102030102-ES0016-R04.1

Spallation Neutron Source Final Safety Assessment Document for Neutron Facilities

Jacob Platfoot
David Freeman
Thomas Copinger

November 2023

OAK RIDGE National Laboratory

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

102030102-ES0016-R04.1

Research Accelerator Division

SPALLATION NEUTRON SOURCE
FINAL SAFETY ASSESSMENT DOCUMENT FOR NEUTRON FACILITIES

Jacob Platfoot, David Freeman, Thomas Copinger

November 2023

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

DOCUMENT APPROVAL RECORD

Spallation Neutron Source Safety Assessment Document
for Neutron Facilities, SNS Document Number 102030102-ES0016-R04.1

This document describes the SNS Neutron Facilities, identifies and analyzes associated hazards, and identifies appropriate controls to mitigate hazards in accordance with DOE Order 420.2D. This document is an update to the previous version (102030103-ES0016-R03, September 2011) with minor updates reflecting the final version of the Accelerator Safety Envelope, Revision 7. The SNS Final Safety Assessment Document for Proton Facilities (102030103-ES0018) serves as a companion document.

Recommended for approval:

11/21/2023

Jacob Platfoot
Accelerator Safety Program Lead
Date

11/28/2023

Fulvia Pilat
SNS Operations Manager
Director, Research Accelerator Division
Date

Approved:

12/01/2023

Jens Dilling
Associate Laboratory Director for Neutron Sciences
Date

CONTENTS

FIGURES

TABLES

ACRONYMS AND ABBREVIATIONS

ac	alternating current
AC	administrative control
ACL	acceptance criteria listing
AE-CM	architect engineer-construction manager
ALARA	as low as reasonably achievable
ANSI	American National Standards Institute
ASE	accelerator safety envelope
ASME	American Society of Mechanical Engineers
ASO	accelerator safety order
B&PV	Boiler and Pressure Vessel
BD	Identifier for Beam Dumps events
BG	Identifier for Target Building General hazard events
BNL	Brookhaven National Laboratory
CA	Identifier for Compressed Air System hazard events
CAC	credited administrative control
CCR	central control room
CCTV	closed-circuit television
CEC	credited engineered control
CEDE	committed effective dose equivalent
CEF	central exhaust facility
CFCC	Conventional Facilities Central Control
CFD	computational fluid dynamics
CFR	Code of Federal Regulations
CHL	central helium liquefier
CLO	Central Laboratory and Office
CM	identifier for cryogenic moderator system hazard events
CMS	cryogenic moderator system
CRL	Central Research Laboratories
CW	Identifier for cooling water loops 2, 3, and 4 hazard events
dc	direct current
DCF	dose conversion factor
DI	deionized
DOE	US Department of Energy
DTL	drift tube linac
EPA	Environmental Protection Agency
EPICS	Experimental Physics and Industrial Control System
ERPG	Emergency Response Planning Guideline
FHA	fire hazards analysis
FM	FM Global (formerly Factory Mutual)
FS	identifier for fire detection and suppression system hazard events
FSAD	final safety assessment document
FSS	fire suppression system
GAR	gold amalgamation room
GW	identifier for mercury off-gas treatment, vacuum, and helium systems hazard events
HA	hazard analysis
HB	identifier for high bay area hazard events
HE	hazard evaluation
HOG	hot off-gas

HUR	hydrogen utility room
HV	Identifier for Confinement Ventilation Systems hazard events
I&C	instrumentation and control
ICRP	International Commission on Radiological Protection
ICS	integrated control system
IEEE	Institute of Electrical and Electronics Engineers, Inc.
IOC	input/output controller
IRM	interlocked radiation monitor
IRP	inner reflector plug
ISA	Instrument Society of America
ISCST	industrial source complex short term
ISM	Integrated Safety Management
ISO	International Organization for Standardization
JHA	job hazard analysis
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LEBT	low energy beam transport
LFL	lower flammability limit
LHe	liquid helium
LLLW	low-level liquid waste
LO/TO	lockout/tagout
LOC	level of control
MAR	material at risk
MCI	maximum credible incident
MOI	maximum off-site individual
MOTS	mercury off-gas treatment system
MPFL	maximum possible fire loss
MPS	machine protection system
MSDS	material safety data sheet
NEC	National Electric Code
NFDD	Neutron Facilities Development Division
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NPH	Natural Phenomena Hazard
NSD	Neutron Scattering Division
OFT	overflow tank
OPM	Operations Procedures Manual
ORNL	Oak Ridge National Laboratory
ORR	Oak Ridge Reservation
OSHA	Occupational Safety and Health Administration
OST	operations shift technician
PC	performance category
PCE	primary confinement exhaust
PCES	primary confinement exhaust system
PF	Proton Facilities
PLC	programmable logic controller
POC	point of contact
PPE	personal protective equipment
PPS	personnel protection system
PPU	Proton Power Upgrade

PW	Identifier for process waste and sanitary waste systems hazard events
RF	respirable fraction
RRF	respirable release fraction
RSO	radiation safety officer
RTBT	ring-to-target beam transport
RWP	radiological work permit
SBC	Standard Building Code
SBMS	Standards-Based Management System
SCES	secondary confinement exhaust system
SCFM	standard cubic feet per minute
SCL	superconducting linac
SH	identifier for core vessel general area, shielding/reflectors/shutters hazard events
SIL	safety integrity level
SLPM	standard liters per minute
SNS	Spallation Neutron Source
TBAC	transfer bay access control
TC	identifier for target bay service general area hazard events
TCR	target control room
TLDs	thermoluminescent dosimeters
TPS	target protection system
TS	identifier for target systems hazard events
TVA	Tennessee Valley Authority
UL	UL Solutions (formerly Underwriters Laboratories Inc.)
UPS	uninterruptible power supply
USI	unreviewed safety issue
UV	identifier for truck bay and utility vault general area hazard events
VESDA	Very Early Smoke Detection Apparatus
WH	identifier for contact waste handling and decontamination area hazard events
WWS	window work station

1. INTRODUCTION

The Spallation Neutron Source (SNS) at the US Department of Energy's (DOE's) Oak Ridge National Laboratory (ORNL) is one of the world's foremost neutron scattering facilities. The facility provides important scientific capabilities for basic research in many fields, including materials 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 1.3 GeV using the 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 beamlines to instrumented experimental areas.

Accelerator-specific hazards associated with SNS are addressed in two separate safety assessment documents. The present document addresses hazards associated with the SNS neutron facilities, which are largely housed in the target building (Building 8700). All other accelerator-specific hazards are addressed in the companion document *Spallation Neutron Source Final Safety Assessment Document for Proton Facilities* (FSAD-PF) [1]. Together, the two documents provide a comprehensive safety assessment for SNS accelerator-specific hazards in compliance with DOE Order 420.2D [2]. All other site hazards are safely managed in accordance with mature ORNL institutional integrated safety management (ISM) programs such as those addressing worker safety and health and radiation protection.

The SNS neutron facilities comprise the mercury target systems, neutron instrument systems, and related support facilities. The target systems comprise components and systems necessary to produce moderated neutron beams, including the mercury target loop, associated cooling loops, the neutron moderators, and other necessary support systems. Neutron instrument systems comprise components and systems associated with the use of moderated neutron beams, including neutron beamlines, shielding, optical beamline components, choppers, and instrument detectors.

Section 2 presents a summary of the overall results and conclusions. Section 3 describes the facility function, location, and management organization, as well as details of major facility components and their operations.

Section 4 presents the safety assessment and includes the identification of hazards and necessary controls to eliminate or mitigate those hazards. Unmitigated (i.e., uncontrolled) and mitigated risks are addressed.

Essential controls, both engineered and administrative, identified as essential for safe operations are referred to as credited controls. Credited controls are described in detail in Section 5, which provides the basis for requirements stipulated by the Accelerator Safety Envelope (ASE). The SNS ASE [3] is issued as a separate DOE-approved document, and the requirements therein are strictly adhered to.

Sections 6 provides references to the portions of the FSAD-PF that describes interfaces between proton and neutron facilities. Section 8 provides references to the portions of the FSAD-PF that describe quality assurance.

Section 7 provides a generic safety analysis for hazards associated with the neutron instrument systems and identifies controls necessary to ensure safe instrument operations. Also provided in Section 7 is the SNS commitment to conduct instrument-specific reviews to assess specific hazards potentially associated with each instrument before it goes into operation.

Section 9 summarizes preparations and planning for the eventual post-operational phase of SNS.

References

[1] *Spallation Neutron Source Final Safety Assessment Document for Proton Facilities,* 102030103-ES0018-R03, Oak Ridge National Laboratory, Oak Ridge, Tennessee, July 2022.

[2] *Safety of Accelerators*, DOE Order 420.2D, US Department of Energy, Washington, D.C.

[3] *SNS Accelerator Safety Envelope*, SNS 102030103-ES0016-R07, Oak Ridge National Laboratory, Oak Ridge, Tennessee, September 2023.

2. SUMMARY AND CONCLUSIONS

The detailed safety analysis presented here verifies that the design of the SNS neutron facilities effectively eliminates or mitigates hazards, primarily by using passive design features. A rigorous and comprehensive process has been employed to identify hazards and to assess the potential ramifications of those hazards. This process resulted in the identification and evaluation of a wide spectrum of potential accidents. All significant hazards associated with the facility and its operations have been assessed and, where needed, controls to effectively eliminate or mitigate risks were developed and implemented. The analyses show that no credible accident, with the energy sources available (including the proton beam, a massive earthquake, potential fires, and combustion of hydrogen in the neutron moderator system), will drive enough mercury or any other radioactive material from the facility to cause other than negligible offsite impact.

2.1 HAZARD IDENTIFICATION AND ANALYSIS

A rigorous approach, largely based on the methodology of DOE-STD-3009 [1] has been employed to identify hazards and to assess the associated risks to workers, the public, and the environment. A screening process was used to identify hazards that are safely managed by other applicable safety and health programs; these hazards are referred to as standard industrial and laboratory hazards. Standard industrial and laboratory hazards are safely managed by implementing appropriate procedures and subject areas in the ORNL Standards-Based Management System (SBMS). The remaining hazards are considered accelerator-specific hazards and have been evaluated as over 180 events representing a comprehensive spectrum of accidents. A qualitative and semiquantitative hazard evaluation (HE) was first performed, and then a subset of representative bounding events in six basic categories was selected for detailed quantitative accident analysis.

Significant hazards associated with the neutron facilities include personnel exposure to the target mercury and personnel exposure to prompt radiation associated with the proton beam, including the associated neutron beams. Mercury becomes radioactive with proton beam irradiation and is chemically toxic. The target system uses approximately 1.6 m^3 of mercury. Radionuclides associated with the target mercury include more than 1,000 short- and long-lived spallation and activation products; however, six radionuclides—^{148}Gd, ^{203}Hg, ^{197}Hg, ^{194}Hg, ^{189}Hg, and ^{178}Ta—dominate the radiological hazard and account for most of the potential radiation doses.

Prompt radiation released from interaction of the proton beam on the mercury produces lethal levels of radiation and is mitigated by massive shielding. Relatively high levels of neutron and gamma radiation are associated with the neutron beamlines of the scattering instruments. These hazards are eliminated or mitigated by using shielding and personnel access control. Necessary active controls, such as the access control protection of the personnel protection system (PPS), have been identified to ensure experimenter and staff safety.

Radiological impacts presented in the safety analyses (Section 4) have been very conservatively assessed. All accident analyses assume the target mercury contains the maximum radionuclide inventory associated with the full operational life of the facility. Conservative accident release fractions, meteorological dispersal conditions, uptake, and dose conversion factors have been used throughout. Deposition of airborne mercury and building wake effects have been conservatively neglected.

Toxicological effects have been conservatively assessed by calculating the amount of mercury released for various accidents as a function of release mechanism and the associated energy source. Controls chosen to eliminate or mitigate radiological effects also eliminate or mitigate toxicological effects.

Proper evaluation of energy sources that have the potential to vaporize mercury into an airborne state is a key focus of the accident analyses. These energy sources include proton beam heating, potential fires, combustion of hydrogen contained in the moderator, and seismic events.

Development of Controls

Credited controls, considered essential for safe operations, have been selected as described in Section 4 using criteria that favor reliance on passive rather than active design features and that favor engineered rather than administrative controls. Mitigation of risks associated with the target facility is largely achieved by passive design features, consistent with criteria.

The configuration of the target facility meets the SNS mission of producing short, intense pulses of neutrons while satisfying safety requirements, foremost of which are the attenuation of prompt radiation and the confinement of target mercury. The massive shielding built into the monolith, service bay structure, and instrument line structures was designed to (1) passively reduce penetrating radiation to levels that are as low as reasonably achievable (ALARA) and allow unencumbered access by experimenters and staff in areas routinely occupied by personnel and (2) passively serve as a seismically qualified confinement barrier for the target mercury.

Confinement of the target mercury is a primary design requirement. The mercury process system is contained in the process bay portion of the service bay; only the target module extends into the core vessel. The entire target service bay is lined with stainless steel and is enclosed by massive shielding designed to withstand natural phenomena, including severe seismic events and high winds. The process bay floor is sloped to direct any inadvertent spillage of mercury into a double-walled stainless-steel collection basin. The core vessel has a passive confinement/drainage system to safely contain any mercury spilled within the vessel. Additionally, the core vessel is surrounded by the massive (~10,000,000 lb) steel shielding structure of the monolith, providing additional assurance of mercury confinement. The facility has been designed to rigorous standards [2, 3] to withstand any credible natural phenomena, including a severe performance category level 3 (PC-3; 2,500 year) earthquake, without excessive release of mercury or other radioactive materials to the workplace or environment. This capability is accomplished by using engineered features such as the PC-3 rated monolith and target service bay structure and cryogenic moderator system (CMS) hydrogen containment and vacuum boundaries.

Active credited engineered controls (CECs) are also employed as needed to protect workers and experimenters from direct exposure and to ensure mercury confinement. For example, the PPS trips the beam in response to access violations into hazardous areas or detection of elevated radiation levels in certain potentially occupied areas. Another example of an active CEC is the target protection system (TPS), which trips the proton beam if the target mercury cooling is lost. Safety requirements for credited controls are specified in the ASE.

Certain credited administrative controls (CACs) have also been identified. To a large extent, required administrative controls are addressed by ISM programs already well established and maintained through the ORNL SBMS (e.g., Radiological Protection, Worker Safety and Health, Fire Protection, Electrical Safety).

2.2 KEY RESULTS

The detailed safety analysis presented here verifies that the SNS target facility design effectively eliminates or mitigates hazards to workers, experimenters, the public, and the environment, primarily by using passive design features.

Off-site consequences, based on very conservative calculations that assume all active and administrative controls fail, are presented. Furthermore, once mercury becomes airborne, it is assumed to escape from the target service bay and travel unimpeded to the off-site receptors, neglecting confinement design features, air cleaning features of the ventilation system, and deposition inside and outside the building that would occur because of mercury vapor condensation. As detailed in Section 4, the mitigated off-site radiological consequences are all below 1 rem, and toxicological effects are all below Emergency Response Planning Guideline level 2 (ERPG-2) [4].

2.3 CONCLUSION

The SNS neutron facilities are well engineered and built to be mechanically and structurally robust to achieve both stringent safety goals and ambitious research and operational goals. Appropriate and effective safety features were identified and incorporated during the design process. The analyses presented in this report clearly show that (1) the risks associated with operation of the SNS neutron facilities are well understood and characterized, and (2) effective controls have been implemented, with heavy reliance on passive design features, to eliminate or mitigate risks to negligible levels. Operation of the SNS neutron facilities has been clearly shown to pose no significant radiological or toxicological risk to the public, even in worst-case accident scenarios. Controls established to protect workers also serve to reduce risk to the public and the environment to negligible levels.

2.4 REFERENCES

1. *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Documented Safety Analyses,* DOE-STD-3009-94, July 1994, US Department of Energy, Change Notice 1, January 2000, Change Notice 2, April 2002.
2. *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities*, DOE-STD-1020-2002, Washington, D.C., January 2002.
3. *Natural Phenomena Hazards Performance Categorization Guidelines for Structures, Systems and Components*, DOE-STD-1021-93, Change Notice 1, Washington, D.C., Reaffirmed April 2002.
4. American Industrial Hygiene Association, Emergency Response Planning Guidelines for Mercury Vapor, 2003.

3. SITE, FACILITY, AND OPERATIONS

The activities of the SNS neutron facilities are centered in the target building. The descriptive information provided in this section clarifies the safety evaluations and requirements derived and presented in Sections 4 and 5. This section covers the following information:

1. An overview of the facility layout and structures.
2. A description of the target facility structure and design basis.
3. A description of the facility process systems and constituent components and instrumentation and controls (I&C).
4. A description of the confinement systems, safety support systems, utilities, and auxiliary systems and facilities.
5. An overview of facility operations, including management organization.

Section 3 of the FSAD-PF describes the SNS complex [1]. The configuration of the target building, illustrated in Figure 3.1, supports the SNS neutron science mission by producing neutrons while satisfying safety needs, especially confinement of the toxic radioactive target mercury and attenuation of penetrating radiation generated by the spallation reaction. Mercury is confined by meeting design standards and by providing credited controls found to be essential by the safety analyses summarized in Section 4. The massive shielding of the monolith, service bay, and instrument line structures reduces penetrating radiation to low levels in locations that may be occupied by workers. Shielding at SNS meets the requirements of 10 CFR 835 [2] to ensure radiation levels are ALARA.

SNS follows a standards-based approach, embracing the ORNL Work Smart Standards and the standards and policies of the ORNL SBMS. Standards that guided the SNS target facility design are documented in the *SNS Standards for Design and Construction of the Target Facility* [6]. The facility is built to codes and standards expected for a major DOE research facility. For example, facility spaces are designed to meet National Fire Protection Agency (NFPA) requirements, such as NFPA 101 [7], regarding to means of egress and fire protection requirements. The building structures are designed and built to DOE structural standards DOE-STD-1020 through DOE-STD-1023 [8–11] and the associated building codes. The service bay and surrounding concrete structures have PC-3 seismic qualification level. They perform passive radiation shielding functions and safety functions to protect the hazardous material within the service bay (i.e., the shielded confinement structure that contains the mercury loop and associated irradiated components handling and packaging equipment) and the monolith.

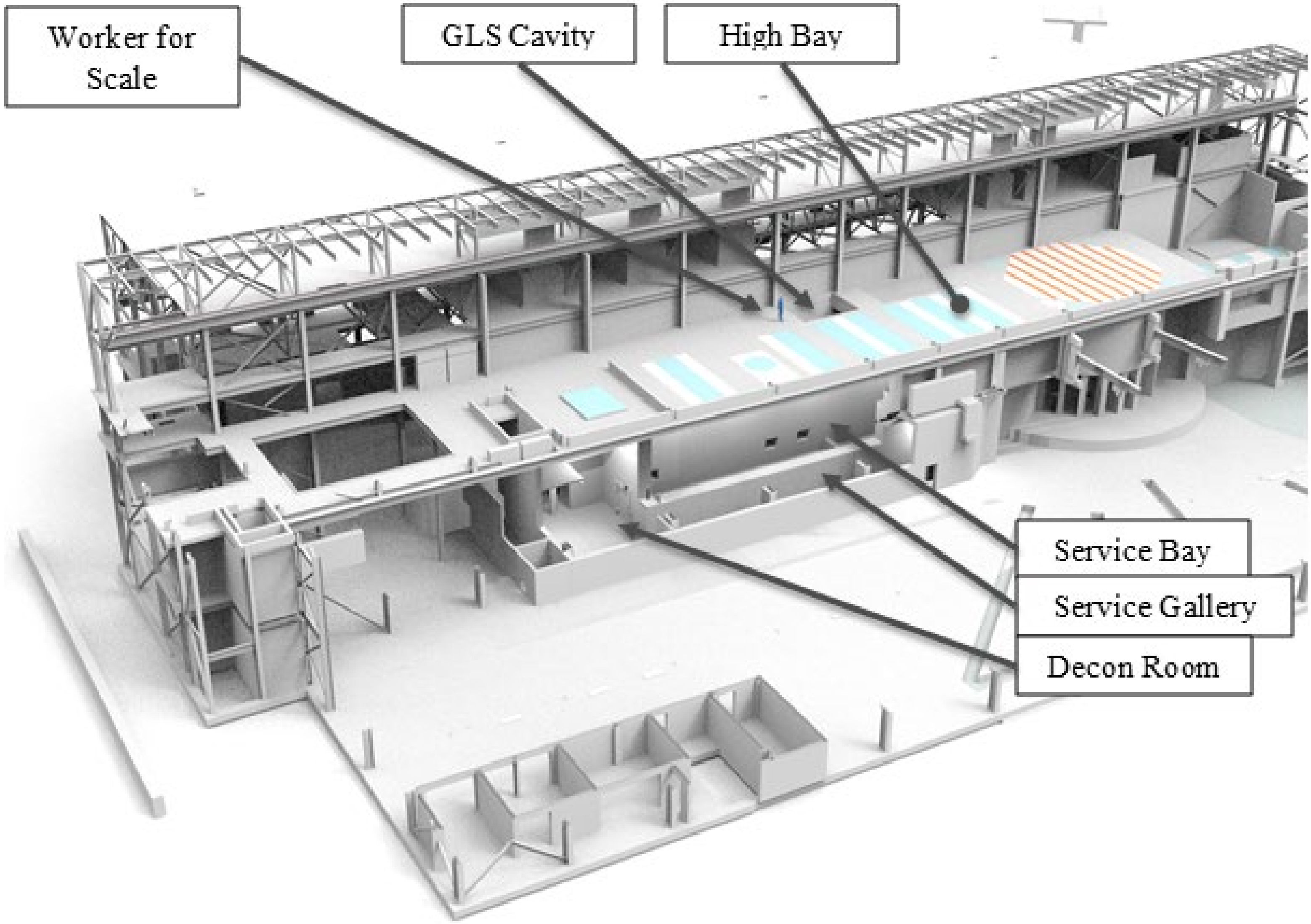


Figure 3.1. SNS target building.

