earth berm require additional consideration with respect to the shield design. In particular, the penetrations include the personnel egresses, truck accesses for the HEBT and RTBT, survey pipes, and ventilation exhaust and intake ducts. Penetration analyses have been performed[4-20,4-21,4-22,4-23] to determine that the dose rate emanating from these penetrations is less than 0.25 mrem/h; this analysis has been verified by surveys at approximately 1 MW beam power. A permanently installed shield wall labyrinth in the HEBT tunnel protects the maintenance and service personnel in the ring from radiation generated by beam spills during the tuning of the linac systems. This shield wall labyrinth is designed for the worst case of 7.5 kW beam power incident to the first dipole face.[4-45]

The RTBT stub (Section 3.2.7.3) was designed consistently with the existing tunnel sections. The concrete and earth berm shielding were determined to provide adequate shielding for operational conditions following the PPU project.[4-48] A shielding plug is included in the design of the RTBT stub to provide a both a physical barrier and radiation shielding, preventing personnel from accessing the beam tunnels via the RTBT stub and limiting the potential radiation levels in the accessible portion of the tunnel. The shielding plug was designed to reduce normal operational radiation levels below 0.25 mrem/hr and accident radiation levels below10 R/hr.[4-49] An interlocked area radiation monitor is also included in the design to ensure prompt beam cutoff in the case of an accidental beam spill that leads to significant radiation levels in the occupiable area of the RTBT stub.

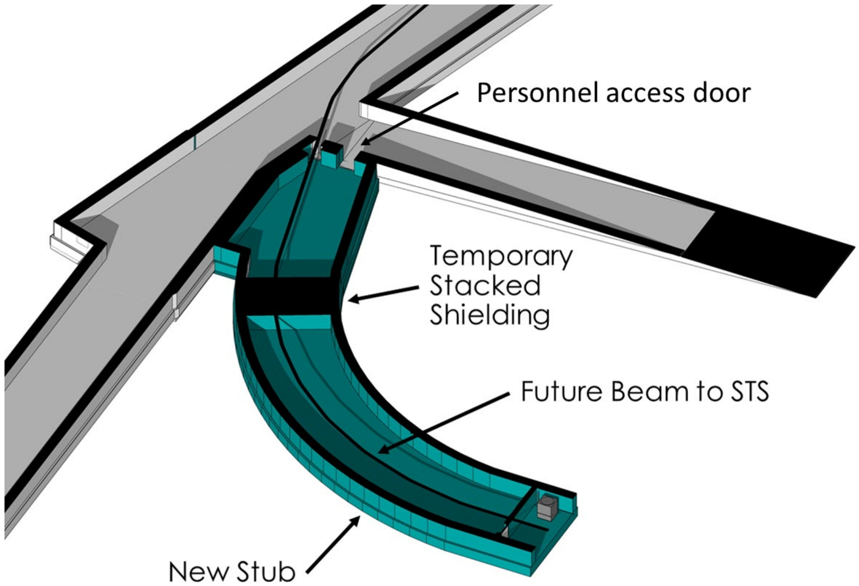

Figure 4.2. RTBT stub.

These beam areas have essentially all the diagnostic capabilities (and mitigation methods) listed for the beam dumps discussed in Section 4.2.1.3. Additional interlocked area radiation monitors are placed outside of the beam enclosure nearest to the points where losses may be expected (such as injection, extraction, and the ring collimators), as well as at the access points to these beam enclosures.

4.2.1.3 Radiation Hazards from Beam dumps

Beam dumps are necessary for proper operation of the SNS accelerator, as discussed in Section 3.2.1.4. Beam dumps activate the dump material, some of which is sufficiently long lived to present a hazard after beam operation has ceased. These hazards include potential exposure to direct radiation and accidentally dispersed particles of activated material.

Three proton beam dumps are located outside the accelerator tunnel: (1) a linac tuning dump designed for 7.5 kW, (2) a ring injection dump designed for 150 kW, and (3) a ring extraction dump designed for 7.5 kW.[4-24] The low-power linac and extraction dumps are designed to be passively cooled, whereas the injection dump is water cooled. The bulk shielding for all dumps has the same design with respect to materials and layout.

The permanent bulk shield region is composed of multi-ton shield blocks with miscellaneous smaller blocks surrounding the beam-stop enclosure and the proton beam tube. The bulk shield blocks are supported by the building concrete structure/foundation and are enclosed in a steel liner. The bulk shield is designed to provide adequate radiation shielding to permit intermittent occupancy in the service area located above the ring injection beam-dump vault and to mitigate significant soil and groundwater activation for all beam dumps (Section 3.2.1.4). To mitigate soil and groundwater activation, the permanent shielding was designed to reduce the neutron flux entering the soil to a level less than 10^4 n/cm^2·sec.[4-25]

The three rooms located above the ring injection beam dump are part of the beam-dump building. They are the dump vault, the utility service vault, and the electrical service vault. The dose rates in these rooms caused by normal beam-dump operation are calculated to be about 1–2 mrem/h, tens of rem/h, and less than 0.25 mrem/h, respectively. The higher dose rates in the utility service vault of the ring injection dump occur only during full-power beam operation and are due to water activation products (including Be-7, which plates out inside cooling water pipes) within the primary cooling loops. As discussed in Section 4.3.3, the PPS controls access to the utility vault of the injection dump. Within minutes after beam cutoff, the radiation level in the injection dump utility service vault will have decreased to the much lower level dominated by the longer-lived Be-7. Localized shielding is used to help mitigate these radiation sources with respect to personnel access for maintenance procedures. Radiological hazards associated with work in the vicinity of high residual activity are safely managed by following the guidance provided by the ORNL SBMS Radiological Protection SBMS subject areas. The walls of the three beam-dump vault rooms are made of ordinary concrete whose thickness is determined by a combination of structural and shielding requirements.

The off-momentum beam stop (described in Section 3.2.1.3) is located inside the HEBT tunnel, and its design is similar to that of the collimators. Like the collimators, it has local shielding to minimize the radiation field in the tunnel when workers access the tunnel after beam operation. The HEBT off-momentum dump is air cooled and designed to operate at 5 kW or less. The beamline connecting to the off-momentum beam stop is equipped with a collection of beam current transformers, beam loss monitors, and thermocouples within each beam dump. Some of these diagnostics are used as inputs to the MPS to remove the beam permit (inhibit the beam) if potentially damaging beam conditions occur. In addition, interlocked area radiation monitors are placed outside the beam enclosures to respond to significantly elevated radiation levels during beam operations.

Exposure to direct radiation resulting from beam dump activation and exposure to released radioactivity is addressed in Section 4.3.3.

4.2.1.4 Radiation Hazards in the RF Test Facility

Conditioning of superconducting cavities takes place in the shielded cave in the RFTF. The conditioning is a controlled process that has the potential to create a high-radiation area because of x-ray production. For this reason, an access control interlock system based on the PPS design, but implemented separately for this facility, is provided. Although the radiation hazard is lower than the radiation hazard in the accelerator tunnel, the test cave access control interlock system is designed and maintained in a similar fashion as the PPS. The RF test cave access control interlock system also provides oxygen deficiency monitoring for the cave, and audible and visible alarms are activated if low oxygen is detected as a result of an inadvertent helium release in the cave (Section 4.2.2). Radiation and low-oxygen hazards in the RFTF are safely managed under the provisions of the ORNL SBMS.

Modules being tested and evaluated in the test cave are considered research and development devices, and radiation-generating-device requirements do not apply. The PPS-like protection system is certified annually and meets the physical control requirements for high and very high radiation areas detailed in 10 CFR 835.502. The test cave facility is not operated unless the access control interlock system is fully functional and in certification.

4.2.2 Oxygen Deficiency Hazards

Cryogenic systems in the SCL and CHL have a recognized ODH because of the relatively large inventory of cryogenic helium involved. Most ODHs at ORNL can be safely managed through the lab-wide SBMS procedures. At the time of installation and commissioning, the SNS linac and CHL were determined to pose unique ODH hazards (e.g., a long tunnel with few exits, large helium inventory, complex cryogenic systems) that merited analysis within the FSAD (Section 4.3.4). ODHs associated with other activities at

SNS that involve the use of gases with the potential to create ODHs are considered standard industrial hazards that are safely managed under the provisions of the SBMS subject areas dealing with ODHs.

The general approach to ODH analysis and control developed for the CHL and linac has been extended to the RFTF. Activities in the RFTF present an ODH when cryogenic helium is piped into the RF test cave for conditioning of cryomodules, which occurs periodically. An inadvertent leak of helium into the test cave could result in a decreased oxygen concentration in the cave. The scale of a potential helium release in the RFTF cave is small compared with potential releases associated with the linac and CHL. An ODH system is provided for the RFTF that is designed and maintained in a similar fashion to the ODH system used to protect the linac and CHL. ODH hazards associated with the RFTF are safely managed under the provisions of the SBMS Cryogenic Safety subject area.

4.2.3 Other Hazards

This section presents a summary of evaluations performed for other hazards present in the accelerator facility. These hazards were determined to be standard industrial hazards adequately managed by ORNL safety management programs in SBMS.

4.2.3.1 Electrical Hazards

As indicated in Section 3.3.5.2, the SNS design requires the power supply connections to certain tunnel magnets to have exposed connectors. Access to these areas is granted to personnel who have the proper training, who plan the work to be done, and who follow procedures for LTV and/or electrical safety in accordance with the SNS OPM and SBMS.

All electrical maintenance, surveillance, etc. is performed according to the requirements of the ORNL SBMS Electrical Safety and Lock/Tag/Verify subject areas.

4.2.3.2 Magnetic Hazards

In a few instances, it may be necessary to work near magnetic elements while they are powered. Appropriate control over access modes and training requirements address these concerns for high magnetic fields. In addition, procedures note that nonferrous materials must be used for work around elements with a high magnetic field, both for the protection of the worker and to eliminate the possibility of damage to equipment.

4.2.3.3 Nonionizing Radiation

With regard to potential sources of nonionizing radiation, the waveguides between the klystrons and the linac accelerating cavities could present an RF hazard if opened while under power. For both concerns, strict configuration control policies are in place for all operating modes, and possible hazards are prominently posted where required. Class IV lasers are in service in proton facilities; they are controlled and used in accordance with ORNL SBMS requirements.

4.2.3.4 Fire Hazards

Fire is a standard industrial hazard controlled through the ORNL SBMS Fire Protection, Prevention and Suppression subject area. The accelerator facilities fire hazard analyses (FHAs) address specific fire hazards in detail. A listing of FHAs is provided in Appendix E.

Fire protection and prevention are ensured through implementation of the ORNL SBMS Subject Area Fire Protection, Prevention and Control. The following material summarizes the results of the SNS accelerator facilities FHA, including two instances where equivalency analyses were performed as required by the unique accelerator-specific configuration of SNS. All facilities are being provided with a level of fire protection that is sufficient to have filled the requirements of the best-protected class of industrial risks and provide protection to achieve multiple layers of protection. Unless otherwise noted below, standard fire protection features for all accelerator facilities and support buildings include emergency lighting and exit signs, egress arrangements in accordance with NFPA 101,[4-5] fire area separation from adjacent buildings, automatic fire sprinkler protection in accordance with NFPA 13,[4-26] a fire alarm system in accordance with NFPA 72,[4-27] and portable fire extinguishers in accordance with NFPA 10.[4-28]

Building fire alarm systems include manual pull stations and occupant alarm notification in accordance with NFPA 101,[4-5] alarm monitoring and supervision of all fire suppression systems, HVAC smoke detection in accordance with NFPA 90A,[4-29] and fire detection for special hazard areas. Fire detection provided for special hazards is noted below.

The maximum possible fire loss for all fire areas is within the limits established by DOE, or else redundant fire protection is being provided that meets DOE objectives. Maximum possible fire loss details are provided in the FHA.

Fire prevention includes the use of a welding/burning/hot work permit system (SNS-specific procedure) to control these ignition hazards and the use of an impairment tracking system (ORNL program) to control the hazards associated with impaired fire suppression systems. Work control procedures are also intended to identify and to prevent potential fire hazards associated with job-specific tasks.

The accelerator facilities FHAs address buildings at the SNS site. The FHAs identify and analyze fire hazards and the fire protection systems required to mitigate the hazards in accordance with applicable DOE Orders. The methodologies for performing an FHA are provided in the Implementation Guide for use with DOE Orders 420.1C, *Facility Safety*, and 440.1, *Fire Safety Program*. These methodologies are used as guidance when performing FHAs.

Fire protection requirements for the facility are based on the codes and standards in effect at the time the facility was designed, which establishes the Codes of Record and the current version of NFPA 101.[4-5]

In a limited number of circumstances, approved equivalency evaluations are referenced when an SNS implementation differs from the NFPA standard. In one instance, SNS required a unique implementation to ensure both fire safety and radiation safety in the accelerator tunnel as documented in *Equivalency Analysis Document—Beam Tunnel Life Safety Features.*[4-30]

- The locking arrangement of two interior PPS gates and one interior PPS door provided for radiation safety does not conform to NFPA 101[4-5] provisions.

- The tread depth on three of the four beam pipe crossover stairs does not meet the dimensional criteria for equipment access stairs outlined by NFPA 101.[4-5]

- The travel distance to an exit from the north section of the ring is 440 ft, which is 40 ft longer than the travel distance to an exit allowed by NFPA 101.[4-5]

Future modifications, if any, will have to meet PPS and fire safety requirements.

4.2.3.5 Control and Use of Hazardous Materials

SNS ensures worker safety regarding hazardous materials in accordance with the ORNL SBMS Subject Area, including the Worker Safety and Health Management System, the Work/Project Planning and Control Management System, and the Chemical Safety Subject Area.

4.2.3.6 Environmental Hazards

Environmental hazards are addressed in Section 4.4.

4.3 HAZARD ANALYSIS

This section describes the hazard analysis performed for the SNS proton facilities. Hazards of the neutron facilities in the target building are addressed in the FSAD-NF.[4-2] The analyses are performed using the methodology described in Section 4.1.

This section focuses on the accelerator-specific hazards identified in Section 4.2. These hazards include potential exposure to beam-induced prompt and residual radiation both inside and outside the accelerator tunnels (including the beam stops) and ODHs associated with the CHL and SCL.

Radiation hazards inside and outside of the accelerator tunnel enclosures are addressed in Section 4.3.1 and Section 4.3.2. Radiation hazards associated with the beam dumps are addressed in Section 4.3.3. ODH hazards are addressed in Section 4.3.4.

4.3.1 Radiation Hazards Inside Beam Enclosures

This section addresses accelerator-specific radiation hazards present inside the beam enclosures (tunnels) including the linac, HEBT, ring, and RTBT. Sources of radiation inside the tunnels may include prompt radiation associated with normal beam operation, prompt radiation due to transient beam faults, and radiation from activated materials.

During routine beam operations, the SNS beam generates prompt radiation (primarily fast neutrons) due to local beam loss at discrete locations of the accelerator lattice. The relatively large ratio of physical apertures to nominal beam sizes, as well as the relatively narrow tuning range of most of the devices in the facility, limits a credible fault of uncontrolled beam loss at any single point. Collimators are placed at strategic locations in the HEBT, the ring, and the RTBT to control beam losses. Bulk shielding is designed to attenuate prompt radiation due to normal local beam losses to meet the defined classifications for areas adjacent to and near the beam enclosures. Dose rates owing to transient excursions (beam faults) greater than this amount have been estimated by detailed calculation and, where necessary, are mitigated by additional shielding and/or PPS interlocked area radiation monitors in the PPS to help protect personnel and ensure the integrity of area classification (further discussion is in Sections 4.1.1.1 and 4.3.2.2). Depending on each area classification, associated access restrictions may apply.

The prompt radiation level inside the tunnel is potentially excessive and presents an unacceptable risk. The PPS is the credited control designated to protect workers from excessive prompt radiation in the tunnel. The PPS is credited for protecting workers in the tunnel by (1) preventing beam operation in tunnel segments not cleared of personnel and (2) shutting off beam if personnel enter a segment where beam is permitted (Sections 3.2.4 and 5.2.1).

Additional non-credited layers of safety include the MPS that provides several means of monitoring beam acceleration, beam loss, and transport and provides an additional beam interlock if the facility is not operating properly. Administrative controls play a significant role in the safe operation of any accelerator facility. These administrative controls include accelerator operating procedures, tunnel sweep procedures, tunnel access, and sweep training. The PPS also provides non-credited features that support sweeps, including warnings in the tunnel before the initiation of beam operations and provides beam status indications at tunnel entrances.

The credited and non-credited mitigation layers combine to make the mitigated risk extremely low. Table 4.1 summarizes the hazard evaluation for workers inside the beam tunnel.

Access control combined with massive shielding protects workers from prompt radiation associated with beam production. Should shielding be inadvertently removed or altered so that it no longer provides sufficient shielding, workers could potentially be exposed to excessive levels of radiation. Section 4.2.1.1 addresses hazards and controls associated with movable shielding. Table 4.2 summarizes the qualitative analysis of risks associated with the inadvertent removal of shielding and finds that the risk is adequately addressed by provisions of the ORNL Radiological Protection Program and layers of safety provided by the mitigative items listed in the table.

Activated structural materials create a residual radiation level inside the tunnel that is an ALARA consideration for personnel who must access the tunnel. Numerous locations within the beam enclosures have residual activation. Controlling worker exposure to activated components is safely managed as part of the ORNL Radiological Protection SBMS.

When RF power is delivered to the linac structures, the x-ray hazard in the linac beam enclosure can create a high-radiation area. Therefore, consistent with requirements for a high-radiation area, access to the linac or HEBT is restricted during RF system operation. Because of the potential x-ray hazard, as well as anticipated residual activity in most of the SNS beam enclosures (after normal operation), these areas are locally shielded and access controlled. The PPS provides the non-credited function of removing power to the RF supplies (klystrons) when the tunnel is open for worker access. In the Klystron Gallery, the klystrons generate x-ray radiation, but shielding is installed to ensure nearly full attenuation of the source term at floor level.

Table 4.1. Qualitative risk assessment for prompt radiation inside the proton beam enclosures

FACILITY NAME: SNS accelerator systems
SYSTEM: Beam enclosures
SUB-SYSTEM: Linac, HEBT, ring, RTBT
HAZARD: Prompt radiation (proton beam) inside beam enclosures

Event	Person inside enclosure during proton beam operation
Possible consequences, hazards	Personal injury or death due to prompt radiation associated with the proton beam. Worker dose could exceed 25 rem
Potential initiators	Person enters enclosure inadvertently; person(s) fails to leave before beam initiated

Risk assessment prior to mitigation

Note: Refer to Figure 4.1 for an explanation of consequence, frequency, and risk levels. "Low" and "Extremely low" risk levels are considered acceptable.

Consequence:	(X) High	( ) Medium	( ) Low	( ) Extremely low
Probability w/o mitigation:	( ) Anticipated high	(X) Anticipated medium	( ) Unlikely	( ) Extremely unlikely
Risk category:	(X) High risk	( ) Medium	( ) Low risk	( ) Extremely low

Does the hazard require a credited control per Section 4.1.2? Y/N _Yes_

Hazard mitigation	1. PPS automatic beam cutoff on access violation (CREDITED) 2. PPS control of critical devices to prevent beam operation in segments not cleared of personnel. (CREDITED) 3. PPS access control features to prevent inadvertent access to beam enclosures during beam operations (e.g., control of magnetic door locks) 4. MPS monitoring and controls 5. Accelerator operations procedures 6. Worker training (e.g., tunnel access and sweep training) 7. PPS beam-on warning lights outside entrances 8. Tunnel sweep procedures performed only by trained, qualified persons 9. PPS features that support conduct of administrative sweep 10. Repeated audible and visual warnings initiated by PPS inside the tunnel before initiation of proton beam allow any remaining unswept person sufficient time to evacuate or actuate a PPS manual beam shutdown station before the beam starts

Risk assessment following mitigation

Consequence	() High	(X) Medium	( ) Low	( ) Extremely low
Probability	( ) Anticipated high	( ) Anticipated medium	( ) Unlikely	(X) Extremely unlikely
Risk category	( ) High risk	( ) Medium	( ) Low risk	(X) Extremely low

Table 4.2. Qualitative risk assessment for inadvertent or unauthorized removal of radiation shielding

FACILITY NAME: SNS accelerator systems
SYSTEM: Areas inside and at the boundary of beam enclosures
SUB-SYSTEM: Linac, HEBT, ring, RTBT
HAZARD: Prompt radiation outside beam enclosures

Event	Removal of necessary radiation shielding within or at boundary of beam enclosure resulting in excess radiation outside of the enclosure
Possible consequences, hazards	Personnel radiation exposure. Passive shielding and inherent factors minimize the possibility of injury due to radiation exposure. 10 CFR 835[4-5] regulations regarding area designations could temporarily be violated for unmitigated event.
Potential initiators	Personnel not following shielding configuration control policies and procedures.

Risk assessment prior to mitigation

Consequence	( ) High	(X) Medium	() Low	() Extremely low
Frequency	() Anticipated high	() Anticipated medium	(**X**) Unlikely	( ) Extremely unlikely
Risk Category	( ) High risk	( ) Moderate	(**X**) Low Risk	( ) Extremely low

Does the hazard require a credited control per Section 4.1.2? Y/N No—Hazard adequately addressed by ORNL Radiological Protection Program and mitigation items as listed below.

Hazard mitigation	1. ORNL Radiological Protection Program 2. Heavy weight of critical shielding is an inherent safety factor helping prevent unauthorized removal of shielding 3. Staff training on shielding configuration control procedures 4. Tailored approach to shielding control: a. Posting and labeling of configuration-controlled shielding. b. Securing shielding to require removal by tooling c. PPS-interlocks for select movable shielding 5. Supervision of SNS radiation safety officer, including use of RS Hold locks and tags where appropriate 6. Inspection tours by operations personnel while securing the beam enclosures and periodic surveys per ORNL SBMS Radiological Protections procedures 7. PPS-interlocked area radiation monitors for beam cutoff.

Risk assessment following mitigation

Consequence	( ) High	( ) Medium	(X) Low	( ) Extremely low
Probability	( ) Anticipated high	( ) Anticipated medium	( ) Unlikely	(X) Extremely unlikely
Risk Category	( ) High risk	( ) Moderate	( ) Low risk	(X) Extremely low

4.3.2 Radiation Hazards Outside Beam Enclosures

The SNS accelerator is designed to produce and transport to the target, essentially undiminished, a beam of pulsed high-energy protons. The many devices in the linac, HEBT, ring, and RTBT are designed to accelerate, accumulate, focus, and shape the beam pulses with only very small losses to ensure that a maximum number of protons reach the target. Shielding is designed to protect personnel outside beam enclosures during routine operational beam losses. A failure of one or more of the accelerator beam conditioning devices could result in misdirection of some fraction of the beam so that it impacts the beam tube and surrounding structures inside the beam enclosure generating greatly elevated radiation fields. A maximum credible fault would be one that produces the greatest beam loss for the longest period of time without transcending the realm of plausibility. A further stipulation is that the loss be such as to cause elevated radiation levels in area(s) outside of the beam enclosures that could be accessed by workers. This section discusses faults that could cause a beam spill, provides bounding dose rate estimates for beam spill accidents, and demonstrates that a combination of inherent factors and automatic control features yields an extremely low mitigated hazard. As discussed in Section 4.2.1.2, increasing the beam energy from 1 GeV to 1.3 GeV increases forward scattering of the generated radiation. Forward directed radiation from a beam spill is a lesser contributor to radiation levels outside of beam enclosures than radiation emitted perpendicular to the beam direction, so the 1 GeV evaluation provided here bounds the potential consequences when operating at greater energy levels, i.e., at 1.3 GeV.

4.3.2.1 Fault Mechanisms

During beam operations, SNS generates prompt radiation owing to local beam loss at discrete locations of the accelerator lattice. The relatively large ratios of physical apertures to nominal beam sizes, as well as the relatively narrow tuning range of most of the devices in the facility, result in very low normal losses. Various equipment faults could allow this ideal situation to degrade. Four types of failure scenarios are presented: (1) magnetics failure, (2) RF failure, (3) control system failure, and (4) human error.

1. Magnetics failure. The failure of the magnetics system to remain at the correct value for beam transport due to possible failure of a magnetic element, the power supply, the control system, or human error leads to unintended beam loss.

   The ratio of the "operating beam emittance" to the physical acceptance is relatively small once the beam is accelerated beyond the copper structures. This means that the likelihood of an off-momentum and/or off-trajectory particle being lost within superconducting accelerator structure or beam transport sections, other than at collimator locations, is quite small. Once lost, that portion of the beam can no longer be lost elsewhere. This is also true in the ring because the collimator acceptance is less than the dynamic aperture of the circulating beam.

   With only a few exceptions the magnetic elements of SNS are constructed using solid core iron yokes; therefore, because of large eddy currents, the magnetic field rise (and fall) time is large (effective persistence of the magnetic field) compared with the nominal beam pulse width of 1 ms. This inherent physical characteristic ensures that the beam control system and MPS are highly likely to stop beam production before a significant portion of the beam can stray out of the beam tube.

   As described in Section 3.2.2.3, the MPS is a protection system designed to prevent damage to and excessive irradiation of accelerator system components. One MPS designed specifically for this purpose is the BLMS, which consists of approximately 260 ion chambers distributed around the linac, ring, and beam transport lines. These ion chambers detect beam loss by detecting the secondary particles from lost beam interactions. Predetermined and experimentally measured loss limits are used to set the maximum acceptable losses allowed by the BLMS. The MPS is designed to prevent the beam from doing damage to equipment and is designed to detect faults and to interrupt the beam very quickly, in many cases within 20 μs. The BLMS is designed to truncate the beam pulse train in mid-pulse, reduce the repetition rate of the accelerator, or turn it off, depending on the severity of the beam loss. Additionally, the MPS is used to detect current failure in several critical beam isolation magnets via PLC analog input modules.

   Other magnetic systems failures are detected and reported via the EPICS. The anticipated response time of EPICS fault detection is 1 s. Section 3.2.2.2 explains the relationship between the PPS, the MPS, and the EPICS-based supervisory control system.

2. RF system failure. Failure of the RF system would lead to the inability of the accelerator system to deliver the full energy of the beam. The most serious of these losses, from an occupational exposure standpoint, might prove to be loss of RF in the first DTL section. Loss of RF phase or amplitude would lead to complete loss of beam in the first DTL section. The MPS monitors these systems and takes the appropriate action.

3. Control systems failure. Control systems failures are assumed to have the same consequences as magnetics or RF system failures.

4. Human error. Failures due to human error are assumed to have the same consequences as magnetics or RF system failures.

As part of the commissioning process, the shielding attenuation factors were verified throughout the SNS accelerator facility using the beam in controlled studies at low average intensity (fault studies).

4.3.2.2 Maximum Credible Beam Spill

Doses outside the beam enclosures during normal beam operation are within the regulatory limits set by 10 CFR 835,[4-4] including the application of ALARA. The areas immediately outside the beam enclosures, including the large area of the top and side of the earth berm, may be posted as controlled or radiation buffer areas should the need arise. The top and sides of the earth berm are not routinely occupied. Personnel inhabit these areas only for specified tasks. As discussed in Section 4.2.1.2, normal radiation levels have been calculated to be in the neighborhood of 0.25 mrem/h for most areas outside the tunnel shielding, with higher levels above the relatively small number of components that have higher expected steady state losses, such as collimators. Radiation dose rate measurements at near-design power levels typically find no measurable radiation in occupied areas adjacent to Proton Facility beam tunnel enclosures.

Radiation levels potentially go up outside beam enclosures during significant localized beam spills as the accelerated charged particles strike the beam tube and surrounding structures. The situation is inherently a transient one. For example, it takes time for actual beam loss conditions to occur (e.g., loss of magnetic flux does not diminish instantly following power supply loss). Several mitigative factors serve to minimize the impact and duration of a high-power localized beam spill including the following:

1. Beam loss monitors tied to the MPS are designed to interrupt the beam in a time frame less than that of a single pulse.

2. An inherent physics-based protection against the most severe beam spills is that a highly localized beam loss at high beam power would cause failure of the beam tube's vacuum boundary, thus inhibiting beam.

3. If such a beam spill were to occur in the superconducting portion of the linac, beam loss, resulting in heating of the niobium structure would lead to beam shutdown through the MPS via the linac vacuum and RF systems in addition to the beam loss monitors.

4. Control room indications provide the operator with timely warnings of significant beam problems allowing the operator to shut the beam down in a controlled fashion. It is speculated that 10 min is a plausible maximum time that such a condition could exist without operator intervention.

5. Because such a spill would be localized by its nature, the probability that an individual would occupy the area adjacent to the spill at the exact time that the spill occurs is small.

Calculations have been completed for a range of highly unlikely, worst-case beam faults. Each of these faults would be highly unlikely because of all the simultaneous failures that would have to take place concomitantly. The results provide bounding estimates of accident-related radiation dose rates outside the enclosures by making the following highly improbable assumptions:

- The entire beam at full 2 MW nominal evaluation power is lost instantaneously at one location and
- The misdirected beam continues in its misdirected path, regardless of
  - the effect of a localized high-power beam loss on the beam tube integrity
  - the automatic beam trip
  - the actions of operations personnel

The purpose of these calculations is to provide sufficient quantification to allow hazard analysis to be completed and mitigation adequacy to be evaluated. The calculations were performed for the linac, HEBT, ring and RTBT portion of the accelerator because this is where, under the hypothetical assumptions described previously, the localized loss of a large fraction of the beam could occur. Two basic failure geometries were investigated:

1. The turning magnets fail such that the spilled beam exits the beam tube in a tangential path toward the tunnel side wall without passing through any other major structures before hitting the side wall. (These magnets are monitored by the MPS.)

2. An unspecified failure causes the beam to hit a major structure (assumed to be a dipole in this case) close to the middle portion of the tunnel.

The results bracket the instantaneous radiation dose rate at the worst point on top of the shielding berm at about 1 rem/h for the first case and at about 20 rem/h for the second case.[4-16] The longer length of shielding berm through which the radiation has to travel contributes to the lower results for the first case. For workers in the Klystron Gallery, penetrations to the linac tunnel provide a path for streaming radiation should a full power beam spill occur in the tunnel adjacent to the penetrations. The streaming path is attenuated by a combination of shielding strategies that include the placement of concrete shield blocks at the penetrations in the Klystron Gallery and the backfilling of the penetrations with polybeads. Resulting accident dose rates in localized areas of the Klystron Gallery at or near penetrations are estimated to be as high as 470 R/h.[4-15] Placement of concrete shield blocks generally makes personnel access to the penetrations difficult. The shielding plug installed in the RTBT stub reduces the worst-case accident dose rate to below 10 R/h on the exterior side of the plug inside the stub tunnel[4-49] and to less than 5 R/hr on the exterior of the berm shielding.[4-52]

For workers inside the ring service building (which is not routinely occupied), the range was from about 3 rem/h (general area) to about 1,000 rem/h directly in front of an unshielded penetration.[4-15, 4-60, 4-61] The calculations indicate that a localized full beam spill could result in significant radiation exposure to an individual in the unlikely event that the individual were standing at the unshielded penetration at the same time a full beam spill occurred in the tunnel adjacent to the same penetration, and that the spill persisted for an extended period of time. The range of dose rates is significant from a hazard analysis perspective, so the adequacy of mitigating factors is evaluated below.

The methods presented in Section 4.1 reveal that doses in the potentially injurious range (i.e., greater than 25 rem) are not feasible for workers outdoors on the berm or in the general areas indoors because of the preponderance of mitigating factors (multiple layers of protection), any one of which would decrease the maximum dose by at least an order of magnitude below the threshold for designating credited controls.

By contrast, workers at worst-case locations inside the ring service building or Klystron Gallery could receive a worst-case accident dose in the injurious range, assuming that the beam tube could survive a sustained 2 MW beam spill and that no automatic controls functioned to terminate the beam spill. Consequently, a credited control is necessary to control risk to a worker standing near the penetrations where excessive accident condition radiation dose is possible. The network of PPS-interlocked area radiation monitors (Section 3.2.4.6), including those positioned to protect locations where maximum credible radiation dose rates are possible, are designated as CECs. If the radiation level should increase to designated set points above the routinely expected levels, then the PPS would automatically cut off the proton beam.

The duration of the beam spill before being terminated is a key part of estimating the consequences of the accident. Because the postulated worst-case dose rates are high, the difference of minutes or potentially even seconds can substantially affect the outcomes. Effort was made to consider the mechanisms and responses of the integrated machine that would lead to the termination of beam without operator intervention. Estimating the time required is speculative because many factors would be involved; however, a point loss would be very rapid. At full or high beam power, it would be on the order of seconds. However, even for a point loss, the spill would not become localized until decay of the turning magnet flux, which takes a few seconds. For a variety of glancing or diffuse beam spills, the beam tube integrity might not be compromised, but such spills would have lower peak dose rates than the point losses evaluated previously. Given the uncertainties, the decision was made to rely on PPS-interlocked area radiation monitors with the additional layer of MPS beam loss interlocks. These layers together provide a high degree of protection, and the inherent system response provides assurance that accident conditions will terminate even without intervention.

Table 4.3 summarizes the hazard evaluation for prompt radiation exposure to workers outside the beam tunnel due to beam spill events inside the tunnel. It considers both the general case of a worker at the worst location on top of the earthen berm and the bounding case for the unlikely event that a worker is standing in front of an unshielded ring service building or high-energy portion of the linac penetration at the same time a full power beam spill occurs in the tunnel adjacent to the same penetration for a sustained period of time. For the case of a worker outdoors, multiple layers of protection, inherent as well as engineered, provide a high degree of protection against excessive radiation exposure due to proton beam spill incidents without the need to designate a credited control. By contrast, the high dose rates at worst-case locations in or near penetrations in potentially occupied areas (e.g., the ring service building, Klystron Gallery, HEBT service building) require that the PPS beam cutoff based on interlocked area radiation monitor signals be designated as a CEC.

Table 4.3. Qualitative risk assessment for prompt radiation outside proton beam enclosures

FACILITY NAME: SNS accelerator systems
SYSTEM: Areas outside beam enclosures
SUB-SYSTEM: Linac, HEBT, ring, RTBT
HAZARD: Prompt radiation (proton beam) outside beam enclosures

Event	Sustained full power beam spill (maximum credible beam spill)
Possible consequences, hazards	Radiation levels above 10 CFR 835[4-5] allowed levels, possible excessive worker exposures, or worker exposures not ALARA. If sustained beam spill is adjacent to unshielded penetration, worker located at the penetration could receive exposure exceeding 25 rem
Potential initiators	Failure of magnet or magnet power supply, RF system failure, control system failure, human error

Risk assessment prior to mitigation

Note: X1 location is a worker at a worst-case location on top of the berm. X2 location is a worker in front of a penetration inside the ring service building or high-energy end of the linac

Consequence	( ) High	(X2) Medium	(X1) Low	() Extremely low
Frequency	() Anticipated high	(X1, X2) Anticipated medium	( ) Unlikely	( ) Extremely unlikely
Risk category	( ) High risk	(X2) Moderate	(X1) Low risk	( ) Extremely low

Does the hazard require a credited control per Section 4.1.2? Y/N Yes (for X2 location)

Hazard mitigation	1. PPS automatic beam cutoff on high radiation detected by interlocked area radiation monitors that protect accessible areas near tunnel penetrations where excessive dose potential exists (CREDITED) 2. Beam information display alerts operator to take action upon indication of significant beam loss 3. Operations personnel training 4. Automatic beam monitoring and control 5. MPS monitoring of beam loss and successive beam current monitors; the MPS removes the beam permit if these devices detect the beam is outside of the nominal operating range 6. Localized beam spill at high beam power would tend to cause failure of beam tube boundary with subsequent loss of beam tube vacuum, effectively cutting off the beam 7. Low occupancy of spaces directly near tunnel penetrations and on berm

Risk assessment following mitigation

Consequence	( ) High	( ) Medium	(X2) Low	(X1) Extremely low
Probability	( ) Anticipated high	( ) Anticipated medium	( ) Unlikely	(X1&X2) Extremely unlikely
Risk category	( ) High risk	( ) Moderate	( ) Low risk	(X1&X2) Extremely low

Table 4.4 presents personnel doses associated with the worst-case beam spill scenarios postulated above assuming that mitigation is provided by the designated control. Doses shown in the table indicate that mitigated doses are below 10 CFR 835 limits.

Table 4.4. Mitigated doses to worst case individual—maximum beam spill

Approximate bounding dose received at worst locations given that only one physical phenomenon or device functions			
Device	**Time required**	**Total dose at worst point berm surface**	**Total dose at worst point unshielded penetration**
MPS	2 machine pulses	Negligible	Negligible
PPS beam cut off by interlocked area radiation monitor	~2 s	~11 mrem	~550 mrem

Any one of the control actions would prevent exposures from causing radiation injury. Therefore, even if an individual worker were located at the worst spot on the berm surface, their risk of radiation injury would be low, even for the beyond-credible events examined. Occupancy of the berm exterior is low because of the small number of tasks that require berm access. Similarly, occupancy of the Klystron Gallery and HEBT service building and ring service building during beam operations is intermittent, with only a small fraction of that occupancy being near the penetrations.

4.3.3 Beam Dumps Hazard Analysis

SNS has three beam dumps located outside of the accelerator tunnels; the linac dump, the ring injection dump, and the extraction dump, as described in Section 3.2.1.4. Because the ring injection dump is the only one of the three beam dumps with building rooms that are accessible by workers, this section applies primarily to the beam injection dump. This dump has a collection of common industrial equipment hazards including pressurized water and gas systems, electrical equipment, and some chemical processing equipment. The standard industrial hazards associated with this equipment are mitigated and minimized by following the appropriate ORNL SBMS standards relating to worker safety. The architectural and structural design of the buildings is in accordance with the appropriate sections of the *Standard Building Code, 1997*[4-6] and the OSHA standards for workplace safety. Two aspects of the operation of the injection dump require additional explanation and may not be covered by normal industrial practices. Both situations, discussed in the following paragraphs, are common to laboratories handling radioactive materials and energetic particle beams.

Operation of the beam dumps at powers significantly beyond the design capacity would significantly damage equipment and has the potential to release radioactive material into the environment where contact with SNS personnel is possible. This hazard has been identified and a risk assessment worksheet has been completed (Table 4.5). The risk associated with this hazard is classified as low for the unmitigated situation and extremely low for the mitigated situation.

Even with no mitigation, the high-power beam would simply heat the beam stop and melt the beam-stop materials. The vacuum window would melt, and the helium from the enclosure would backfill into the proton beam tube. Any molten materials would drop out of the beam into the cavity below. The water-cooling system would be melted and open to the helium atmosphere in the beam-stop enclosure. This would add water vapor to the helium in the proton beam tube. Filling the accelerator beam tubes with helium and water vapor (instead of high vacuum) would cause the beam to shut down, and energy deposition at the beam stop would cease. The helium in the enclosure is normally exhausted to the hot off-gas system, and it would contain any water vapor.

Another related hazard is the failure of the ring injection beam dump cooling system. Even with the power at design levels, sustained operation with no cooling water flow would result in the same risk as the excessive power condition evaluated in Table 4.5. The MPS monitors water flow, water temperature, thermocouples, and differential pressure to protect the equipment. Appendix C addresses airborne radioactive material hazards involving the beam dumps (injection dump in particular), including spillage of activated cooling water, and concludes that the hazard is minor and that no CECs are necessary. Direct radiation hazard owing to spillage of injection dump cooling water is negligible because the dominant activation radionuclides are short-lived, and spilling the water allows them to decay quickly.

The ring injection dump is equipped with several different types of sensors to protect these areas. The passive dumps are equipped with thermocouples at the beam stop to protect the equipment. The access to the MPS inputs is restricted to qualified personnel. These inputs are bypassed only as prescribed in the SNS OPM.[4-8]

The MPS instrument package installed to protect the beam dump and surrounding equipment consists of instrumentation such as loss monitors, current monitors, harps, and several sensors monitoring the dump. Any abnormality from these sensors causes the beam to turn off and alert operations to the fault. The loss monitors indicate a fault if the measured losses or radiation levels exceed a predetermined limit. The current sensors indicate a fault if the measured current difference from an upstream sensor and the current measured in the dump line exceed a predetermined limit. In addition, a monitor is used for the source to measure the duty factor of the beam. It is designed to inhibit beam if the source delivers more beam than the present operational configuration of the machine allows. The harps give a measure of the charge distribution upstream of the window and dump and of the current at this device. A fault is indicated if the current density increases beyond a predetermined limit. The sensors in the dump controls include temperature, flow, and pressure of the dump cooling system. Any parameters exceeding predetermined settings cause a fault and turn off the beam.

Table 4.5. Qualitative risk assessment for the beam injection dump excessive beam power or failed cooling system

FACILITY NAME: SNS accelerator
SYSTEM: Beam dumps
SUB-SYSTEM: All
HAZARD: Excessive beam power

Event	Proton beam energy or currents that exceed the design limits (or failed cooling system)
Possible consequences and hazards	Damage to beam stop, potential release of activated materials
Potential initiators	Failure of the magnet control system, failure of the beam diagnostics system, failure of the cooling system

Risk assessment prior to mitigation

Note: Refer to Figure 4.1 for an explanation of consequence, frequency, and risk levels. "Low" and "Extremely low" risk levels are considered acceptable.

Consequence	( ) High	( ) Medium	(X) Low	( ) Extremely low
Probability	( ) Anticipated high	(X) Anticipated medium	( ) Unlikely	( ) Extremely unlikely
Risk Category	( ) High risk	( ) Moderate	(X) Low risk	( ) Extremely low

Does the hazard require a credited control per Section 4.1.2? Y/N No

Hazard mitigation	1. Inherent beam shutoff caused by loss of vacuum in beam tubes once excessive heating begins damaging beam dump components 2. Confinement of airborne radioactivity by helium enclosure and hot off-gas system 3. Magnet control system designed with high-integrity lockouts that prevent excessive power density beams from striking the beam dump 4. Cooling system flow rates, differential pressures, and temperatures are monitored and alarmed. In the case of the injection dump, the MPS provides a high-integrity lockout when cooling-water flow is lost 5. MPS software interlocks monitor delivered beam power throughout the linac and stop beam production if delivered beam power to a beam dump approaches the limit

Risk assessment following mitigation

Consequence	( ) High	( ) Medium	(X) Low	( ) Extremely low
Probability	( ) Anticipated high	( ) Anticipated medium	(X) Unlikely	( ) Extremely unlikely
Risk category	( ) High risk	( ) Moderate	( ) Low risk	(X) Extremely low

Normal operation of the ring injection beam dump involves production of ^{16}N and other radionuclides in the water-cooling loops and some radiolytic decomposition of the water. The decay tank is purged to maintain the gas space below the lower flammability limit ($\ll$4% H_2). This activated water emits a strong gamma radiation dose during beam operation and is contained in shielded piping runs inside the shielded utility vault. SNS personnel could be exposed to this radiation without the proper protection. This hazard is identified, and its evaluation is summarized in Table 4.6. The unmitigated risk associated with this hazard is classified as high because (1) the radiation level inside the vault during operations has not been fully characterized by measurements, and (2) it is assumed that, with no administrative controls on vault access, the exposure time could be significant.

The PPS is credited for protecting workers in the ring injection dump by (1) preventing beam operation in the ring segment when not cleared of personnel and (2) shutting off the beam if personnel enter a segment where beam is permitted (Sections 3.2.4 and 5.2.1). The PPS protection of the ring injection dump is part of the PPS ring segment, as described in Section 3.2.4. This need for crediting the PPS for protecting the ring injection dump may be revisited should a future safety evaluation indicate crediting is not warranted.

Table 4.6. Qualitative risk assessment for the beam injection dump personnel radiation exposure

FACILITY NAME: SNS accelerator
SYSTEM: Beam dumps
SUB-SYSTEM: All
HAZARD: Personnel radiation exposure

Event	Person inside injection dump utility vault during full power beam operation
Possible consequences and hazards	Radiation levels in the utility vault are assumed to be high enough to lead to health effects for credible exposures
Potential initiators	Workers access the utility vault during full beam power operation

Risk assessment prior to mitigation

Consequence	( ) High	(X) Medium	( ) Low	( ) Extremely low
Probability	(X) Anticipated high	( ) Anticipated medium	( ) Unlikely	( ) Extremely unlikely
Risk category	(X) High risk	( ) Moderate	( ) Low risk	( ) Extremely low

Does the hazard require a credited control per Section 4.1.2? Y/N Yes

Hazard mitigation	1. PPS automatic beam cut-off on access violation (CREDITED) 2. PPS control of critical devices to prevent beam operation in segments not cleared of personnel. Note that the ring injection dump is included as a part of the ring segment. (CREDITED) 3. The PPS controls access to the utility vault, limiting inadvertent access during operation 4. PPS beam-on warning lights outside entrances 5. Sweep procedures performed only by trained, qualified persons 6. PPS features that support conduct of administrative sweep 7. ORNL Radiological Protection Program, including Radiological Work Permit access control and posting of radiological areas as required 8. Work procedures and worker training 9. Repeated audible and visual warnings initiated by PPS inside the tunnel before initiation of proton beam allow any remaining unswept person sufficient time to evacuate or actuate a PPS manual beam shutdown station before the beam starts

Risk assessment following mitigation

Consequence	( ) High	() Medium	( ) Low	(X) Extremely low
Probability	( ) Anticipated high	( ) Anticipated medium	( ) Unlikely	(X) Extremely unlikely
Risk category	( ) High risk	( ) Moderate	( ) Low risk	(X) Extremely low

4.3.4 Excessive Beam Power to Target Station

Since the initial phases of the SNS construction project, the design basis for the target station was a nominal beam power of 2 MW. The original beam characteristics assumed for design calculations was a nominal beam energy of 1 GeV and nominal beam current of 2 mA. When the Proton Power Upgrade project plan was developed, the decision was made to modify these nominal beam parameters to 1.3 GeV and 1.5 mA, requiring an evaluation of potential adverse effects to the target due to the increased beam energy. The intent of the PPU project is to increase the power of the SCL to allow generation of 2.8 MW so that it can supply both the existing target at 2 MW and the planned Second Target Station at 700 kW. This increase introduces the possibility that beam power significantly in excess of the nominal 2 MW design power could be sent to the target.

Before this long-range vision for SNS was articulated, serious consideration was not given to the potential for excessive beam power being sent to the target because it was so implausible. This was born out in that it took more than a decade for the integrated SNS facility to develop the technical and operational infrastructure necessary to reliably operate at 1.4 MW. However, development has continued, bringing into sight a likely future where the SNS accelerator can deliver well more than 2 MW of power. This reality introduced the need to revisit the 2 MW design basis of the target.

The design of that portion of the target facility that immediately surrounds the beam interaction with the mercury target is vital to safe operation of SNS. An immense amount of radiation is produced each time a beam pulse enters the target, demanding massive amounts of steel, concrete, water, and polymer shielding to attenuate the various types of radiation generated and prevent excessive heating of the materials over weeks of continuous operation. This design is strongly influenced by beam energy and power parameters. Similar arguments are valid for other target systems such as cooling water loops, the mercury process loop, and off-gas treatments systems.

Because the effects of increased beam power delivered to target are so numerous and widespread, determining the nominal beam power that could lead to a hazardous condition would require a major effort. Therefore, the decision was made to maintain the existing power limitations and develop a dedicated high-integrity system to monitor the beam power sent to the target and shut off beam before the power limit is exceeded. This function is considered essential to safe operation of SNS and is thus selected as a credited engineered control.

The operational stance of the SNS strongly influences the probability that excessive power is delivered to the mercury target. Increasing total beam power, by raising current and energy, is a complex undertaking requiring the adjustment of numerous operational parameters. Adjustment of individual parameters can typically only increase power by about 10 kW or less without retuning the machine to prevent excessive beam losses. During the initial operational cycles of the PPU project, although 2 MW beam powers are credible, the intended operational powers will be well below 2 MW. Once 2 MW operations are achieved, increasing the beam power significantly above 2 MW would be unlikely without a coordinated operator effort. However, operation of the future Second Target Station, which would require the accelerator to produce a total beam power of 2.8 MW, with about 800 kW directed to the other target, would be expected to introduce a more credible scenario for sudden, excessive power being delivered to the mercury target.

4.3.5 Oxygen Deficiency Hazard Analysis

During conceptual and preliminary design, ODHs in the linac and CHL were addressed with Jefferson Lab as a partner laboratory. Jefferson Lab scientists and engineers worked with SNS to finalize the designs that are closely based on the Jefferson Lab cryogenic systems design that had proved effective. Throughout the course of design, commissioning, and operation of the CEBAF, the Jefferson Lab personnel completed hazard analysis, held extensive reviews, and conducted a large-scale helium spill test in the CEBAF linac tunnel using the actual linac cryogenic helium system. The tests conducted in the CEBAF beam enclosure showed that the extremely cold liquid helium spilled in the tunnel vaporizes quickly, readily becomes buoyant (and visible because of condensed moisture) and flows out the vents that are placed in the tunnel ceiling inside the partial height lintels.

Cryogenic systems are a necessary component of experimentation in particle beam physics. Several categories of hazards are associated with cryogenic systems: brittleness of structural material, over-pressurization transients, exposure to extreme cold, and oxygen enrichment/displacement. To a large extent, these hazards were addressed in the design stage because no amount of operational alteration can completely compensate for safety shortcomings in design. SNS used computational fluid dynamics (CFD) and analytic modeling to study the movement of accidentally released helium and the resulting oxygen displacement as part of its comprehensive hazard analysis process during the design process. CFD modeling supported the findings of the CEBAF spill tests and aided in the formation of *Safety for Cryogenic Operations at SNS.*[4-31] Based on CEBAF designs, active and passive ventilation features are provided in the linac tunnel and in the CHL facility.

Although the SNS design for cryogenic safety is closely based on proven Jefferson Lab configurations and concepts, SNS-specific hazard analysis was performed to ensure that the cumulative effect of minor differences would not in any way constitute a deficit in safety performance.

4.3.5.1 Oxygen Deficiency Hazard Analysis Methodology

The general approach used to address operational cryogenic safety was consistent with *Safety for Cryogenic Operations at SNS*[4-31] and, in some respects (e.g., oxygen deficiency), paralleled the process developed at Fermilab and subsequently adopted for use at BNL and Jefferson Lab. Essentially, this involved the use of design parameters in a hazard analysis model that started by identifying the maximum credible unmitigated release and characterizing the source term of released helium. The source term and the geometry of the enclosing environment were then used as inputs to general ventilation or other models as a means of estimating the resultant oxygen level.

The next step is to determine if the risk is great enough to require mitigation. Based on risks associated with accident consequences and estimated occurrence frequencies, appropriate controls were selected to ensure safety. Mitigating features that are established to reduce either the frequency or severity of the anticipated event may be designated as CECs in accordance with the criteria presented in Section 4.1.2. The number of mitigating features, in concert with the anticipated hazard level, is used to specify the SIL for one or more of the automatic mitigating systems (e.g., oxygen sensors/alarms).

SNS has adopted 19.5% oxygen as the nominal setpoint for the evacuation-related ODH alarm threshold based on the OSHA definition of an oxygen-deficient atmosphere and a corresponding minimum acceptable effective evacuation setpoint of 132 Torr oxygen partial pressure (corresponding to 18% relative oxygen concentration at nominal atmospheric pressure) based on the American Conference of Government Industrial Hygienists definition of the threshold for an oxygen-deficient atmosphere[4-36] The difference between the nominal and minimum acceptable setpoints establishes a suitable limit on the allowable variation in initiation of an evacuation alarm owing to parameters such as atmospheric humidity, pressure, and instrument drift.

An oxygen level that is rapidly fatal or incapacitating can be readily determined by considering oxygen needs of oxygen-sensitive tissues. Suppose a person breathes air containing 5% oxygen at standard temperature and pressure rather than the 20.9% that is normal. Water has a vapor pressure of 47 mm of mercury at normal body temperature, and this must be subtracted from the barometric pressure to achieve the “dry” state. The partial pressure of 5% oxygen that is inhaled is then $0.05(760 - 47) = 35.65$ mmHg. Under normal conditions, tissues within the body that need oxygen for cellular respiration have an oxygen partial pressure of 30–40 mmHg: venous blood being pumped to the lungs for oxygenation is at equilibrium with the tissues at about 35 mmHg. Because the blood arriving at the lungs finds the air at relatively the same oxygen partial pressure, it receives no oxygen from the lungs. That blood is pumped to the brain, which immediately “turns off” because of oxygen deprivation, and the person loses consciousness. Holding the breath works, at least until the next breath, because the oxygen partial pressure from air in the lungs after normally oxygenating blood on the first pass is around 70 mmHg, thus acting as a reservoir. However, if that person must release the held breath and gulp air that has 5% or less oxygen, collapse would be sudden.

Based on this physiological rationale, SNS has adopted 5% as its "highest" severity (death or permanent disability) category for risk analysis. The "medium" (oxygen between 5% and 12.5%), "low" (oxygen between 12.5% and 16%), and "extremely low" (oxygen above 16%) categories are taken from the American National Standards Institute respiratory protection standard (Z88.2 [1992]).[4-32] ANSI[4-32] specifies 12.5% as immediately dangerous to life or health (30 min escape time), and the more conservative OSHA lists 16% as the level above which oxygen deficiency would not interfere with an individual's ability to escape from a dangerous atmosphere. The fact that worker evacuation times from SNS cryogenic areas would be well below 30 min provides additional assurance that these category definitions are appropriate for risk analysis.

4.3.5.2 Oxygen Deficiency Hazard Analysis Results

The hazard analysis methodology discussed has been applied to ODHs associated with a cryogenic release in the linac[4-33] and in the CHL facility.[4-34] The linac hazard analysis is provided in Appendix F as an example of the level of detail applied. A summary of analysis results is provided in this section.

Linac/HEBT and Adjacent Structures Oxygen Deficiency Hazard Analysis Results

The analysis assumes two bounding helium release scenarios that include a short-term (<1 min) cryomodule-supplied leak of about 1,000 liters of cryogenic helium and a long-term (up to 4 h) refrigerator-supplied release of 150 g/s due to a cryogenic helium line breach in the linac tunnel. Impacts of accidental helium release scenarios are assessed for workers in the tunnel and for workers located in adjacent structures outside the tunnel, including the Front-End building (mezzanine and main level), Klystron Gallery, and/or ring/RTBT. Table 4.7 summarizes the ODH risk assessment for a cryogenic release in the tunnel.

The helium releases considered (short term and long term) are relatively large leaks. Such releases would involve energetic and noisy cryogenic helium expansion that would produce a significant cloud of condensing moisture in the air. Such a release is assumed to be readily detectable by workers in the general vicinity of the release, who could escape serious injury by seeing and fleeing (i.e., walking away) from the release site in accordance with training. Other workers in the tunnel might be unaware of the release. They might be located far from the release site or enter the tunnel after the release has terminated. For the short-term cryomodule-supplied leak, the analysis shows that workers in the tunnel but not in the vicinity of the leak (or entering the tunnel after the leak terminates) are not at risk because of the limited amount of helium released.

The available inventory of cryogenic helium in the tunnel is not a bounding factor in the assessment of ODH in the tunnel. The long-term release rate and duration is estimated based on limitations of piping size and plant capacity. The short-term release is based upon the bounding volume of a single cryomodule (600 L nominal, 1,000 L assumed). Thus, variation in the total cryogenic inventory of the tunnel does not affect the ODH of the tunnel, except that the ODH is considered eliminated if no cryogenic helium is in the tunnel. Normal operational variation of the inventory in the tunnel does not affect the assumed magnitude of ODH potential in the tunnel, and neither do changes or upgrades in the SCL section such as the addition or removal of cryomodules.