3.1 SITE

The SNS site, including key structures and facilities, is described in the FSAD-PF [1]. The present document focuses on the neutron facilities and related support facilities that are primary housed in the target building.

As discussed in Section 3 of the FSAD-PF [1], activities at the SNS site are expected to continue to evolve and expand, and additional on-site structures and facilities will be planned and erected to support the facility's science mission. For example, the Shull Wollan Center was constructed by the state of Tennessee and is located adjacent to the Central Laboratory and Office Building (CLO). It includes laboratory facilities and offices and is operated by ORNL in conjunction with the University of Tennessee, Knoxville. Activities conducted within the facility involve standard industrial and laboratory hazards, which are safely managed in accordance with ORNL SBMS. Some work may involve routine radiological hazards encountered in laboratory environments such as the handling of calibration sources and low-activity materials associated with neutron scattering and the use of radiation-generating devices, x-ray microscopes, and other tools. Radiological hazards are managed under the ORNL SBMS Radiological Protection program.

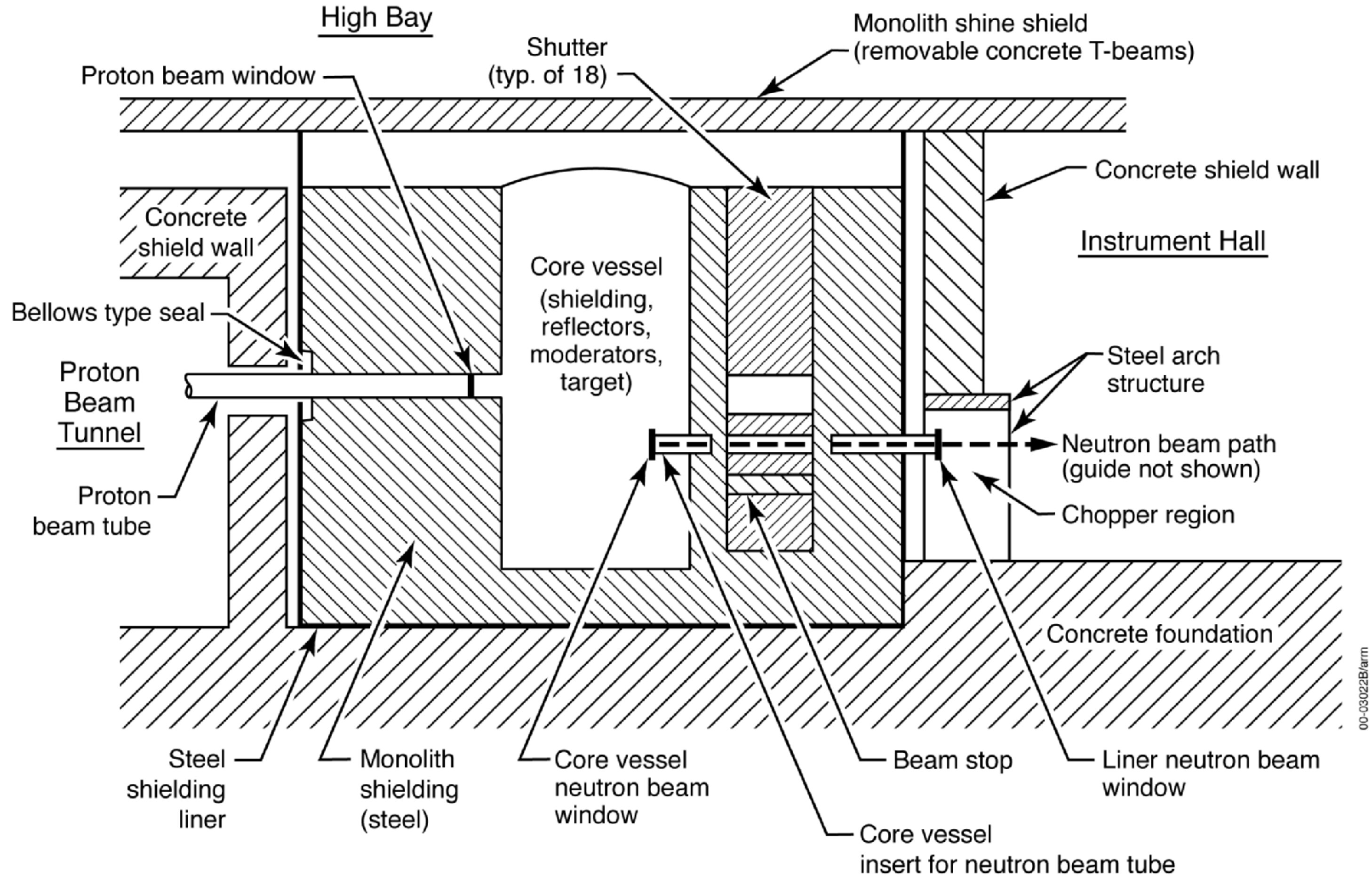
3.2 FACILITY LAYOUT AND STRUCTURES

The target building contains the neutron facilities and the final portion of the proton facilities. The proton beam tunnel terminates in the west end of the target building. The proton beam window serves as the interface between the proton facilities and the neutron facilities in the monolith. Interfaces between the proton facilities and neutron facilities are outlined in Section 6 of the FSAD-PF [1]. Figure 3.2 includes the proton beam window in the monolith schematic.

The target building design provides maximum utility for research operations by placing the research instruments at ground level arrayed around the central monolith and the target service bay complex in the instrument hall. The high bay area above the target service bay has operating room for the 50 ton high bay crane to lift heavy components into and out of the monolith, service bay, and ring-to-target beam transport (RTBT) tunnel that terminates in the monolith. The basement beneath the instrument hall and service bay houses the cooling systems, utilities, and confinement ventilation features.

The building is divided into zones to facilitate the safe conduct of research and research support operations. The flow of workers and researchers is regulated by an ORNL standard automatic card key system at external and internal entryways and by administrative controls and training. Researchers are generally limited to access of the instrument halls and contiguous areas that directly support the neutron instruments. Staff are allowed greater access into the occupied parts of the service bay complex, the basement, and the high bay, depending upon training and need.

Division of the building into three ventilation confinement zones roughly parallels personnel zoning. This arrangement limits the potential spread of contamination and minimizes the exposure of workers. The innermost primary confinement zone, serviced by the primary confinement exhaust (PCE) system, is normally kept under a negative pressure with respect to the secondary confinement zone, which is, in turn, maintained by the secondary confinement exhaust (SCE) system at a negative pressure with respect to the balance of the building. The outermost part of the building, comprising the instrument hall and the east end of the basement area, is provided with conventional industrial HVAC and is not a confinement zone. Ventilation systems are discussed in detail in Section 3.3.9.



Note: The schematic cross-section above was selected to show the proton beam tube and a typical neutron beam path.

Figure 3.2. Schematic illustration of monolith cross section.

The target building has four main levels: (1) basement, (2) instrument floor, (3) high bay, and (4) truss levels. General floor plans for the basement level, instrument floor level, and high bay level are depicted in Figure 3.3 through Figure 3.5. The service bay abuts the monolith, an approximately 33 ft diameter by 28 ft height cylinder principally consisting of keyed steel shielding blocks surrounding the core vessel assembly. Openings in the monolith provide pathways for the neutron beam tubes radiating outward into the instrument halls. A single opening provides a channel for the final length of proton beam tube that terminates at the proton beam window.

3.2.1 Instrument Floor

The instrument floor is the main level of the target building. It includes north and south instrument halls, the remote handling control room, and the service bay complex.

The service bay complex is centrally located between the north and south instrument halls. Three rooms surround the service bay: (1) the service gallery (on the north side), (2) the manipulator gallery (on the south side), and (3) the decontamination room (on the east side). These three rooms provide accessible spaces for workers performing service bay related operational or maintenance functions. The service bay and provisions for the remote handling operations necessary for operation of highly activated equipment in the service bay are described in Section 3.3.5.

The service bay concrete structure and adjacent concrete structures support the upper building floors and provide for utility pathways while providing radiation shielding and confinement of the target mercury. The service bay wall design ensures that credible fires in fire zones outside the service bay cannot cause significant releases of mercury. The outer wall of the service bay complex is a 2 h rated firewall that separates the service bay complex from fire zones in the outer part of the building. The firewall and related concrete structures are seismically qualified to PC-3 (Section 3.2.5).

3.2.2 Basement

The basement floor level (~20 ft below the instrument hall floor level) contains the utility vaults, mechanical equipment, a mercury adsorber system, PCE filtration equipment, SCE filtration equipment, waste-handling systems, and the basement target control room (TCR). The basement provides facilities necessary to support target systems, including the following:

- Access area to service bay bottom-loading port,
- Confinement ventilation system air treatment equipment such as the charcoal adsorbers and HEPA filters,
- Facilities for low-level liquid waste (LLLW) processing,
- Mercury Target Development Laboratory,
- Mercury off-gas treatment system (MOTS),
- Neutron Instrument Sample Handling Laboratory,
- A large truck bay.

The TCR, located in the basement, includes space for operator workstations, equipment racks, and I&C-related systems. The target systems may be operated either from the TCR or from the central control room (CCR) in the CLO across the street from the target building.

The utility vaults contain activated cooling water system components (Section 3.3.6). The rooms are fitted with conventional handling equipment needed to support hands-on maintenance of water cooling system components such as pumps, heat exchangers, filters, and ion-exchange units. Access control and shielding protect personnel during vault access. During beam operations, routine personnel access to the utility vaults is precluded by radiation levels associated with the activated cooling water systems.

The utility vault in the basement contains three of the four target cooling water loops, including pumps, heat exchangers, filters, ion-exchange columns, storage tanks, and valves. Control systems for the utility systems are in the TCR and CCR. Utility control cabinets and the helium and nitrogen gas distribution systems are in the basement.

Commercial lifting devices for handling items such as pumps and motors are provided, and the filters and ion-exchange columns have built-in shielding. Separation, shielding, or both protect cooling loop equipment and components (e.g., instrumentation) unable to withstand the background radiation during operations. Physical barriers (e.g., labyrinth entrances and controlled access) complement the confinement exhaust systems, which are designed to prevent the spread of contamination and to protect operations personnel.

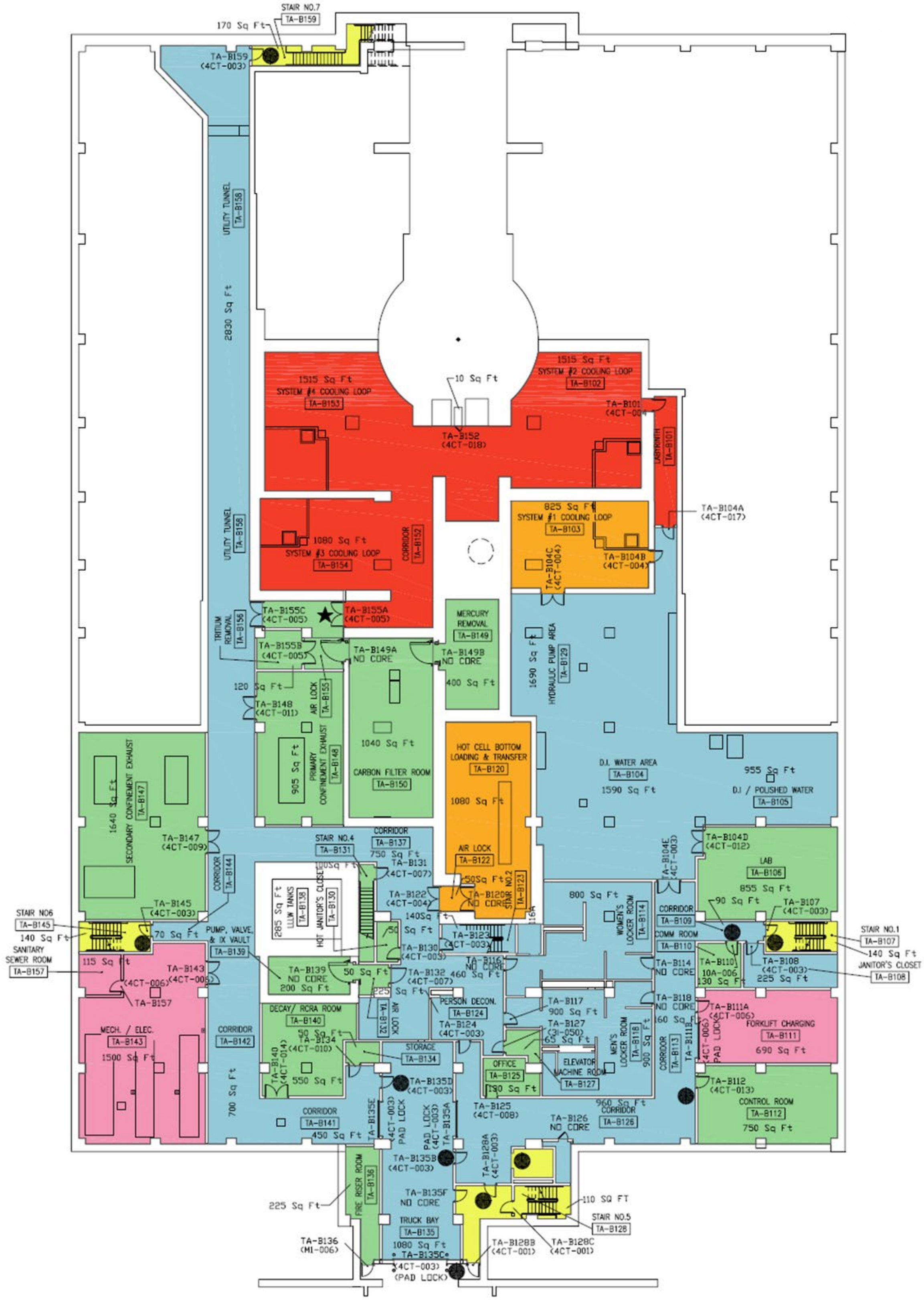


Figure 3.3. Plan view of target building—basement level.

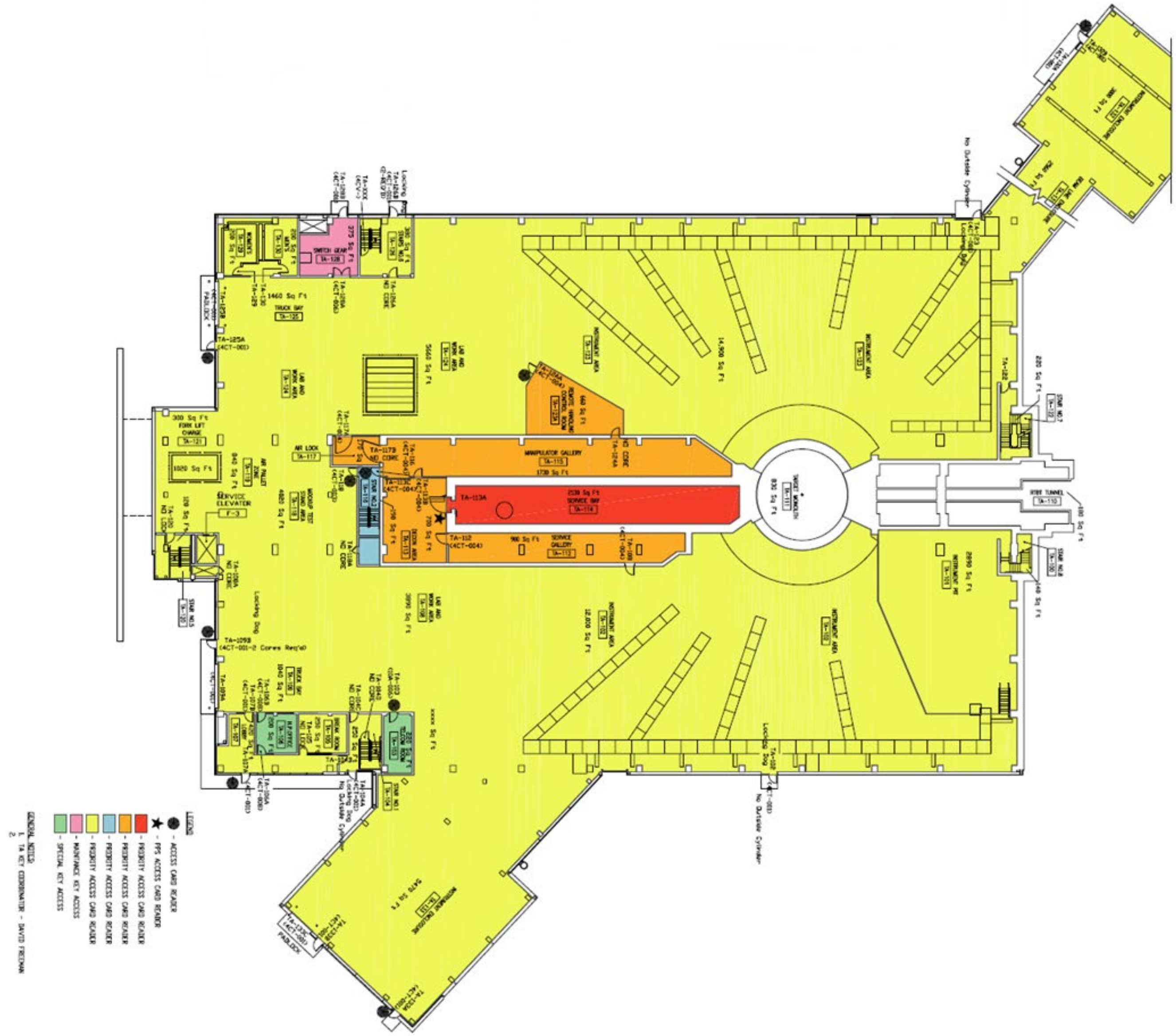


Figure 3.4. Plan view of target building—instrument level.

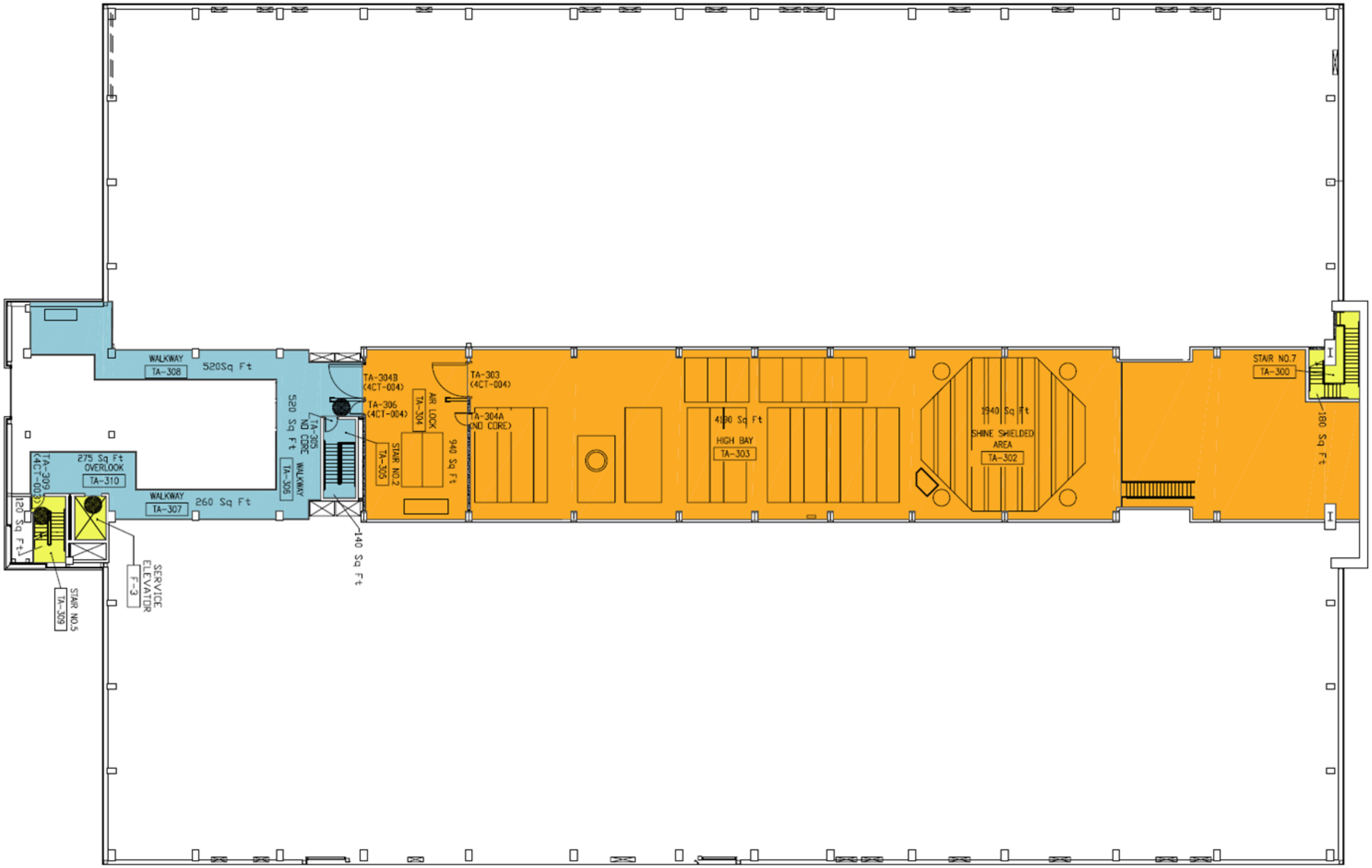


Figure 3.5. Plan view of target building—high-bay level.

Features (e.g., isolation valves) are provided to facilitate isolation of systems and services from equipment and to facilitate control, handling, and isolation of the heavy water inventory that may be used in the reflector cooling loop. Equipment components (e.g., header isolation valves and liner) can withstand the anticipated background radiation doses in the utility vault area. Features facilitate the handling and transport of shielded equipment components (e.g., ion exchange columns, filters, and heat exchangers) and unshielded components to other areas in the utility vault basement for regeneration and/or other disposition.