A cryomodule-supplied helium release would vaporize and quickly become buoyant. Lintels mounted at the ceiling on either side of the SCL portion of the linac provide passive partial confinement of released helium. Ceiling dampers (associated with ductwork of the two EVS exhaust fans) in the SCL ceiling are normally automatically opened when the tunnel is accessible. Should a release occur when the tunnel is accessible, most of the helium could be expected to rise and quickly vent through the EVS ductwork to the outdoors by natural convection. In the analysis that follows, no credit was taken for helium flowing out of the ceiling dampers. For the long-term release, oxygen levels throughout the linac/HEBT tunnel could eventually reach lethal levels, neglecting helium flow out of the EVS ductwork. Such a leak would likely be identified quickly, and manual and/or automatic actions to effectively stop/reduce/ventilate the leak would likely be taken within a time frame of about 30 min to 1 h, before the oxygen concentrations throughout the linac/HEBT tunnel would drop to levels associated with serious injury. Nonetheless, in this scenario, the release is assumed to continue for 4 h (e.g., because operators are unable to stop the leak or because prolonged staff absence keeps the leak from being identified). Therefore, a credited control is required to protect workers in the tunnel.

Table 4.7. Qualitative risk assessment for ODH in the linac tunnel and adjacent structures

FACILITY NAME: SNS accelerator systems
SYSTEM: SCL tunnel
SUBSYSTEM: Cryogenic helium system, SCL
HAZARD: Oxygen deficiency

Event	Helium release inside tunnel
Possible consequences, hazards	Should a sufficient volume of helium be released within the tunnel, workers in the tunnel or desiring entry into the tunnels could be at risk of asphyxiation because of low oxygen levels. A sustained release could potentially leak sufficient helium to create an asphyxiation risk in adjacent structures. An oxygen-deficient atmosphere creates the potential for unconsciousness, serious injury, permanent disability, and/or death
Potential initiators	Human error, maintenance error, boundary failure, excess pressure, mechanical failure, and so on

Risk assessment prior to mitigation:

Consequence	(X) High	( ) Medium	( ) Low	( ) Extremely low
Frequency	( ) Anticipated high	(X) Anticipated medium	( ) Unlikely	( ) Extremely unlikely
Risk category	(X) High risk	( ) Medium	( ) Low risk	( ) Extremely low

Does the hazard require a credited control per Section 4.1.2? Y/N **Yes**

Hazard mitigation	1. Cryogenic system boundary integrity 2. ODH system that monitors oxygen levels in the linac and provides alarms to warn workers to evacuate or not to enter the linac/HEBT tunnel (CREDITED) 3. Automatic initiation of the EVS upon detection of low oxygen levels in the linac (CREDITED) 4. Personnel trained to see and flee upon identification of a helium release 5. Cryogenic system process controls and alarms 6. Cryogenic system operating procedures 7. SCL ceiling dampers automatically opened when tunnel is accessible to personnel 8. Training, LTV, operating procedures and/or job hazard analysis (JHA) for cryogenic unit maintenance 9. Placement of ceiling lintels that helps confine leaked helium to the superconducting section and vent it to the atmosphere through ceiling dampers

Risk assessment following mitigation

Consequence	( ) High	( ) Medium	( ) Low	(X) Extremely low
Probability	( ) Anticipated high	(X) Anticipated medium	( ) Unlikely	( ) Extremely unlikely
Risk category	( ) High risk	( ) Moderate	( ) Low risk	(X) Extremely low

The credited ODH system monitors oxygen levels in the linac tunnel and provides alarms to warn workers to evacuate (or not to enter) the linac/HEBT tunnel when hazardous oxygen levels exist. The credited ODH system is described in Sections 3.2.5 5.2.2. Additional non-credited protective features are normally available for workers in the tunnel (e.g., robust cryogenic system boundary design, automatically opened ceiling dampers, ceiling lintels, cryo-system alarm and control system, tunnel exhaust systems, work control).

Over time, such a long-term helium release could potentially disperse out of the linac/HEBT tunnel and into structures adjacent to the linac/HEBT tunnel (Front-End building, ring/RTBT, and Klystron Gallery). Barriers that could affect the distribution of helium do exist between these structures and the linac/HEBT tunnel. Barriers include (1) sealed penetrations between the linac and the Klystron Gallery, (2) the shield wall dividing the ring from the HEBT, and (3) the shield wall between the linac and the front end. Furthermore, the configuration of the ventilation systems in the linac, ring/RTBT, and Front-End building could affect the distribution of a helium release. Conservative bounding assumptions were made to account for the potential effects on helium distribution.

Because of the relatively large volume of the tunnel and adjacent structures, the release would have to continue for some time before oxygen levels in adjacent areas could be significantly affected. For all scenarios evaluated, oxygen levels in adjacent areas remained above 16% after the first hour of the long-term leak.

The workers in the Klystron Gallery are not at risk from an accidental helium release in the linac tunnel because of the large dilution volume of the Klystron Gallery.

The minimum oxygen concentration in the ring/RTBT is bounded by assuming no leakage into the Front-End building or Klystron Gallery and no leakage out of the EVS ductwork. Oxygen concentrations in the ring/RTBT would fall to 16% after about 2 h and to 12.5% after about 3 h. At the end of the 4 h release, oxygen levels would drop to a minimum of 10.2%, which is in the “medium” consequence severity category. The associated risk category was found to be “medium.” A credited control is required to protect workers in (or entering) the ring/RTBT in accordance with the criteria presented in Section 4.1.

The oxygen concentrations in the Front-End building are bounded by assuming no leakage into the ring/RTBT or Klystron Gallery and no leakage out of the EVS ductwork. The resulting oxygen concentration in the Front-End building would fall to 16% after about 2 h to a minimum of about 11.0% at the end of the release, assuming the Front-End building HVAC is operating. The Front-End building HVAC normally runs continuously, mixing the atmosphere throughout the building (including the mezzanine) and providing some fresh makeup air to the building. Without the HVAC, levels in the mezzanine would fall to a minimum of 4.3%, which is in the “high” severity category. A credited control is required, regardless of HVAC status, to protect workers in the Front-End building.

The EVS is credited with protecting workers in the Front-End building (including the mezzanine and main level) and in the ring/RTBT by confining the helium release to the linac tunnel area via forced exhaust directly to the outdoors. The EVS is automatically actuated upon receipt of a low-oxygen signal from the credited linac ODH system. The EVS also provides the non-credited function of significantly improving oxygen concentrations inside the tunnel by exhausting released helium and drawing fresh air into the linac. The credited EVS system is described in Section 3.2.6 and Section 5.2.3. The EVS does not require a credited backup power system in the event of a loss of power scenario because loss of site power is not an initiating event for a long-term helium release. The probability that an undetected randomly occurring helium release in the linac would occur concurrently with a loss of off-site power, and that a worker would enter the affected zone(s) is considered beyond credible. The linac ODH system monitors power to the EVS and provides a warning should power be lost.

Some additional non-credited protective features are normally available for workers in the Front-End building or ring/RTBT (e.g., robust cryogenic system boundary design, automatically opened ceiling dampers [when tunnels are accessible], ceiling lintels, cryo-system alarm and control system, work control).

CHL ODH Analysis Results

As described in Sections 3.2.1.5 and 3.2.5, two rooms within the CHL present ODHs because of the relatively large inventory of helium and nitrogen associated with the cryogenic plant. Table 4.8 summarizes the ODH risk analysis associated with the CHL.

The cold box room uses liquid nitrogen to cool the helium. Assuming no leakage out of the open fan ceiling vents, liquid nitrogen or helium accidentally released would have the potential to cause oxygen concentrations to drop below 5%, requiring the designation of a credited control to protect the worker inside or attempting entry into the cold box room when hazardous oxygen levels exist. The ODH system is credited to warn workers to evacuate (or not to enter) the cold box room. The ODH system has warning alarms and blue light warning stations (Sections 3.2.5 and 5.2.2). Released helium would tend to rise and nitrogen would tend to sink because of their gaseous density. The ODH system is fitted with multiple oxygen sensors located at both high and low positions to ensure both helium and nitrogen releases are readily detected.

Some additional non-credited protective features are normally available for the worker in the cold box room (e.g., robust cryogenic system boundary design, open ceiling fan vents, auto-initiation of ceiling fans on detection of low oxygen concentrations, cryogenic plant alarms, work control). The ODH system in the cold box room performs the non-credited function of sending a signal to start the two ceiling fans. Each ceiling fan is rated at 9,500 cfm.[1,2]

Significant quantities of warm helium are involved in the compressor room. Because of the heat generation associated with compressor operation, the compressor room was designed with passive ventilation features consisting of open wall and ceiling vents. The passive ventilation features provide an abundant flow of outdoor air for removal of compressor heat by natural circulation. The ceiling vents are equipped with exhaust fans that may be used as desired to increase ventilation. For the unmitigated hazard analysis, the compressor room was assumed to be a closed building. Assuming a closed building, a large breach in the compressor system could release enough helium to cause oxygen concentrations to drop below 5%, requiring designation of a credited control to protect the worker inside or attempting entry into the compressor room.

The existing open wall and ceiling vents are credited with mitigating potential ODHs in the compressor room. The helium in the compressor system is not cryogenic. Although the passive ventilation features were originally provided for the purpose of room air temperature comfort, they also serve to effectively vent helium by natural convection in the event of a leak from the helium compressors or associated piping. A helium release would flow by natural circulation out the credited ceiling vents, with the large outdoor air inlets letting outdoor air in to replace the helium-air mixture flowing out through the ceiling. This is consistent with the basic design purpose of the compressor room air inlets. The analysis[4-34] shows that inlet and outlet vent areas exceeding 33 ft^2 each provide adequate passive natural circulation capability without crediting the fans that assist the ceiling vents. The ceiling vents have total area of about 40 ft^2, and the wall panels have an air inlet area exceeding 300 ft^2. The analysis demonstrates that the existing wall and ceiling vents promote sufficient natural circulation to mitigate the oxygen deficiency into the low-risk category. A similar analysis[4-35] was performed to show that a release from the Cryogenic Test Facility helium dewar system is bounded by the compressor system breach.

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[1] Drawing H9.10.60, Rev 1, CHL/RF Mechanical Equipment Schedules, 7/31/2001.

[2] Drawing H8.91.61, Rev 1, CHL/RF Miscellaneous Control Diagrams CHL/RF Systems, 7/31/2001.

Some additional non-credited protective features are normally available for the worker in the compressor room (e.g., robust system boundary design, automatic oxygen sensor based ODH alarms, ceiling fans, cryogenic plant alarms, work control).

Table 4.8. Qualitative risk assessment for ODH in the CHL facility (cold box and warm compressor room)

FACILITY NAME: SNS accelerator systems
SYSTEM: CHL facility
SUBSYSTEM: Cryogenic helium system
HAZARD: Oxygen deficiency

Event	Helium release inside CHL facility cold box or compressor area; nitrogen release in cold box room
Possible consequences, hazards	Insufficient oxygen, lung damage, unconsciousness, death
Potential initiators	Boundary failure, excess pressure, maintenance error

Risk assessment prior to mitigation

Note: X1 refers to an individual in or entering the cold box portion of the CHL. X2 refers to an individual in or entering the CHL warm compressor room.

Consequence	(X1) High	(X2) Medium	( ) Low	( ) Extremely low
Frequency	( ) Anticipated high	(X1, X2) Anticipated medium	( ) Unlikely	( ) Extremely unlikely
Risk category	(X1) High risk	(X2) Medium	( ) Low risk	( ) Extremely low

Does the hazard require a credited control per Section 4.1.2? Y/N Yes

Hazard mitigation	1. Cryogenic system boundary integrity 2. Automatic oxygen sensor based ODH warnings in the cold box room (CREDITED) 3. For compressor room, sidewall air inlet vents and roof-level vents are adequate to prevent overall room oxygen concentration from sinking to dangerous value except in the immediate vicinity of the leak (CREDITED) 4. Automatic oxygen sensor based ODH warnings in the compressor room 5. Automatic initiation of ventilation exhaust fan in the cold box room 6. Training and LTV procedures and JHA for cryogenic unit maintenance. Access to areas with potential large-scale release is limited to personnel having training in signs of, and response to, cryogenic release. See-and-flee training for cryogenic discharges that create fog by condensing atmospheric moisture 7. Cryogenic operations procedures and CHL worker training

Risk Assessment Following Mitigation

Consequence	( ) High	( ) Medium	(X2) Low	(X1) Extremely low
Probability	( ) Anticipated high	(X1, X2) Anticipated medium	( ) Unlikely	( ) Extremely unlikely
Risk category	( ) High risk	( ) Moderate	(X2) Low risk	(X1) Extremely low

4.3.6 Summary of Credited Controls Identified in Hazard Analysis

Table 4.9 provides a summary of hazards determined to require credited controls, the location of the hazards, and the designated CEC.

Table 4.9. Summary of proton facilities CECs

Hazard	Location	CEC	Section 4 hazard analysis reference(s)
Prompt radiation inside beam enclosures	All beam enclosures (linac, HEBT, ring [including injection dump], and RTBT)	PPS beam cutoff on access violation PPS control of critical devices	Section 4.3.1 Table 4.3.1
Prompt radiation outside beam enclosures	Areas adjacent to beam enclosures	PPS interlocked area radiation monitors	Section 4.3.2 Table 4.3
Prompt radiation and/or decay radiation from short-lived water activation radionuclides	Ring injection dump vault	PPS beam cutoff on access violation PPS control of critical devices	Section 4.3.3 Table 4.6
ODH associated with cryogenic helium used in SCL	Linac/HEBT tunnel, ring/RTBT tunnel, Front-End building (including mezzanine) Adjacent areas	Linac ODH system Linac EVS	Section 4.3.4 Table 4.7
ODH associated with cryogenic helium and N_2 processed in CHL to support SCL	CHL cold box room	CHL ODH system	Section 4.3.4 Table 4.8
ODH associated with helium used in CHL compressor system	CHL compressor room	Sidewall air inlet louvers, roof exhaust vents	Section 4.3.4 Table 4.8

4.4 ENVIRONMENTAL HAZARDS

DOE policy stipulates that work will be conducted safely and efficiently and in a manner that ensures protection of workers, the public, and the environment. The policy notes that "The ultimate safety goal is zero accidents, work-related injuries and illnesses, regulatory violations, and reportable environmental releases." Furthermore, throughout the life cycle of the facility, "appropriate mechanisms are in place to ensure that exposures to workers, the public, and the environment to radiological and nonradiological hazards are maintained below regulatory limits." This section describes the programs and methodologies used to achieve expectations of this policy with respect to environmental hazards.

At ORNL, demonstration of environmental excellence is promoted through high-level policies that clearly state expectations for continual improvement, pollution prevention, and compliance with regulations and other requirements. In accordance with DOE Order 436.1, Departmental Sustainability[4-53], UT-Battelle has developed and implemented an environmental management system (EMS), modeled after International Organization for Standardization (ISO) 1400: 2015[4-54], to measure, manage, and control environmental impacts. The EMS is a continuing cycle of planning, implementing, evaluating, and improving processes and actions undertaken to achieve environmental goals.

UT-Battelle's EMS encompasses a fully integrated set of environmental management services for activities and facilities. These services "include pollution prevention, waste management, effluent management, regulatory review, reporting, permitting, and other environmental management programs." The EMS uses the UT-Battelle Standards-Based Management System (SBMS) to establish environmental policy and translates environmental laws, applicable DOE orders, and other requirements into laboratory-wide documents (procedures and guidelines). In addition, the EMS is an element of the Integrated Safety Management System (ISMS) wherein environment, safety, and health (ES&H) requirements and controls are woven into all work activities and to ensure protection of the workers, the public, and the environment.

4.4.1 National Environmental Policy Act (NEPA)

The National Environmental Policy Act (NEPA) requires federal agencies to assess the environmental impact of all major federal actions significantly affecting the quality of the human environment. The DOE complies with the requirements of NEPA 1969, as amended (42 U.S.C. 4321 et seq.); the President's Council on Environmental Quality (CEQ) regulations for implementing the procedural provisions of NEPA (40 CFR parts 1500-1508), and the DOE regulations for implementing NEPA requirements (10 CFR 1021). DOE's policy is to follow the letter and spirit of NEPA, comply fully with the CEQ regulations, and apply the NEPA review process early in the planning stages for DOE proposals.

In compliance with NEPA requirements, the DOE prepared an Environmental Impact Statement (EIS) evaluating construction and operation of an accelerator-based research facility, SNS, at ORNL. The Final Environmental Impact Statement[4-55] was issued April 23, 1999. Based on the analysis contained in DOE/EIS-0247, the respective Record of Decision was issued June 18, 1999 (64 FR 35140). In February 2000, a Supplement Analysis was approved for replacing a portion of the ambient-temperature linac in the original project baseline with an SCL.

DOE/EIS-0247 examined not only construction and operation of SNS in its present configuration, but also proposed upgrades: adding a Second Target Station, increasing proton beam power to 2 MW, and increasing proton beam power to 4 MW.

4.4.2 Air Emissions: Clean Air Act

The Clean Air Act[4-56], passed in 1970 and amended in 1977 and 1990, forms the basis for the national air pollution control effort. This legislation established comprehensive federal and state regulations to limit air emissions and encompasses four major regulatory programs: the national ambient air quality standards, state implementation plans, new source performance standards, and Rad-NESHAPs. Airborne emissions from DOE Oak Ridge facilities are subject to regulation by the US Environmental Protection Agency (EPA) and the Tennessee Department of Environment and Conservation (TDEC) Division of Air Pollution Control.

The SNS is responsible for permitting, compliance, inspection, and documentation to ensure operations remain compliant with all federal and state air pollution control regulations. At present, boilers located in the CLO Building and the CUB are operational and permitted in the sitewide ORNL (UT-Battelle) Title V Major Source Operating Permit.

Of special note, the US Environmental Protection Agency (EPA) has promulgated national emission standards for emissions of radionuclides other than radon from DOE facilities. The final rule can be found in Title 40 of CFR 61, Subpart H, also incorporated in the Tennessee Air Pollution Control Regulation 1200-3-11-.08: *National Emission Standards for Hazardous Air Pollutants; Standards for Emissions of Radionuclides Other Than Radon from Department of Energy Facilities*[4-57]. This regulatory standard limits the annual effective dose (ED) that any member of the public can receive from DOE facilities to 10 mrem/year. As defined in the preamble of the final rule, the entire DOE facility on the ORR must meet the 10 mrem/year ED standard. In other words, the combined ED from all radiological air emission sources from Y-12, ORNL, ETTP, Oak Ridge Institute for Science and Education, and any other DOE operation on the reservation must meet the 10 mrem/year standard. Compliance with the standard is demonstrated by emission sampling, monitoring, calculations, and radiation dose modeling in accordance with approved EPA methodologies and procedures. DOE estimates the ED to many individuals or receptor points in the vicinity of ORR, but the dose to the maximally exposed individual determines compliance with the standard. As a result of airborne radioactive emissions from SNS operations, people living in the vicinity of the ORR are exposed to low levels of radiation. However, emissions are well within the respective Rad-NESHAP dose limit for the ORR. In 2021, radioactive emissions from SNS operating at 1.4 MW contributed 0.08 mrem to the maximally exposed individual, or 0.8% of the 10 mrem/year limit. Radioactive emissions from SNS operations are also permitted in the sitewide ORNL (UT-Battelle) Title V Major Source Operating Permit.

4.4.3 Water Emissions: Clean Water Act

The objective of the Clean Water Act[4-58] is to restore, maintain, and protect the integrity of the nation's waters. The CWA serves as the basis for comprehensive federal and state programs to protect the nation's waters from pollutants. One of the strategies developed to achieve the goals of CWA was the EPA's establishment of limits on specific pollutants allowed to be discharged to US waters by municipal sewage treatment plants (STPs) and industrial facilities.

4.4.3.1 National Pollutant Discharge Elimination System

EPA established the NPDES permitting program to regulate compliance with pollutant limitations. The program was designed to protect surface waters by limiting effluent discharges into streams, reservoirs, wetlands, and other surface waters. EPA has delegated authority for implementation and enforcement of the NPDES program to the state of Tennessee. The SNS discharges are regulated under the ORNL NPDES Permit, a sitewide wastewater discharge permit issued by the state.

4.4.3.2 Oil Pollution Prevention

CWA Section 311 regulates the discharge of oils or petroleum products to waters of the United States and requires the development and implementation of spill prevention, control, and countermeasures (SPCC) plans to minimize the potential for oil discharges. These requirements are provided in 40 CFR 112, "Oil Pollution Prevention." Each ORR facility implements a site-specific SPCC plan.

4.4.3.3 Prevention of Radioactive Contamination of Groundwater

DOE Order 458.1[4-59] is the primary requirement for a site-wide groundwater protection program at ORNL. The groundwater protection program is designed to address concerns associated with the spallation and neutron activation of soils in the shielding berm. SNS operations have the potential to induce radioactivity in the shielding berm surrounding the linac, rings, and/or beam transport lines. The result would be radioactive contamination of berm soils by radionuclides. A principal issue of concern for stakeholders is the possibility that water will infiltrate the berm soils and transport radionuclide contamination to saturated groundwater zones, especially those that are, or could become, sources of potable water.

SNS has implemented facility design and construction features to minimize the mobility of activation products in the site hydrologic system. The SNS groundwater protection program incorporates engineering-designed controls to address concerns associated with the spallation and neutron activation of soils in the shielding berm. Specifically, the shielding berm has been designed and constructed to isolate radionuclide contamination generated by the SNS particle beam and to provide radiation protection for outside areas around the beam and ring tunnel. The amount of such activation is minimized by beam loss control and passive shielding. Nevertheless, the berm is constructed of compacted native soils and is engineered to isolate activation products by minimizing the amount of water infiltrating the berm. The berm design encompasses installation of a near-surface geomembrane fabric integrated with a water interceptor/collection system comprising graveled collection areas and header-outlet piping to divert water from the berm to discharge points. Thus, the major objective of the SNS strategy is to prevent any migration of radionuclides to groundwater.

The SNS site is located atop Chestnut Ridge, northeast of the main ORNL facilities. The site slopes to the north and south, and small stream valleys, populated by springs and seeps, lie on the ridge flanks. Surface water drainage from the site flows into Bear Creek to the north and White Oak Creek to the south. The site is a hydrologic recharge area underlain by geologic formations that form karst geologic features. Groundwater flow directions at the site are based on the generally observed tendency for groundwater to flow parallel to geologic strike (parallel to the orientation of the rock beds) and via karst conduits that break out at the surface in springs and seeps located downgradient of the SNS site. A sizable fraction of infiltrating precipitation (groundwater recharge) flows to springs and seeps via the karst conduits. SNS operations have the potential to introduce radioactivity (via neutron activation) in the shielding berm surrounding the SNS linac, accumulator ring, and/or beam transport lines. A principal concern is the potential for water infiltrating the berm soils to transport radionuclide contamination generated by neutron activation to saturated groundwater zones. The ability to accurately model the fate and transport of neutron activation products generated by beam interactions with the engineered soil berm is complicated by multiple uncertainties resulting from a variety of factors, including hydraulic conductivity differences in earth materials found at depth, the distribution of water-bearing zones, the fate and transport characteristics of neutron activation products produced, diffusion and advection, and the presence of karst geomorphic features found on the SNS site. These uncertainties led to the initiation of the groundwater surveillance monitoring program at the SNS site. Before SNS operations, a baseline groundwater monitoring program was implemented in 2004–2006. This baseline program was transitioned to an operational groundwater monitoring program in parallel with commencement of operations at SNS. The operational groundwater monitoring program will continue for the duration of SNS operations. The objectives of the groundwater monitoring program include (1) maintaining compliance with applicable DOE requirements and environmental quality standards and (2) providing uninterrupted monitoring of the SNS site.

4.4.4 Waste Management

The waste generated by SNS is a subset of the waste generated by ORNL. It is managed through programs maintained by the respective transportation and waste management programs. In general, waste streams that can be managed on-site are addressed on-site, either by disposal in DOE-owned and operated landfill(s) or by treatment at DOE-owned liquid and/or gaseous waste treatment facilities (currently operated by the Oak Ridge office of Environmental Management). Waste streams that cannot be managed on-site are sent for off-site treatment and/or disposal at commercial or DOE facilities that have been approved for receipt of DOE/SNS waste.

A comprehensive waste management plan for SNS operational wastes that addresses the management of solid industrial, hazardous, radioactive, mixed, and special waste was issued June 2002. The SNS Waste Management Plan included an updated forecast delineating categories, types, and quantities of wastes anticipated as the result of normal operations. It also includes a description of management options for each waste category and type. Information pertaining to waste categories and respective regulations is provided in the following subsections.

4.4.4.1 Solid Industrial Waste

The regulation of nonhazardous (solid industrial) waste is the responsibility of the state of Tennessee, pursuant to Subtitle D of the RCRA.[4-39] The proposed management of nonhazardous solid industrial waste at SNS focuses on source reduction (via design, modification of practices to reduce materials usage, reuse of products and packages, and recovery for recycling). Presently, DOE has operating landfills for disposition of industrial solid waste and construction demolition on the ORR. Solid industrial waste from SNS is disposed in a permitted landfill.

4.4.4.2 Special Waste

The regulation of special waste is the responsibility of the state of Tennessee. Special waste is regulated as a subset of solid industrial waste and therefore is administered by the Tennessee Division of Solid Waste Management. Special waste generated by SNS may be disposed in an on-site permitted landfill or processed in a permitted processing facility when a special waste approval from the Tennessee Division of Solid Waste Management is obtained. Examples of special wastes are sludge, process filters, sandblast grind media, and paint chips.

4.4.4.3 Hazardous Waste

In general, EPA has authorized regulation of hazardous waste by the state of Tennessee pursuant to Subtitle C of RCRA.[4-39] Under Subtitle C, the TDEC oversees all aspects of the management of hazardous waste, from the point of generation to the treatment, storage, and disposal. In addition, the 1984 RCRA[4-39] amendments established land disposal restrictions, which prohibit the land disposal of untreated hazardous wastes. Hazardous waste from SNS will be sent for off-site treatment and/or disposal according to applicable laws and regulations.

4.4.4.4 Radioactive Waste

The regulation of radioactive waste is the responsibility of DOE pursuant to DOE Order 435.1.[4-42] Radioactive liquid waste from SNS is sent for on-site treatment at permitted facilities. Radioactive solid waste is sent for off-site treatment and/or disposal according to applicable laws, regulations, and policies.

4.4.4.5 Mixed Waste

The *Federal Facility Compliance Agreement* was signed on October 6, 1992,[4-39] to bring federal facilities into full compliance with RCRA.[4-39] RCRA requires that DOE facilities provide comprehensive data to EPA and state regulatory agencies on mixed-waste inventories, treatment capacities, and treatment plans for each site. TDEC is the authorized regulatory agency under the act for DOE facilities in the state of Tennessee. The proposed management of mixed waste at SNS focuses on elimination and/or minimization of hazardous materials (through administrative and design controls, modification of operational practices to minimize usage of hazardous materials, substitution of nonhazardous materials for hazardous materials, and recovery for recycling). Mixed waste from SNS will be sent, according to current planning, for on-site treatment at permitted facilities or off-site treatment and/or disposal according to applicable laws and regulations.

4.5 REFERENCES

4-1 *Spallation Neutron Source Quality Manual,* SNS-QA-P01, 102040000-QA0001-R05, Spallation Neutron Source, Oak Ridge National Laboratory, May 2007.

4-2 *Spallation Neutron Source Final Safety Assessment Document for Neutron Facilities*, 102030102-ES0016, Spallation Neutron Source, Oak Ridge National Laboratory, September 2011.

4-3 *SNS Shielding Policy*, SNS 102030000-ES0008, Spallation Neutron Source, Oak Ridge National Laboratory, November 2005.

4-4 Title 10 CFR, *Energy*, Part 835, "Occupational Radiation Protection," 10 CFR 835, US Department of Energy, Washington, DC.

4-5 *Life Safety Code*, NFPA 101, National Fire Protection Association, Quincy, MA, current edition, 2000.

4-6 *Standard Building Code, 1997*, by Southern Building Code Congress International, Inc., Birmingham, AL, 1997.

4-7 *Accelerator Facility Safety Implementation Guide for DOE 420.2C*, DOE G 420.2-1A, "Safety of Accelerator Facilities," August 1, 2014.

4-8 *Spallation Neutron Source Operations Procedures Manual*, https://neutrons.ornl.gov/x/operations/SNS_OPM_Folder_Tree, Spallation Neutron Source, Oak Ridge National Laboratory.

4-9 J. O. Johnson, *WBS 1.6.10.2 Accelerator & Target Station Neutronic & Shielding Analysis,* SNS-106100000-DC0001-R00, Oak Ridge National Laboratory, May 2000.

4-10 I. Remec, *Dose Rate Determination At The Surface Of The Cask Containing The SNS Inner Plug,* SNS-106100200-TR0052-R00, Oak Ridge National Laboratory, October 2001.

4-11 F. X. Gallmeier, *Dose in the Front End Building Due to Radiation Back-streaming From the SNS Linac*, SNS-106100200-TR0011-R00, Oak Ridge National Laboratory, September 2000.

4-12 J. O. Johnson, *The Spallation Neutron Source (SNS) Proton Beam Transport System Shielding Analyses*, SNS-106100200-TR0010-R00, Oak Ridge National Laboratory, October 1999.

4-13 N. Catalan-Lasheras (ed.) et al., *Accelerator Physics Model of Expected Beam Loss Along the SNS Accelerator Facility During Normal Operation*, SNS/AP Technical Note 07, Spallation Neutron Source Project, Oak Ridge National Laboratory, March 2001.

4-14 F. X. Gallmeier, *Klystron Shielding Calculations*, SNS-106100200-TR0014-R00, Oak Ridge National Laboratory, September 2000.

4-15 I. Popova, *Dose Rates at Chipmunks around Accelerator in Case of a Beam Spill*, SNS Report No. 106100200-TR0178-R01, Oak Ridge National Laboratory, February 2010.

4-16 F. Gallmeier, *Dose Equivalent Rates on Top of the SNS Accelerator Earthberm Due to a Full Beam Loss in the HEBT Arc*, SNS 1060100200-TR0061-R00, Oak Ridge National Laboratory, December 2001.

4-17 I. Popova, *Dose Rates in Klystron Gallery due to Accident Beam Loss in SCL Section Addition 1*, SNS-106100200-TR0119, R00, Oak Ridge National Laboratory, December 2005.

4-18 J. A. Bucholz, *Dose Rates Outside The SNS RTBT Shield during The Design Basis Accident And under Nominal Conditions,* SNS-106100200-DA0009-R00, Oak Ridge National Laboratory, October 2001.

4-19 C. O. Slater, *SNS Bulk Shielding: RTBT Target Backstreaming*, SNS-106100200-TR0024-R00, Oak Ridge National Laboratory, September 2000.

4-20 F. X. Gallmeier, *Shielding Calculations for the Truck Access in the SNS HEBT*, SNS-106100200-TR0018-R00, Oak Ridge National Laboratory, September 2000.

4-21 I. Popova, *Neutron and Gamma Source Terms Around the Egress Adjacent to the SNS Accumulator Ring*, SNS-106100200-TR0020-R00, Oak Ridge National Laboratory, September 2000.

4-22 I. Remec, *Calculation of Dose Rate in the Ring South Access Tunnel*, SNS-106100200-TR0021-R00, Oak Ridge National Laboratory, September 2000.

4-23 C. O. Slater, *Shield Penetrations: Truck Access Way, HEBT-Ring-RTBT*, SNS-106100200-TR0023-R00, Oak Ridge National Laboratory, September 2000.

4-24 J. A. Bucholz, *Neutronic Feasibility Calculations for a Passive Linac Beam dump and a Passive Ring Extraction Beam dump*, SNS-106100200-DA0004-R00, Oak Ridge National Laboratory, February 2001.

4-25 J. A. Bucholz, *Shielding and Activation Analyses for the SNS 200 kW Ring Injection dump*, SNS-106100200-DA0003-R00, Oak Ridge National Laboratory, May 2000.

4-26 *Standard for the Installation of Sprinkler Systems*, NFPA 13, National Fire Protection Association, Quincy, MA, current edition, 1999.

4-27 *National Fire Alarm Code*, NFPA 72, National Fire Protection Association, Quincy, MA, current edition, 1999.

4-28 *Standard for Portable Fire Extinguishers*, NFPA 10, National Fire Protection Association, Quincy, MA, current edition, 1998.

4-29 *Standard for the Installation of Air-Conditioning and Ventilating Systems*, NFPA 90A, National Fire Protection Association, Quincy, MA, current edition, 1999.

4-30 J. A. Eckroth, *Equivalency Analysis Document—Beam Tunnel Complex (LINAC, HEBT, RING, RTBT) Life Safety Features*, SNS 102030103-ES0021-R01, Oak Ridge National Laboratory, July 2006.

4-31 *Spallation Neutron Source Personnel Safety for Cryogenic Operations*, SNS 102030103-PC0001-R00, Oak Ridge National Laboratory, August 2002.

4-32 *Respiratory Protection*, ANSI Z88.2-1992, American National Standards Institute, New York, NY, 1992.

4-33 *ODH Analysis for the LINAC and Associated Structures*, SNS 102030103-CA0001-R01, Oak Ridge National Laboratory, 2019.

4-34 J. Jankovic, *CHL Facility Oxygen Deficiency Hazard Analysis and SIL Level Determination*, SNS 102030103-CA0002-R00, Oak Ridge National Laboratory, December 2002.

4-35 *USI Evaluation of Cryogenic Test Facility (CTF) Helium Dewar System*, SNS 102030103-ES0046-R00, Oak Ridge National Laboratory, July 2013.

4-36 *2006 TLVs and BEIs based on the Documentation of the Threshold Limit values for Chemical Substances and Physical Agents*, American Conference of Governmental Industrial Hygienists, ACGIH Worldwide Signature Publications, Cincinnati, Ohio, 2006.

4-37 "Construction and Operation of the Spallation Neutron Source Facility," *Final Environmental Impact Statement,* DOE/EIS-0247, Office of Science, US Department of Energy, Washington DC, April 1999.

4-38 S. M. Trotter and J. R. DeVore, *Spallation Neutron Source Waste Management Plan*, 102030000-TR0002, Spallation Neutron Source, Oak Ridge National Laboratory, June 2002.

4-39 *Oak Ridge National Laboratory Work Smart Standards,* "Other Industrial, Radiological, and Non-Radiological Hazard Facilities," Oak Ridge National Laboratory, July 1996, Revision Change No. 20, August 2002.

4-40 L. R. Dole et al., *Migration of Activation Products from the Oak Ridge Spallation Neutron Source Facility Shield Berm on Chestnut Ridge on the Oak Ridge Reservation*, SNS Report No. 108030200-TR0001-R00 (ORNL/TM-1999/290), Spallation Neutron Source, Oak Ridge National Laboratory, November 1999.

4-41 *Mitigation Action Plan for the Spallation Neutron Source*, DOE-0247-MAP-R0, US Department of Energy, Washington, DC, October 1999.

4-42 *Radioactive Waste Management, Office of Environmental Management*, DOE Order 435.1, US Department of Energy, July 1999, Change Notice No. 1, August 2001.

4-43 F. X. Gallmeier, *Egress Shielding Studies*, SNS-106100200-TR0013-R00, Oak Ridge National Laboratory, September 2000.

4-44 F. X. Gallmeier, *Shielding Calculations for the Exhaust Vents of the SNS Accelerator System*, SNS-106100200-TR0015-R00, Oak Ridge National Laboratory, September 2000.

4-45 F. X. Gallmeier, *Determination of the Thickness of the HEBT Traverse Shield Wall*, SNS-106100200-TR0019-R00, Oak Ridge National Laboratory, September 2000.

4-46 F. X. Gallmeier, *Estimation of the Doses in the Target Building, CLO Building, and at the Site Boundary Due to Skyshine from Operational Proton Beam Losses in the SNS Ring Collimator Section*, SNS-106100200-TR0056-R00, Oak Ridge National Laboratory, November 2001.

4-47 E. Tanke et al., *DTL Tank Shielding Needs in the SNS Front-End Building*, SNS/AP Technical Note, Number 11, Spallation Neutron Source, Oak Ridge National Laboratory, September 2001.

4-48 *Soil Thickness above RTBT/RTST for Proton Power Upgrade Condition*, 106100200-DA0110-R00, October 2019.

4-49 *Shielding Plug for RTBT Stub*, 106100200-DA0113-R00, October 2019.

4-50 *Conceptual Design Report, Proton Power Upgrade Project*, ORNL/TM-2016/672-R1, Spallation Neutron Source, Oak Ridge, TN, February 2018.

4-51 F. Gallmeier, *Accelerator Shielding for PPU Beam Conditions*, P05020202-TRT10000-R00, Spallation Neutron Source, Oak Ridge, TN, June 2022.

4-52 I. Popova, *Soil Thickness above RTBT/RTST for Proton Power Upgrade Construction*, 106100200-DA0110-R00, Spallation Neutron Source, Oak Ridge, TN, October 2019.

4-53 *Departmental Sustainability*, DOE Order 436.1, Office of Management, US Department of Energy, May 2011.

4-54 *Environmental Management Systems*, ISO 14001:2015, International Organization for Standardization, September 2015.

4-55 *Construction and Operation of the Spallation Neutron Source Facility*, *Final Environmental Impact Statement,* DOE/EIS-0247, Office of Science, US Department of Energy, Washington, DC, April 1999.

4-56 *Clean Air Act*, 42 U.S.C. §§7401-7671q, 1970.

4-57 *National Emission Standards for Hazardous Air Pollutants; Standards for Emissions of Radionuclides Other Than Radon from Department of Energy Facilities*, 65 FR 29933, May 2000.

4-58 *Clean Water Act*, 33 U.S.C. §§1251-1387, 1972.

4-59 *Radiation Protection of the Public and Environment*, DOE Order 458.1 Chg 4, Office of Environment, Health, Safety, and Security, US Department of Energy, September 2020.

4-60 F. Gallmeier, *Prediction of the Dose Rates at the Accelerator Tunnel Penetrations*, 106100200-TR0116-R00, Spallation Neutron Source, Oak Ridge, TN, November 2005.

4-61 I. Popova, *Hand Estimation for Radiation outside HEBT Penetrations, behind Truck access door and In the PPS room during the accidents*, 106100200-TR0121-R00, Spallation Neutron Source, Oak Ridge, TN, January 2006.

5. CREDITED CONTROLS AND BASIS FOR THE ACCELERATOR SAFETY ENVELOPE

5.1 INTRODUCTION

The ASE provides a concise framework of limitations on accelerator operation for the assurance of worker safety and that of the environment and the public. The SNS ASE[5-1] addresses requirements associated with both the proton facilities and the neutron facilities. This section explains the development and structure of the ASE and develops the basis for ASE requirements for credited controls related to proton facilities. Section 5 of the FSAD-NF addresses credited controls and ASE basis associated with neutron facilities.

The ASE defines the physical and administrative bounding conditions and controls for safe operations based on the hazard analysis (Section 4). The hazard analysis identifies a needed safety function which drives the development of operability requirements and compensatory measures. The safety function, operability requirements, and compensatory measures are included in the ASE to ensure that each CEC can perform its intended safety function whenever the hazardous condition exists. Surveillance requirements are also identified to ensure continued reliability of each CEC.

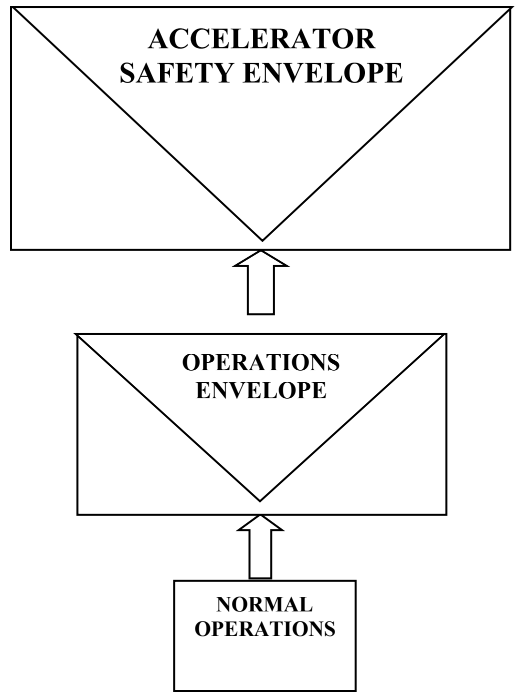
Although ASE requirements are essential for safety, many additional protections exist outside the ASE. For example, the ORNL SBMS Radiological Protection requirements are implemented throughout ORNL (including SNS) and supplemented by SNS-specific procedures as appropriate to help ensure that worker exposure to all forms of radiation is ALARA.

The hazard analyses of Section 4 have identified the following systems as CECs: (1) the PPS, (2) ODH systems in the linac tunnel and in the CHL, (3) the linac EVS, and (4) the CHL compressor room passive ventilation features. These systems and features have been determined to be essential for ensuring the safety of workers.

The safety analysis relies on assumed operational parameters for the facility. A maximum average beam power of 2.0 MW and linac energy of 1.3 GeV are foremost among them. Operation outside these bounds would necessitate deliberate and thorough reevaluation of the safety of the facility based upon the new bounding conditions.

The Implementation Guide[5-2] for DOE O 420.2[5-3] explains the role of the operations envelope in relation to that of the ASE.

> It may be advisable to establish an "accelerator operations envelope" (AOE) with limits more conservative than those addressed in the ASE as an aid to ensure the ASE is not exceeded. Other limitations, controls, and restrictions not directly based on the SAD safety analysis also could be addressed in the AOE…Variation outside an established accelerator operations envelope, but within the ASE, merits appropriate attention but does not require termination of activities or notification of DOE.



The SNS operations procedures support an operations envelope in the spirit of the Implementation Guide. As illustrated in the chart, the operations envelope is not a part of the ASE but is a part of the overall administrative control of the accelerator (Section 3.3.3 discusses SNS operations procedures).

5.2 PROTON FACILITIES CREDITED CONTROLS

CECs are identified in the hazard analysis presented in Section 4. This section addresses the credited safety function, functional requirements, and operability requirements for each CEC. The general requirement is that the CEC is required to be operable when the hazard is or could be present. A CEC is considered operable when it is capable of performing its intended safety function; that is, the CEC is aligned and configured such that it will perform its safety function upon demand.

Operability requirements are provided in the ASE and identify the conditions that require the CEC to be operable, typically based on the presence or potential for the hazard from which the CEC provides protection. If the conditions described in the operability requirements exist, then the CEC is required to be capable of performing its intended safety function. For example, the linac ODH system is required to be operable if cryogenic helium, the source of the ODH, is present in the tunnel. Conversely, the linac ODH system is not required to be operable in the absence of cryogenic helium in the linac tunnel.

Compensatory measures are approved alternative actions provided in the ASE to ensure safety when a CEC is required but not fully capable of performing its intended safety function. They are provided to allow smooth operational transitions with preapproved actions while ensuring continued safe operations.

Bypass procedures have been implemented to govern the use of routine bypasses needed for maintenance and testing and to accommodate limited system impairments while ensuring a CEC remains capable of performing its intended safety function. These procedures require the use of appropriate mitigating controls to ensure safety. These measures are reviewed and approved by line management. The bypass procedures ensure compliance with the ASE and may involve implementation of compensatory measures. They also enforce disciplined management of the configuration of CECs.

Surveillance requirements are included to provide assurance that each CEC will be periodically tested and verified to be able to perform its credited function. In general, active CECs are tested annually not to exceed 15 months, and passive CECs are typically maintained using configuration control processes, although some passive CECs do require periodic inspection.

5.2.1 Personnel Protection System

5.2.1.1 Safety Function

The primary safety function of the PPS is protection of workers against prompt accelerator radiation. Among the various functions provided by the PPS (Section 3.2.4), the following are credited safety functions:

- Prevent beam operation in a segment unless its associated exclusion areas are cleared of personnel (beam containment).
- Shut off beam if personnel enter an exclusion area associated with a segment where beam is permitted (access violation).
- Shut off beam if radiation levels set by the SNS RSO are reached at PPS interlocked area radiation monitor locations.
- Prohibit beam to the target when the target cart is out of the “cart inserted” position (basis provided in FSAD-NF).[1]
- Shut off beam to prevent beam directed to the target from exceeding the beam power limit defined in the SNS ASE (BPLS).

5.2.1.2 System Description

The PPS is designed to provide the credited safety functions identified in Section 5.2.1.1. The PPS is also designed to provide additional non-credited safety related functions as described in Section 3.2.4.

Several credited functions of the PPS require it to shut off the proton beam. This is accomplished through PPS control of critical devices in the front end, as described in Section 3.2.4.4. Removing power to these devices ensures that no further beam production occurs without deliberate operator action and greatly reduces radiation fields in the accelerator tunnels.

Prompt radiation levels inside the exclusion areas are potentially injurious during beam operations. The PPS protects workers from this hazard by preventing beam in a segment unless its associated exclusion areas have been cleared of personnel (beam containment). Administrative sweeps conducted by trained personnel in accordance with approved procedures ensure exclusion areas are cleared of personnel. Non-credited features of the PPS support the sweep process as described in Section 3.2.4.5. The PPS-protected exclusion areas are defined in Section 3.2.4.3 and include the accelerator tunnels and ring injection dump utility vault. To ensure beam containment, the PPS controls the power to critical devices to ensure beam

[1] The credited function of prohibiting beam to target based on target cart position is addressed in the FSAD-NF and has been listed here for completeness.

cannot be transmitted from active (cleared) segments to downstream segments unless their associated exclusion areas have been cleared of personnel. The critical devices are defined in Section 3.2.4.4.

The PPS also automatically shuts off beam if personnel enter an exclusion area associated with a segment where beam is permitted (access violation). The PPS identifies an access violation by monitoring access points, usually via limit switches associated with doors, as described in Section 3.2.4.5.

To ensure that radiation levels outside the accelerator tunnels do not result in excessive dose, the PPS uses interlocked area radiation monitors (Fermilab-style Chipmunks or the equivalent) described in Section 3.2.4.6. If any radiation monitor indicates a radiation level exceeding the set point, as established by the SNS RSO (typically set at the lower threshold for a high-radiation area), then the PPS trips the beam by disabling front-end critical devices. The SNS RSO establishes the radiation level trip set points for the interlocked area radiation monitors and the quality factor settings for the monitors. The RSO, subject to review by the Radiation Safety Committee, determines the location and the number of interlocked area radiation monitors.

The BPLS is a subsystem of the PPS that is designed to measure the beam power being sent to the mercury target and trip the beam if the average beam power exceeds a threshold selected to prevent beam power from exceeding the ASE requirements. A detailed description is provided in Section 3.2.4.7. DC current transformers measure RTBT.DH13 magnet current, which directly correlates to beam energy, for the BPLS PLC. The BPLS PLC uses the beam energy and power threshold values to calculate a charge threshold and provides that threshold to the FPGA components, the DPU and PSI. The DPU and PSI receive beam current data from the FCTs via an analog-to-digital converter. The DPU and PSI independently calculate the total charge based on the FCT data and compare it against the charge threshold provided by the BPLS PLC. The DPU evaluates against the PPS threshold and requests a PPS trip via the BPLS PLC if the threshold is exceeded. The PSI evaluates against the MPS threshold and requests an MPS trip if the threshold is exceeded.

5.2.1.3 Functional Requirements

The PPS is required to provide the credited safety functions listed in Section 5.2.1.1. The credited safety functions of the PPS must be operable as necessary to support the operational configuration of the machine during operations with beam. Common operational configurations are listed on Table 3.4. As determined in the hazard analysis (Section 4.3), the PPS is credited with protecting workers in the tunnel and ring injection dump by (1) preventing beam operation in a segment if its associated exclusion areas are not cleared of personnel and (2) shutting off the beam if personnel enter an exclusion area associated with a segment where beam is permitted. The PPS is required to control the appropriate critical device(s) so that beam delivery to a PPS-protected exclusion area is prohibited unless the exclusion area has been cleared of personnel. Additionally, the PPS is required to shut off beam by disabling front end critical devices whenever access control devices indicate that personnel may have entered an exclusion area associated with a segment where beam is permitted.

The hazard analysis also determined the need for the PPS to protect accessible areas where excessive dose potential exists during beam spill/fault conditions (e.g., near tunnel penetrations). The PPS is required to monitor radiation levels in designated locations outside of the accelerator tunnels with interlocked area radiation monitors and to shut off the beam if radiation levels set by the SNS RSO are exceeded. PPS-interlocked area radiation monitors are required in occupiable areas (including Klystron Gallery and ring service building penetrations) where excessive dose potential exists, as determined by the SNS RSO.

To satisfy the safety function to prevent exceeding the ASE power limit, the BPLS portion of the PPS must be able to measure the proton beam current and energy, calculate average power for a rolling period of 1 min or less, and shut off beam if the average power exceeds a threshold value selected to ensure delivered power remains within the ASE limits. The selected threshold should account for measurement error and a conservative time delay to trip the beam once requested.

Operability

The PPS protects personnel from the prompt radiation produced by the accelerated beam. Thus, the PPS is required to be operable in an area unless prompt radiation hazards from beam operations are prevented in that area by LTV of a critical device. To support operational flexibility and improve beam availability, a segmentation approach has been implemented that identifies critical devices to be used to robustly ensure that beam is either not produced or not transported beyond an operable segment. This approach is detailed in Sections 3.2.4.3 and 3.2.4.4, especially Table 3.4. Table 3.4 describes several operational configurations that support accelerator operations important to safely reaching reliable operation at full power to the first target station. The segmentation design allows the PPS to permit and monitor access on a segment-by-segment basis, so the beam can be safely operated in one portion of the accelerator, such as the linac and HEBT in linac tuning mode, while other portions are accessible, such as the ring and RTBT. This also allows some portions of the PPS to be inoperable during limited operational modes; however, any segment that is operating with beam must have an operable PPS to perform the safety functions for that segment (e.g., tripping the beam, access violation, or excessive radiation).

- Those functions of the PPS required to support the applicable operational configuration are required to be operable during operations with beam.

Each operational configuration has a defined destination for beam delivery as described in Table 3.4. Each operational configuration identifies those segments which are “No Access,” thus requiring that the PPS access control functions be operable in those segments. Interlocked area radiation monitors protect personnel from prompt radiation that would be produced by excessive beam loss, thus interlocked area radiation monitors must be operable whenever there are beam operations in those portions of the accelerator where beam loss could produce hazardous levels of radiation outside the exclusion areas. The target cart position interlock and beam power limiting system portions of the PPS provide protection for accidents associated with target operations, thus these two functions must be operable for all operations with beam to target. If the PPS for a segment is inoperable, then the beam must be prohibited as described below in the compensatory measures.

The BPLS portion of the PPS protects personnel in the target building from the potential adverse effects of excessive beam power to the target. However, the accelerator is not capable of producing a beam in excess of 2 MW without the addition of cryomodules beyond those that were initially installed in the machine. Therefore, with 23 cryomodules or fewer installed, there is no risk of sending excessive beam power to the target.

- The BPLS portion of the PPS is required to be operable during beam operations to the target whenever more than 23 cryomodules are in service in the SCL system.

Compensatory Measures

The PPS is required to be operable in any segment where beam could be produced or delivered, but it is permissible for the PPS to be inoperable in segments where beam is precluded as allowed by the segmentation approach. Because an inoperable PPS does not actively monitor the access status of a segment, administrative lockout of critical devices is used to ensure that beam operations are precluded in a segment with an inoperable PPS. It is expected that PPS control of critical devices in operating segments would identify an inoperable segment as not ready to receive beam and prohibit beam production and transport if the machine configuration could potentially send beam to that segment.

- Operations with beam to segments with an inoperable PPS shall be prohibited and controlled in accordance with the appropriate lockout of PPS critical devices.

As described in Section 3.2.4.4, beam delivery to the First Target Station with the target cart retracted would result in extreme radiation levels inside the target building. To prevent this event, a target cart position switch has been installed. This switch senses whether the target cart is fully inserted. This function is essential to safety, but because the position switch is located inside the target service bay, repair or replacement of the switch may be difficult and time consuming if it fails. Therefore, a temporary bypass option that allows continued operation while the repair or replacement is planned and prepared is desirable. If the target cart position switch is not operable, then two potential configurations are acceptable. (1) Beam to target is prevented: a critical device is locked and tagged as a radiation safety hold in the de-energized mode thus preventing beam transport to target. (2) Beam to target allowed with the following restrictions: the TPS shall be operable, the RSO and SNS operations manager (or designees) visually verify that the target cart is fully inserted into the target cart tunnel, the cart hydraulic drive unit is locked out and tagged as a radiation safety hold such that it cannot be energized. Beam to target can be allowed when diverse, independent methods are implemented to ensure the target cart is fully inserted. The TPS is designed to prevent beam to target unless the mercury target is ready to receive beam, which requires the target cart to be fully inserted as described in the FSAD-NF.[5-5] Visual verification of the target cart position provides a simple means of ensuring the target cart is inserted, and lock out of the hydraulic drive prevents accidental/incidental movement of the target cart after its position is verified. Neutronics subject matter experts indicate that the massive shielding of the target cart is sufficient to prevent significant consequences in the target building even if beam is sent to the mercury target when it is not filled.

Increasing the power output of the accelerator typically requires a coordinated, deliberate effort of the accelerator operations team and support personnel. Increasing either the beam energy or current requires incremental changes to numerous parameters, which are rebalanced at each step to prevent excessive beam loss and component activation. Consequently, the potential for an individual operator error to result in a dramatic change in beam power is minimal. The parameter manipulations normally available to and used by operators allow some control over beam power, but only within a range of about 100 kW. Therefore, by limiting the allowed operational power to below 1.8 MW and implementing tighter administrative and software constraints on key parameters that would require modification to significantly increase power, power can be maintained below the ASE limit of 2 MW with a high degree of certainty.

A procedure has been implemented to manage the machine settings most influential to operating beam power if the BPLS is inoperable. Prior to operations at 60 Hz, machine tuning is performed at a repetition rate of 1 Hz, which allows the machine settings to be established while maintaining delivered beam power about 1/60 (1.7%) of the intended operational power. For example, machine settings for 2 MW would be established at an actual power of about 33 kW. Once the machine settings are established, the values are documented on a checklist that is then used to input parameter limitations for the machine settings being controlled. The limitations prescribed by the checklist give operators room to adjust the machine to maintain operational power in response to drift (e.g., ion source performance changes) but limit the total increase in power from baseline to about 50 kW at 60 Hz. Thus, when these limits are implemented with a machine setup for 1.8 MW operation or less, a substantial margin ensures that the ASE beam power limitation will not be exceeded.

If the BPLS is required but inoperable, operation with beam to target may be permitted at a nominal beam power of 1.8 MW or less using approved SNS procedures that develop and document parameter constraints to ensure beam power to the target does not exceed 2 MW. The SNS operations manager is responsible for authorizing operations with beam to target while the BPLS is inoperable to develop parameter constraints. During these operations, the repetition rate of the accelerator is limited to 1 Hz. Once the parameter constraints are documented and implemented, the SNS operations manager approves the commencement of 60 Hz operations under the documented parameter constraints. The documented parameter constraints are maintained in the CCR and adherence to the parameter constraints is verified by the control room shift supervisor every shift. This process may be repeated as needed by accelerator operations personnel to ensure that the documented parameter constraints remain up to date and provide sufficient flexibility for routine beam production needs.

5.2.1.4 System Evaluation

The PPS achieves high system reliability by incorporating protection system design features that have been proved in other major DOE accelerator facilities. In addition, the PPS has used established industry standards (e.g., ANSI/ISA-84.00.01, *Functional Safety: Safety Instrumented Systems for the Process Industry Sector*) to guide the entire safety life cycle from design, procurement, fabrication, and testing to operation and maintenance. According to this standard, the PPS safety functions have been evaluated and categorized as to SIL. The credited PPS safety functions are designed to meet or exceed SIL 2, according to the standard.

As described in Section 3.2.4, the PPS employs a one-out-of-two logic structure, or the equivalent, combined with fail-safe design features (e.g., trip on loss of power) to perform SIL-2 safety functions with assurance of high reliability. The measures taken to ensure that the digital environment is consistent with a critical safety system are described in Section 3.2.4.

The ability of the PPS to reliably control the state of the accelerator (e.g., to cut off the beam when safety cannot be ensured) depends on its control of designated critical devices that control the ability to produce beam or to contain beam within certain segments. PPS control of the critical devices is implemented in accordance with fail-safe principles as described in Section 3.2.4.4.

5.2.1.5 Assurance of Continued Operability

Annual certification in accordance with approved SNS procedures ensures continued operability of the PPS.