Design features, such as pits in the basement floor slab, support draining utility cooling water piping to dump or storage tanks. The vaults have features such as lined, sloped surfaces to facilitate the collection and disposition of leaked process materials from process equipment. Such features are designed to prevent the inadvertent loss of contaminated material to areas of lower contamination potential. Surface preparation and construction materials are compatible with the materials to be contained and have suitable radiation resistance.

The Mercury Target Development Laboratory provides a workspace for activities such as mercury process experiments and materials testing. Nonradioactive (or very slightly activated) mercury is used in the lab. Toxicological mercury hazards and radiological hazards (if any) are identified and controlled in accordance with the ORNL SBMS program.

A truck loading bay approximately 40 ft long with a 16 ft rollup door to the outside and vertical hatch access between the high bay and basement is provided. The access hatch is 8 × 16 ft. The 50-ton high bay bridge crane has a total reach that allows it to reach near the floor of the truck bay to lift items through the port access to the high bay.

The basement also contains a storage area for activated components. This area allows for storage of reusable components while they decay to levels that allow maintenance workers to refurbish them. Access is provided from the truck bay to move components into storage. Depending on the activation level of the components being stored, shielding is provided to maintain ALARA radiation levels for workers in the basement. Nuclear material control and accountability areas have also been designated in the basement for the management of heavy water in loop 4 and storage of makeup inventory.

The sample handling laboratory provides workspace to handle samples associated with neutron beam experiments. Samples exposed to beamline neutrons can be expected to become slightly activated. Hazards associated with activities conducted in the sample handling laboratory are identified and controlled in accordance with the ORNL SBMS program.

The basement area also contains other building support equipment and services such as HVAC components and electrical equipment. The communications room houses building communication equipment. A separate area contains the building deionized water supply system.

The area under the target service bay is configured to transfer the extremely heavy loads of the target area shielding to the building foundations. For example, the target monolith rests on an approximately 20 ft tall by 42 ft diameter reinforced concrete pedestal.

3.2.3 High Bay

The high bay is enclosed by a steel superstructure extending above the concrete shielding floor that separates it from the target service bay and the RTBT tunnel below. The primary purpose of the high bay is to provide crane access (50-ton) for removal and installation of components in the service bay, RTBT, and monolith. The floor between the high bay and monolith is a concrete shine shield that consists of 18 in. thick concrete T-beams that are removed using the 50-ton crane for monolith access.

A pedestal manipulator can be fixed to any of five mounting posts surrounding the monolith to allow tasks to be performed remotely on activated components within the monolith. The pedestal manipulator deploys a dexterous manipulator to remotely perform maintenance operations on activated and contaminated components in the high bay. The high bay crane is used to move the pedestal manipulator to each of five possible locations.

Parts of the floor between the high bay and the service bay consist of concrete T-beams. Removal of the service bay T-beams is expected to be rare but is allowed under provisions that ensure personnel safety and if the configuration is consistent with the evaluations performed in this document. Planned access to the service bay is provided by removing the top-loading port shield plug.

3.2.4 Truss Level

The hydrogen utility room (HUR) (Section 3.3.3.2) and associated maintenance area are located at the west end of the facility. The truss level also houses various work and storage areas and HVAC equipment.

3.2.5 Natural Phenomena Qualification

Target building structures and CECs are designed for applicable natural phenomena threats in accordance with DOE-STD-1020-94, *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities* [8], which requires the evaluation and design for flooding, high winds/tornadoes, and earthquakes. For evaluation of the natural phenomena hazards (NPHs), building structures and equipment are classified into PCs using the guidance of DOE-STD-1021-93, *Natural Phenomena Hazards Performance Categorization Guidelines for Structures, Systems, and Components* [9].

The target building and its contents are designated as either PC-0, -1, -2, or -3 in accordance with DOE standards [8, 9], based on the role and function of the building structure or system under consideration. Facility structural elements, components, and key systems are placed in seismic qualification categories per the following general rules. In some cases, more than one bullet applies, and the highest applicable category is used.

- The hydrogen boundary is assigned to category PC-3 to prevent off-site release in the event of a severe seismic event by preventing potential fire and/or hydrogen explosion.
- CECs credited with protecting workers against releases of hazardous material resulting from a seismic event are assigned to category PC-2. The seismic qualification of these CECs is directed at ensuring the function would be performed in the earthquake.
- Items that can affect the life safety of workers in the facility are assigned to category PC-1 (these are identified in *SNS Seismic Basis of Design, Volume I, Target Facility and Equipment* [12]).
- Items not addressed by the above requirements are assigned to category PC-0.
- In addition to the above primary seismic qualification category assignments, seismic design requirements have been imposed based on evaluations of interaction between lower-categorized and higher-categorized items, also known as 2-over-1 analysis. Such requirements are needed to implement the seismic interaction requirements of DOE-STD-1021-93 [9].

The safety analyses of Section 4 have guided the implementation of DOE seismic qualification requirements to define a subset of the CECs that perform specified safety functions during a seismic event. The target building is qualified at PC-2 for flooding and high winds because these events have no potential to affect the public through release of hazardous materials from SNS. Seismic qualification of a system in a facility must be performed as a coordinated whole and not in isolation. The structures surrounding a protected system must be qualified or evaluated appropriately such that their design can be shown to be consistent with the desired degree of protection. Key structures surrounding the hydrogen boundary are qualified to the PC-3 level or evaluated at PC-3 accelerations not to fail and cause failure of the hydrogen boundary. The surrounding structures are qualified against the mission of preventing hydrogen leakage. The hydrogen boundary PC-3 requirement necessitates the building’s basic concrete structures to be PC-3 qualified, and the building’s steel superstructure is designed not to collapse under PC-3 accelerations.

3.3 FACILITY SYSTEMS

3.3.1 Target and Mercury Process Systems

The mercury target and its surrounding components transform pulses of protons into pulses of neutrons that are transported down the beam tubes of the neutron instruments. Target systems are generally designed to operate at powers up to 2 MW. Pulses extracted from the ring pass directly to the ring extraction dump unless diverted to the target through the active use of magnet RTBT.DH13. Magnet RTBT.DH13 diverts protons down the RTBT tunnel to the target. The target has a high-integrity interlock system, the TPS, to ensure that beam cannot be sent to the target unless the mercury loop is operating within a specified range of mercury flow rate and temperature.

Heat is removed from the target via a flowing mercury system. The amount of heat dissipation in the mercury, approximately 60% of the proton beam energy, requires a flow to transport the heat from the mercury to an intermediate water-cooling loop that ultimately rejects heat to the tower water cooling system. The other 40% of the proton beam energy is dissipated in the target shroud, moderators, reflectors, and shield blocks. Flowing light-water coolant loops and one heavy-water coolant loop cool the target shroud, moderators, reflectors, and shielding. Light water may be used in the heavy-water cooling loop; however, heavy water is desirable because of its superior neutronics properties. Safety instrumentation and non-safety instrumentation both provide operator information and automatic control to ensure the proton beam is not directed onto the target unless specified conditions are met.

To reach the target mercury, the proton beam must pass through the double-walled, water-cooled shroud of the target module and the wall of the mercury vessel. The incident proton beam impinges on the front of the double-walled water-cooled shroud. Radiation and cavitation damage to the target module materials (stainless steel) necessitates periodic replacement of the target module. In this operation, the target process system must be drained, and the mobile part must be disconnected from stationary parts. The necessary operations are accomplished remotely, primarily using manipulators. The service bay is designed such that all required activities can be accomplished remotely, without human entry. Although the design goal is for no human entry, workers may enter the service bay under appropriate safeguards and controls.

The basic configuration of the service bay and monolith is largely a function of two needs:

1. Provide shielding barriers against prompt accelerator radiation to minimize radiation levels in occupied spaces.
2. Confine the radioactive mercury.

The confinement features are in addition to the boundaries of the mercury process system. These features include the PCE system as well as features built into the target service bay floor structure to ensure a mercury spill would be channeled to the collection basin. This basin is in a concrete silo at the low point of the target service bay.

The target system shielding was designed (i.e., thickness and composition set for service bay walls and the monolith) in accord with the SNS shielding policy [3] to ensure ALARA radiation levels. The SNS shielding policy implements the requirements of 10 CFR 835, "Occupational Radiation Protection" [2]. The determination of monolith shielding thickness and other important shielding parameters is documented in the report *Two-Dimensional Shielding Analysis of the SNS Target Station Shutters, Shutter Beam Stops, Un-instrumented Neutron Beamlines, and Biological Shielding Monolith* [22]. Because the mercury reservoir (pump tank) is purged with helium gas and the loop must be opened periodically for target module replacement, provisions for the removal of mercury vapor and volatile radionuclides from the helium are required. An in-cell mercury condenser is provided in the service bay to remove mercury vapor from the helium purge. An off-gas system, described in Section 3.3.7, serves to remove xenon, iodine, and tritium gases and residual mercury vapor from the helium purge.

The SNS target assembly includes a target module mounted on a target carriage that moves on, and is propelled by, the carriage transport system.

As illustrated in Figure 3.6 and Figure 3.7, the target module is an assembly of stainless-steel vessels that mounts to a weldment at the end of the mercury loop piping assembly on the target carriage. Part of the module is a flange of approximately 25 in. diameter that incorporates an inflatable metal "bellows" seal comprising two concentric stainless-steel contact surfaces separated by an actively pumped cavity that separates the core vessel and service bay volumes. The location of the target module is shown at the end of the target plug in Figure 3.8. The term target plug or cart refers to the assembly that combines the target module, lengths of mercury loop piping, the carriage, and the shielding.

The target cart includes connecting piping from the mercury vessel to the mercury process loop. It also provides connections for services to the target such as shroud cooling water, the target vent line, helium supplies for target gas injection, and nitrogen for the target module flange seal. These services have connection points in various locations at the rear of the cart and must be disconnected before target cart retraction. The services that are provided for the target module (e.g., cooling water, vent line, helium) are generally connected by jumpers from the target cart to the target module as part of target changeout.

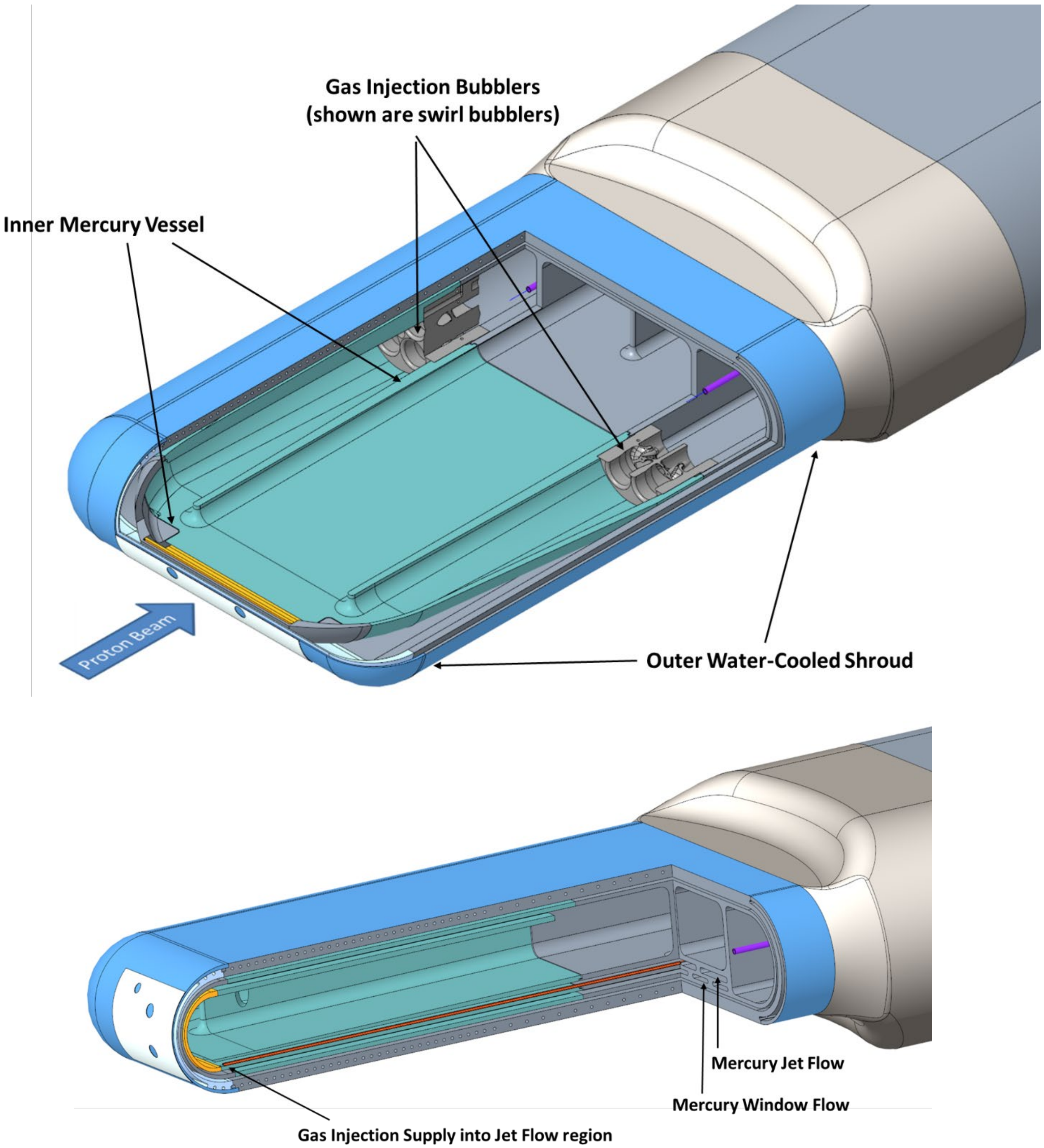


Figure 3.6. Target module illustration showing internal mercury flow passages.

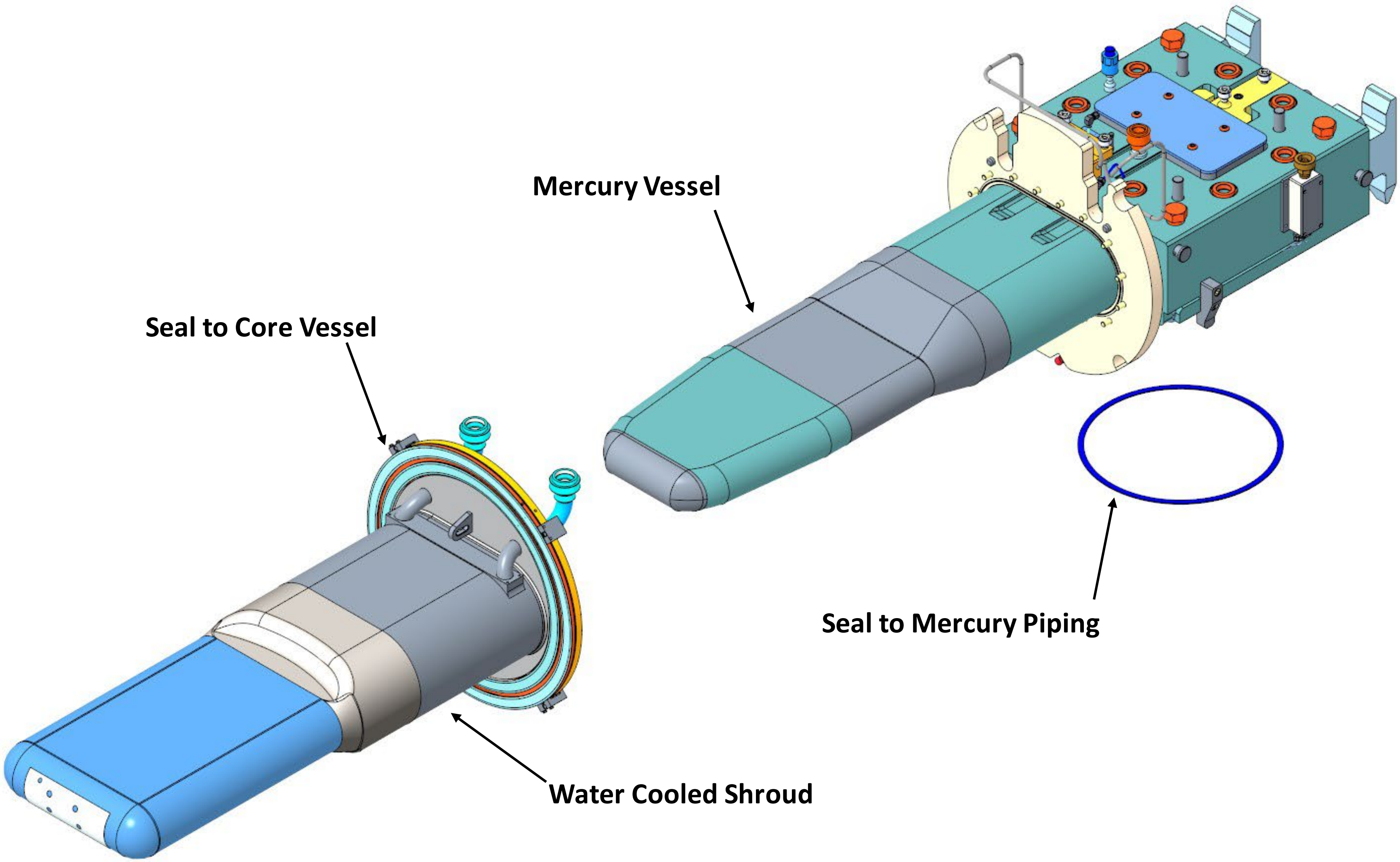


Figure 3.7. Exploded view of target module.

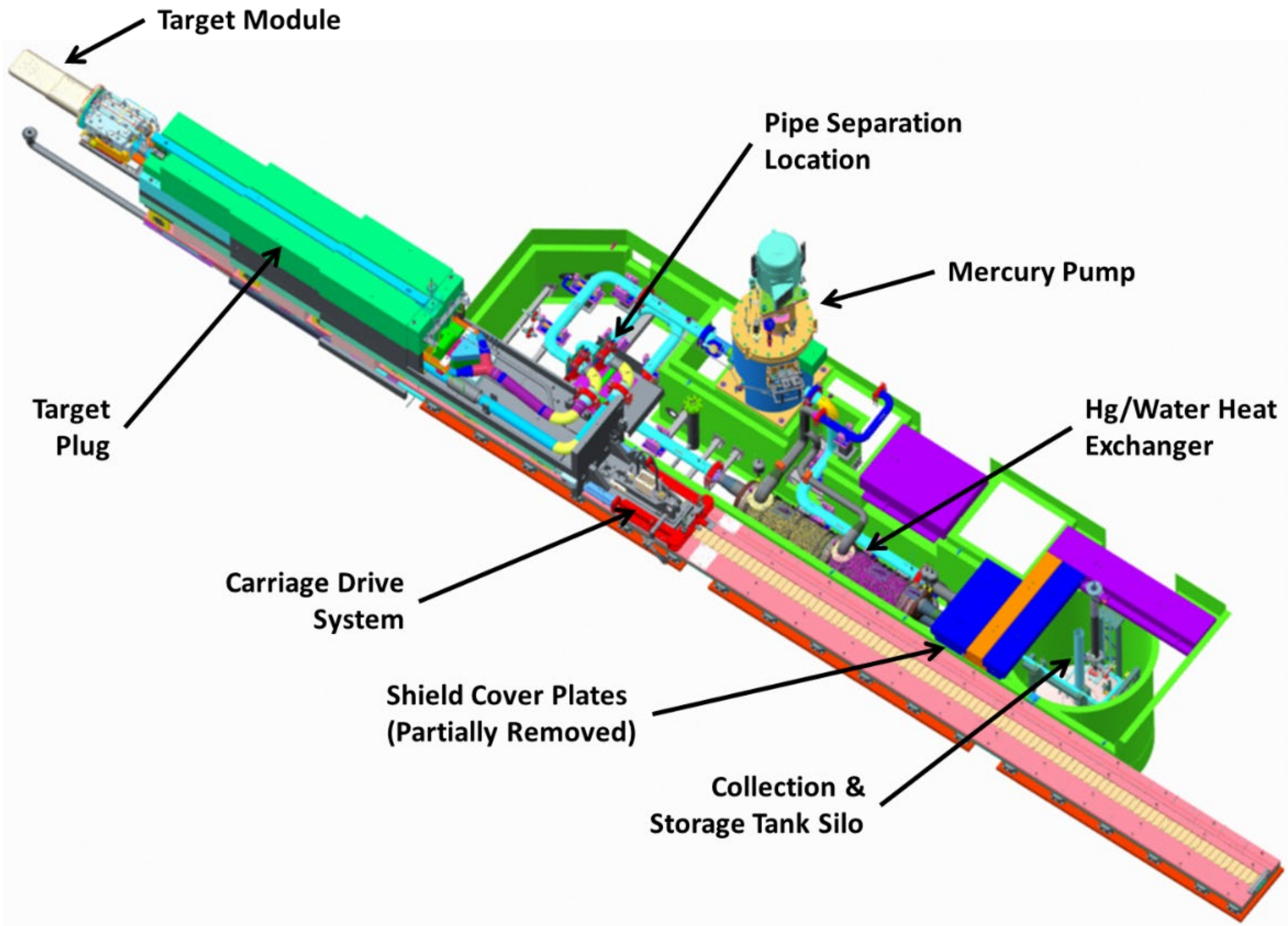


Figure 3.8. Components of the mercury target system.

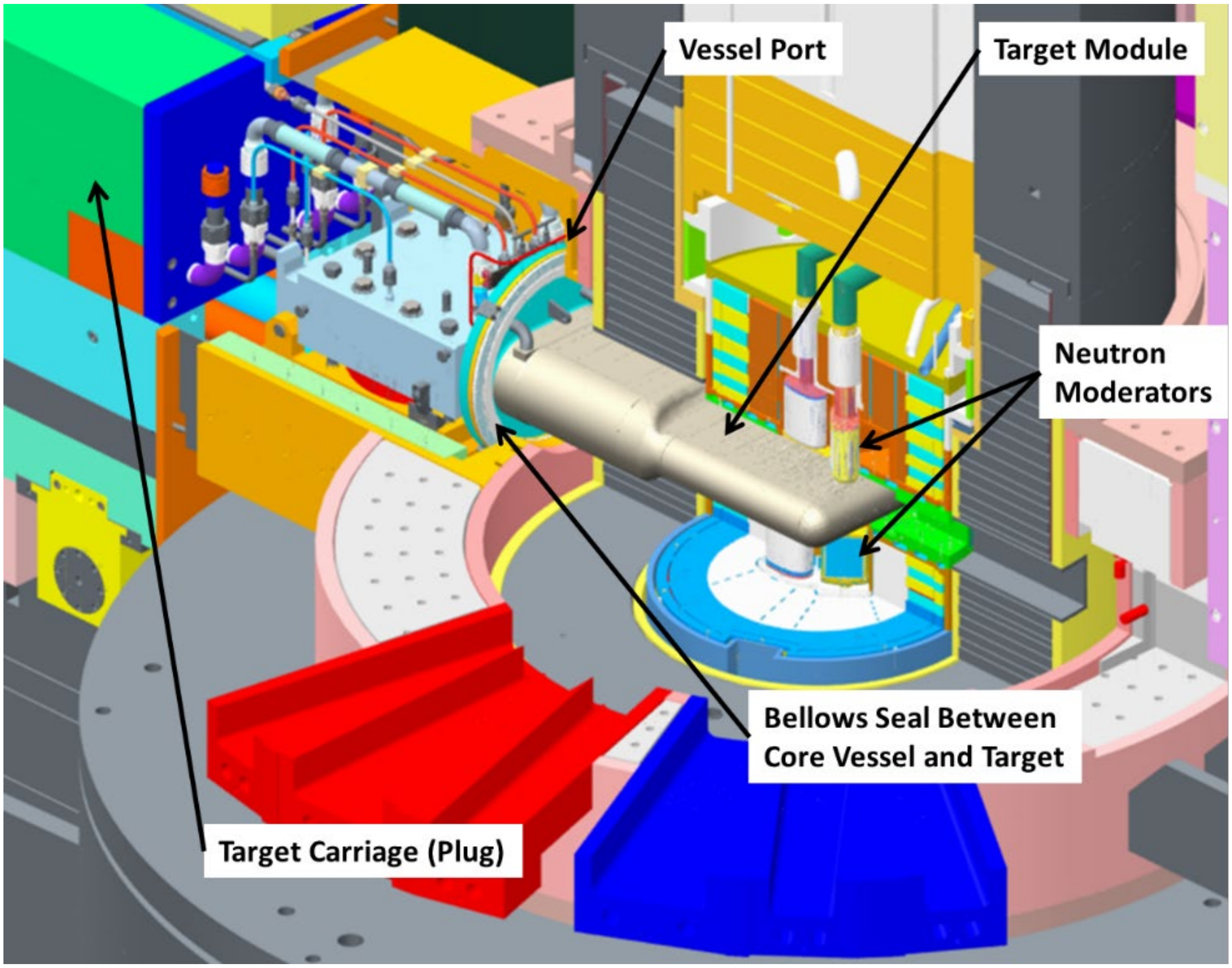


Figure 3.9. Target module interface with core vessel.

In front of the inflatable seal flange, the module consists of two nested vessels: an inner mercury vessel for containing the target mercury and an outer water-cooled shroud for containing mercury that may leak from the inner vessel. These vessels are of welded fabrication. The forward section of both vessels receives nuclear heating load from the incident proton beam as well as the neutrons and gammas produced by proton beam interactions with the mercury. These sections, or beam windows, are constructed with double walls equipped with well-defined coolant flow conditions in the gaps between the walls. The walls of the inner mercury vessel are cooled by flowing mercury, whereas the outer vessel is cooled by water, resulting in its designation as the water-cooled shroud. The mercury used to cool the beam windows of the mercury vessel is supplied separately from that in the bulk portion of the target. This window flow reunites with the bulk flow at a point inside the module for the return to the cooling loop. The proportion of window flow to bulk flow is determined by the design of the flow paths inside the target to yield window flow in the desired range. Helium gas is mixed with the mercury flow to improve the lifetime and reliability of the target. Optimization of the target module design is ongoing with the goal of increasing performance. For example, the jet flow design feature, as shown in Figure 3.10, provides a sweeping flow of mercury at the nose, which reduces cavitation damage. Other flow schemes may be employed as target development matures.

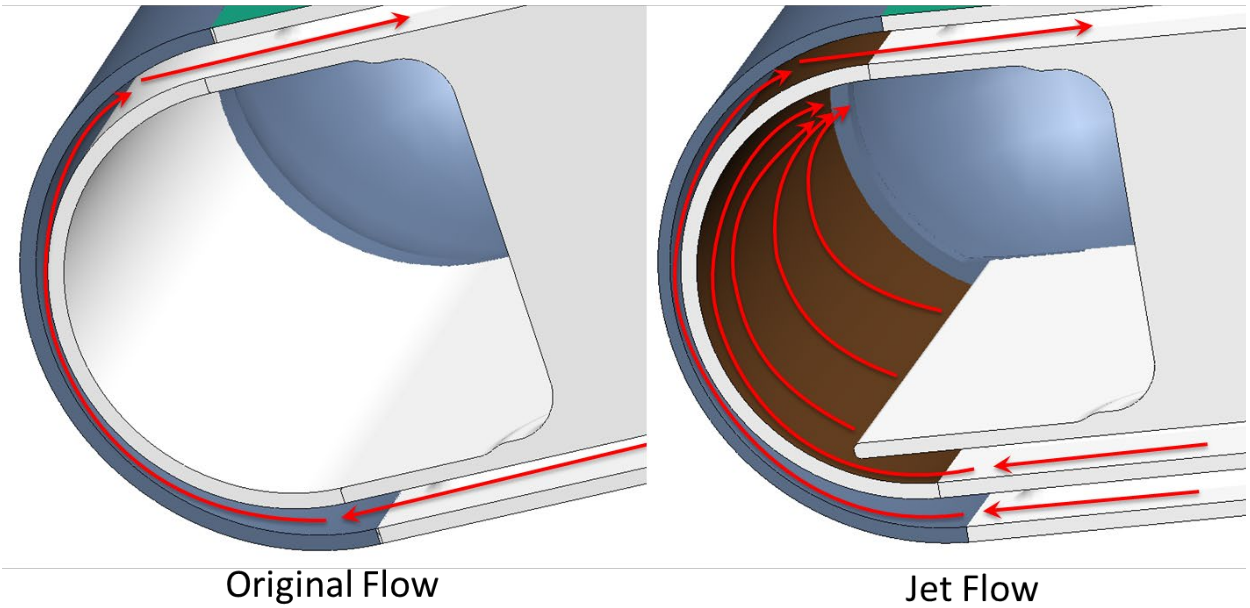


Figure 3.10. Target window flow examples.

When the high-power proton beam hits the target, a strong pressure wave propagates in the mercury and into the vessel wall because the temperature in the mercury increases rapidly. These pressure waves induce cavitation damage and high stresses on the target vessel, which both limit the target's lifetime. To reduce these effects, helium gas is injected near the beam interaction area to soften the pressure impulse in the mercury. By providing a small, compressible volume of gas in the liquid, the helium bubbles greatly reduce the magnitude of the pressure wave. Gas injection has been demonstrated to dramatically reduce cavitation damage at relatively low flows of 1–2 standard liters per minute (SLPM) and is expected to provide additional mitigation at the increased design flows associated with the Proton Power Upgrade (PPU) project upgrades described here.

Helium is injected by bubblers in the split mercury supplies of the mercury target, referred to as bubbler flow, and near the inside bottom of the target nose, referred to as wall flow. Bubbler flow and wall flow are independently supplied with helium, allowing up to 10 SLPM each. The helium is carried by the flowing mercury out of the target, eventually escaping the mercury process system either through the target vent line or by reaching the pump tank where it naturally rises to the free surface. In either case, the injected helium passes into the MOTS. The helium can be supplied either from the building utility or by the gas injection recirculation system, which draws on the MOTS and recompresses the primarily (>99%) helium effluent back into the gas injection supply system.

The mercury vessel and water-cooled shroud provide redundant barriers against mercury leakage into the core vessel. The mercury vessel and water-cooled shroud are separated by a helium-filled interstitial region. Two instruments are provided to detect leakage into the interstitial space. The first employs a heated resistance temperature detector concept to detect the presence of liquid and discriminate between water and mercury. The second monitoring instrument is an electrical conductivity probe that detects when mercury is between the contacts.

The module section to the rear of the inflatable seal flange is a block of stainless that has machined internal passages that direct the flowing mercury into the respective passages in the forward mercury vessel. Concentric knife edges are machined into the lower surface of the rear sections for sealing mercury passages with soft iron gaskets. A seal plate with knife edges on both the top and lower surfaces seals the mercury passages to the service bay and provides the ability to replace the frequently used sealing surface.

The water lines on the module, as well as the nitrogen, helium, and vacuum lines needed to operate the seals, are connected to the respective utility lines on the carriage by demountable jumpers. Other jumpers connect from the carriage to points on the target module used for venting the mercury lines during filling and operation and for interfacing to instrumentation installed on the target module.

The target module is designed for periodic remote replacement. Before the target module is replaced, the mercury is drained to the storage tank, piping connections are disconnected in the service bay, and the target carriage locking mechanism is released. The target plug (including the target module) can then be driven from the operational position back into the service bay, where the replacement can commence using specially designed remote manipulator equipment.

The carriage is mounted on wheels that move along precisely aligned rails to allow the target to be installed and removed. Once in position, the target carriage is preloaded with tension against the core vessel to facilitate proper sealing and then locked to prevent movement. The carriage assembly includes passive shielding that surrounds the piping connecting the target module to the process systems. Figure 3.8 shows the target plug and the mercury process system.

A system of mechanical levers driven by pressurized water actuators drives the carriage between its withdrawn position in the service bay and its operational position inserted into the target tunnel. The water pressure is within the range of a standard industrial hazard. The quantity of water in the actuator system would not challenge the storage capability within the service bay if a line failure occurred.

The mercury process loop contains approximately 1.4 m^3 (~19,000 kg) of mercury circulating at a rate of about 114–325 kg/s. The pump speed is varied between 150 and 400 rpm, as appropriate based on beam power, to maintain loop temperatures within the desired operational range. The pressure of the mercury as it flows through the target module region is approximately 0.3 MPa. Normal design loop temperatures are about 60°C at the inlet to about 95°C at the outlet during normal operation, although the operational mercury temperature can be lower owing to factors such as power and water temperatures. This nominal is based on 2 MW beam power with a pump speed of 350 rpm.

The western half of the service bay contains the components required to process, circulate, and cool the mercury as well as the cooling water in the shroud surrounding the target, as shown in Figure 3.8. The mercury loop includes the piping, valves, main circulating pump, and mercury-to-water heat exchanger, along with storage tank and control and monitoring sensors necessary for operation. Because the mercury is radioactive, the system is in the service bay and is designed to be operated and maintained remotely. Components expected to require replacement are connected by remotely operated flanged connections. As detailed in the following subsections, the stainless-steel liner of the process bay is designed to allow spilled mercury to gravity-drain to the collection basin. A double-walled heat exchanger configuration provides an extra barrier between the flowing mercury and its coolant water in the heat exchanger.

3.3.1.1 Mercury Pump Tank

The mercury pump tank is a large reservoir of mercury from which the mercury pump takes suction. The pump tank and overflow tank (OFT) serve as the high point in the mercury process loop, providing a surge volume and free surface. Level measurement is provided by two instruments: a helium bubbler and an array of heated resistance temperature detectors. An exhaust path is provided in the lid of the pump tank that connects to the MOTS via the OFT. A rupture disk is also connected to the lid of the pump tank to provide overpressure protection for the tank as well as the credited function described in Section 5.2.19.

As part of the PPU project, a secondary tank called the OFT was connected to a horizontal pipe built into the mercury pump tank. The liquid connection point is located at a bubbler level of about 80%; above this level, liquid mercury is expected to freely flow between the two tanks. A gas jumper connects the top of the pump tank to the top of the OFT and maintains the two gas spaces at equilibrium. The OFT provides additional surge volume for the pump tank once the mercury loop is filled to the operating level. This additional volume makes the mercury process loop more stable when faced with dynamic volumetric effects resulting from gas bubbles within the loop, especially resulting from target gas injection. The top of the OFT is above the top of the mercury pump tank, but system interlocks protect against overfilling the mercury pump tank. Figure 3.11 depicts the arrangement of the mercury pump tank, OFT, and various connections.

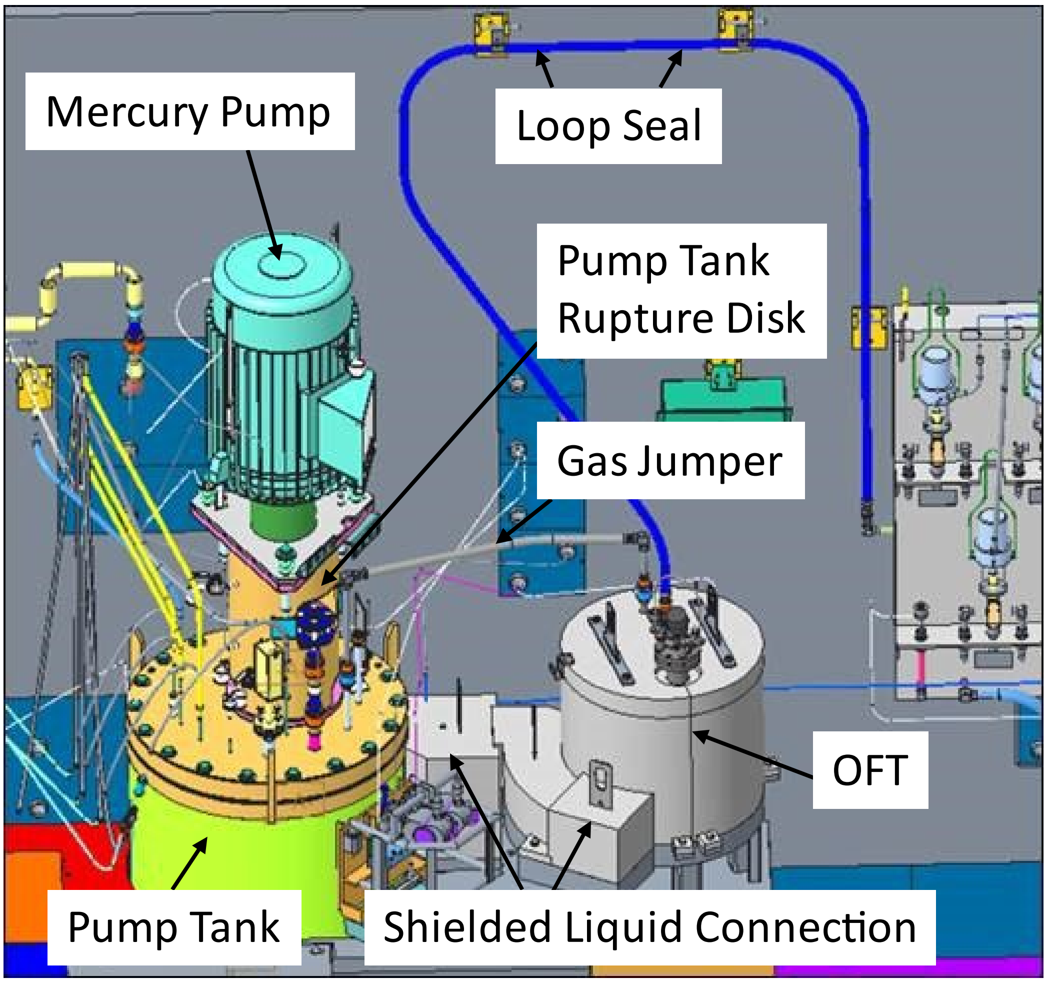


Figure 3.11. Mercury pump tank and overflow tank.

3.3.1.2 Mercury Storage Tank and Collection Basin

As shown in Figure 3.8 and Figure 3.12, the storage tank and the collection basin are both in a compact arrangement in a cylindrical silo surrounded by concrete. The enclosed storage tank is suspended above the collection basin at an elevation below any part of the mercury loop. This configuration allows gravity drainage from the loop to the storage tank. The mercury loop is drained to the storage tank for various reasons (e.g., safe storage during extended outages, replacement of the target module). Helium pressure is increased in the storage tank gas space to refill the loop. The elevated helium pressure on top of the mercury during the loop filling operation forces the mercury into the pipe that connects the loop with the storage tank. During operation, about 1.4 m^3 of the mercury inventory is in the loop, and about 0.2 m^3 is in the storage tank. After loop drainage, the entire inventory (~1.6 m^3) is held in the storage tank. To prevent certain potential reservoir overfill scenarios, the total volume of mercury committed to the mercury system is limited to 1.85 m^3 (ambient temperature). The mercury storage tank was designed to include a level bubbler as is used in the mercury pump tank, but the level sensor was never successfully brought into service. Because depleting the mercury inventory in the storage tank during a filling evolution leads to a rapid injection of gas into the loop and potentially significant consequences, processes have been developed to evaluate the mercury inventory in the tank before a filling operation and to monitor the approximate inventory of the tank while it is pressurized to fill the mercury loop.

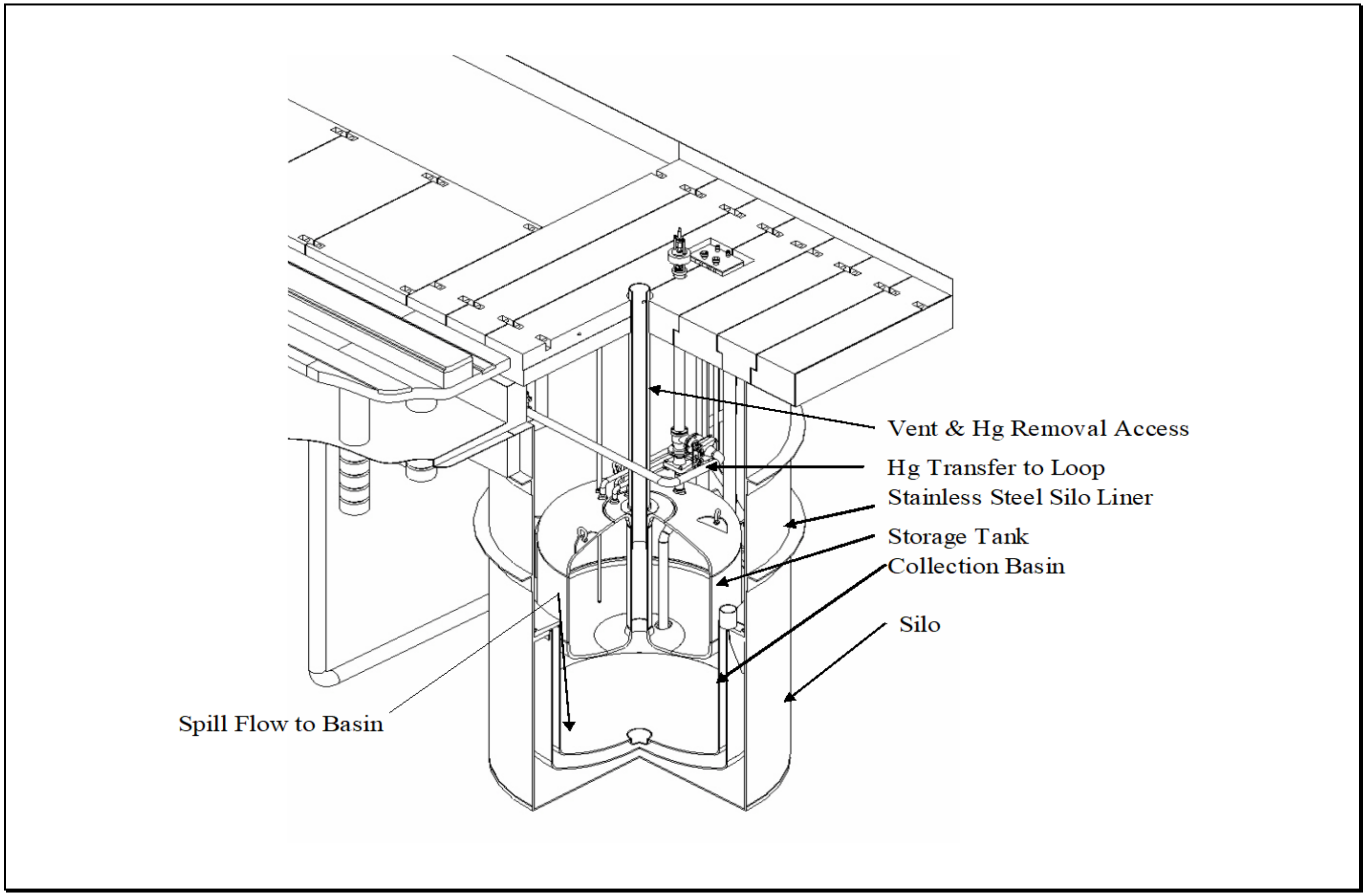


Figure 3.12. Storage tank and collection basin general arrangement.

The wall of the upper part of the silo is covered by a stainless-steel liner connected at the top to the floor liner and at the bottom to the collection basin. A continuous stainless-steel path toward the collection basin is thus formed for the flow of all spilled mercury. Thermal analysis [14] has shown under the worst-case spill conditions that the mercury temperature in the collection basin remains in an acceptable range without active cooling.

The collection basin is constructed as a double-walled stainless-steel vessel open at the top and installed to be structurally independent from the surrounding concrete pit. The basin is deep enough to contain the entire mercury inventory in the volume below the storage tank. Spilled fluids reach the collection tank through the open annulus between the storage tank and the silo wall.

The storage tank is a cylindrical vessel with dished heads. A circular passage connects the heads along the axial centerline. In addition to providing a duct for air cooling of the storage tank, this passage can be used to access the collection basin for removal of contained liquids. A small depression in the collection basin directly below the passage minimizes the amount of residual liquid that remains after pumping.