5.2.2 Oxygen Deficiency Hazard Systems

5.2.2.1 Safety Function

The linac ODH system monitors oxygen levels in the linac/HEBT tunnel and provides audible and visual alarms inside the tunnel and visual alarms at entrances to warn workers to evacuate or not enter upon detection of low oxygen levels.

The linac ODH system sends a signal to start the EVS (Section 5.2.3) upon detection of low oxygen levels within the linac tunnel.

The CHL ODH system monitors oxygen levels in the CHL cold box room and provides audible and visual alarms inside the area and visual alarms at entrances to warn workers to evacuate or not to enter upon detection of low oxygen levels.

5.2.2.2 System Description

The linac ODH system measures oxygen levels with multiple oxygen sensors mounted on the ceiling in the SCL portion of the tunnel. The linac and HEBT portion of the accelerator tunnel share a common atmosphere with no barriers to restrict atmospheric mixing (other than the ceiling lintels described in Section 3.2.7.3). Upon detection of low oxygen levels, the linac ODH system provides audible and visual alarms to warn individuals that may be in the linac and HEBT tunnels. The linac ODH system also provides warning beacons at entrances to the linac and HEBT tunnels to warn personnel desiring entry if hazardous conditions exist. The linac ODH system sends a signal to start the EVS upon detection of low oxygen levels within the linac tunnel. The EVS (described in Section 5.2.3) ventilates and exhausts tunnel atmosphere to the outdoors.

The CHL ODH system provides monitoring and alarm functions for three zones within the CHL: the cold box room, the control room, and the warm compressor room. The portion of the CHL ODH system that provides protection of the cold box room is credited. The cold box room has multiple sensors sampling elevated locations to detect helium leaks and near the equipment floor to detect nitrogen leaks. The ODH system provides audible and visual alarms upon detection of low oxygen levels to warn individuals inside the cold box room to evacuate. Warning beacons are installed at each entry door to the cold box room to alert personnel seeking entry.

5.2.2.3 Functional Requirements

The linac ODH system is required to monitor oxygen levels in the linac tunnel atmosphere and to provide visual and audible alarms inside the tunnel and visual alarms at entrances to warn workers to evacuate or not to enter when hazardous oxygen levels exist. The linac ODH system is required to send a signal to start the credited EVS (Section 5.2.3) upon detection of low oxygen levels within the linac tunnel.

The CHL ODH system is required to monitor oxygen levels in the CHL cold box room atmosphere and to provide visual and audible alarms inside the area and visual alarms at entrances to warn workers to evacuate or not enter upon detection of low oxygen levels. Oxygen monitors are required to be positioned to detect both helium and nitrogen releases.

Linac ODH Operability

The linac ODH system is required to be operable when a significant ODH could exist as a result of the release of cryogenic helium from the linac system. A significant ODH is assumed to exist when cryogenic helium is present in the SCL system. If the linac ODH system becomes inoperable when cryogenic helium is present in the SCL system:

- Personnel shall be evacuated from and excluded from entering the linac/HEBT tunnel.
- Since the linac ODH cannot initiate the EVS, action is required as described in Section 5.2.3 for an inoperable EVS.

Personnel access to the linac tunnel is prohibited when the ODH system is inoperable unless appropriate compensatory measures have been implemented.

Because operability of the EVS relies on the linac ODH system, the EVS becomes inoperable any time the linac ODH system becomes inoperable. Compensatory measures associated with an inoperable EVS are addressed in Section 5.2.3.

CHL ODH Operability

The CHL ODH system is required to be operable when a significant ODH could exist as a result of the release of an inert gas (helium and/or nitrogen) from the CHL system. An ODH is assumed to exist when cryogenic helium or nitrogen is present in the CHL system. If the CHL ODH system becomes inoperable when cryogenic helium or nitrogen is present in the CHL system:

- Personnel shall be evacuated from and excluded from entering the CHL cold box room.

ODH System Compensatory Measures

Compensatory measures have been identified to allow safe entry into linac/HEBT or CHL if one of the ODH systems becomes inoperable.

- Entry into the linac/HEBT tunnel or CHL cold box room when the associated ODH system is inoperable is permitted in accordance with approved procedure(s) that require (1) a safety watch[2] and portable ODH monitoring for each person or (2) use of breathing apparatus.

The noise and vapor cloud associated with a significant cryogenic leak in the vicinity of workers would be readily identified, prompting timely evacuation in accordance with access training. Workers remote from the vicinity of the leak will be alerted to evacuate by portable oxygen monitoring, ensuring timely evacuation before the oxygen concentration is sufficiently low to cause potential injury. The use of appropriate breathing apparatus in accordance with approved procedures protects workers in the tunnel should hazardously low oxygen levels exist.

5.2.2.4 System Evaluation

The linac and CHL ODH systems are safety instrumented systems designed and maintained to provide reliability of safety function commensurate with the risk of the hazard. Although the PPS and ODH alarm systems are separate, they share the same basic design approach. The ODH systems achieve high system reliability by incorporating system design features that have been proved in other major DOE accelerator facilities. In addition, the ODH systems use established industry standards (e.g., ANSI/ISA-84.00.01, *Functional Safety: Safety Instrumented Systems for the Process Industry Sector*) to guide the entire safety life cycle from design, procurement, fabrication, and testing, to operation and maintenance.

5.2.2.5 Assurance of Continued Operability

Annual certification of the linac ODH system and CHL ODH system in accordance with approved SNS procedures ensures continued operability.

5.2.3 Emergency Ventilation System

5.2.3.1 Safety Function

The EVS prevents an ODH from propagating outside of the linac/HEBT tunnel by ventilating the linac tunnel upon receipt of a signal from the linac ODH system.

[2] The safety watch would be an individual responsible for maintaining awareness of surroundings to identify signs of a helium leak and promptly warning others to evacuate in the event of a leak.

5.2.3.2 System Description

The EVS is an active ventilation exhaust system actuated automatically whenever the linac ODH system detects low oxygen level in the linac tunnel. The EVS can also be started and stopped manually from the Central Control Room in accordance with approved operating procedures. The EVS includes a limited portion of the tunnel ventilation system originally intended to serve as a smoke removal system for the tunnel. The EVS is credited for the protection of workers in the Front-End building (including the mezzanine) and the ring/RTBT tunnel; however, its operation would also speed the recovery of safe oxygen levels inside the tunnel in the event of a significant helium release.

The EVS consists of the following parts of the linac smoke removal system: (1) two exhaust blowers located atop the linac berm, (2) ductwork connecting each blower to the interior tunnel atmosphere, (3) a blower inlet damper in each duct, (4) a wall intake damper in the front-end entrance labyrinth, and (5) associated infrastructure and instrumentation. The linac ODH system directly controls the blower motor starters and blower inlet dampers as needed to perform the safety function. In addition, the EVS automatically opens a wall intake damper to admit air directly from the outdoors into the linac tunnel at the entrance labyrinth between the front-end entrance and linac. Each of the two EVS blowers is rated at about 10,000 cfm.

The linac ODH system interfaces with parts of the smoke removal system that are not part of the EVS. Upon detection of low oxygen levels in the linac tunnel, the linac ODH system sends a start signal to the smoke removal makeup air fans in the front end and in the HEBT section (i.e., the upstream and downstream entrances of the linac tunnel). Although beneficial, these parts of the linac smoke removal system are not part of the EVS because they are not necessary to perform the safety function of the EVS.

5.2.3.3 Functional Requirements

The EVS is required to prevent an ODH from propagating outside of the linac/HEBT tunnel by ventilating the linac tunnel upon receipt of a low-oxygen-level signal from the linac ODH system (Section 5.2.2).

Operability

The EVS is required to be operable when a significant ODH could exist in the Front-End building (including the mezzanine) or ring/RTBT tunnel as a result of the release of cryogenic helium from the linac system within the linac tunnel. A significant ODH is assumed to exist in the Front-End building or ring/RTBT tunnel whenever cryogenic helium is present in the SCL system. If the EVS becomes inoperable when cryogenic helium is present in the SCL system:

- Personnel shall be evacuated from and excluded from entering the ring/RTBT tunnel and Front-End building (including mezzanine).

Because operability of the EVS relies on the linac ODH System, the EVS becomes inoperable when the linac ODH System becomes inoperable. However, up to three individual ODH sensors may be out of service (i.e., faulted or in maintenance mode) without rendering the ODH system inoperable for purposes of EVS operability. The analysis presented in Appendix F demonstrates that an extended helium leak in the linac could propagate into adjacent spaces, which is conservatively estimated to take more than an hour (compare Figure F-8 to Figures F-9 and F-10). For this event to occur, all of the atmosphere inside the linac would need to become hazardous such that leakage out of the linac also has a hazardously low oxygen concentration. Therefore, fewer ODH sensors are necessary in the linac to ensure EVS initiation than the number that are installed to ensure prompt initiation of personnel evacuation. As such, the EVS may be considered operable with up to three ODH sensors out of service.

Compensatory Measures

The following compensatory measures have been identified to allow safe entry into the Front-End building (including mezzanine) and ring/RTBT tunnel in the event the EVS becomes inoperable.[3]

- Entry into the ring/RTBT tunnel and/or Front-End building (including mezzanine) when the EVS is inoperable is permitted in accordance with approved procedures(s) that require 1) a safety watch[4] and portable ODH monitoring for each person or (2) use of breathing apparatus.

Workers remote from the vicinity of the leak will be alerted to evacuate by portable oxygen monitoring, ensuring timely evacuation before the oxygen concentration is sufficiently low to cause potential injury. The use of appropriate breathing apparatus in accordance with approved procedures protects workers in the tunnel should hazardously low oxygen levels exists.

Given the delay between initiation of a cryogenic release in the SCL and the development of a significant hazard in adjacent areas, provisions to identify and respond to a cryogenic release in the linac tunnel can be implemented to safely allow occupancy of the front end (including the mezzanine) and ring/RTBT. Additional compensatory measures have been identified to allow occupancy of the adjacent areas should the EVS become inoperable.

- If the linac ODH system is capable of providing notification of an ODH alarm to the CCR upon detection of low oxygen levels in the linac tunnel, then entry into the ring/RTBT tunnel and/or Front-End building (including mezzanine) when the EVS is inoperable is permitted using approved procedures that ensure:
  - The central control room is continuously staffed with procedures in place that direct evacuation of the ring/RTBT tunnel and Front-End building (including the mezzanine) upon receipt of the linac ODH alarm.

In this case, the Linac ODH system is available to provide warning alarms to the CCR, but the tunnel ventilation portion of the system is unavailable. The CCR staff act in accordance with procedures to ensure workers in the front end (including mezzanine) and ring/RTBT are evacuated in a timely fashion.

Another case for which a compensatory measure is provided occurs when the linac ODH system cannot provide the required signal to initiate the EVS automatically, but the ventilation components of the EVS are available to be started manually from the CCR.

- If the EVS is capable of ventilating the linac tunnel upon manual initiation from the CCR, then entry into the ring/RTBT tunnel and/or Front-End building (including mezzanine) when the EVS is inoperable is permitted using approved procedures that ensure:

[3] Because operability of the EVS relies on the linac ODH System, the EVS becomes inoperable any time the linac ODH system becomes inoperable.

[4] The safety watch would be an individual responsible for maintaining awareness of surroundings to identify signs of a helium leak and promptly warning others to evacuate in the event of a leak.

- o The CCR is continuously staffed with procedures in place to initiate the EVS upon receipt of notification of a potential ODH condition, and

- o A safety watch (1) continuously occupies the linac/HEBT tunnel in accordance with the provisions of Section 5.2.2 and (2) is assigned the responsibility of promptly notifying the Central Control Room to manually start the EVS in the event of a cryogenic helium release in the tunnel in accordance with approved procedure(s).

In this case, the safety watch continuously occupies the linac/HEBT tunnel with the purpose of identifying a helium leak should one occur. The safety watch then notifies the Central Control Room and the Central Control Room staff manually starts the EVS. Once initiated, the EVS prevents an ODH from propagating outside of the linac/HEBT tunnel by ventilating the linac tunnel.

5.2.3.4 System Evaluation

The maximum credible accident release rate of cryogenic helium in a postulated extended release is 150 g/s (Appendix F). This rate is equivalent to about 1,900 cfm at room temperature and atmospheric pressure. Because the EVS blower nominal capacity is about 10,000 cfm per blower, the rate of a single exhaust blower is sufficient to confine the accidentally released helium to the linac. Therefore, the EVS may be considered operable with either of the two fans operational for a limited time. Additionally, the EVS may be considered operable for a limited time should the wall intake damper in the front-end entrance labyrinth fail to open because operation of the EVS blowers would be sufficient to maintain negative pressure in the tunnel to prevent significant helium from propagating outside of the linac/HEBT tunnel.

The analysis indicates that a long-term accidental release would have to persist for more than 1 h before it would significantly affect adjacent areas. Therefore, a brief impairment of the EVS would not have a significant effect on safety in the front end or ring/RTBT.

5.2.3.5 Assurance of Continued Operability

Annual certification of both the EVS system and linac ODH system in accordance with approved SNS procedures ensures continued operability of the EVS. The annual certification of the linac ODH system is required because operability of the EVS relies on the linac ODH system.

5.2.4 Central Helium Liquefier Compressor Room Passive Ventilation Features

5.2.4.1 Safety Function

The CHL compressor room open side wall air inlet vents and roof-level vents passively provide a sufficient source of outdoor air for natural convection flow to protect workers from a potential leak from the helium compressors or associated piping.

5.2.4.2 System Description

The CHL compressor room passive ventilation features consist of the open side wall vents and roof level ceiling vents. The helium compressors operate continuously and lose considerable heat to the air of the compressor room, so these passive ventilation features help to maintain habitable temperatures. Side wall vents with an area larger than about 300 ft^2 are built into the compressor room north and south walls to allow relatively cool outdoor air to enter the building. Roof-level ceiling vents with an area of about 40 ft^2 provide a passive natural convection pathway to the outdoors. Ceiling vents are equipped with fans that may be used to assist with ventilation as desired; however, the fans are not required for safety and are not required for the passive ventilation features to perform their safety function.

The helium compressor system includes the helium compressors and associated piping and components that are in the CHL compressor room.

5.2.4.3 Functional Requirements

The CHL compressor room open sidewall and roof-level ceiling vents are required to provide a sufficient source of outdoor air and pathway for natural circulation flow to protect workers from a leak when helium is loaded in the compressor system.

Operability

The CHL passive ventilation features are required to be operable when a significant ODH could exist as a result of the release of helium from the compressor system. A significant ODH is assumed to exist when helium is loaded in the compressor system. If the passive ventilation features are not operable when helium is loaded in the compressor system:

- Personnel shall be excluded from the CHL compressor room.

Compensatory Measures

Compensatory measures to allow safe entry into CHL compressor room in the event the passive ventilation features are not operable follow:

- Entry into the CHL compressor room when the passive ventilation features are inoperable is permitted in accordance with approved procedure(s) that require (1) a safety watch[5] and portable ODH monitoring for each person or (2) use of a breathing apparatus.

Signs of a significant helium leak from the compressor system in the vicinity of workers might be identified depending on local circumstances. Workers who are remote from the vicinity of the leak or unable to identify the leak will be alerted to evacuate by portable oxygen monitoring, ensuring timely evacuation before the oxygen concentration is sufficiently low to cause potential injury. The use of appropriate breathing apparatus in accordance with SBMS protects workers in the area should hazardously low oxygen levels exist.

5.2.4.4 System Evaluation

The helium in the compressor system is not cryogenic. Although the passive ventilation features are provided for the purpose of room air temperature comfort, they would be beneficial in the event of a leak from the helium compressors or associated piping. Calculations[5-4] show that inlet and outlet vent areas exceeding 33 ft^2 each provide adequate passive natural circulation capability without crediting the fans that assist the ceiling vents. The ceiling vents have total area of about 40 ft^2, and the wall panels have an air inlet area of about 300 ft^2. Therefore, if the installed vents are unobstructed, a sufficient vent area is available to protect workers. Changes to the existing passive ventilation side wall and ceiling level vent areas (e.g., partial reduction of side wall vent area) may be evaluated for operability using the

[5] The safety watch would be responsible for maintaining awareness of surroundings to identify signs of a helium leak and promptly warning others to evacuate in the event of a leak.

Unreviewed Safety Issue process to ensure the configuration continues to provide the passive ventilation safety function specified in Section 5.2.4.1.

5.2.4.5 Assurance of Continued Operability

The ventilation features are passive and are configuration controlled via SNS procedures.

5.3 REFERENCES

5-1 *SNS Accelerator Safety Envelope (ASE): For Full Power Operations of the Front End, Linac, Ring, Transport Lines, Beam dumps, and Target*, SNS 102030103-ES0016-R05, Oak Ridge National Laboratory, May 31, 2007.

5-2 DOE G 420.2-1A, *Accelerator Facility Safety Implementation Guide for DOE O 420.2-C, Safety of Accelerator Facilities*, Office of Science, US Department of Energy, Washington, DC, January 2014.

5-3 DOE Order 420.2, C *Safety of Accelerator Facilities*, Office of Science, US Department of Energy, Washington, DC, July 2011.

5-4 J. Jankovic, *CHL Facility Oxygen Deficiency Hazard Analysis and SIL Level Determination*, SNS Document No. 102030103-CA0002-R00, Oak Ridge National Laboratory, December 2002.

5-5 *Spallation Neutron Source Final Safety Assessment Document for Neutron Facilities*, 102030102-ES0016, Spallation Neutron Source, Oak Ridge National Laboratory, September 2011.

6. INTERFACE BETWEEN PROTON AND NEUTRON FACILITIES

This safety assessment document addresses the safety of SNS proton facilities, which begin at the front end and extend to the terminus of the ring-to-target beam tube in the target building, at the upstream side of the window that allows protons to enter the core vessel that houses the target. The FSAD-NF[6-1] addresses the SNS target facility and neutron scattering instruments. This section summarizes the interfaces between the proton facilities and neutron facilities.

Most SNS facilities and equipment are part of the proton facilities. The proton facilities include not only the major accelerator segments—such as the front end, linac, ring, and transport systems—but also several essential support buildings such as the Klystron Gallery and the HEBT, ring, and RTBT support buildings. Infrastructure buildings such as shops, labs, the CLO Building, and utility buildings are mentioned in Section 3, but they pose only standard industrial hazards that are addressed by existing ORNL SMBS standards and requirements. Thus, the safety of infrastructure buildings is not evaluated in Section 4. The activities of the neutron facilities take place primarily in the target building and its attached satellite buildings.

The purpose of this section is to explain the physical and operational interfaces between the proton and neutron facilities.

6.1 DEFINITION OF PROTON AND NEUTRON FACILITIES

The neutron facilities occupy the target building and attached instrument satellite buildings, except for the part of the RTBT tunnel that extends into the target building. The RTBT proton beam tunnel is part of the proton facilities. Other on-site facilities are considered part of the proton facilities; however, parts of the TPS are in the proton facilities (Section 6.2).

Figures 6.1 and 6.2 provide a general depiction of the boundary between the proton facilities and the neutron facilities in the target building.

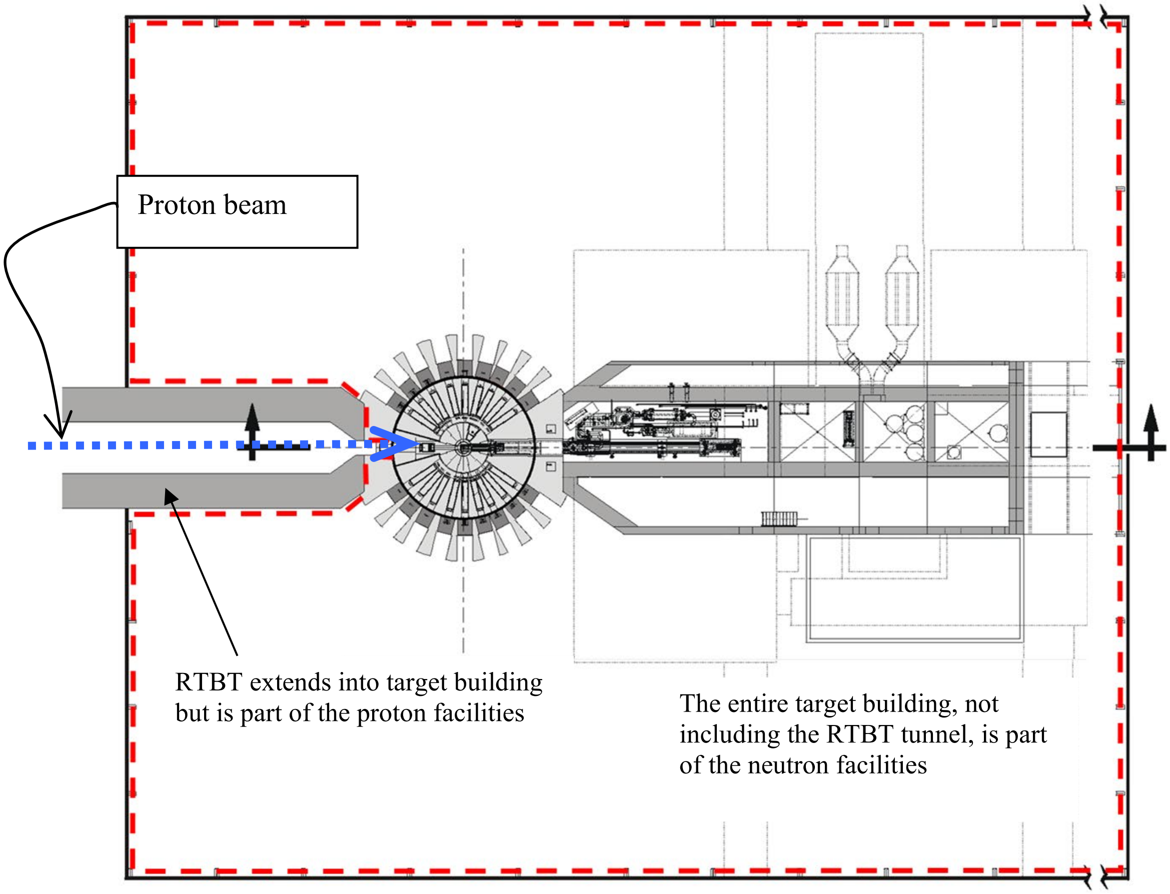


Figure 6.1. Target building horizontal section through proton beamline.

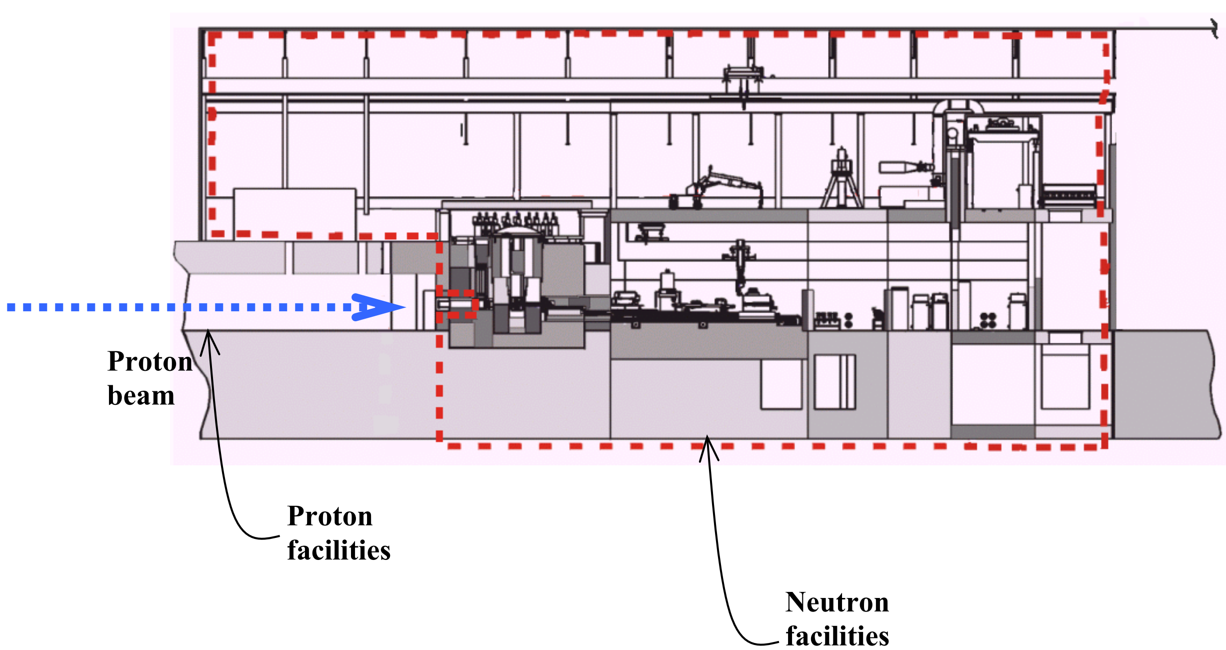


Figure 6.2. Target building vertical section through proton beamline.

6.2 PHYSICAL INTERFACES BETWEEN PROTON AND NEUTRON FACILITIES

Proton and neutron facilities are separated by distance and/or solid walls. The accelerator proton beam tube passes into the monolith up to the point of connection to the proton beam window, which is defined as part of the neutron facilities. The TPS instrumentation and control cables reach into the proton facilities to connect with vital TPS parts as follows:

- The TPS owns breakers in the Front-End building that it deenergizes to cut off the proton beam when the target is not appropriately configured to accept proton beam.

- The TPS senses the status of AC and DC power interruption devices that feed the RTBT dipole magnet RTBT.DH13 in the RTBT service building. The TPS logic will allow operations personnel to place the TPS in bypass mode when it senses that neither AC nor DC power is provided to RTBT.DH13. When the TPS is in bypass mode it does not cut off the proton beam in response to either low-mercury pump-developed head or low-mercury pump power.

- The TPS and other neutron facility control, information, and/or alarm functions are displayed in the neutron facility part of the central control room in the CLO Building.

The integrity of the TPS, including the above-defined components, must be maintained. Design features are provided to facilitate maintaining the required configuration control and integrity. For example, the TPS cutoff breakers in the front end are in dedicated, clearly identified, locked cabinets. The TPS is designed and must continue to be maintained throughout the facility life to applicable design standards. No work will be performed on any part of the TPS without prior configuration control review and approvals (details in the FSAD-NF section on CECs).[6-1]

6.3 FUNCTIONAL INTERFACES

6.3.1 Infrastructure

Proton facilities and neutron facilities share infrastructure services and resources. Table 6.1 provides some examples. Changes in the usage or status of shared infrastructure services and resources that could affect either the proton facilities or neutron facilities are coordinated by SNS management. The proton facilities and the neutron facilities both depend on ORNL services such as the ORNL Fire Department.

Table 6.1. Examples of shared infrastructure services or services provided by proton facilities to neutron facilities

Service	Purpose	Interface point
Electrical power	Supply power to active functions	Breakers
Tower cooling water	Provide the heat sink for water-based cooling systems	Piping connections to heat exchangers
Chilled water	Provide lower-temperature water for certain functions (e.g., air conditioning)	Piping connections to heat exchangers
Ventilation routing	Direct potentially contaminated target building discharge air to the SNS 80 ft stack	Discharge of primary confinement system, secondary confinement exhaust system, and hot off-gas system blowers
Emergency electrical power	Ensure continuity of power to the more important systems	Connections to safety-related systems

Note: None of the above features or services are considered CECs.

6.3.2 Functional Interfaces That Help Ensure Safety

This section highlights functional interfaces between proton facilities and neutron facilities that involve CECs or that otherwise help ensure safety. Table 6.2 identifies the equipment or systems involved, the actions taken, and the applicable phases of operations.