3.3.1.3 Mercury Spill Drainage Design Features and Function

The process bay part of the service bay (i.e., the west approximately half of the service bay that contains the mercury loop) is designed to allow mercury spillage to drain to the collection basin by gravity. The key to this design is the 1° nominal slope specified for the stainless-steel floor liner underneath mercury loop components. This feature mitigates a loss of mercury confinement event by minimizing the surface area of mercury exposed to air and the exposure time as it is draining to the collection basin. The drainage feature is a passive credited design feature and is explained in more detail in Section 5.2.9.

Figure 3.13 shows the drainage areas and directions of floor slope. The carriage track area (i.e., the southern ~5 ft wide by 48 ft long section of the process bay) is sloped north toward a trough that is approximately 48 ft long by 2 in. wide by 9 in. average depth and is sloped toward the notch between the track area and the collection basin. The carriage tunnel floor is sloped east to direct leaks in the tunnel back toward the carriage track area and collection trough. The floor of the sunken heat exchanger pit is sloped to the east, toward the collection basin.

The steel shielding that surrounds the mercury loop is an additional feature of the mercury process system and service bay that would help minimize the extent of contamination following a mercury spill event. This shielding includes the approximately 12 in. thick steel beams that cover the trench that holds the heat exchanger and collection basin as well as the approximately 4 in. thick steel “doghouse” shielding cabinets that enclose the pump discharge (cold leg) piping and part of the hot leg piping (i.e., before it turns down through a hole in the 12 in. shielding to enter the trench on its way to the heat exchanger). This shielding minimizes background radiation in the service bay during operation so that electrical cables and other sensitive components can have an adequate service life. The safety benefit is that leaks or breaks in the mercury loop would occur inside a largely closed space inside the service bay. Figure 3.14 illustrates the mercury loop with shielding installed. Another benefit of this shielding would come about in the highly unlikely event of a significant fire in the service bay, whereby the radiation shielding would provide thermal shielding for the mercury loop piping inside.

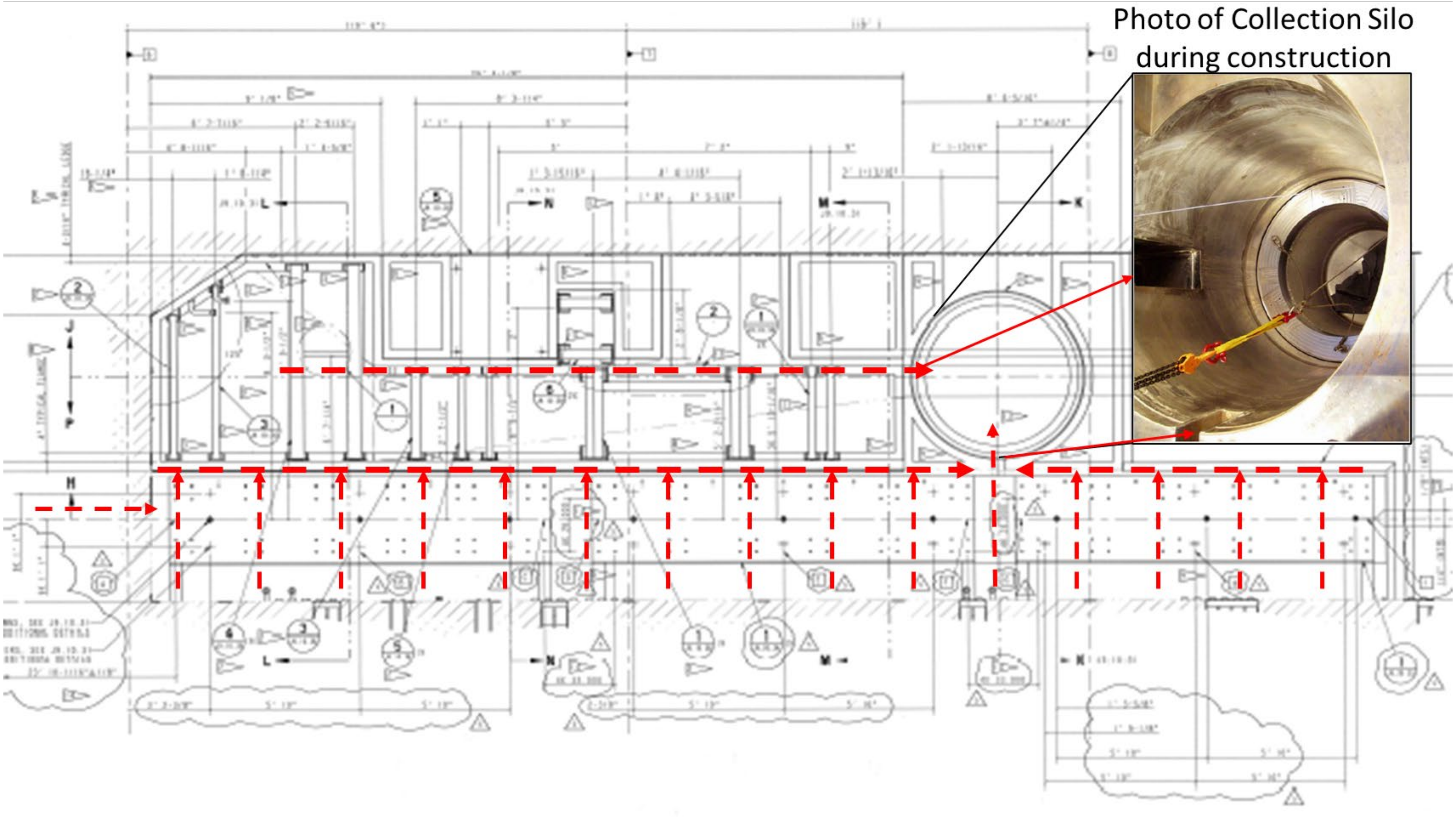


Figure 3.13. Process bay spill drainage directions and areas.

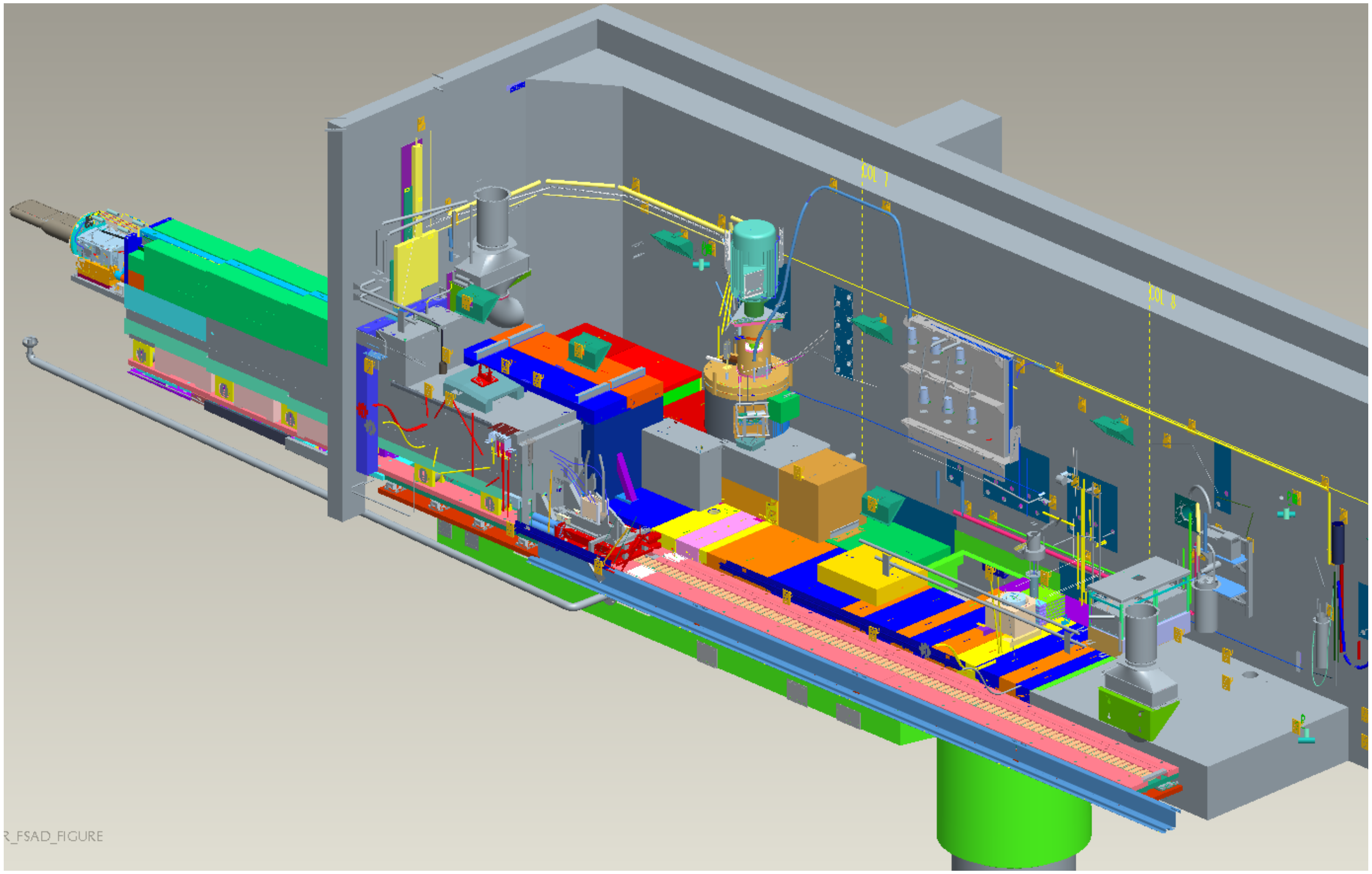


Figure 3.14. Isometric view of process bay. The mercury loop shielding is shown with target plug carriage inserted into the monolith in operational position. The part of target service bay to south (left) of carriage tracks is omitted for clarity.

3.3.1.4 Double-Walled Heat Exchanger Design

The mercury-to-water heat exchanger uses a robust double-walled heat exchanger design to minimize the risk of contaminating the cooling water with the highly radioactive target mercury. The heat exchanger is designated as a credited design feature, as described in Section 5.2.13. Figure 3.15 shows a schematic of the double-walled arrangement and associated instrumentation; Figure 3.16 provides pictorial views. The target mercury flows inside the tubes, and essentially unirradiated static mercury resides between the concentric tube walls and cooling water flows outside the tubes. Although the interstitial mercury is described as “unirradiated,” the unirradiated mercury is expected to absorb stray neutrons and eventually become slightly radioactive. Calculations indicate that the degree of radioactivity will lead to dose rates on the order of a few millirem per hour on contact. To achieve the heat transfer benefit of interstitial mercury, the gap has sufficient width to allow the filling to ensure that bubbles and gas pockets are minimized.

During normal operations, the interstitial mercury is maintained at a higher pressure than the circulating, irradiated mercury and the cooling water. Because of the pressure differential, a through-wall failure of the inner tube would result in transfer of interstitial mercury into the circulating, highly radioactive mercury. Likewise, a through-wall fault of the outer tube would result in the loss of interstitial mercury into the cooling water. Simultaneous faults of both inner and outer tube would result in transfer of cooling water into the irradiated mercury because cooling water is kept at a higher normal pressure than the circulating, irradiated mercury. Before each mercury loop fill, the heat exchanger integrity is verified by vacuum pumping the loop and monitoring the vacuum rate of decay. Furthermore, the pressure and level in the interstitial space is continuously monitored, and associated alarms and automatic responses are triggered if pressure is lost or level falls too low.

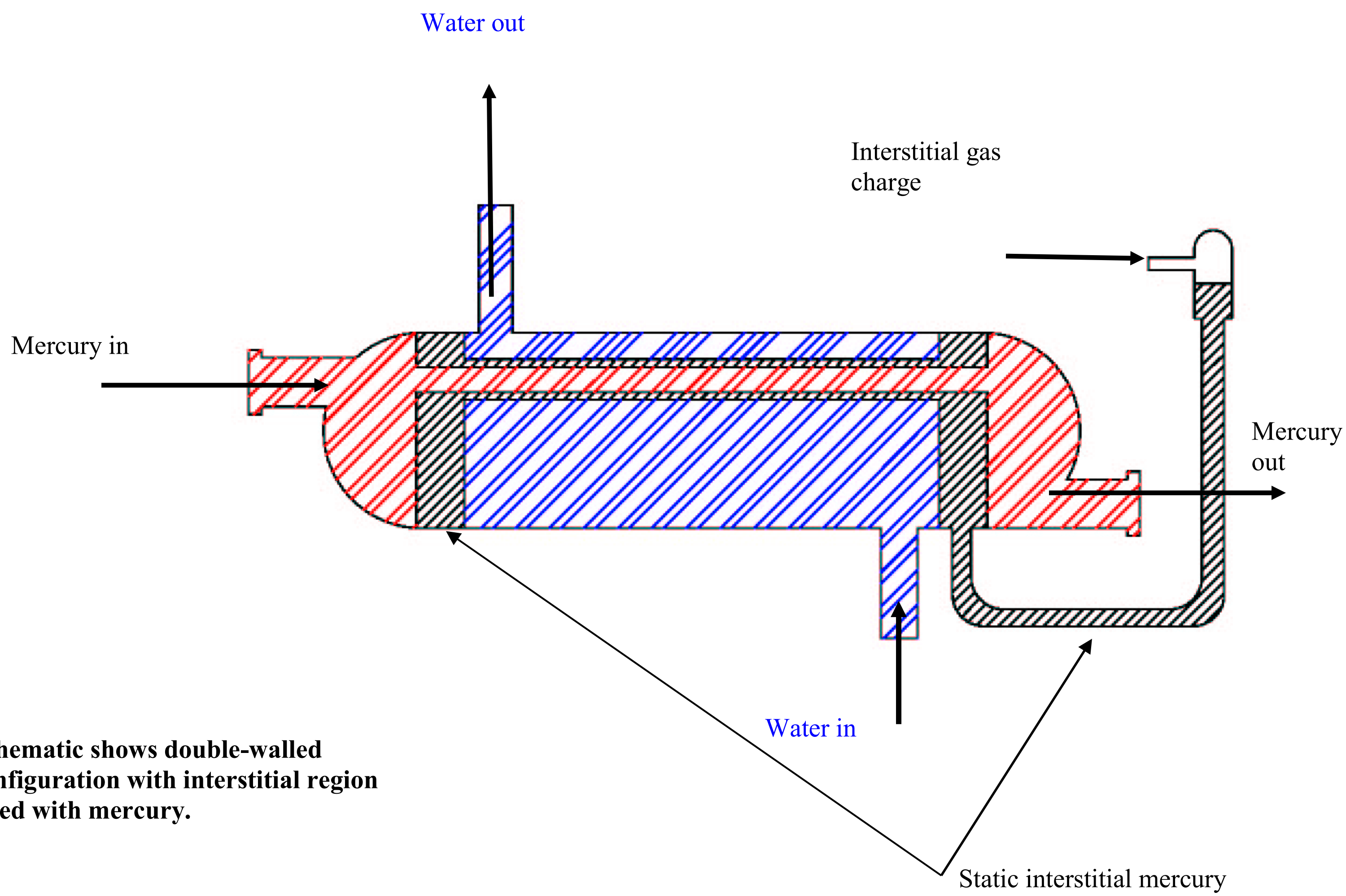


Figure 3.15. Double-walled mercury–water heat exchanger schematic.

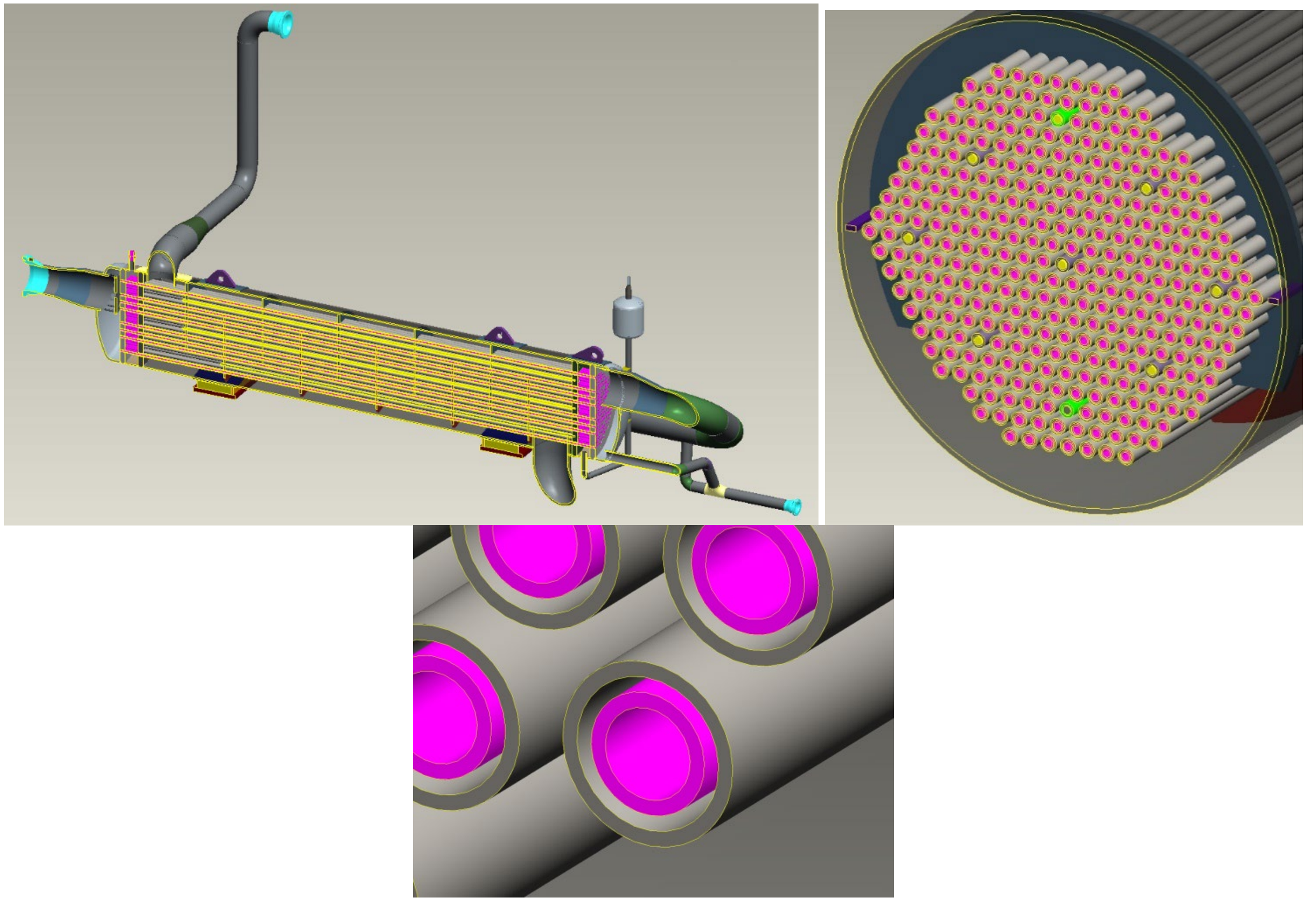


Figure 3.16. Double-walled mercury–water heat exchanger pictorial schematic.

3.3.2 Core Vessel and Internals

The core vessel (Figure 3.17) contains the inner and outer reflector plugs and the moderators and is designed to confine vapor and liquid spills. The core vessel interfaces with the target module and the proton beam window. Design features of the core vessel are credited for mitigating certain accident scenarios involving spilled mercury (Sections 5.2.3, 5.2.4, and 5.2.8). The operating environment inside the vessel is normally helium at slightly sub-atmospheric pressure.

The 316 stainless-steel core vessel has been designed and fabricated to requirements guided by the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code, Section VIII. Although the vessel is not ASME stamped, design calculations were independently reviewed as would be required for stamped vessels. The vessel is protected from overpressure by a rupture disk having relief characteristics certified by the manufacturer. In the event of an overpressure within the core vessel, the rupture disk opens, and the vessel is vented to its inert-gas-purged vent line. The hydrogen-safe vent is designed to accommodate release of helium, hydrogen, and air from the core vessel. The core vessel is designed to withstand either vacuum or an overpressure of 1 atm (i.e., internal pressure between 0 and 2 atm [29.4 psia]). However, in operation, the core vessel rupture disk is set to actuate at 7 psi over atmospheric pressure.

The core vessel provides credited confinement functions, as further described in Section 5. These functions include retaining liquid mercury that could be spilled inside the core vessel and maintaining a confinement barrier against release of mercury vapor into the monolith bulk shielding after a spill. Liquid can be retained within an approximately 0.7 m^3 (183 gal) void volume at the bottom of the vessel. Mercury vapor leakage is minimized by the core vessel, the neutron beam windows, the gas-pressurized seals (on the proton beam window and target ports), and the passive seals around penetrations.

The core vessel drain line allows removal of any liquids spilled into the core vessel. As shown in Figure 3.18, the drain line terminates in a standpipe that can be remotely accessed in the service bay. A blind flange closes the standpipe to facilitate closure and contamination control in the service bay [19, 20]. The standpipe is designed to accommodate the maximum feasible spillage of mercury into the core vessel without overflowing mercury into the target service bay.

The core vessel has 20 ports: 18 neutron beam ports, a proton beam port, and a target port. The neutron beam windows, which are part of the core vessel inserts, provide the pressure boundary at the inlets of the neutron beam ports. The vessel inserts hold the neutron beam tubes and are sealed to the vessel port with a double metal vacuum O-ring. Studs in the core vessel flanges and remotely installed nuts secure the core vessel inserts to the vessel flanges and provide the necessary sealing force. The neutron beam windows are aluminum to enhance neutron transmission. The proton beam window and the target module are sealed to the vessel using inflatable-metal seals. These two inflatable seals use an active system that relies on an inert gas-pressurized stainless-steel bellows to maintain contact with the vessel-sealing surface.

3.3.2.1 Proton Beam Window

The proton beam window separates the helium or rough vacuum environment inside the core vessel from the high vacuum inside the proton beamline. The window is thin, made of Inconel 718, aluminum 6061, or other suitable material as determined by engineering analysis, and actively cooled by water loop 2. The proton beam window is periodically replaced because of accumulated material damage caused by proton fluence. To facilitate replacement of this intensely heated and irradiated structure, pneumatic (inert gas) seals and a vertical assembly and removal path are incorporated into the design. Expected service life of the proton beam window assembly is estimated to be about 1.5–2 years at maximum beam power, depending on the design.

3.3.2.2 Inner Reflector Plug

The inner reflector plug (IRP) is composed of three elements: (1) the upper inner plug, (2) the intermediate inner plug, and (3) the lower inner plug (Figure 3.17). The moderator vessels are integrated with the lower IRP. The IRP is replaced periodically as a unit, including the moderator vessels, coolant lines, and cryogenic transfer lines. New units may incorporate design improvements, such as increases in lifetime or reliability.

The lower IRP consists of an aluminum shell that holds beryllium reflector material and stainless-steel shielding. The aluminum shell prevents the beryllium from being a toxic metal hazard to workers. The intermediate and upper IRPs are stainless or carbon steel. Some neutron beam channels are cadmium lined for neutron physics reasons.

The IRP has specially designed structures to provide the following:

- Chambers that hold the moderator vessels in place,
- Channels for cryogenic and coolant lines,
- An opening for target module insertion and an open pathway for the proton beam to reach the target module,
- Open channels for the neutron beams.

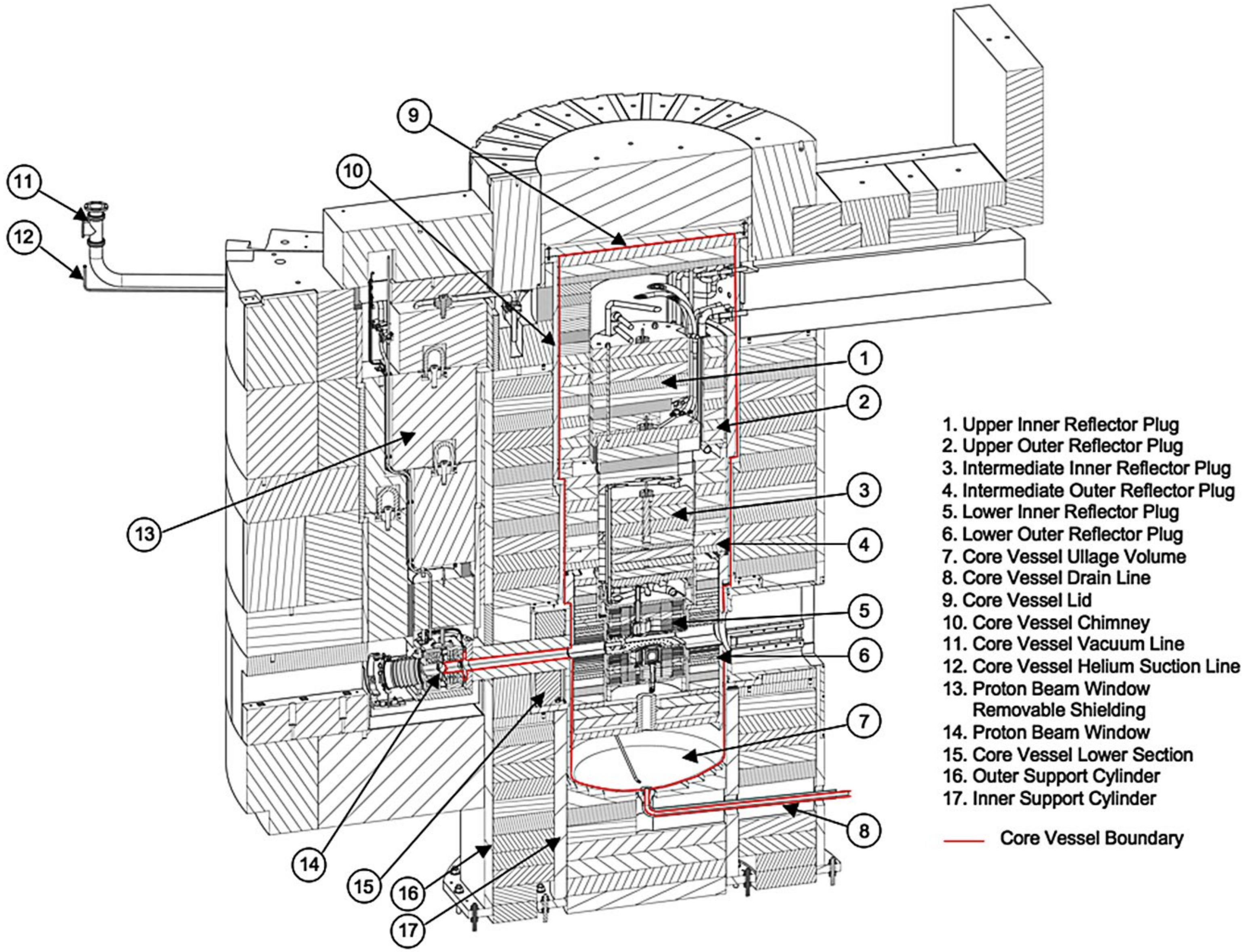


Figure 3.17. Core vessel and internals.

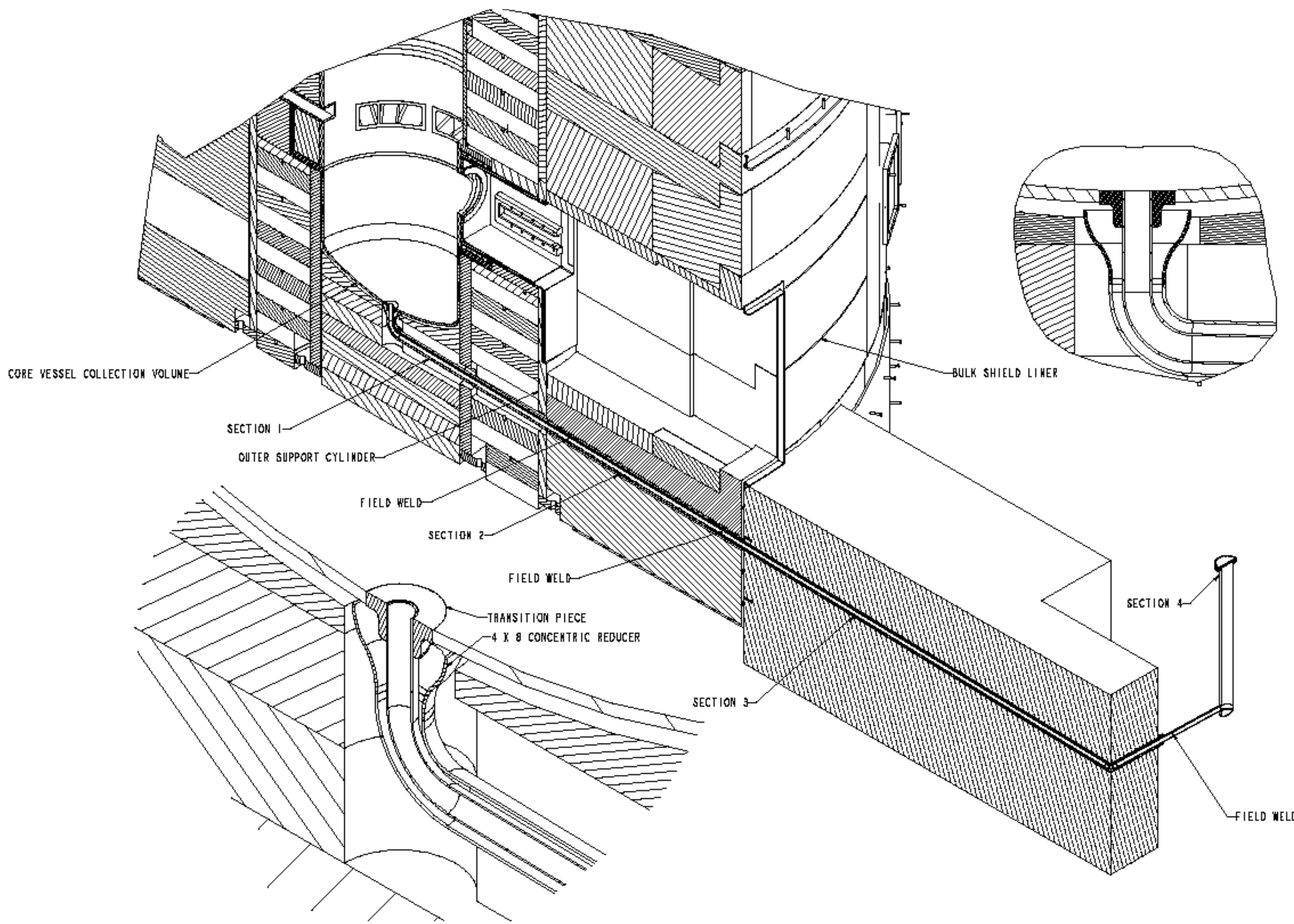


Figure 3.18. Core vessel drain line.

The lower and intermediate IRPs are cooled by coolant loop 4 (Section 3.3.6). The upper IRP is passively cooled by conducting heat to the actively cooled plugs. Maximum operating water pressure in coolant loop 4 is approximately 70 psig.

The IRP elements are connected so they can be installed as one unit. They are designed with removable connecting bolts between the sections so that the unit can be removed in pieces sized for shielding containers. The IRP may be replaced as research priorities change. However, neutronic considerations associated with the burnup of neutron poisons and decouplers such as gadolinium and cadmium features associated with the moderators limit replacement to around once every 3 years at maximum beam power. In addition to these neutronic considerations, the IRP would also require replacement owing to material damage from irradiation.

3.3.2.3 Outer Reflector Plugs

The outer reflector plug is composed of three elements: (1) the lower outer plug, (2) the intermediate outer plug, and (3) the upper outer plug.

The lower outer plug is made of stainless steel. The intermediate and upper outer plugs are stainless steel and stainless-steel-encased carbon steel.

The lower and intermediate plugs are cooled by water loop 4. The upper outer plug is cooled via conduction to the actively cooled components.

3.3.2.4 Core Vessel Atmosphere Control

Controlling the atmosphere inside the core vessel is necessary for operational purposes. The operating environment inside the vessel is helium slightly below atmospheric pressure. The helium atmosphere promotes heat conduction between the CMS outer vacuum boundary and the CMS water cooling jacket. It also prevents the formation of corrosive nitrogen compounds and minimizes formation of volatile radionuclides. Because of the core vessel radiation environment, elastomer seals are generally avoided, except for the ethylene propylene radiation-resistant concentric O-rings that seal the vessel lid (Part 9 in Figure 3.17) to the vessel chimney at the top of the shield stack. Controlling the atmosphere inside the core vessel is not a safety requirement because the CMS hydrogen boundary is credited with preventing hydrogen release inside the core vessel. The CMS vacuum boundary is the second credited control against hydrogen release and possible formation of combustible hydrogen air mixture in the core vessel. These credited safety functions are discussed further in Section 5.

The design of the core vessel made provision for operation of the core vessel with either a helium atmosphere or at a rough vacuum. However, IRP designs through IRP-4 rely upon the helium atmosphere for heat transfer to prevent accelerated aging of aluminum components in the CMS. Thus, operation with the core vessel at a rough vacuum for an extended time would require design changes in the IRP.

Although an inert atmosphere is required only for operational purposes, atmosphere control provides an uncredited layer of safety by normally excluding significant oxygen from the core vessel. In the highly unlikely event that the cryogenic moderator hydrogen and the vacuum boundaries (both CECs) should both fail and leak hydrogen into the core vessel, the resulting atmosphere inside the core vessel would not be combustible.

The vacuum pumps used to evacuate the core vessel before backfilling with helium (capacity ~150 ft^3/min) exhaust to the PCES upstream from the sulfur-impregnated charcoal adsorbers. These filters prevent excessive mercury release in the unlikely event of mercury leakage to the core vessel under vacuum conditions when the vacuum pump exhaust could be transporting mercury vapor.

3.3.3 Moderator Systems

Neutrons produced in the spallation reaction are born with kinetic energies too high to be useful for neutron scattering. The process of slowing down high energy neutrons to lower energies is referred to as moderation. Neutrons produced in the spallation reaction are moderated to lower energies by scattering in the moderators. Four moderators are positioned near the mercury target module where neutrons are produced. Three of the four moderator systems employ cryogenic supercritical hydrogen, and the fourth moderator uses ambient water to reduce neutron energies. The neutron beamlines view various portions of the moderators to receive moderated neutrons.

As addressed in Section 4, the hydrogen used in the moderators introduces significant safety hazards if it were to escape into the core vessel. The CMS is designed with essential safety features to prevent leakage into the core vessel. These safety features include the CMS hydrogen and vacuum boundaries, which are described in the following subsections and in Section 5.

Operations and maintenance of the CMS are in accordance with safety procedures executed by trained and qualified individuals under supervision of the CMS system engineer or other qualified supervisor.

3.3.3.1 Cryogenic Moderator System

Figure 3.19 shows the four moderator vessels arranged above and below the target inside the core vessel. Figure 3.20 shows the location of the CMS components and transfer lines in the target building. The innermost boundary confining the cryogenic hydrogen (primary confinement barrier) is enclosed within the vacuum boundary (secondary confinement barrier). The outer cooling water layer is present for the moderator vessels and in cryogenic transfer lines in the lower part of the core vessel (Figure 3.21). The CMS cannot physically be operated with a degraded vacuum layer because the resulting system temperature increase would result in discharge of the hydrogen inventory to the outdoors through the spring-loaded relief valve or rupture disc.

The CMS consists of three separate cryogenic moderating loops of essentially the same design. These systems provide three volumes of supercritical hydrogen at 20 K, which yields a neutron spectrum that is well matched to many research needs. Neutron-absorbing materials are used in decoupled and poisoned moderator vessels (Figure 3.19) to control the shape of neutron pulses produced by the moderators. Decoupled moderators have a cadmium coating on the unviewed surfaces of the moderator vessel or on the surfaces of the pocket around the vessel. Poisoned moderators have a gadolinium plate in the moderator vessel.

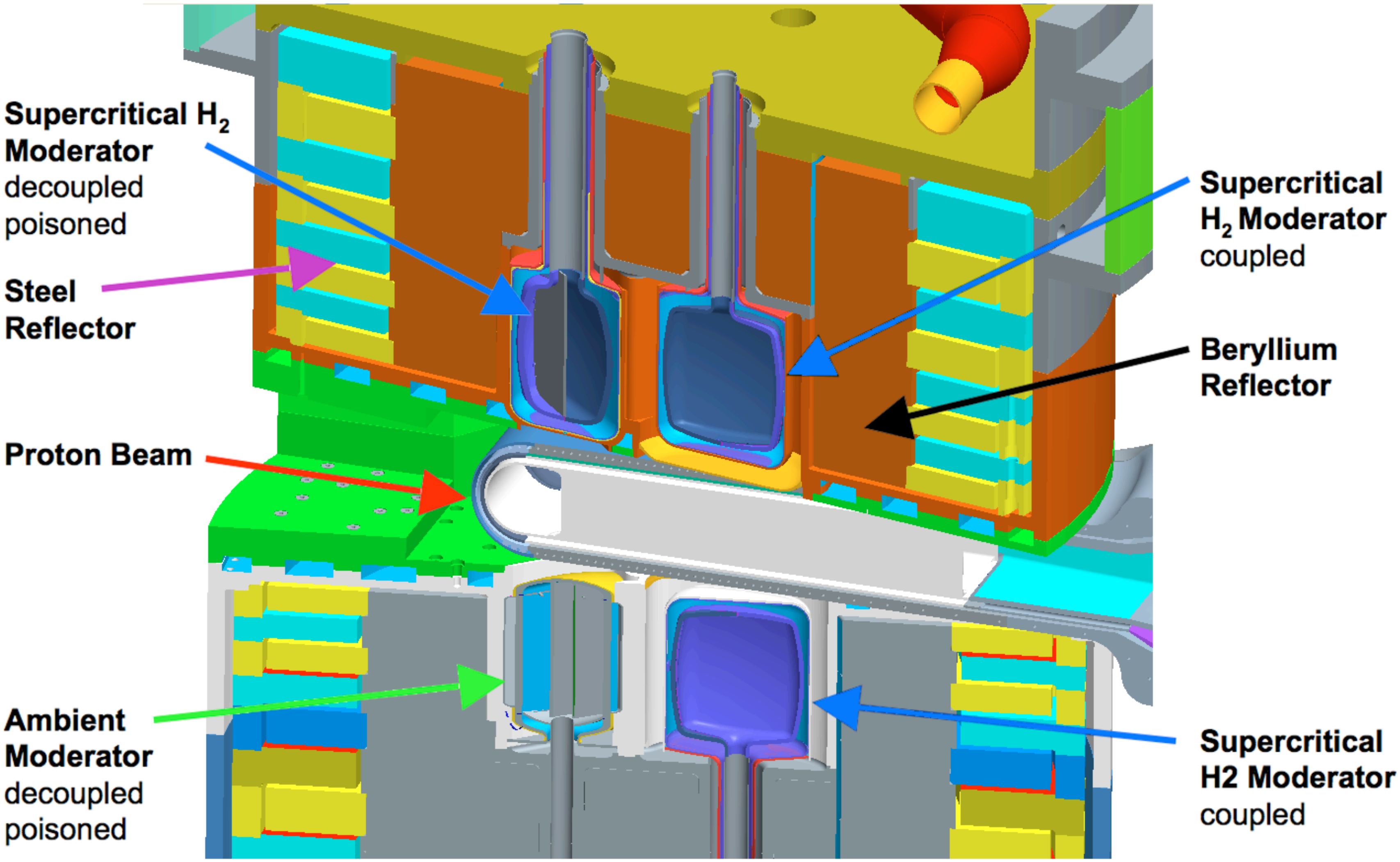


Figure 3.19. Configuration of the moderator vessels above and below the mercury target inside the core vessel.

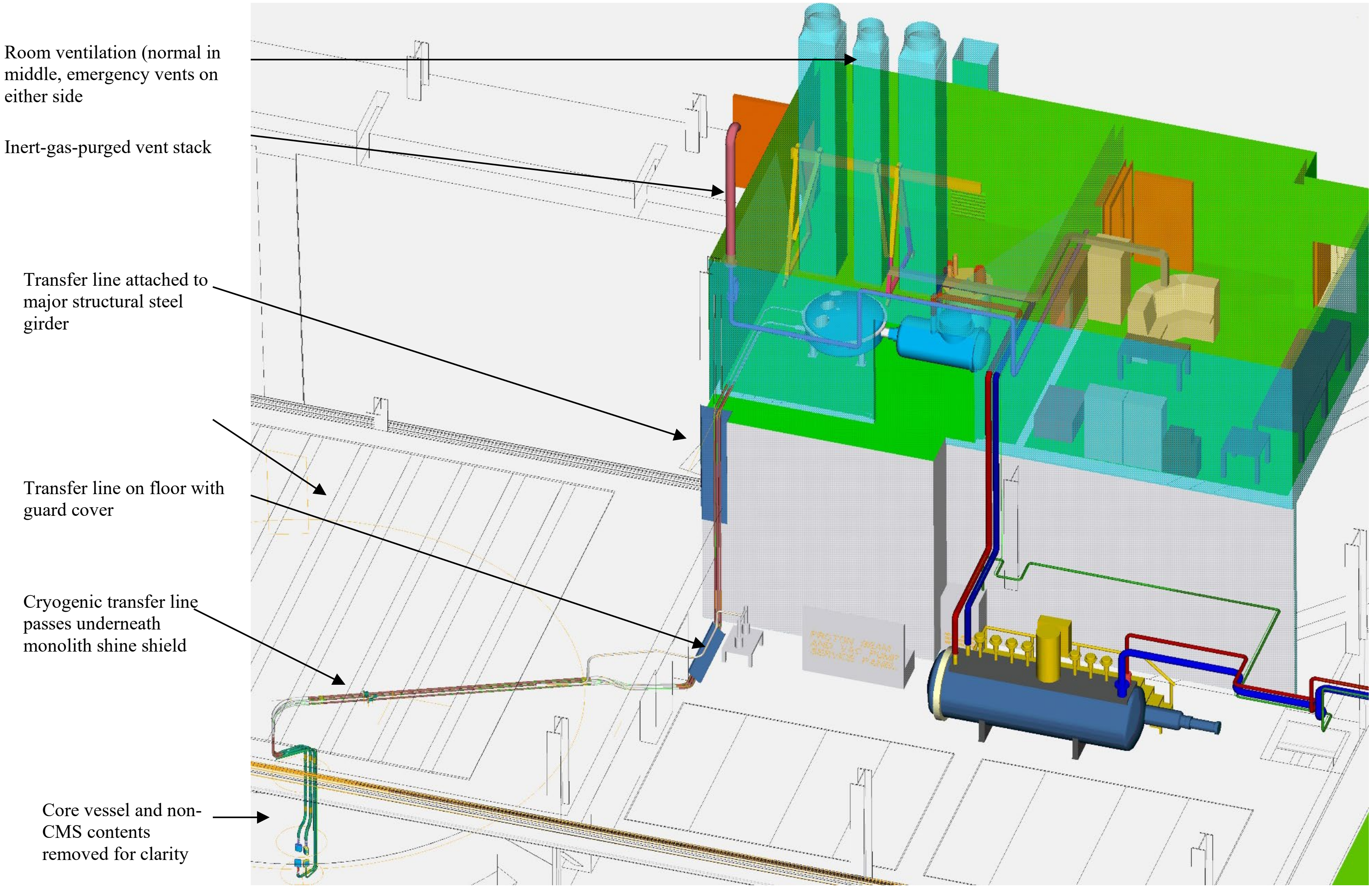


Figure 3.20. Route of CMS cryogenic transfer lines between monolith and hydrogen utility room.