Table 6.2. Functional interfaces that help ensure safety

Equipment involved	Requirement	Applicability
Proton beam power control—normal full beam power	Proton beam power is controlled so that total power on the target shall not exceed 2 MW by more than 10% averaged over any 1 min period.	ASE, operations envelope
TPS and power supply connected to RTBT. DH13	The TPS prevents proton beam operation when the target mercury loop parameters are out of range.[6-1] The TPS bypass mode is selected by operators to monitor power supplies to RTBT.DH13 to prevent beam-to-target and safely allow linac or ring tuning operations when the target loop is not ready to receive beam.	ASE, configuration control, maintenance, operations
Target cart	The target PPS monitors the output of a position switch that indicates when the target cart is out of the “cart inserted” position in the monolith so that the PPS can prevent beam-to-target when the target cart is not inserted.	ASE, configuration control, maintenance, operations
PPS	The PPS cuts off the proton beam at the front end upon receipt of the beam cutoff request signal from the target segment of the PPS.	ASE, configuration control
Power supply to RTBT.DH13	A key switch with a removable key is provided and maintained to allow target personnel to perform manual lockout when the target cart is not in the “cart inserted” position.	Configuration control, operations

6.4 OPERATIONAL INTERFACES

The physical and functional dependencies of SNS have not led to operational safety interface issues between the operations of proton facilities and neutron facilities. An integrated central control room is provided in the CLO Building for integrated operations. The SNS Conduct of Operations program is implemented with training and procedures that ensure active coordination between the proton and neutron operations. SNS review committees such as the Radiation Safety Committee provide independent review in the case of hazards evaluation to help ensure that interface issues are identified, evaluated, and resolved.

6.5 REFERENCES

6-1 *Spallation Neutron Source Final Safety Assessment Document for Neutron Facilities*, 102030102-ES0016, Spallation Neutron Source, Oak Ridge National Laboratory, September 2011.

7. QUALITY ASSURANCE

QA is an integral part of the design, procurement, fabrication, construction, commissioning, and operations of the SNS facility. The primary objective of the SNS Quality Management System (QMS) is to safeguard the integrity, reputation, and operational excellence of SNS. All SNS personnel are required to implement the QMS requirements in their work. The SNS operations manager is the senior management representative responsible for the development, implementation, assessment, and continual improvement of the SNS QMS through the Spallation Neutron Source Quality Manual.[7-1] The manual defines the QA processes as well as the responsibilities for them and implements QA criteria and suspect/counterfeit item (S/CI) prevention requirements of DOE Order 414.1D.[7-2] This order is flowed down and implemented lab-wide through the adoption of ANSI/ISO/ASQ Q 9001-2015, *Quality Management System—Requirements*, as the appropriate voluntary national or international consensus standard, where practicable and consistent with contractual or regulatory requirements. The SNS QMS is designed to meet or exceed the requirements of this order and this standard.

The SNS quality program is implemented using quality procedures and guidelines and is deployed into other management systems, such as the SNS OPM, system and equipment test plans, a Document Control Center, and action tracking systems. The SNS quality program uses a graded approach to administer the appropriate application of quality practices. Special attention is given to items and services affecting the safety and operational reliability of the facilities.

SNS uses both external and internal assessments at multiple levels of detail to identify and correct problems hindering SNS from achieving its objectives. Assessment activities ensure condition of facilities, equipment, and engineered safety systems continue to function as designed and ensure that the implementation of procedures, controls, and personnel training continue to be appropriate for changing conditions. Management assessment results focus on means to improve the quality of work performed.

The SNS QA group performs independent assessments to ensure compliance with specified requirements and identify opportunities for improvement. Independent assessments evaluate the adequacy and effectiveness of activities governed under the SNS QMS.

A formal equipment and activity acceptance system is deployed throughout the SNS facility. This acceptance system uses a written and responsible verification strategy for items and activities involving quality and safety issues, using documented acceptance checklists. The SNS QA group monitors the acceptance of completed components, their installation, and their use throughout the facility life cycle. Equipment within the SNS facility is under configuration control to ensure that design changes or temporary modifications do not negatively affect its contributions to facility safety.

The SNS QA program includes appropriate attention to software QA. Two types of software QA are considered: software used in real-time applications in CECs, and software used to calculate safety-related design information.

Real-time safety-related applications. The CECs that are interlock-type systems are the PPS (throughout the accelerator from the front-end ion source to the neutron instruments in the target building), the TPS, and the transfer bay access control interlock. The TPS and transfer bay access are relay- or analog-logic based systems and are controlled under the hardware configuration control program. The PPS is a combination of hardware equipment status contacts and Allen-Bradley PLC controllers.

The PPS configuration is controlled by reviewed and approved system drawings and a detailed, signed-off testing/commissioning procedure that verifies proper system operation. It includes new items of equipment as they have been readied for commissioning/operation.

The testing/commissioning procedure is reviewed by the systems engineer, appropriate controls engineer, and operations. Test data are reviewed and approved by the same authorities approving the testing and commissioning procedure before placing the PPS into service.

The revised PLC software is assigned a new version number identifier, and it is placed into a centralized repository/database called the Concurrent Versions System (CVS). The CVS is a commercially obtained program that retains the various versions of software, including the explanation of the differences and reasons for differences between software versions.

Codes for calculation of safety-related design information. Radiological shielding analysis reports are prepared in accordance with established SNS procedures requiring the use of appropriate calculational methodologies. The codes used for calculations are obtained from recognized code repositories, such as the Radiation Shielding Information Center or Idaho National Laboratory, that maintain the configuration management of these codes. Shielding design inputs to these codes are under configuration management at SNS, uniquely identified, and stored in the CVS. Shielding design analysis reports provide traceability to the specific codes used and describe the details of the models used in performing the calculations. Results of the analyses are validated through radiation surveys of the installed shielding during facility startup at initially low levels of power and revalidated, as needed, in conjunction with major power increases or facility design modifications.

7.1 REFERENCES

7.1 *Spallation Neutron Source Quality Manual*, SNS-QA-P01, 102040000-QA0001-R07, Oak Ridge National Laboratory, April 2019, R07.

7.2 *Quality Assurance*, DOE Order 414.1D, Office of Environment, Safety, and Health, US Department of Energy, Washington, DC, May 2013.

APPENDIX A. FREQUENCY AND PROBABILITY GUIDELINES FOR HAZARD ANALYSIS

Initiating Events Category

Assigning frequency to one of the three major categories is judgment-based, aided as practicable with operating data and considering factors such as preventive maintenance, which can affect failure frequencies. The frequency estimation does not have to be precise because each category encompasses two orders of magnitude.

Rationale 1: Categories based on expert opinion or common knowledge of rate of approximate frequency of occurrence:

- Anticipated events are those that occur at least once in the life of any given accelerator. Frequency is in excess of 10^{-2}/year.
- Unlikely events are those that may not have occurred at any given accelerator but that have probably occurred at least once in accelerators of the free world. Frequency is between 10^{-2}/year and 10^{-4}/year.
- Extremely unlikely events are events thought to be possible even though they may never have happened at any accelerator facility. However, they must be physically possible and credible events.
- Beyond extremely unlikely events are, in the professional judgment of responsible engineers and scientists, not credible events. Similar events must never have occurred in an accelerator facility (otherwise they would be in a higher frequency category).

Rationale 2: Frequency categories based on known equipment failure rate data. The following are examples based on data taken from Tables 3, 4, and 5 of the *JNAL ES&H Manual* (No. 6500-T3, beginning at page 8 of 14):

- Power supply failure: 3×10^{-6}/h or 0.015 per 5,000-h operating year. If any one of ten power supplies causes the same fault, then the frequency is 0.15/year, an Anticipated Event.
- Welds leak at a rate of 10^{-9}/h. If each weld is in a stressed condition for 5,000 h/year and there are 10 welds of concern, then the approximate event frequency is 5×10^{-5}/year, an Extremely Unlikely Event. If the number of welds that could unleash the hazard of interest is 100, then the frequency is 5×10^{-4}/year, an Unlikely Event.

Mitigating Actions Category

To understand the effectiveness of mitigating actions, either administrative or automatic, it is necessary to assign an approximate conditional probability of success in the given circumstance. Given that the hazard-related initiating event has occurred, what is the likelihood of success for the mitigating action. Some example guidelines are as follows:

Automatic Action, Safety Instrumented System:

Between 0.99 and 0.999 for a SIL-2 (Safety Integrity Level 2) system, and between 0.9 and 0.99 for a SIL-1 system.

High-Integrity Non-Safety System:

Given the financial consequences involved, action of the Machine Protection System is designed to provide a success probability of between 0.9 and 0.99 for threats that it is designed to counter.

Personal Self-Protective Actions:

If the worker is specifically trained to evacuate on a given signal (e.g., ODH, radiation alarm), then it is highly likely (probability > 0.99) that the worker would evacuate within about 30 s.

If diagnosis and deduction is necessary (even for a trained worker), the worker may still evacuate with high certainty but only after a sufficient delay (e.g., 2 to 5 min).

Evacuation is highly likely even without specific training for unambiguous trouble signs such as obvious smoke or flames or severe earthquake shaking.

Even a loud, obvious alarm cannot be assumed to elicit quick evacuation without training. For example, personnel (e.g., riggers) in the building for a pickup or delivery cannot be assumed to evacuate without being told. In an incident that occurred several years ago, riggers covered their ears and stayed inside the building until specifically instructed to evacuate by one of the building personnel. Similarly, only ODH-trained workers are assumed to evacuate following an ODH alarm.

Other Administrative Actions:

Other administrative actions must be evaluated on a case-by-case basis that considers appropriate training and frequency of training. Administrative actions credited in an SNS hazard analysis must be consistent with the experience of SNS personnel at other DOE accelerator facilities. Actions noted in the hazard analysis must be only those expected to come under strict management control and surveillance at a well-managed accelerator facility.

APPENDIX B. SHIELDING ANALYSIS METHODOLOGY

Shielding calculations at SNS use several techniques and programs to complete the required calculations in the most efficient manner. Most of the programs are distributed through national radiation shielding centers such as the Radiation Safety Information Computational Center.[B-1] A listing of all major programs used in the SNS neutronic design is given in Table B-1. All of the codes or code systems listed in Table B-1 have been rigorously tested and benchmarked in applications similar to the design and analysis of SNS. Furthermore, a series of experiments have been conducted at BNL and LANL to simulate the SNS target environment, and the applicable codes have been used to benchmark the calculational methodology through comparisons with the experimental data. Some techniques required the development of cross section libraries and programs allowing techniques to be used together, called "coupling codes." All locally developed programs and data are documented in detail in the SNS Document Control Center. This appendix will present in general the programs used to complete shielding calculations for SNS and will provide references in which specific details can be found.

Many calculations are completed using the Monte Carlo method using Monte Carlo N-Particle Code (MCNPX).[B-2] The Monte Carlo method allows arbitrarily complex geometry models, and MCNPX provides multi-particle transport accurately up to several GeV. These qualities make MCNPX uniquely applicable to many radiation-transport and shielding problems at SNS. One major drawback of the Monte Carlo method is the amount of time required to complete the analysis. This issue was addressed at SNS by the implementation of parallel processing with MCNPX via Parallel Virtual Machine[B-3] by Gallmeier.[B-4] This improvement was later formalized in MCNPX and expanded to other message passing interfaces to form the basis of the current MCNPX parallel processing capability. MCNPX is typically used to generate source terms and to transport particles through several meters of shielding (~5 m) without a beam extraction line.

For shields thicker than ~5 m without beam extraction lines allowing significant penetration, such as the accelerator tunnel shielding, the discrete ordinates method is much faster and can yield accurate answers to transport problems. At SNS, the Dynamic Object-Oriented Requirements System (DOORS),[B-5] including the one-dimensional code ANISN, the two-dimensional code DORT, and the three-dimensional code TORT, are used for these analyses. Because MCNPX is used to generate the source term, a method must be implemented to couple the Monte Carlo source terms with the discrete ordinates transport codes. This process was completed by Gallmeier and Pevey.[B-6, B-7] During this process, it became clear to the authors that it would also be possible to couple several different two-dimensional transport calculations on translated or rotated axes, avoiding difficult and memory-consuming three-dimensional calculations. One application of this technique is the analysis of a labyrinth used to shield the entrance to the accelerator tunnel. The coupling code for this technique was written by Lillie.[B-8]

Discrete ordinates calculations, or any transport calculations, for that matter, are only as good as the cross-section database used for the analysis. At SNS, the incident protons, at 1 GeV, will be capable of producing neutrons of up to 1 GeV in energy. In addition, energy and power upgrades have been discussed since early in the project. With this in mind, a new transport cross section library, with the maximum energy extended to 2 GeV, was constructed by Lillie and Gallmeier.[B-9] This cross-section library is used for all discrete ordinate calculations at SNS.

Activation analysis is usually included in the shielding discussion, since activated components typically require some shielding for maintenance or disposal operations. Two activation systems are used at SNS. The first, based on the ORIHET system, is the Activation Analysis System.[B-10] The second, involving CINDER'90,[B-11] is not as easy to use and is not currently released to the public; but it has proved to reliably predict dose rates and decay heat when compared with experimental data. The SNS neutronics team is working with the CINDER'90 authors to have the code publicly released and to complete the manual. Comparisons with the Activation Analysis System and CINDER'90 [B-12] have shown that the codes agree reasonably well, although CINDER'90 includes data for more metastable states, leading to some disagreement at short times.

REFERENCES

B-1 B. L. Kirk, "The Radiation Safety Information Computational Center (RSICC)—Preserving the Legacy," *Proceedings of the 11th ANS Radiation Protection and Shielding Topical*, pp. 627–629, September 2000.

B-2 *MCNPX, Version 2.4.0*, LA-UR-02-5253, the MCNPX Team, Los Alamos National Laboratory, August 2002.

B-3 A. Geist et al., *PVM3 User Guide and Reference Manual*, ORNL/TM-12187, Oak Ridge National Laboratory, 1994.

B-4 F. X. Gallmeier and P. D. Ferguson, "MCNPX Running Parallel under PVM," *Proceedings of the 12th ANS Radiation Protection and Shielding Topical*, ISBN: 8-89448-667-5, 2002.

B-5 R. A. Lillie, *Discrete Ordinates: The Workhorse of Deterministic Transport Methods*, SNS SNS-101040000-DE0001-R00, Oak Ridge National Laboratory, September 2000.

B-6 F. X. Gallmeier, *Monte Carlo To ANISN (MTA) User's Manual*, SNS-101040200-DE0001-R00, Oak Ridge National Laboratory, September 1999.

B-7 F.X. Gallmeier, R.R. Pevey, Creation of Interface Utilities to allow Coupled Monte Carlo-Discrete Ordinates Shielding Analyses, Third International Topical Meeting on Nuclear Applications of Accelerator Technology, Long Beach, California, November 14-18, 1999, American Nuclear Society, pp 404-409 (1999).

B-8 R. A. Lillie, *DTD: A Coupling Code for Two-Dimensional R-Z Cylindrical Geometries*, SNS-101040200-DE0002-R00, Oak Ridge National Laboratory, September 2000.

B-9 R. A. Lillie and F. X. Gallmeier, *HILO2k: A New HILO Library to 2 GeV*, SNS-101040100-TR0001-R00, Oak Ridge National Laboratory, September 2000.

B-10 G. S. McNeilly, *The Activation Analysis System (AAS)*, SNS-101040200-TR0003-R00, Oak Ridge National Laboratory, September 2000.

B-11 W. B. Wilson and T. R. England, *A Manual for CINDER'90 Version C00D and Associated Codes and Data*, LA-UR-00-Draft, Los Alamos National Laboratory, April 2001.

B-12 P.D Ferguson, I. Remec, F.X. Gallmeier, W.B. Wilson, Transmutation Studies for Tungsten and Mercury Targets with the CINDER'90 and ORIHET'95 Codes, In Proceedings of 12th Biennial RPSD Topical Meeting, Santa Fe, NM, USA, April 14-18, 2002, American Nuclear Society, ISBN: 8-89448-667-5 (2002).

Table B.1. List of codes and principal applications to the SNS neutronic and shielding analysis

Code name	Analysis type	Principal application
CALOR	Complete radiation transport code system (all energies)	Neutronics, energy deposition, material damage and activation, shielding
HETC	High-energy (E > 20 MeV) hadron transport	Neutronics, energy deposition, material damage and activation, shielding
SPECT	High-energy hadron transport analysis	Neutronics, energy deposition, material damage and activation, shielding
MCNP	Low-energy (E < 20 MeV) neutron, photon, and electron transport	Neutronics, energy deposition, material damage and activation, shielding
MCNPX	Complete radiation transport code system (all energies)	Neutronics, energy deposition, material damage and activation, shielding
LAHET	High energy (E > 20 MeV) hadron transport and analysis	Neutronics, energy deposition, material damage and activation, shielding
MORSE	Low-energy neutron and photon transport	Neutronics, energy deposition, Shielding
MICAP	Low-energy neutron and photon transport	Energy deposition, material damage and activation
EGS4	Electron, positron, and photon transport	Energy deposition, shielding
ORIHET95	Depletion and isotope production and decay heat analysis	Activation, decay heat, radionuclide inventory
CINDER'90	Depletion and isotope production and decay heat analysis	Activation, decay heat, radionuclide inventory
ANISN	1D low-energy neutron and photon transport	Energy deposition, material damage and activation, shielding
DORT	2D low-energy neutron and photon transport	Energy deposition, material damage and activation, shielding
TORT	3D low-energy neutron and photon transport	Energy deposition, material damage and activation, shielding
CASL	3D semi-empirical shield analysis	Shielding
HILO	Multi-group cross section library to extend ANISN/DORT/TORT energy range up to 2 GeV	Energy deposition, material damage and activation, shielding

APPENDIX C. AIRBORNE RADIOACTIVE MATERIAL HAZARDS FOR THE SNS RING INJECTION BEAM DUMPS

To consider airborne hazard potential with the ring injection dump, the consequences of an injection dump coolant spill are analyzed.

The rationale for concentrating on the injection dump is that it has, by far, the highest radionuclide inventory. The Spallation Neutron Source design parameters for the beam dumps (Section 3.2.1.4) specify a design beam power of 7.5 kW with a 10% duty factor for the linac and ring extraction dumps, in contrast to the 150 kW design beam power with 100% duty factor for the injection dump. The linac and ring extraction dumps operate at a power of less than 4% for a fewer number of hours relative to the injection dump (500 h/year instead of 5,000 h/year). The linac and ring extraction dumps log no more than 0.4% of the integration dump's integrated irradiation. Therefore, the two 7.5 kW dumps accumulate only 0.4% of the injection dump's long-lived spallation products. The high-energy beam transport arc "off-momentum" dump continuously receives some beam at the level of approximately 2 kW.

Airborne radioactivity concentrations following a water spill accident were predicted[C-1] for an assumed spill in the injection dump utility vault (concrete building surrounding the active components of the dump's cooling and cooling water purification system). Conservative assumptions were made regarding evaporation of water, its radioactive contaminants, and their accumulation in the atmosphere of the dump. The result showed that the total concentration of radioactivity in the vault's air could reach 12 times the composite level allowed under routine occupational conditions (i.e., 12 times the composite-derived air concentration for the radionuclides involved per 10 Code of Federal Regulations 835). This accident concern is obviously not significant even with static air because of limited occupancy. Moreover, the vault is actually a ventilated space (exhausted to the main ventilation stack), so the attainable concentration would be considerably less than 12 times the routine occupational limit reported. Therefore, this situation does not need further detailed evaluation or indicate the need for credited controls.

REFERENCES

C-1 G. B. Stapleton and R. M. Harrington, *Injection dump Potential Airborne Release Concentrations*, 102030103-ES0004-R00, Oak Ridge National Laboratory, August 2000.

APPENDIX D. SAFETY FOR CRYOGENIC OPERATIONS AT THE SPALLATION NEUTRON SOURCE

Appendix D has been deleted because it was largely a reproduction of SNS 102030103-PC0001-R00, *Spallation Neutron Source Personnel Safety for Cryogenic Operations*, August 2002. Salient portions have been integrated into Appendix F.

APPENDIX E. SPALLATION NEUTRON SOURCE SITE AND BUILDING FIRE HAZARDS ANALYSIS

The fire hazards assessment documents completed for the Spallation Neutron Source (SNS) site and buildings are listed below. Copies of these documents are available through the Oak Ridge National Laboratory document control system:

- Fire Hazard Analysis for the SNS accelerator facilities, Buildings 8100, 8200, 8300, 8340, 8413, 8423, 8520, 8540, 8550, and 8918, (EDRM# 19592)
- Fire Protection Engineering Assessment for Buildings 8310, 8320, 8330 (EDRM# 20808)
- Fire Protection Engineering Assessment for the Accelerator Support Office Complex – Building 8350 (EDRM# 22014)
- Fire Hazard Analysis for the SNS target building, Buildings 8700, 8702, 8705, 8707, 8711, 8713, 8714, 8760, 8770, & 8780 (EDRM# 19591)
- Fire Protection Engineering Assessment for SNS Central Laboratory and Office - Building 8600 (EDRM# 19793)
- Fire Protection Engineering Assessment for the Site Utilities Buildings – Buildings 8910, 8911, 8912, 8913, 8914, 8915, and 8950 (EDRM# 20807)
- Fire Protection Engineering Assessment of the Receiving Acceptance Testing Storage (RATS) Building 8920 (EDRM# 21412)

APPENDIX F. LINAC OXYGEN DEFICIENCY HAZARD ANALYSIS

The Oxygen Deficiency Hazard (ODH) Analysis for the linac and adjacent structures (102030103-CA0001-R01) is provided here as Appendix F.

Title: ODH Analysis for the LINAC and Adjacent Structures	**SNS Number: 102030103-CA0001-R01**
	Sheet 1 of 25

Computer programs used, if any, including version number and V&V status:

2D CFX Simulations (M. Wendel) used for qualitative evaluations of helium behavior in tunnel.

Purpose and objective:

To assess potential oxygen deficiency hazards associated with the cryogenic helium system in the LINAC and to identify appropriate controls to mitigate those hazards.

Conclusion:

In the event of a catastrophic cryogenic release from the supply system, sufficient helium could be released to reduce the oxygen concentrations in the LINAC/HEBT and adjacent structures (RING/RTBT and Front End) to hazardous levels. Without providing some form of warning and control, unsuspecting staff could be at risk of asphyxiation. Credited oxygen sensor system provides warnings to alert persons in or desiring entry into the LINAC/HEBT. Credited initiation of the EVS fans by the credited oxygen sensor signal provides mitigation for individuals in the adjacent structures.

Revisions

Revision Number	Revision Description
R01	This revision updates LINAC ODH analysis to better support the results and conclusions presented in Section 4 of the FSAD-PF [1]. This revision updates the analyses to better reflect current conditions and operations and additionally corrects some errors. Conservative bounding assumptions are made. Salient portions of the *Safety For Cryogenic Operations at SNS* [2] have been incorporated to better describe the ODH risk approach. Time dependent oxygen concentrations following postulated releases are presented.

Sign-Off

Revision Number	Originator (Print) Sign/Date	Verification/ Checking Method	Verifier/Checker (Print) Sign/Date	Manager (Print) Sign/Date
Original (Rev. 0)	/s/ John Jankovic, 8/13/2002	Hand calculations, engr judgement	/s/R. M. Harrington 8/17/2002	/s/F.C. Kornegay, 8/19/2002
Revision 01	D. Freeman (date) 2/22/2019 [signature]	R.M. Harrington Independent Verifier [signature] 3/5/19	Jake Platfoot (date) [signature] 2/22/2019	Sam Mckenzie (date) 3/7/19 [signature]

Summary of hazard analysis results—linac cryogenic helium release				
Event: Helium release inside tunnel: 1) A helium line ruptures, releasing helium into the linac tunnel at 150 g/s; the leak may persist for up to 4 h. 2) A short-duration cryomodule leak releases up to 1,000 L of cryogenic helium at a rate of 5,048 g/s.				
Possible consequences and hazards: Should a sufficient volume of helium be released within the tunnel, workers in the tunnel or desiring entry into the tunnels could be at risk of asphyxiation owing to low oxygen levels. A sustained release could leak sufficient helium to create an asphyxiation risk in adjacent structures. An oxygen-deficient atmosphere creates the potential for unconsciousness, serious injury, permanent disability, and/or death.				
Potential initiators: Human error, maintenance error, boundary failure, excess pressure, mechanical failure.				
Risk assessment prior to mitigation:				
Severity:	High (**X**)	Medium ( )	Low ( )	Extremely low ( )
Probability:	Anticipated—high ( )	Anticipated—medium (**X**)	Unlikely ( )	Extremely unlikely ( )
Risk Category:	High risk (**X**)	Medium risk ( )	Low risk ( )	Extremely low ( )
Does the hazard require a credited control? Yes or No: **Yes**				
Hazard mitigation	1. ODH system monitors oxygen levels in the linac and provides alarms to warn workers to evacuate (or not to enter) the linac/HEBT tunnel (CREDITED). 2. Automatic initiation of the emergency ventilation system (EVS) upon detection of low oxygen levels in the linac (CREDITED). 3. Personnel trained to see and flee upon identification of a helium release. 4. Cryogenic system boundary integrity. 5. Cryogenic system process controls and alarms. 6. Cryogenic system operating procedures. 7. Superconducing linac (SCL) ceiling louvers automatically opened when tunnel is accessible to personnel. 8. Training, lock/tag/verify (LTV), operating procedures and/or job hazard analysis (JHA) for cryogenic unit maintenance. 9. The placement of ceiling lintels helps confine leaked helium to the superconducting section and vent it to the atmosphere.			
Risk Assessment After Mitigation:				
Severity:	High ( )	Medium ( )	Low ( )	Extremely low (**X**)
Probability:	Anticipated-high( )	Anticipated-medium (**X**)	Unlikely ( )	Extremely unlikely ( )
Risk category:	High risk ( )	Medium risk ( )	Low risk ( )	Extremely low (**X**)

1.0 Source Terms

The hazard analysis considers both long- and short-term duration releases of cryogenic helium from the superconducting linac (SCL).

1.1 Refrigerator-supplied (long-duration) release source term

The helium release rate is limited by the capacity of the refrigerator and is maximally 150 g/s (data provided by SNS cryogenic engineering). This value is believed to bound any credible line leak, including a guillotine break, and can be validated as follows.

Storage conditions:	3 atm, 4.6 K
Conditions at release point:	1 atm, 294 K

Liquid/gas ratio (liquid at storage conditions, gas at 70°F (294 K) and 1 atm v/v) is given by

ρ LHe at 4.6 K and 3 atm = 141.92 g/L,

ρ GHe at 70 °F and 1 atm = 0.1656 g/L,

$$\text{Expansion ratio} = \frac{141.92\ \text{kg/m}^3}{0.1656\ \text{kg/m}^3} = 857:1.$$

The line diameter ranges from 0.75 to 1.5 in., so the maximum hole area ranges from 0.0031 ft^2 to 0.012 ft^2.

Assuming that the liquid helium is at its saturated vapor pressure, is choked, has two-phase flow discharge, and experiences a guillotine line break or puncture, the mass flow rate is approximated by

$$Q_m = \frac{\Delta H_v A}{V_{fg}} \sqrt{\frac{g_c}{C_p T}}$$ (Chemical Process Safety, Prentice Hall, 1990, page 115),

$$Q_m = \frac{(10.27\ \text{BTU/lbm})(0.0031\text{ft}^2)}{15.717\ \text{ft}^3/\text{lbm}} \sqrt{\frac{(32.2\ \text{lbm·ft} \cdot \text{lbf}^{-1} \cdot s^{-2})(778\ \text{ft} \cdot \text{lbf} \cdot \text{BTU}^{-1})}{(1.24\ \text{BTU} \cdot (\text{lbm·R})^{-1})(8.28\ R)}}$$

$$Q_m = \frac{(10.27\ \text{BTU/lbm})(0.012\text{ft}^2)}{15.717\ \text{ft}^3/\text{lbm}} \sqrt{\frac{(32.2\ \text{lbm·ft} \cdot \text{lbf}^{-1} \cdot s^{-2})(778\ \text{ft} \cdot \text{lbf} \cdot \text{BTU}^{-1})}{(1.24\ \text{BTU} \cdot (\text{lbm·R})^{-1})(8.28\ R)}}$$

$Q_m = 0.1\ \text{lbm} \cdot s^{-1} = 45\ g \cdot s^{-1}$ for a 0.75 in. diameter hole
$Q_m = 0.387\ \text{lbm} \cdot s^{-1} = 176\ g \cdot s^{-1}$ for a 1.5 in. diameter hole.

An 0.75–1.5 in. diameter opening is one that could result from a sheared line or vessel puncture. Therefore, modeling for risk analysis using 150 g/s as suggested by SNS cryogenic engineering is consistent with the estimated peak discharge rates associated with credible line break or puncture.