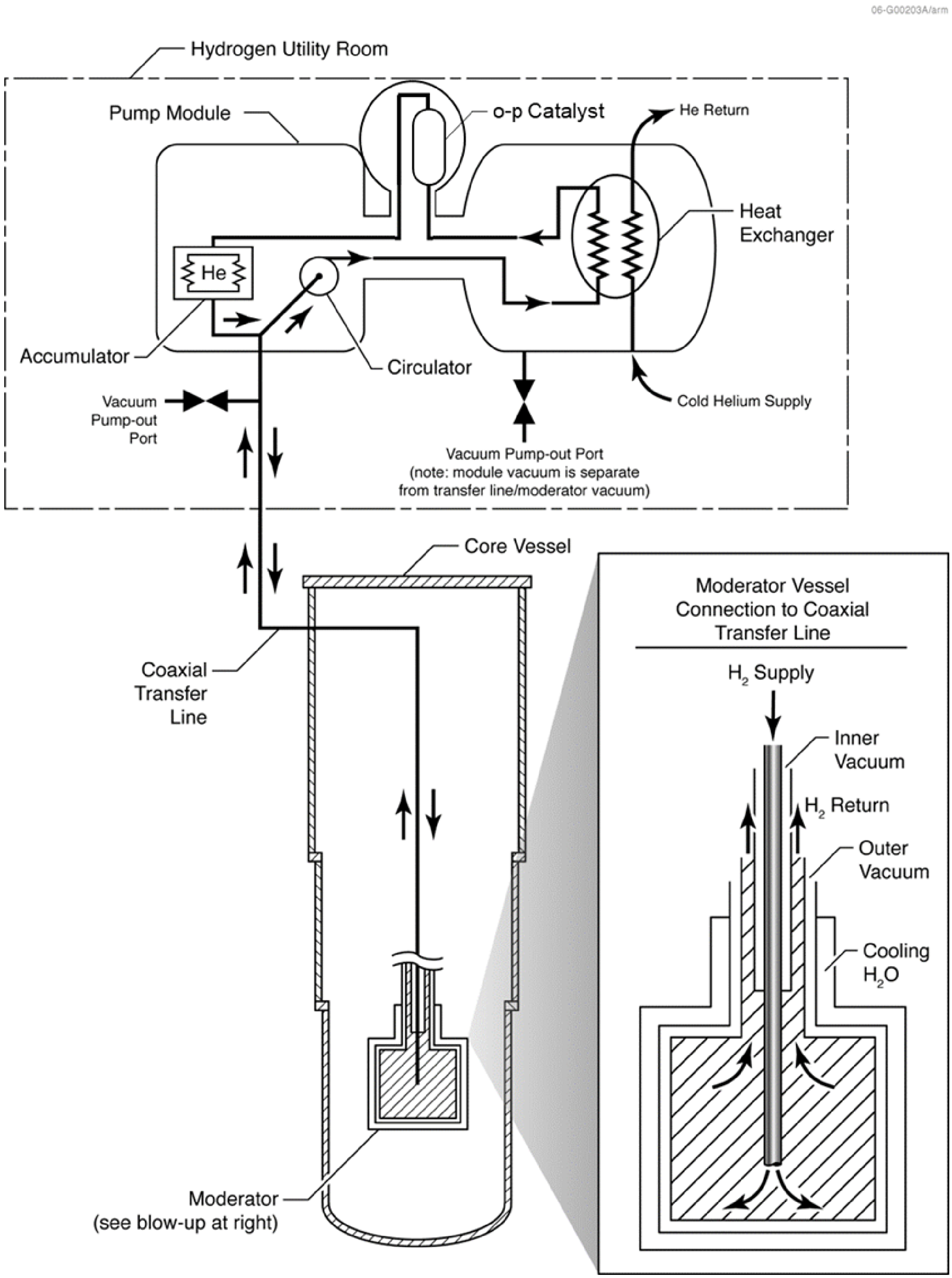


Figure 3.21. Cryogenic moderator system schematic layout.

Each loop comprises a moderator vessel inside the core vessel, a coaxial transfer line to carry the cryogenic hydrogen to and from major components, and, in the HUR, a circulator, a heat exchanger, a catalyst module and an accumulator. Transfer line cryogenic boundaries are made of Invar and ambient boundaries of stainless steel to minimize differential thermal contraction. The HUR is discussed in Section 3.3.3.2. The circulator provides motive power to move the supercritical hydrogen around its circuit between the heat exchanger (in the HUR) and the moderator vessel in the core vessel, although natural circulation also promotes system flow. Cryogenic helium circulated through the heat exchanger removes heat that the cryogenic hydrogen absorbs from surroundings and from incident gamma rays and neutrons (significant near the target module).

After the heat exchanger, each loop is provided with an iron oxide ortho-para catalyst bed designed to give a high fraction of para-hydrogen in the supply to the moderators. A high fraction of para-hydrogen improves the quality of the neutron beam provided to the instruments. The iron oxide catalyst is contained within the module by inlet- and outlet-retention elements welded into each end. The retention elements ensure that catalyst media cannot circulate in the CMS loop, potentially becoming activated (Section 5.2.21).

The accumulator has stainless steel bellows to accommodate expansion associated with normal and anticipated off-normal operational temperature fluctuations without the need to add or subtract hydrogen to or from the system. The accumulator minimizes pressure changes that would otherwise accompany temperature changes. For example, the circulator outlet pressure is nominally about 15 bar for an approximately 14 bar (203 psia) inlet pressure when the system is at temperature with the proton beam off, but the accumulator allows the pressure to increase only to 16 bar (232 psia) when the beam reaches full power.

The moderator vessel and several meters of the transfer line inside the core vessel receive significant neutron and gamma irradiation. To maintain temperatures within normal design range, CMS boundaries in this zone that are not in direct contact with the cryogenic hydrogen are cooled by a water jacket that surrounds the outer layer. The water jacket also performs a neutron pre-moderation function for some moderators by helping slow the neutrons before they reach the cryogenic hydrogen. Cooling water for all three cryogenic moderators and for the ambient (water-only) moderator is provided by cooling loop 3, described in Section 3.3.6.1.

The following functions are needed for CMS operation:

- Gas management—vacuum and helium purging, hydrogen filling.
- Normal operation—circulation, cooling, and pressure control (accumulators).
- Hydrogen venting—spring-loaded relief valves and rupture discs that discharge to the inert-gas-purged vent line for discharge to the atmosphere above the target building roof. The hydrogen does not become significantly activated during operation, so this discharge path is a negligible accident or environmental source term.

All the active functions are in the HUR, except for control valves in the hydrogen supply cabinets, which are located outside near the helium compressor building. In the HUR, the three heat exchangers (i.e., of each of the three CMS subsystems) are held inside a vacuum vessel called the heat exchanger module. The three hydrogen circulators and three accumulators are inside the pump module. The iron oxide catalyst is in the catalyst vessel. The pump module, catalyst vessel, and heat exchanger module are interconnected by the vacuum system (Figure 3.21). The vacuum system for these modules is separate from the vacuum for the transfer line and moderator vessel. Thus, a hydrogen leak inside the pump or heat exchanger module cannot flow through the vacuum layer down into the core vessel.

No CMS instrumentation or control devices are located inside the core vessel. The instrumentation is indicated on control panels in the room adjacent to the HUR and is provided to the Experimental Physics and Industrial Control System (EPICS) digital information bus.

The system must be charged with hydrogen before cryogenic operation is achieved. Multiple precautions—including the use of high-purity hydrogen and an interlocked hydrogen fill system—are taken to minimize the opportunity for introduction of oxygen into the system. The charging operation is initiated at ambient temperature by purge and vent cycles: vacuum pump-down followed by helium fill to remove residual oxygen from all parts of the system. Then, the hydrogen piping on the suction side of the circulator is connected to the hydrogen supply by opening three isolation valves. A pressure regulating valve in the ambient hydrogen supply line controls the hydrogen supply pressure during filling to the desired system operating pressure of 14 bar (203 psia). As the initially ambient-temperature system cools, the pressure decreases slightly, and the pressure regulator automatically admits more ambient hydrogen to hold pressure approximately constant. A major leak in the ambient hydrogen charging line could rapidly release a significant quantity of hydrogen into the HUR. To combat this, a flow orifice is incorporated in the charging line near the cylinder manifold to limit the maximum break flow to within the ventilation capacity of the HUR ventilation fans (Section 3.3.3.2).

When the system has been cooled to the desired operating temperature, the three isolation valves are closed, disconnecting the system from the hydrogen supply. The system now operates on this inventory of hydrogen until a major maintenance shutdown necessitates discharge of the hydrogen from the system by releasing it to the atmosphere. This discharge is achieved by turning off the helium refrigerator and opening an isolation valve to allow a regulating valve to vent the hydrogen to the inert-gas-purged vent stack for discharge to the environment above roof level. This mode of controlled venting maintains 14 bar (203 psia) at the circulator inlet to ensure supercritical conditions during the return to ambient temperature. After the system reaches ambient temperature, another valve is opened to allow the system to reach atmospheric pressure. If a more rapid venting must be accomplished, then the regulating valve can be bypassed. Multiple vacuum pump-down and inert gas purging cycles remove residual hydrogen from the system before it is opened for maintenance. Any maintenance of the CMS that involves opening the hydrogen boundary will involve venting the entire hydrogen inventory to prepare for the maintenance. Venting the entire hydrogen inventory before the maintenance ensures safe conditions during the maintenance and minimizes the opportunity for oxygen to be introduced into the system after the maintenance.

A major key to reliable CMS operation is the ability to maintain a high-vacuum envelope as thermal insulation around all parts of the system that contain cryogenic hydrogen. The ~20 K hydrogen temperature is very sensitive to the heat input and, therefore, to leakage of gases into the vacuum-insulating layer. The vacuum utilities (pumps) are designed to provide pump-down to the required vacuum (~10^{-6} torr), and are connected during initial pump-down. After initial pump-down, the vacuum volume is isolated from the vacuum pump by closing the valves. The vacuum insulation will not normally be connected to a vacuum pump but will be reconnected periodically as needed to maintain a high vacuum insulation layer between cryogenic hydrogen and surfaces at ambient temperature. Highly engineered barriers minimize the chance of leakage. Any significant leakage of hydrogen into the vacuum barrier allows greater than normal heat transfer and increases the hydrogen temperature. If sufficient leakage brings the vacuum into the range of 10^{-2} torr or greater, then temperature and pressure would rapidly increase, requiring venting to control the pressure. System pressure would be controlled without operator intervention by the 18 bar (261 psia) spring-loaded relief valves and the 19 bar (275.5 psia) rupture discs, discharging into the inert-gas-purged vent line.

Key to CMS safety are the redundant barriers against hydrogen release within the core vessel and the protection of the barriers against internal overpressure as well as external threats. The hydrogen boundary is the primary barrier, and the vacuum boundary is the secondary barrier against uncontrolled hydrogen release.

Vessels that form the hydrogen primary boundary and the vacuum boundary are designed and built according to a tailored quality plan developed to provide protection equivalent to a B&PV code stamp while allowing for design constraints unique to the application and leveraging capabilities unique to ORNL. Further detail on this plan is provided in Sections 5.2.1 and 5.2.2. The design and fabrication of all piping meets the requirements of ASME B31.3, minimizing the probability of leakage. Pressure relief features (i.e., in addition to manual venting capability) are listed as follows. Pressure relief devices are certified by the vendor per ASME.

- Hydrogen boundary: 19 bar (275.5 psia) rupture disk and 18 bar (261 psia) spring-loaded relief valve,
- Vacuum boundary: 2 bar (29 psia) rupture disc.

Within each of the three CMS loops, the hydrogen and vacuum volumes are contiguous throughout, with one exception: the pump/heat exchanger/catalyst module vacuum is separate from the transfer line/moderator vessel vacuum. This configuration enables the relief device to relieve pressure buildup at any point in the entire volume, including points within the core vessel that are farthest from the relief device. The design provides relief for each of the following pressure buildup conditions:

- Sudden and total loss of vacuum to 1 atm (helium or air)—expanding hydrogen is relieved through an 18 bar (261 psia) spring-loaded relief valve and/or a 19 bar (275.5 psia) hydrogen rupture disk within acceptable pressure for hydrogen boundary (no hydrogen leakage to vacuum layer).

- Leakage of cryogenic hydrogen into vacuum space—relief through hydrogen and vacuum rupture discs is accommodated within the design pressure of hydrogen and vacuum boundaries and within allowable combined thermal and pressure stress limits of vacuum boundary that experiences rapid temperature decrease caused by contact with cold hydrogen.

Water leakage into the vacuum insulation space could occur in the moderator vessel or in the several meters of transfer line that is cooled by the water jacket (the outermost layer). In this case, the water would freeze rapidly, but neither thermal stress nor physical pressure owing to the newly formed ice is expected to cause the hydrogen boundary to fail. Water vapor subliming from the ice could spoil the vacuum, causing the cryogenic hydrogen to heat and possibly cause automatic venting of hydrogen from the system. The vacuum boundaries are designed and tested for external as well as internal pressure to ensure that boundary failure does not occur and allow water to leak. Cooling water chemistry is maintained as needed to achieve low rates of aluminum corrosion.

A through-wall flaw in the transfer line outer vacuum boundary would allow ambient air to flow into the vacuum space if it occurred between the core vessel and the pump module (which is in the HUR). If the leak were large, then the normal high vacuum would be degraded immediately, and the affected CMS unit would self-vent to the outdoor environment through the hydrogen-safe relief line. If the leak were small, then the less volatile components of the in-leaking air (e.g., O_2 and N_2) may solidify on the inner boundary of the (outer) vacuum space. The possibility that a significant quantity of air might solidify on cold surfaces of the vacuum space is mitigated by operational practices. For example, during cryogenic operations, the vacuum space is generally maintained statically (i.e., without active vacuum pumping). If significant vacuum degradation is identified, then the cause is investigated. Residual gas analysis or other suitable techniques can be used to determine the cause of the degraded vacuum. Corrective and mitigative actions are implemented based on the results. In the case of air in-leakage, one possible mitigation would be to periodically warm the affected CMS to allow solidified gaseous elements to be vented.

In the unusual event that one or more of the CMS loops were to lose cryogenic cooling, beam-on-target power is limited to ensure the affected moderator vessel does not overheat. For example, the maximum design temperature for the installed aluminum moderator vessels is 393 K. Above this temperature, the T6 temper state may be lost and allowable stresses reduced. Operational limitations are implemented to account for requirements such as this.

Protection of the hydrogen boundary is important to safety throughout the system. Preventing an uncontrolled release of hydrogen is an industrial safety concern, as addressed in Section 3.3.3.2. Hydrogen release into the core vessel would also be a hazardous material safety-related concern, as described in Section 4.

The hydrogen boundary is credited as a hydrogen confinement barrier. Although hydrogen escape into the core vessel is the hazardous material safety concern, the hydrogen boundary is designed to high quality standards throughout the cryogenic system (inside and outside the core vessel). This boundary is credited beyond the boundary inside the core vessel because hydrogen leaking into the vacuum volume could escape into the core vessel if the vacuum boundary were also leaking. To provide a credited, independent (secondary) barrier against uncontrolled leakage of hydrogen into the core vessel, the vacuum boundary is designated as a CEC. The crediting extends to the hydrogen rupture discs and the vacuum region rupture discs and includes the need for a clear vent pathway to the exterior of the building.

Outside the core vessel, the line is protected at the PC-3 level against seismically induced failure modes (crimping, crushing) that could prevent the flow of hydrogen from inside the core vessel to the rupture discs in the HUR. Other failure modes (e.g., shearing, leakage) are not of radiological safety concern outside the core vessel.

Figure 3.20 shows the location in the target building of the CMS hydrogen boundary components and transfer line from the core vessel through the monolith, up along the south wall of the high bay, and into the HUR. The transfer line for each CMS traverses the high bay in a way that it is protected against inadvertent impacts from operational activities (e.g., forklifts, cranes). This protection is achieved by routing the transfer line near major structural elements such as the large steel girder it follows up to the HUR. The hydrogen boundary inside the core vessel is seismically protected at the PC-3 level against all failure modes. The line is supported as needed, and the path inside the core vessel is protected by its installation in the large metallic reflector and shielding segments inside the core vessel.

3.3.3.2 Hydrogen Utility Room

The major hazard in the HUR is inadvertent hydrogen combustion. Design features included to mitigate the hazard are described and evaluated in the target building fire hazards analysis (FHA) document [15], which is summarized here. Although the cryogenic hydrogen does not become significantly activated in service, it may become contaminated in service. Therefore, appropriate surveys are performed as needed to control radiological hazards when equipment must be opened for maintenance. The hydrogen is vented and purge and vent cycles are completed before the equipment is opened.

The HUR houses active CMS components, including circulators, valves, and heat exchangers. The HUR has its own ventilation system, which includes redundant active exhaust paths. The normal exhaust path and blower operate continuously during normal operation. The two emergency vent paths (one blower in each) remain in standby for actuation upon detection of excessive hydrogen in the HUR. The emergency blowers are powered by an uninterruptable power system (UPS) and activate automatically upon detection of hydrogen in the room atmosphere. If the level exceeds 25% of the lower flammability limit (LFL) (i.e., >1% hydrogen by volume), then a local alarm sounds, and the emergency blowers actuate. If the level is 50% of the LFL or more, then the system triggers the building's fire alarm system to initiate a precautionary evacuation. Loss of exhaust air flow is indicated in the control room.

The HUR is located on the truss level above the south instrument hall of the target building. The north wall of the HUR forms part of the south wall of the high bay. The floor is reinforced concrete; the walls are gypsum-based drywall and extend such that the metal decking roof of the building forms the ceiling of the HUR. The nearest personnel access to the truss level is from the stairwell on the southwest side of the building. The HUR includes two personnel doors: one communicates directly with the truss level and the other with the adjacent control room that, in turn, opens to the truss level.

The HUR is a Class I, Division 2, Group B space defined by the National Electric Code (NEC) as a space in which the flammable gases are normally confined within closed containers or closed systems from which they can escape only in case of accidental rupture or breakdown of such containers or systems. The HUR is designed to follow the applicable requirements of NFPA 50A, 50B, 69, and 70. If the hydrogen sensors detect a hydrogen release, then an alarm is activated, and the emergency exhaust blowers are energized to vent the HUR at an enhanced rate to maintain the room below 60% of the LFL for hydrogen. The cryogenic hydrogen inventory can also be vented outside the facility by remote manual operator actions from the control room.

Instrument and electrical connections inside the HUR are designed to be hydrogen safe per NFPA-70. Valve operators are pneumatic and employ nonincendiary controls. The room ventilation system is designed to prevent hydrogen explosions per NFPA-69; therefore, the building is not equipped with blowout panels.

The HUR is seismically qualified to withstand a PC-3 earthquake without causing a failure of the CMS venting capability. This qualification is a hazardous material safety requirement. Because the HUR normal and emergency (forced) ventilation could be lost during a PC-3 seismic event, the CMS hydrogen boundary in the HUR is qualified against failure resulting from a PC-3 earthquake. The HUR is required to have ceiling vents to prevent buildup of hydrogen after a PC-3 seismic event. The two emergency exhaust vents provide a hydrogen vent path even though the blowers would, presumably, not be running after a PC-3 seismic event. The PC-3 seismic design of the CMS hydrogen boundary ensures that any leakage after a seismic event would not exceed the capability of the ceiling vents to passively vent the HUR.

3.3.3.3 Ambient Moderator System

One ambient moderator system is included for research applications that require higher energy neutrons. The ambient moderator vessel contains water that is circulated between the moderator vessel and heat exchangers in the basement as part of cooling loop 3 (Section 3.3.6).

3.3.4 Target Monolith

The target monolith includes the shielding and shutter equipment external to the core vessel assembly (~168 in. diameter) extending out to the interface with the instrument halls at the chopper archways (~408 in. diameter). The design accommodates major interfaces such as the cooling water systems, the RTBT beamline, and the instrument halls. Figure 3.22 depicts a half section of the monolith and core vessel in the direction parallel to the plane of the incident proton beam.

The monolith design includes a drain for potential liquid accumulation in the liner. The drain line is located at the center low point of the monolith liner and leads down and radially outward to a cavity in the concrete monolith pedestal where it can be accessed from the utility vault in the basement. The cavity in which the drain line terminates is a small pit sized to accumulate approximately 1 m^3 of liquid at or below the level of the door that separates the cavity from the basement. This door is also a fire barrier. Instruments at or near the drain line termination alert operators to the presence of liquid inside the drain line. These instruments are designed to distinguish between water and mercury. Mercury in the drain line is a very low probability event that would require failure of multiple independent boundaries, including failure of the core vessel boundary (Section 3.3.2). A severe seismic event could cause such failures. The cavity and fire door are PC-3 seismically qualified structures.

Figure 3.23 shows a schematic of the bulk shielding drain line configuration. To initiate removal of fluid from the drain line, operators would, after satisfactory radiation and contamination surveys, open the cavity door and make drain line connections to route the fluid to the desired destination.

3.3.4.1 Shutters

The shutter system is an integral part of the target monolith. The shutter system provides a safe, nonobtrusive method to close a beamline, allowing access to downstream parts of the neutron beamline. The shutters have a position indicator that is part of the PPS so that certain unsafe activities would cause alarms and/or proton beam shutdown. For example, such activities could include opening the door to an instrument enclosure. Controlling the position of a shutter is normally a PPS activity.