The associated maximum volumetric release rate is given by

$$\left(\frac{150\ \text{g}}{\text{s}}\right)\left(\frac{\text{L}}{0.1656\ \text{g}}\right)\left(\frac{60\ \text{s}}{\text{min}}\right)\left(\frac{\text{ft}^3}{28.3\ \text{L}}\right) \approx 1{,}920\ \text{ft}^3/\text{min}.$$

The maximum release duration was established as 4 h during an ODH meeting held on March 8, 2002. In attendance were George Dodson, Mario Giannella, Mike Harrington, Paul Wright, Sam McKenzie, Ron Cornwell, and John Jankovic.

1.2 Cryomodule-supplied (short-duration) release source term

A maximum of 1,000 L of liquid helium at a maximum release rate of approximately 5,000 g/s is postulated as the bounding release from a cryomodule pressure relief plate (by SNS cryogenic engineering). The 1,000 L assumption is reasonable based on an approximate liquid inventory of a cryomodule (~750 L) and associated supply and return piping.

The assumed release rate of about 5,000 g/s is a reasonable bounding value associated with a beam pipe breach that floods the interior of the cryomodule with air. The internal surface area of a high-beta cavity is about 1.3 m^2 [3], and the average heat flux from condensing air on the inner surface of the cavity can be estimated at about 20,000 W/m^2 [4]. Each cryomodule contains four cavities. The associated release rate for an entire cryomodule can be calculated using the latent heat of helium of 20.6 J/g (at 15 psia) [5] as follows:

$$\text{Vaporization rate (g/s)} = 4(1.3\ \text{m}^2)(20{,}000\ \text{W/m}^2)/(20.6\ \text{J/g}) = 5{,}048\ \text{g/s}.$$

Maximum volumetric release rate associated with an assumed release of 5,048 g/s is given by

$$\left(\frac{5{,}048\ \text{g}}{\text{s}}\right)\left(\frac{\text{L}}{0.1656\ \text{g}}\right)\left(\frac{60\ \text{s}}{\text{min}}\right)\left(\frac{\text{ft}^3}{28.3\ \text{L}}\right) \approx 64{,}600\ \text{ft}^3/\ \text{min}.$$

Volume at 70ºF and 1 atm is given by

$$(1{,}000\ \text{L})\left(\frac{\text{ft}^3}{28.3\ \text{L}}\right)(857) \approx 30{,}280\ \text{ft}^3.$$

The release duration can be estimated by

$$\left(\frac{30{,}280\ \text{ft}^3}{64{,}600\ \frac{\text{ft}^3}{\text{min}}}\right) \approx 0.47\ \text{min}.$$

2.0 Dimensions

Linac/HEBT dimensions used:

Lintel depth	2.5 ft
Distance between lintels	798 ft
HEBT to Front-End length	1,057 ft
HEBT to Front-End width	14 ft
HEBT to Front-End height	10 ft
HEBT length	400 ft
HEBT width	17 ft
HEBT height	13 ft

Structure volumes used:

Linac/HEBT total volume	236,380 ft^3
Near field (volume above 7.5 ft)	74,395 ft^3
Far field (volume below 7.5 ft)	161,985 ft^3
Front-End building total volume	229,367 ft^3
Main level	192,605 ft^3
Mezzanine	36,762 ft^3
Ring/RTBT	299,000 ft^3
Klystron facility	1,060,719 ft^3

3.0 Oxygen Calculation Methodology

Various methodologies can be applied to calculate oxygen concentrations for a release of helium in air based on release rate and relative volumes. In this calculation, a mass balance model is adopted that assumes each control volume is well mixed (homogenous concentration). In most cases, two control volumes are selected for a coupled approach in which helium is released into volume 1, the "near field," and the outflow from the volume 1 serves as the inflow to volume2, the "far field." A diagram showing the general case is presented below in Figure F-11.

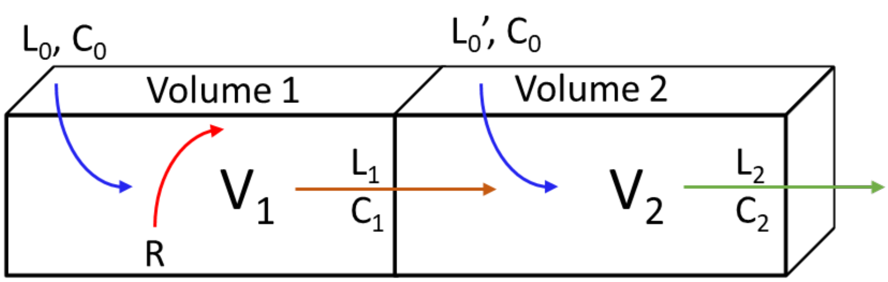


Figure F-1. Diagram of mass-balance model.

The mass balance for the control volume receiving the helium release, V_1, can be written as:

$$\frac{dC_1(t)}{dt} = \frac{C_0 L_0}{V_1} - \frac{C_1(t) L_1}{V_1}, \tag{3.1}$$

where

C_0	=	oxygen concentration in outside air, vol/vol, unitless
$C_1(t)$	=	oxygen concentration in volume 1, unitless

$C_2(t)$	=	oxygen concentration in volume 2, unitless
L_0	=	flow from outside to volume 1, (cfm)
L_0'	=	flow from outside to volume 2 (cfm)
L_1	=	flow from volume 1 to volume 2 (cfm)
L_2	=	flow from volume 2 out (cfm)
R	=	helium release rate into volume 1 (cfm)
V_1	=	control volume 1 (ft³)
V_2	=	control volume 2 (ft³)
t	=	time (min)

A general solution to this equation can be obtained using the boundary condition $C_1(0) = C_0$:

$$C_1(t) = C_0\left(\frac{L_0}{L_1} + \left(1 - \frac{L_0}{L_1}\right)e^{-\frac{L_1}{V_1}t}\right). \tag{3.2}$$

The equilibrium condition can then be evaluated:

$$\lim_{t\to\infty} C_1(t) = \frac{C_0 L_0}{L_1}. \tag{3.3}$$

The mass balance for the second control volume can be written as

$$\frac{dC_2(t)}{dt} = \frac{C_0 L_0'}{V_2} - \frac{C_1(t)L_1}{V_2} - \frac{C_2(t)L_2}{V_2}. \tag{3.4}$$

A general solution to this equation can be obtained using the boundary condition $C_2(0) = C_0$:

$$C_2(t) = C_0\left(K_1 + K_2 e^{-\frac{L_1}{V_1}t} + (1 - K_1 - K_2)e^{-\frac{L_2}{V_2}t}\right), \tag{3.5}$$

where

$$K_1 = \frac{L_0' + L_0}{L_2}, \text{ and}$$

$$K_2 = \frac{L_1 - L_0}{L_2 - L_1\frac{V_2}{V_1}}.$$

The equilibrium condition can then be evaluated:

$$\lim_{t\to\infty} C_2(t) = \frac{C_0(L_0' + L_0)}{L_2}. \tag{3.6}$$

The general solutions for the coupled mass balance scenario enable evaluating oxygen concentration for a variety of circumstances that could arise. Two arrangements are used in this calculation. The first divides the linac atmosphere into two control volumes, which are illustrated in Figure F-12.

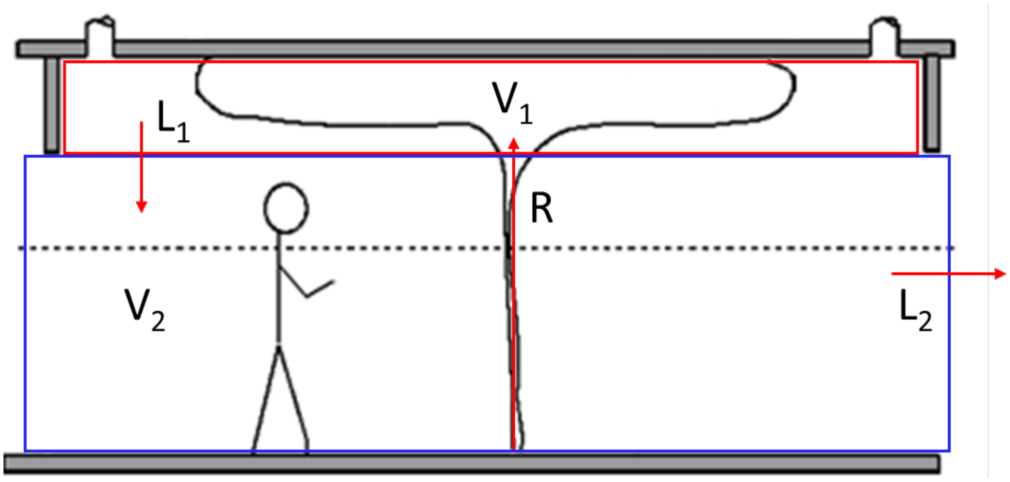


Figure F-1. Diagram of the mass balance model as applied to the linac tunnel.

The buoyancy of the released helium carries it rapidly to the ceiling of the linac, where it is partially confined by the lintels on either end of the superconducting section of the linac. The helium mixes with air in this upper volume, and then the diluted mixture is forced down into the main atmosphere, to which workers might be exposed. The use of this model for evaluating worker risk inside the linac tunnel is based upon the results of 2D simulations using computational fluid dynamics (CFD). As shown in Figure F-3, the CFD simulation shows that the gaseous helium rises quickly to ceiling level and mixes with local atmosphere and remains stratified to the upper portion of the tunnel. To evaluate effects on workers in the tunnel, the upper portion of the tunnel (h > 7.5 ft) is defined volume 1, clearly above the workers' breathing level. The lower portion (h < 7.5 ft) is defined as volume 2. Assuming no ventilation ($L_0 = L_0' = 0$ and $L_1 = L_2 = R$), Eqs. 3.2 and 3.3 reduce to the following:

$$C_1(t) = C_0 e^{-\frac{R}{V_1}t}, \tag{3.7}$$

$$C_2(t) = C_0 \left[\left(\frac{V_1}{V_1 - V_2} \right) e^{-\frac{R}{V_1}t} + \left(1 - \frac{V_1}{V_1 - V_2} \right) e^{-\frac{R}{V_2}t} \right]. \tag{3.8}$$

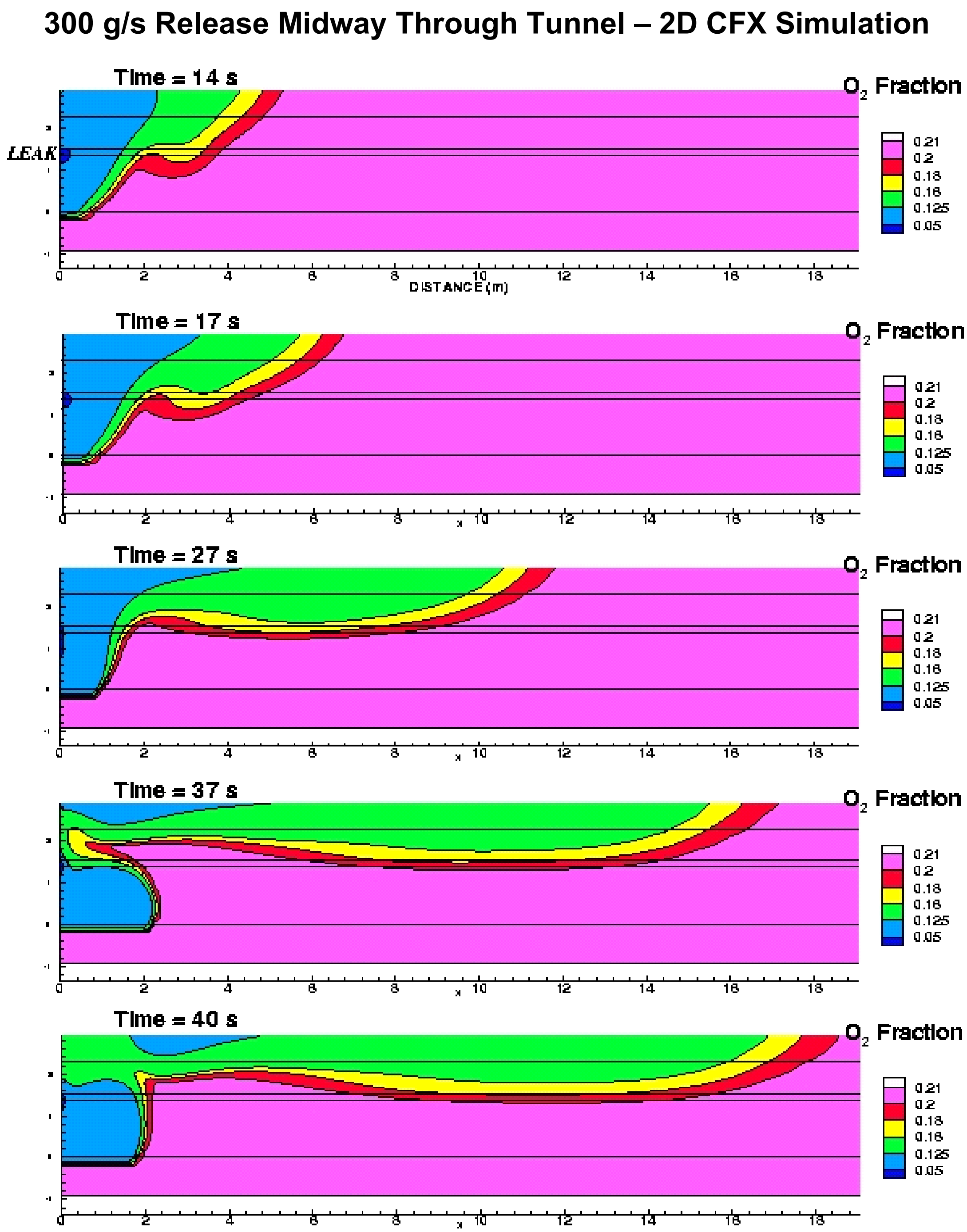


Figure F-3. Results of 2D CFD model of a cryogenic helium release in the linac tunnel.

To evaluate effects on workers in adjacent structures outside the linac/HEBT tunnel, the linac/HEBT tunnel is defined as control volume 1, and an adjacent structure is defined as control volume 2. Various ventilation arrangements are considered. The possibility that atmosphere from the linac/HEBT could simultaneously leak into multiple adjacent structures is also considered, as illustrated in Figure F-44. Four adjacent structures are considered, the Front-End mezzanine, the Front-End main, the ring/RTBT, and the Klystron Gallery.

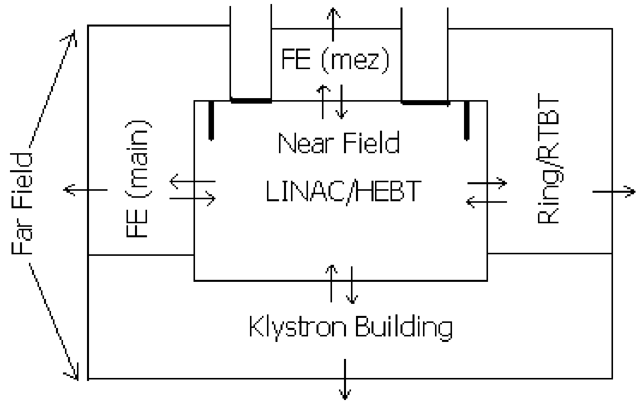


Figure F-4. Mass balance model as applied to linac tunnel with divided flow to adjacent structures.

Effects on adjacent structures are evaluated by including a fractional term (α) to reflect the portion of the total flow out of control volume 1 (e.g., linac/HEBT), that enters the second control volume (e.g., adjacent structure) of concern. Because the various adjacent structures do not influence one another's atmosphere, these structures are treated independently by substituting αL_1 for L_1 in the balance equations for control volume 2 (Eq 3.4). The solution becomes

$$C_2(t) = C_0\left(\frac{L_0' + \alpha L_0}{L_2} + \left(\frac{\alpha(L_1 - L_0)}{L_2 - L_1\frac{V_2}{V_1}}\right)e^{-\frac{L_1}{V_1}t} + \left(1 - \frac{L_0' + \alpha L_0}{L_2} - \frac{\alpha(L_1 - L_0)}{L_2 - L_1\frac{V_2}{V_1}}\right)e^{-\frac{L_2}{V_2}t}\right). \quad (3.9)$$

In mitigated scenarios, ventilation may be used to maintain the oxygen concentration inside the affected space. Ventilation can be performed via supply or exhaust. For supply ventilation, one or both of L_0 *and* L_0' have a (typically constant) value. A comprehensive solution can be developed to accommodate several potential supply ventilation arrangements by making substitutions into Eq. 3.7 such that $L_0 = Q$ (representing fan forced fresh air into the linac/HEBT), $L_0' = Q'$ (representing fan forced fresh air into volume 2), $L_1 = Q + R$, and $L_2 = Q + R + Q'$. These substitutions yield Eq. 3.10:

$$C_2(t) = C_0\left[K_1 + K_2 e^{-\frac{(Q+R)}{V_1}t} + (1 - K_1 - K_2)e^{-\frac{Q'+\alpha(Q+R)}{V_2}t}\right], \quad (3.10)$$

where

$$K_1 = \frac{Q' + \alpha Q}{Q' + \alpha(Q + R)},$$

$$K_2 = \frac{\alpha R}{Q' + (Q + R)\left(\alpha - \frac{V_2}{V_1}\right)}.$$

Another mitigation technique involves implementing exhaust ventilation at a rate of Q on control volume 1. This scenario is only meaningful if the exhaust ventilation (Q) exceeds the release rate (R), otherwise it simplifies back to the scenario with no ventilation. For $Q > R$, $L_1 = Q$ and $L_0 = Q - R$. Because exhaust ventilation in excess of the release rate draws air into control volume 1, consideration of control volume 2 loses meaning, so it will not be included here. The following simplification can then be derived:

$$C_1(t) = \frac{C_0}{Q}\left(Q - R\left(1 - e^{-\frac{Q}{V_1}t}\right)\right). \qquad (3.11)$$

The methodology described here is consistent with the approach described in Reference [2]. There are differences in nomenclature, such as the use of near-field and far-field to denote control volume 1 and control volume 2, respectively, but the mathematical basis and applicability of the results remain. The methodology presented here expands upon the past work and attempts to provide additional clarity regarding the assumptions and intermediate steps.

4.0 Oxygen Deficiency Risk Matrix – Consequence Severity and Accident Frequency Categories

The oxygen deficiency risk matrix [2] used for hazard analysis is presented in Figure F-55.

Consequence severity					
	High **$O_2 < 5\%$** **death or permanent disability**	-Low- marginally acceptable	-Medium- not acceptable	-High- not acceptable	-High- not acceptable
	Medium **$5\% \leq \%O_2 < 12.5\%$** **serious injury**	-Extremely low- OK	-Low- marginally acceptable	-Medium- not acceptable	-High- not acceptable
	Low **$12.5\% \leq \%O_2 < 16\%$** **minor injury**	-Extremely low- OK	-Extremely low- OK	-Low- marginally acceptable	-Low- marginally acceptable
	Extremely Low **$O_2 \geq 16\%$** **no injury**	-Extremely low- OK	-Extremely low- OK	-Extremely low- OK	-Extremely low- OK
		Extremely Unlikely ($<10^{-4}$/year)	**Unlikely (between 10^{-4} and 10^{-2}/year)**	**Medium (between 10^{-2} and 10^{-1}/y)**	**High (above 10^{-1}/y)**
Accident frequency					

Figure F-5. Oxygen deficiency risk matrix from Reference [2].

As specified in Reference [1], a credited control is required to protect against credible accidental releases that could cause a worker to experience breathing air with an oxygen concentration below 12.5% by volume.

5.0 Linac Helium Release Scenarios and Analysis

Two helium release scenarios are evaluated: a refrigerator-supplied leak and a cryomodule-supplied leak. Effects of accidental helium release scenarios are assessed for three different worker groups: X1, X2, and X3. X1 refers to a worker(s) in the tunnel in the vicinity of the release. X2 refers to (1) worker(s) in the linac/HEBT tunnel far enough away from the leak that they are unaware the leak is occurring or (2) worker(s) entering the tunnels at some time after a release has initiated. Worker X3 is in or enters an adjacent structure (Front-End mezzanine, Front-End main level, Klystron Gallery, or ring/RTBT) and is unaware of the leak.

The CFD model results presented in Figure F.3 show that a large release of helium pools on the floor beneath the leak site and immediately rises to the ceiling. The low oxygen level danger zone between 5% and 12.5% (shown in blue) is shown to be localized to within a few meters of the plume area immediately above and adjacent to the pool. Away from the localized high-concentration plume, the helium stratifies, dilutes, and moves horizontally along the ceiling with oxygen concentrations greater than 12.5%. The lowest oxygen concentration band between 12.5% and 16% (shown in green) is near the ceiling. It is assumed that a trained worker in the vicinity of such a release would quickly recognize the release (“see” the vapor cloud and hear the associated noise) and would “flee” away from the cloud. Assuming a walking speed of 5 ft/sec (i.e., the value used in designing escape routes for fire protection), an individual walking away from the release would be able to safely evacuate the linac.

5.1 Release Scenario 1 – Refrigerator-Supplied Release (150 g/s for 4 h):

A refrigerator supply line release of 150 g/s is assumed to occur as described in Section 1.1. Such a leak would likely be identified quickly by operators, and manual and/or automatic actions to effectively stop/reduce/ventilate the leak would likely be taken within about 30 min to 1 h. If the release is terminated within 1 h after initiation, then oxygen levels in adjacent areas for all scenarios evaluated here remain above 16%. Although this outcome is considered likely, this analysis conservatively assumes that the release continues at a constant rate for 4 h (e.g., operators unable to stop leak, leak not identified because of prolonged staff absence, automatic cryosystem control actions ineffective). People may or may not be present in the linac/HEBT and/or adjacent structures when the leak occurs. The two EVS ceiling dampers are normally automatically opened when the tunnel is accessible and closed when the tunnel is in beam permit.

5.1.1 Linac/HEBT Tunnels:

If the linac tunnel is occupied, the accidental release is assumed to be readily apparent to linac occupants in the vicinity of the leak. Such a release would be highly energetic and easily detected by visual and audible means. Training to see and flee from a recognized cryogenic release mitigates risk to worker X1. The EVS ceiling dampers are automatically opened when the tunnel is accessible. With the ceiling dampers open, most of the released helium would escape the tunnel due to natural buoyancy.

Worker X2 is assumed to be in or entering the tunnel but is far enough removed from the release that they are unaware of the leak. Alternately, worker X2 may enter the tunnel at some time after the leak has terminated but before the released helium has dissipated to safe levels. Figure F.6 shows unmitigated oxygen concentrations within the tunnel associated with the release, neglecting passive ventilation out of the EVS ceiling dampers. Oxygen concentrations calculated using the coupled mass balance model for the linac tunnel using Equations 3.7 and 3.8 are presented in Figure F.6. Additionally, Figure F.6 shows a trace of the calculated oxygen concentration in the tunnel assuming a well-mixed tunnel (i.e., neglecting buoyancy, Equation 3.7 with $V = V_1 + V_2$) to provide perspective.

As shown in Figure F-6, the oxygen concentration in the breathing zone for a worker, assumed to be the far field (h < 7.5 ft) decreases below 16% into the "Low" consequence severity category over the time frame of about an hour and into the Moderate consequence severity category (<12.5 %) after about 80 min. As the leak continues, the associated oxygen levels continue to deplete into the "High" Consequence severity category (below 5%). The risk to worker X2 is "High-Not Acceptable." A Credited Control is required to protect worker X2 as described in Section 4.0.

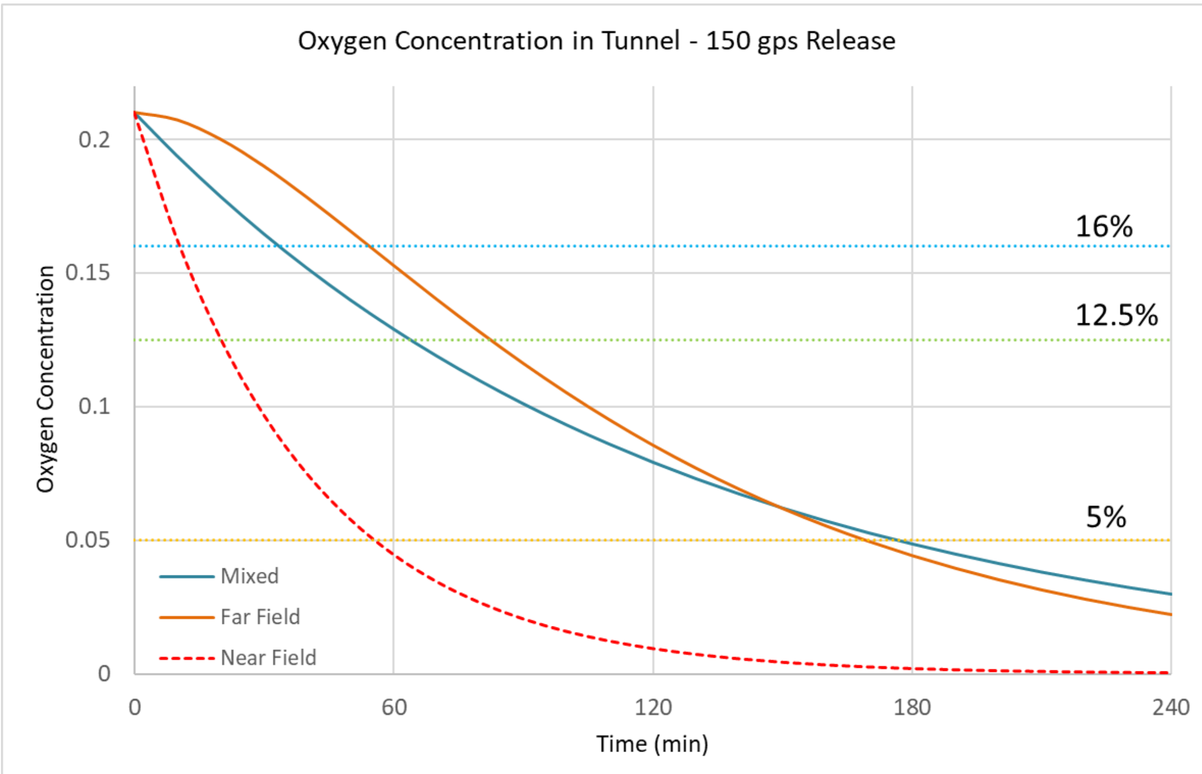


Figure F-6. Oxygen concentration v. time in the linac/HEBT tunnel using the coupled (near field far field) and well-mixed models.

5.1.2 Adjacent Structures

Helium released in the linac/HEBT tunnel will dissipate by leaking into adjacent structures and/or out of the linac ceiling dampers. Four adjacent structures are considered as shown in Figure F-6: the Klystron Gallery, Front-End mezzanine, Front-End main, and ring/RTBT. Barriers exists between the adjacent structures that could impact the distribution of a helium release depending on the configuration at the time of the postulated helium release. Barriers include (i) sealed penetrations between the linac and the Klystron Gallery, (ii) the shield wall between the ring from the HEBT, and (iii) the shield wall between the linac and front end. Bounding assumptions are made to account for the potential impacts of these barriers on helium distribution.

The Klystron Gallery penetrations have been mostly sealed for the purposes of preventing transmission of fire. Assuming restricted leakage into the Klystron Gallery leads to a higher inventory of helium to disperse within the other adjacent structures. This effect is bounded by assuming no leakage into the Klystron Gallery when assessing impacts on the other adjacent structures.

A stacked shield wall separates the ring from the HEBT. The shield wall is equipped with a personnel door and a set of louvers located above the personnel door. Should the louvers and the door be closed, leakage of atmosphere from the linac/HEBT into the ring/RTBT would be significantly impeded, potentially limiting dispersion to the linac/HEBT and front end, resulting in lower oxygen concentrations in those areas.

The linac is separated from the Front-End building by a shield wall equipped with a large equipment shield door that is opened as needed during maintenance periods to allow passage of large equipment items. Normal personnel entry is through a double door entryway. There are several penetrations in the shielding between the linac and front end; however, penetrations are normally tightly packed with shielding material. When the Front-End shield door is shut, leakage of helium into the front end would be significantly impeded, potentially limiting dispersion to the linac/HEBT and ring/RTBT structures leading to lower oxygen concentrations in those areas.

Unimpeded Leakage into Front End and Ring/RTBT Tunnel

Table 1 presents oxygen concentrations associated with a 150 gps helium release that persists for 4 h assuming no leakage into Klystron Gallery or out through the EVS ceiling louvers. Leakage into the Front-End building (mezzanine and main) and ring/RTBT is assumed to be unimpeded. This can be modeled using Equation 3.10 with $Q = 0$ and $\alpha = 0.5$ for leakage into each building.

The HVAC system in the Front-End building normally runs continuously, circulating air throughout the building (~19,000 cfm) with a small amount ($Q' = 800$ cfm) of fresh air intake [6]. Circulating air is pulled into the mezzanine level through a floor grate and exhausted throughout the building. With the HVAC system operating, helium leaked into the Front-End building would be well mixed throughout the building (i.e., between the Mezzanine and Main Level). This can be modeled by assuming the Front-End mezzanine and Front-End main are a single volume. Resulting oxygen concentrations are presented in the "FE HVAC On" column of Table F.1. The results show that the HVAC, which normally runs continuously, can serve a non-credited protective function of maintaining oxygen concentration in the front end (14.5%) in the "Low – Minor Injury" consequence severity category. The oxygen concentration in the ring/RTBT is 14.1%, which is in the "Low – Minor Injury" category.

Although the Front-End HVAC normally operates continuously, the system could be out of service when a helium leak occurs. For this scenario, some stratification could be assumed for leakage into the Front-End building. This stratification is modeled by assuming half the helium leaking into the Front-End building travels into the relatively small volume of the mezzanine, and the other half is assumed to leak into the Front-End main. This is modeled by assuming $Q' = 0$ and $\alpha = 0.25$ for both the mezzanine and the main. The resulting oxygen concentrations are presented in the presented in the "FE HVAC Off" column of Table F.1. The resulting oxygen concentration in the Mezzanine is considered bounding. In this case, oxygen levels in the mezzanine are reduced to 6.4%, which would require a credited control to protect workers potentially in the mezzanine.

Table F.1. Oxygen concentrations for release scenario 1. Assumes unimpeded leakage into front end and ring/RTBT

Areas involved	% Oxygen - Front-End HVAC off	% Oxygen - Front-End HVAC on
Front-End main	15.3	14.5
Front-End mezzanine	6.4	14.5
Ring/RTBT	14.1	14.1

Bounding Leakage into the Front-End Building

Normally the louvers over the ring-to-HEBT personnel door remain open, which would allow a leakage pathway into the ring/RTBT. Table F.2 presents oxygen concentrations for the Front-End areas, assuming no leakage into the ring/RTBT (e.g., personnel door and associated louvers of the ring–HEBT shield wall are closed). Furthermore, no leakage is assumed into the Klystron Gallery or out through the EVS ceiling louvers. Resulting oxygen levels in the Front-End areas are lowered because of the increased inventory. The resulting oxygen concentration in the front end is 11.0%, assuming the HVAC is operating normally. Without the HVAC, levels in the Mezzanine fall to 4.3%, which is in the “High” severity category.

Table F.2. Oxygen Concentrations for Release Scenario 1. Assumes No Leakage Across ring-HEBT Wall

Areas involved	% Oxygen - Front-End HVAC off	% Oxygen - Front-End HVAC on
Front-End main	11.7	11.0
Front-End mezzanine	4.3	11.0

Depending on the configuration of the ring ventilation system, fresh air drawn into the ring may outflow from the ring into linac/HEBT, which would serve to push the linac/HEBT atmosphere into the Front-End building. Additionally, the fresh air inflow into the linac/HEBT would dilute the atmosphere in the tunnel. The effect of air flow from the ring during a 150 gps helium release on oxygen levels in the Front-End building has been evaluated. The time-dependent oxygen concentration in the Front-End building has been calculated using Equation 3.10 for a range of air inflow rates up to 10,000 cfm. The results are presented in Figure F-77. The results show that oxygen concentrations in the Front-End building are not significantly degraded by air inflow from the ring. In the long time frame (~180 min), oxygen concentrations are always improved by the dilution provided by the fresh air inflow. In shorter time frames, the oxygen concentrations may decrease a little more quickly depending on flow rate, but the decrease is not significant. For example, the time to reach 12.5% is not appreciably reduced with air inflow; for inflows greater than 1,600 cfm, the level never decreases below 12.5%. At flow rates below 1,600 cfm, the time to reach 16% may be reduced by about 15 min. For air inflow rates greater than 5,300 cfm, the oxygen concentration never goes below 16%.

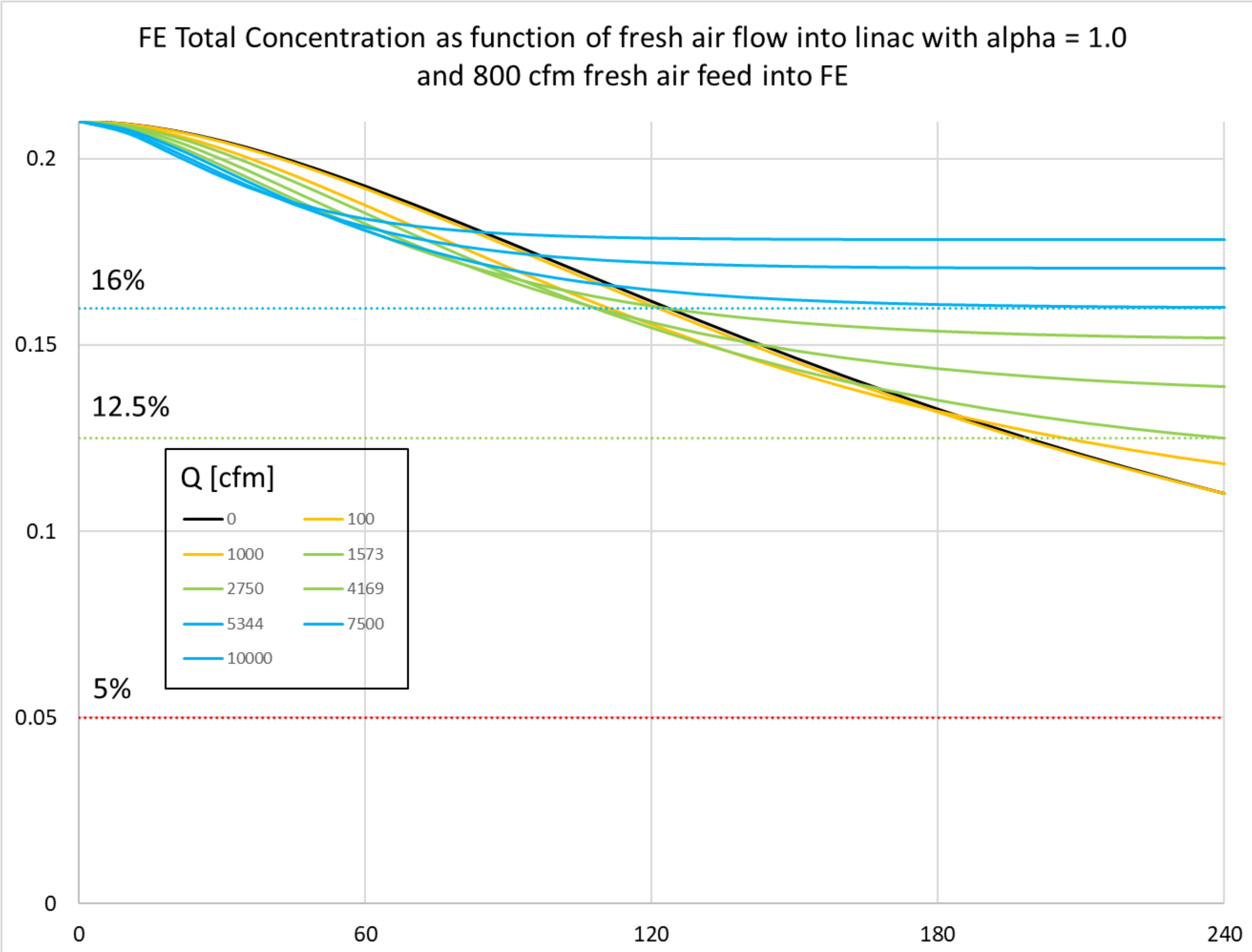


Figure F-7. Time-dependent oxygen concentration in the Front-End building for a range of air inflow rates from the ring ventilation system.

A similar analysis was performed for the Front-End mezzanine (HVAC off) that showed similar results. In the longer time frames, oxygen concentrations are always improved by the dilution provided by the fresh air inflow; in the shorter time frames, oxygen concentrations decreased a little more quickly depending on flow rate. For example, the time to reach 12.5% is not appreciably reduced with air inflow and for inflows greater than 2,800 cfm, the level never decreases below 12.5%. At flow rates less than 2,800 cfm, the time to reach 16% is reduced by less than 10 min. For air inflow rates greater than 6,200 cfm, the oxygen concentration never goes below 16%. Therefore, oxygen concentrations in an adjacent structure are not significantly degraded by air inflow into the linac/HEBT.

As previously stated, such a leak would likely be identified quickly, and action to stop/reduce/ventilate the leak would be taken within about 30 min to 1 h, which would keep oxygen levels above 16% in the "extremely low consequence – minor injury" category. The leak would have to persist for more than 100 min for oxygen concentrations to dip below 12.5% into the "low" consequence severity category.

Bounding Leakage into the Ring/RTBT

The minimum oxygen concentration in the ring/RTBT is bounded by assuming no leakage into the Front-End building. Additionally, when the tunnels are accessible (i.e., entry allowed into the ring/RTBT), the EVS ceiling dampers are normally automatically opened. For this case, leakage out of the ceiling vents is neglected. Oxygen concentrations in the ring/RTBT assuming helium disperses only between the linac/HEBT and ring/RTBT are calculated using Equation 3.10 with $\alpha = 1.0$. The time-dependent oxygen concentration in the ring/RTBT is shown in Figure F-88. The oxygen concentration falls to 16% after about 130 min and falls to 12.5% after about 190 min. The oxygen concentration reaches a minimum of 10.2%, which requires a credited control to protect workers in the ring/RTBT.

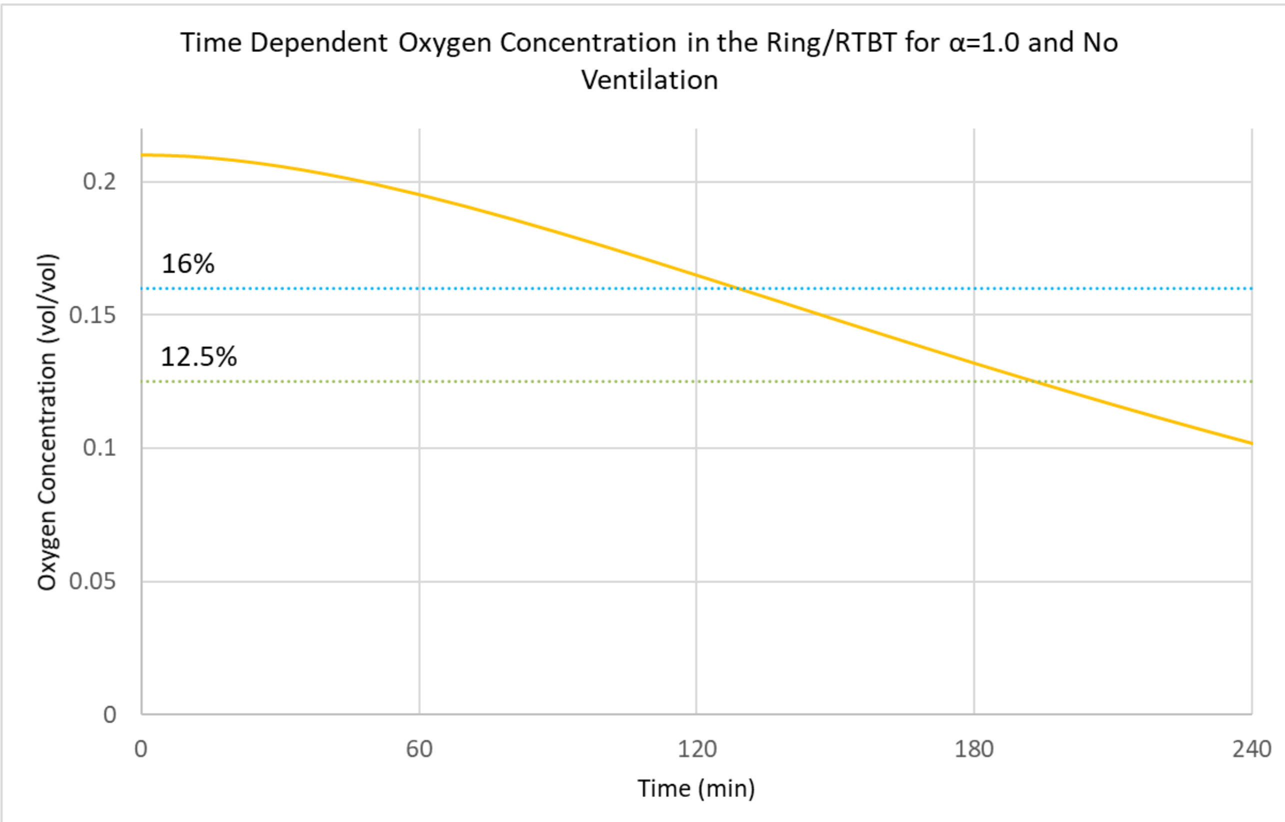


Figure F-8. Oxygen concentration in the ring/RTBT assuming α = 1 and no ventilation.

Bounding Leakage into the Klystron Gallery

The worst-case bounding oxygen concentrations in the Klystron Gallery are estimated by assuming unimpeded leakage into the Klystron Gallery and further assuming no leakage into either the Front-End or ring/RTBT. Helium leaked into the Klystron Gallery would be diluted by the relatively large volume of the building. Assuming that helium disperses only between the linac/HEBT and the Klystron Gallery ($\alpha =$ 1.0) yields a minimum oxygen concentration in the Klystron Gallery of 16.6%, which is considered "extremely low" consequence. Therefore, the Klystron Gallery is not at risk, even with open penetrations.

ODH Analysis Summary for Scenario 1

Linac/HEBT – Cryogenic safety training mitigates risk to worker X1. Oxygen concentrations throughout the tunnel reach lethal levels over time, resulting in an unacceptable risk to worker X2. A credited control is required. As described below, the ODH system that monitors oxygen levels in the linac and provides alarms to warn workers to evacuate (and not to enter) the linac/HEBT tunnel is designated as a credited engineered control to protect workers from this accident scenario.

Front-End building – Bounding front-end oxygen concentrations in the mezzanine dip below the 12.5% threshold requiring a credited control about 100 min after the start of the unmitigated release. Oxygen concentration never goes below 11% with the HVAC operating in the Front-End building, regardless of the leakage assumptions across the ring to HEBT wall barrier. As described below, the emergency ventilation system (EVS) designed to confine released helium within the linac tunnel region is designated as a credited engineered control to protect workers from this scenario.

Ring/RTBT – Bounding oxygen concentrations in the ring/RTBT fall below 12.5% within a time frame on the order of 190 min. As described below, the EVS is designed to confine released helium within the linac tunnel region and is designated as a Credited Engineered Control to protect workers from this scenario.

Klystron Gallery - Oxygen concentrations predicted for the ring/RTBT and Klystron Gallery remain in the Extremely low consequence category regardless of bounding leakage assumptions. Personnel in these areas are not at risk from this accident scenario.

<u>Mitigation – Credited Controls</u>

The credited ODH system monitors oxygen levels in the linac and provides alarms to warn workers to evacuate (or not to enter) the linac/HEBT tunnel, providing protection for worker X2. The credited ODH monitoring system also automatically initiates the credited EVS. The EVS provides sufficient exhaust ventilation to confine helium within the linac region of the tunnel thus protecting worker X3 located in adjacent structures (Front-End building and ring/RTBT) in the event of a prolonged release. Each of the two EVS fan is rated at 10,000 cfm, which is significantly greater than the postulated 1,920 cfm release rate. Operation of a single fan would be sufficient to confine released helium within the tunnel region, effectively protecting worker X3.

The EVS would also have a non-credited beneficial impact on oxygen concentrations in the linac/HEBT. The oxygen concentration in the linac/HEBT can be calculated using the equilibrium equation (Eq. [3.3]) for exhaust-dominated flow (exhaust fan flow exceeds fan forced supply flow):

$$\lim_{t\to\infty} C_1(t) = \frac{C_0 L_0}{L_1}$$

where

L_1	=	EVS exhaust fan flow (cfm)
R	=	helium release rate (1,920 cfm)
L_0	=	fresh air flow into linac ($L_1 - R$)

If the EVS operates both fans as designed, then the resulting equilibrium oxygen concentration in the linac/HEBT tunnel would be 19.0%. With only one fan operating, the equilibrium oxygen concentration would be 17.0%.

The ODH system also sends a delayed, non-credited signal to initiate the “smoke removal” ventilation mode in the linac, which secures recirculation ventilation units in the linac tunnel and starts makeup air units to supply air from the HEBT and front end. The makeup air supply is roughly equivalent to the capacity of a single EVS fan. With both EVS fans operating, this supply does not exceed the exhaust flow. However, if only one EVS fan is operating, then the sum of the supply and release rates may exceed exhaust flow. The effect of this would be to allow flow in excess of the exhaust rate to propagate into adjacent structures, such as the front end. However, sufficient dilution would be provided to prevent a significant hazard in any adjacent space. The associated equilibrium oxygen concentration in the linac calculated using Eq. 3.3 for supply-dominated flow (i.e., fan forced supply air exceeds exhaust fan flow):

$$\lim_{t\to\infty} C_1(t) = \frac{C_0 L_0}{L_1}$$

where

R	=	helium release rate (1,920 cfm)
L_0	=	fresh air flow into linac (~10,000 cfm)
L_1	=	flow out of the linac ($L_0 + R$ = 11,920 cfm)

The associated equilibrium oxygen concentration is 17.6%, which represents the lowest oxygen concentration that would be available to leak into adjacent structures. For supply-dominated flow, the equilibrium concentration is not a function of the exhaust fan flow rate because it is assumed that flow out of the control volume is equal to the fan forced supply flow into the volume plus the release flow. This is an acceptable condition, well above the 16% criteria. However, it is preferred to confine the release to the linac tunnel rather than ventilate into adjacent areas, so both EVS fans should be in service as much as practical.

5.2 Release Scenario 2 – Cryomodule Supplied Helium Release

A cryomodule-supplied release of 1,000 L cryogenic helium is assumed to occur at a rate of 5,048 g/s for about 28 s. Workers are assumed to be present in the linac/HEBT, adjacent structures, and control room (i.e., not in beam permit). The two EVS ceiling dampers are normally automatically opened when the tunnel is accessible and closed when the tunnel is in beam permit. The accidental release is assumed to be readily apparent to linac occupants in the vicinity of the leak (worker X1), either because they were involved in an activity that produced the release, or because they noticed visual or audible cues. SNS training requires immediate evacuation. With the ceiling dampers open, most of the released helium would escape the tunnel because of natural buoyancy; however, no leakage of helium through the dampers is assumed. Associated near field/far field oxygen concentrations inside the linac/HEBT tunnel are calculated using Eqs. 3.7 and 3.8, as shown in Figure F-9.

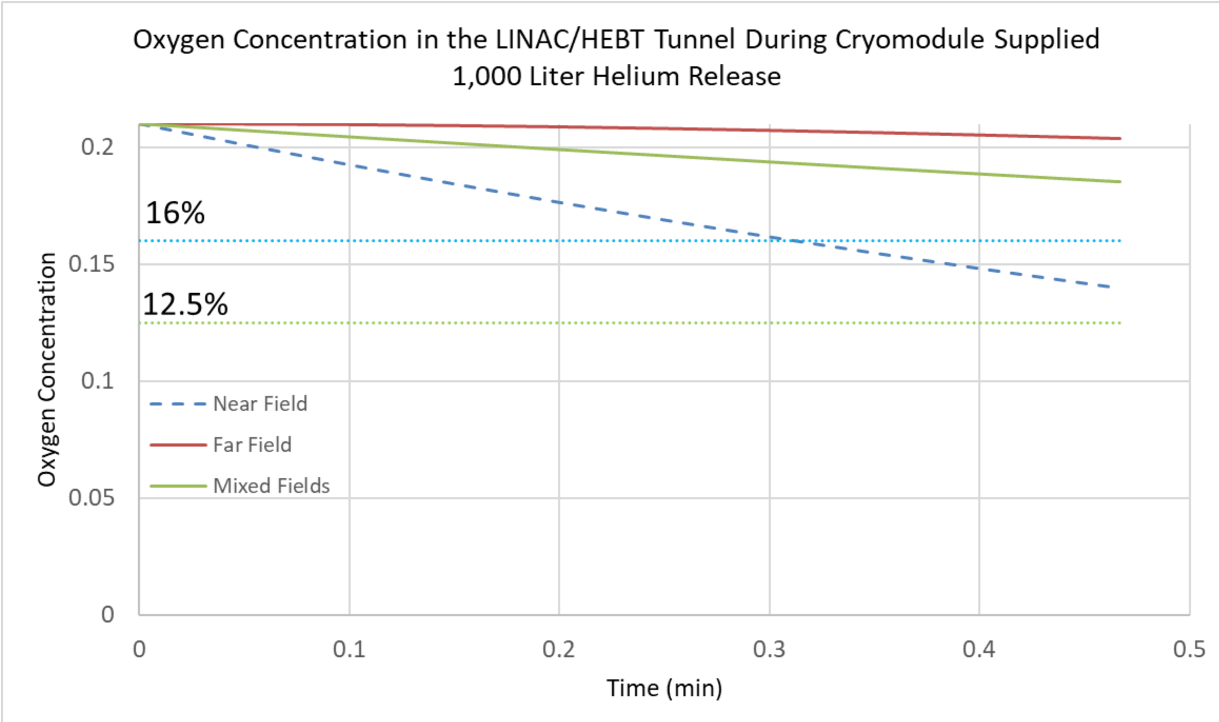


Figure F-9. Oxygen concentration in the linac/HEBT for cryomodule release (no ventilation).

Linac/HEBT during release:

Cryogenic safety training mitigates risk to worker X1 from oxygen deficiency hazards associated with the plume. As shown in Figure F-9, the far field concentration (h < 7.5 ft) stays above 20%. The minimum oxygen level in the far field (h < 7.5 ft) is 20.4%, whereas oxygen levels in the near field (h > 7.5 ft), which is not normally occupied, reach 14%. Assuming no stratification leads to a mixed oxygen concentration of 18.6%, which is above the threshold for the "extremely low" (no injury) consequence category. Therefore, worker X2 is not at risk.

Adjacent structures:

Atmosphere leaking out of the linac/HEBT tunnel into adjacent structures would be further diluted and dispersed within the adjacent structure volumes. The total amount of helium released is insufficient to significantly impact the atmosphere in adjacent structures. Oxygen concentrations for adjacent structures remain in the "extremely low" consequence severity category; therefore, worker X3 is not at risk.

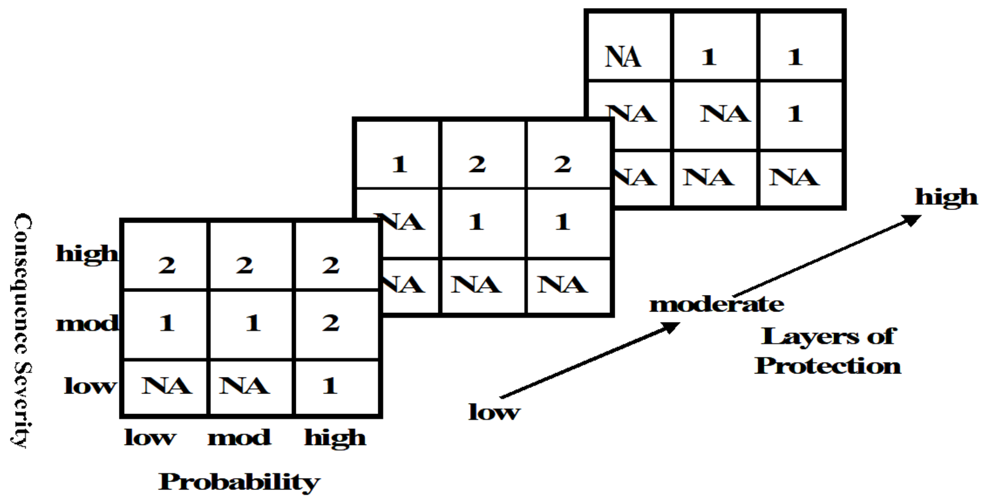
Conclusions for Scenario 2:

Cryogenic safety training mitigates risk to worker X1. Workers X2 and X3 are not at risk because of the limited amount of helium released.

6.0 Safety Integrity Level (SIL) Determination

As identified in Section 5.1, Credited Controls are required to protect worker X2 and worker X3 from oxygen deficiency hazards associated with a postulated long-term helium leak. The credited ODH system monitors oxygen levels in the linac and provides alarms to warn workers to evacuate (or not to enter) the linac/HEBT tunnel, providing protection for worker X2. The credited EVS automatically initiates upon detection of low oxygen concentrations in the linac and confines helium to the linac region of the tunnel, providing protection for worker X3.

The system for detecting a release, warning individuals in the tunnel or seeking to enter the tunnel, and initiating the mechanical ventilation falls into a safety integrity level (SIL) of one using the guidance provided in in Figure F-10, which is reproduced from Reference [2]. The determination is based on a "moderate" to "high" consequence severity category, moderate probability of occurrence, and layers of protective features (automatic tunnel ventilation, oxygen sensor/alarm system, cryogenic plant alarm system, automatically opened ceiling louvers, front-end ventilation system).



<u>Consequence severity (conservative minimum oxygen concentration as $\%O_2$)</u>

Extremely low	$\%O_2$	$\geq 16\%$
Low	12.5%	$\leq \%O_2 < 16\%$
Moderate	5%	$\leq \%O_2 < 12.5\%$
High	$\%O_2$	$< 5\%$

Likelihood of occurrence for initiating events (conservative accident release as failure per year, "f")

Extremely unlikely	f	$< 10^{-4}$/y
Low	10^{-4}/y	$\leq f < 10^{-2}$/y
Moderate	10^{-2}/y	$\leq f < 10^{-1}$/y
High	f	$> 10^{-1}$/y

<u>Effectiveness of protection layers (n) *not dependent on personnel actions whose effectiveness cannot be verified*</u>

Low	n = one or less protective systems in place
Moderate	n = two protective systems in place
High	n = more than two protective systems in place

Figure F-10. Establishing safety system requirements (numbers in boxes are safety integrity level [SIL]). Reproduced from Reference [2].

7.0 <u>Summary and Conclusions</u>

In the event of a cryogenic release from the supply system, sufficient helium can be released to reduce the oxygen concentrations in the linac/HEBT, Front-End building and ring/RTBT tunnel to unacceptable levels. Without providing some form of warning and control, unsuspecting staff inside or entering these areas could be at risk of asphyxiation. The ODH system that provides warnings to alert persons in or desiring entry into the linac/HEBT tunnel is credited to protect workers from hazards within the tunnel. Credited initiation of the EVS fans by the ODH system provides adequate mitigation for individuals in the adjacent structures.

REFERENCES

[1] *Final Safety Assessment Document for Proton Facilities (FSAD-PF)*, SNS 102030103-ES0018-R03, December 2010.

[2] *SNS Personnel Safety for Cryogenic Operations*, SNS 102030103-PC0001-R01, August 2002.

[3] Email from B. Degraff to D. Freeman, “RE: Help with words”, 2 October 2018.

[4] Weber, C., Henriques, A., et. Al., “Safety Studies on Vacuum Insulated Liquid Helium Cryostats”, IOP Conf. Series: Materials Science and Engineering 278 (2017) 011269.

[5] *Perry’s Chemical Engineers Handbook*, 7th edition, Table 2-264.

[6] *SNS FELK Air Balance Report*, SNS 108030100-VS0027-R00.