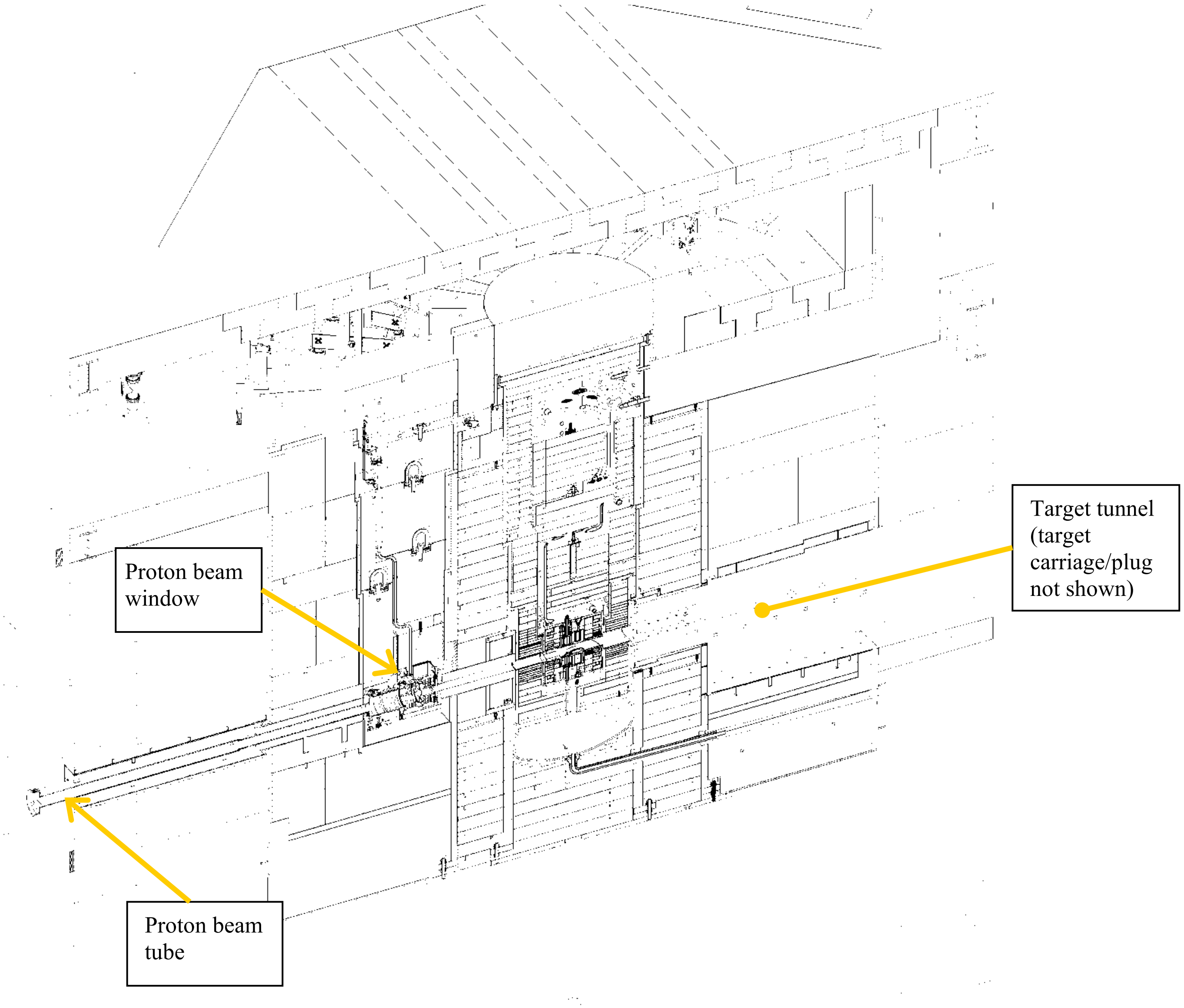


Figure 3.22. Target monolith cross-section view.

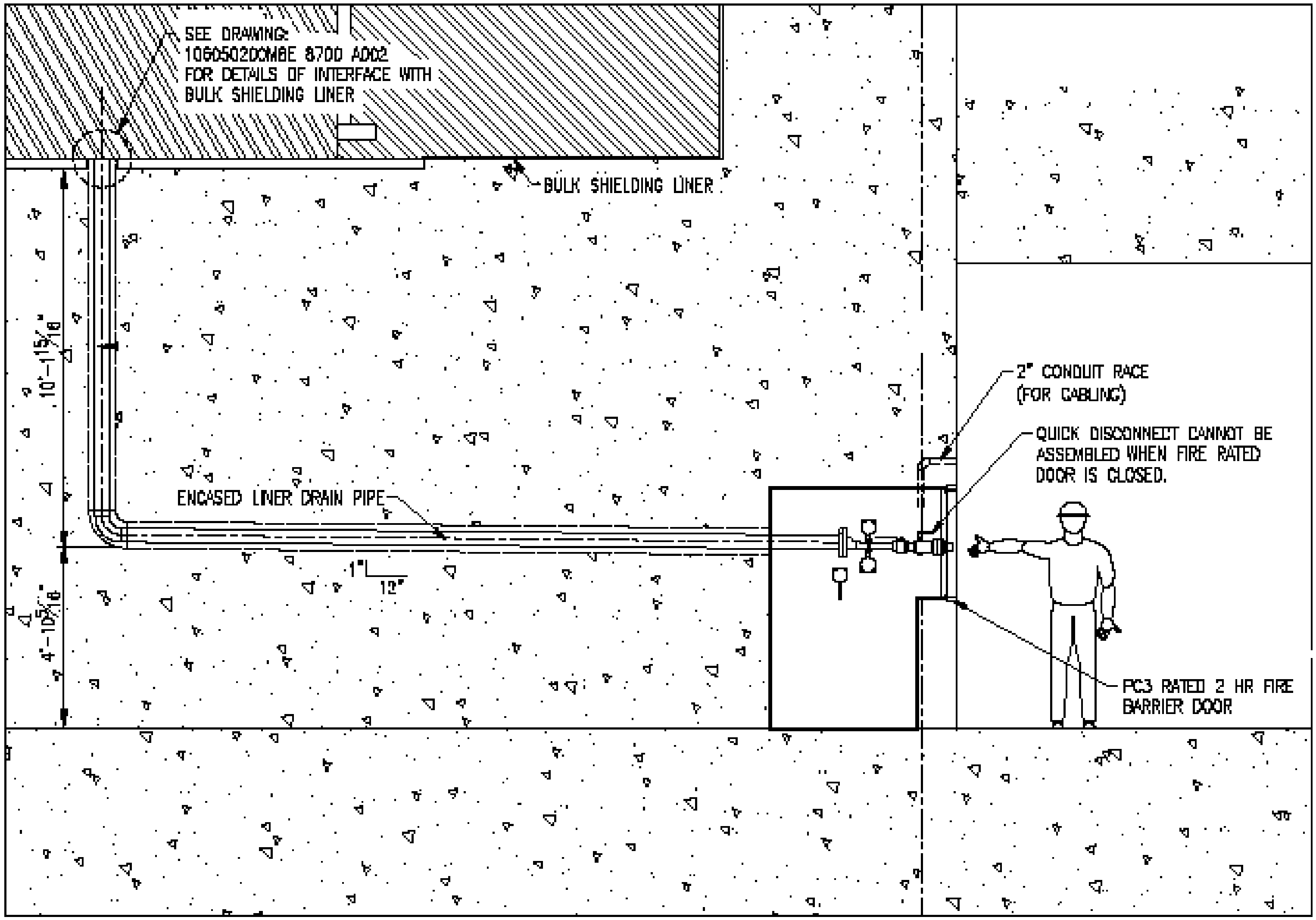


Figure 3.23. Schematic diagram of bulk shielding liner spill drainage provision.

The two broad types of shutters are single-channel shutters and multichannel shutters. The single-channel shutters each include a single large steel assembly that weighs about 30 tons and serves a single instrument. The multichannel shutters are wider and comprise three major steel segments weighing a total of about 50 tons. Multichannel shutters can serve two or more instruments. Both types of shutters operate in the same manner. Figure 3.24 locates typical shutters in the monolith. A typical single-channel shutter is shown on Figure 3.25 in both the operational and closed position. Some of the principal features of the shutter system are labeled in the figure.

The shutters have a vertical stroke of about 20 in. and move upward to close the beam. This operation was carefully chosen because the shutter insert floats in an oversize cavity. In the operational position, the shutter insert is supported on kinematic mounts that accurately align the insert with the core vessel insert. This ensures neutron guide alignment, greatly increasing the neutron beam flux.

The hydraulic system that powers the hydraulic cylinders uses water because the system is designed for a relatively low pressure at 15.5 MPa (2,250 psia) and relatively slow stroke speed at 20 in./min. Water does not degrade significantly at the radiation levels expected in the shutter drive access room and is desirable to control the amount of flammable hydraulic fluid near the target. The rod lockers located at the top of the drive rods are designed to clamp the drive rods when the hydraulic system pressure falls below set pressure. Thus, a shutter can be placed in the closed position (up) and the hydraulic system can be depressurized, and the shutter will remain in the closed position. Additionally, a manual safety pin can be used to lock the drive system in the closed position.

The independent indicator switches and indicator rod are shown in Figure 3.26. This equipment is part of the PPS (Section 3.3.8). It cannot control the shutters. The indicator rod has no loads on it other than the force of the position switch actuators. It is firmly fixed to the top of the shutter.

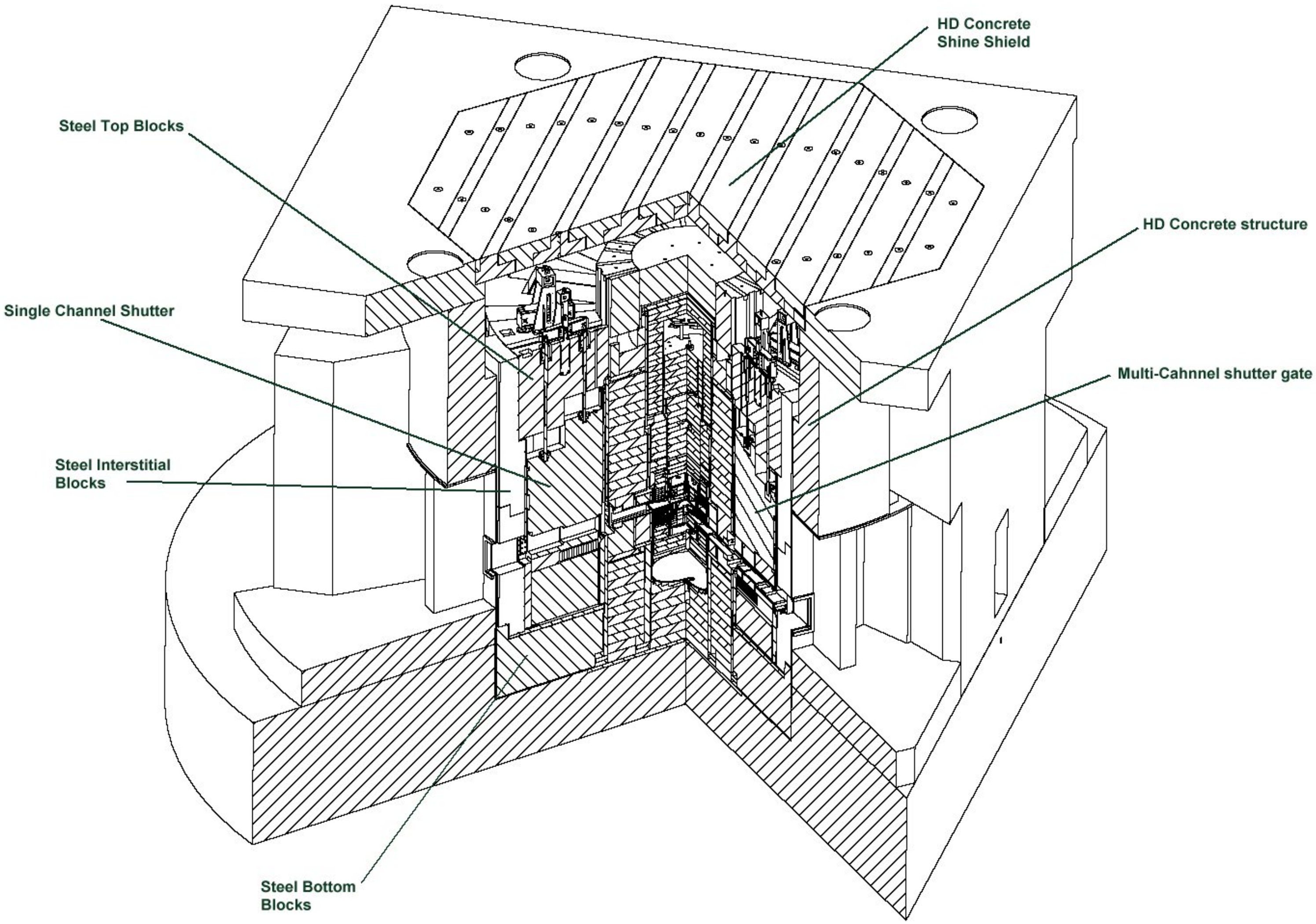


Figure 3.24. Location of shutters in context of monolith structure.

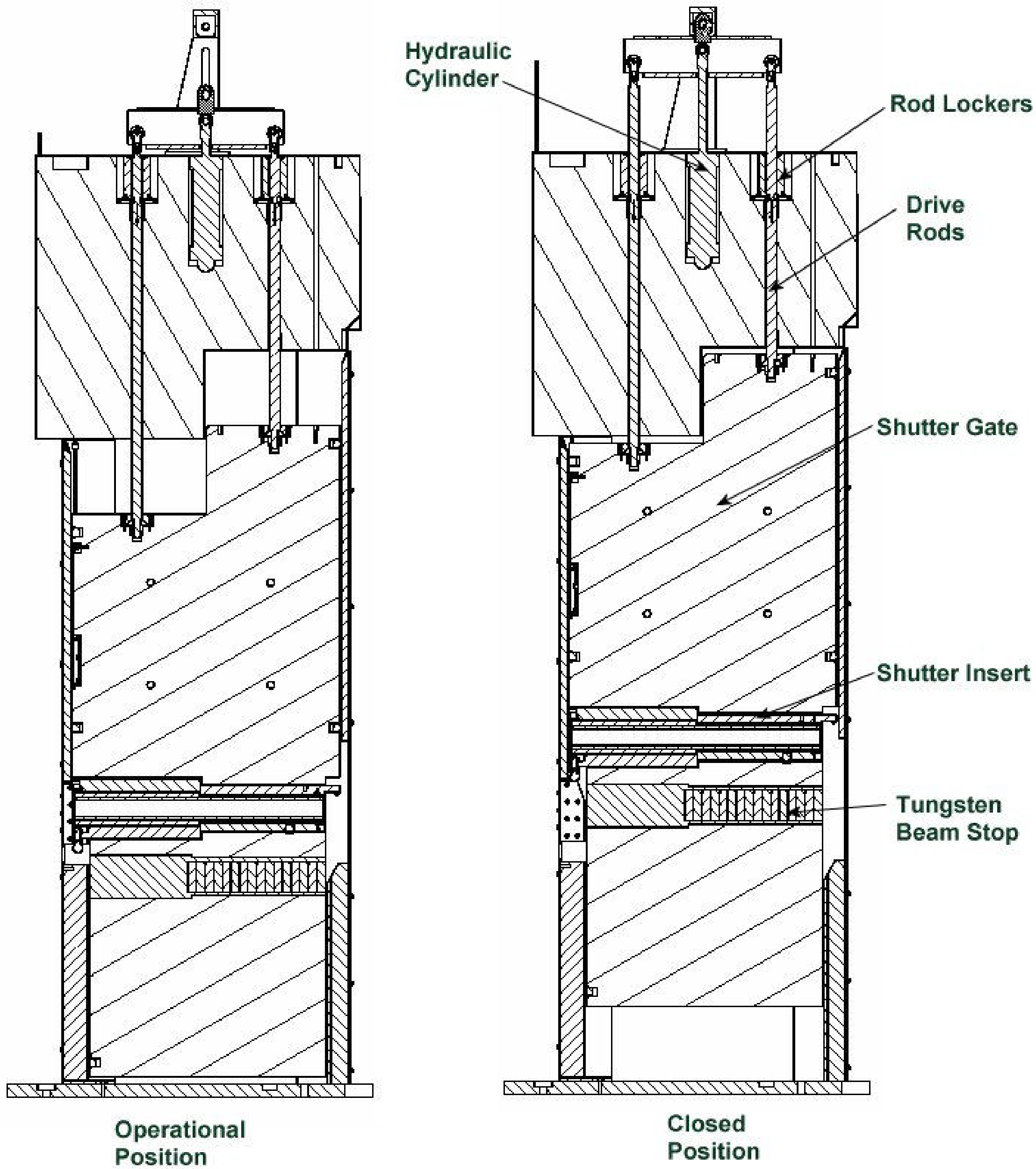


Figure 3.25. Typical shutter.

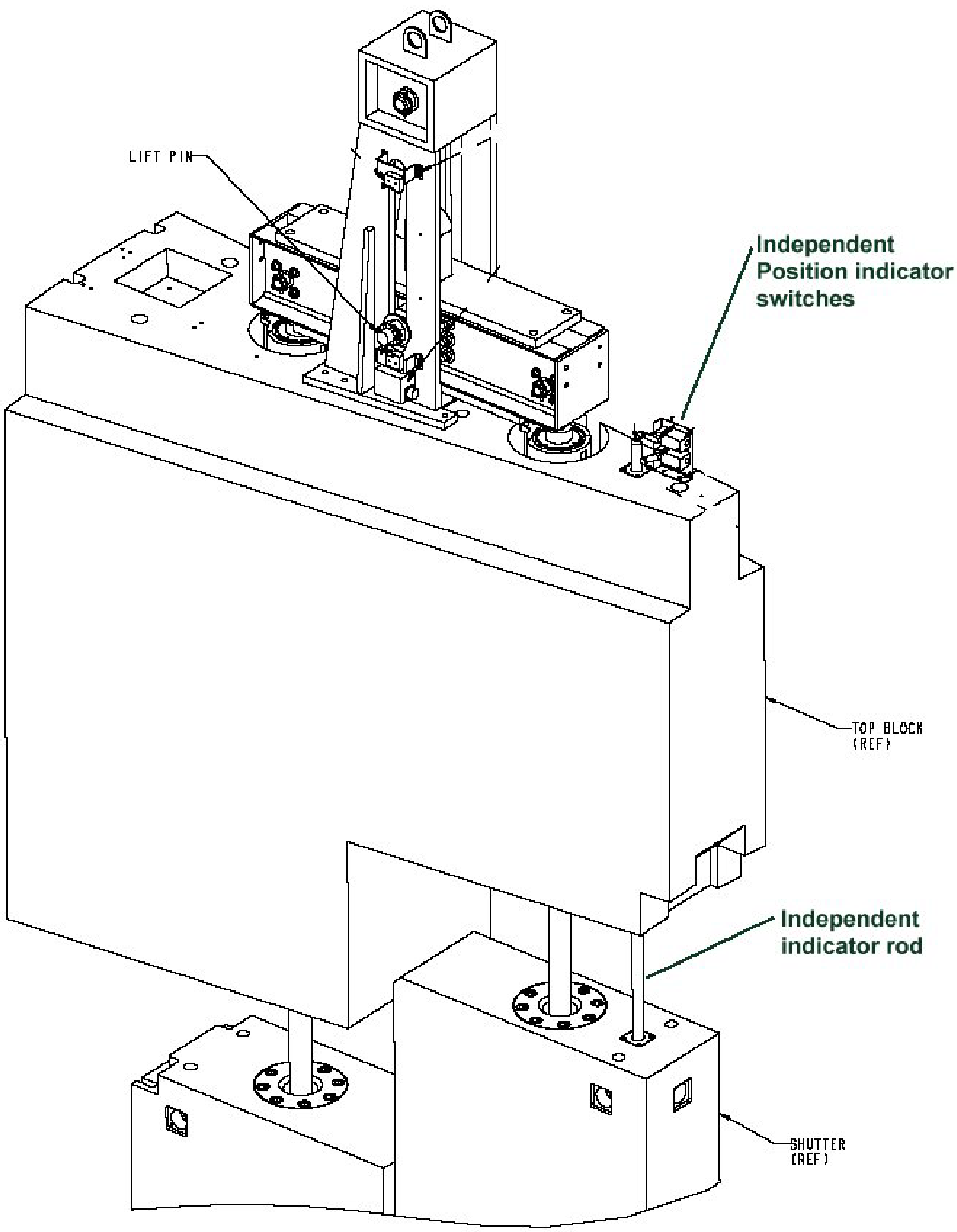


Figure 3.26. Shutter position indicators.

3.3.5 Service Bay and Remote Handling Systems

Figure 3.27 shows the location of different parts of the service bay complex. Workers routinely or periodically occupy the manipulator gallery, decontamination area, and the service gallery. Operations within the process and maintenance bays are designed to be accomplished remotely without personnel entry. Control of access to the transfer bay is described in Section 3.3.8.4.

3.3.5.1 Service Bay

The service bay provides confinement of mercury-related contamination, shielding for radiation associated with operation and maintenance of target systems, facilities and equipment to support remote handling, and facilities to accommodate transfer of components into and out of the bay. Remote handling and material transfer are addressed in Section 3.3.5.2.

The service bay structure includes the heavy concrete shielding provided by the approximately 40 in. thick walls, a stainless-steel liner inside the bay, and utilities. The structural envelope of the target service bay is equivalent to a 2 h fire barrier and is a CEC for fire events. The concrete wall between the instrument hall and the service and manipulator galleries is also a 2 h firewall. The fire barrier (shown in Figure 3.4) is seismically qualified to PC-3 (Section 3.2.5).

The service bay (Figure 3.27) consists of (1) the interconnected mercury process bay and maintenance bay and (2) the adjoining transfer bay separated from the maintenance bay by the steel intrabay shield doors.

The process bay contains the target mercury process loop components, including the power cables and the entire system for circulating and cooling the mercury—the pumps, piping and pipe support structures, vessels, heat exchanger, and local shielding. Water cooling is piped to the secondary side of the mercury heat exchanger. Piping and pipe support structures are on both sides of the bay penetrations that connect to the process equipment in the utility vault.

The process bay is designed to contain any spilled mercury associated with operations and maintenance of the target loop. In this area, the stainless-steel-lined concrete floor is sloped to direct spills to the collection basin, which can hold 100% of the mercury. The process bay houses the target, target plug/carriage assembly, and carriage rails for moving the target plug between its withdrawn position in the process bay and its operational position inserted into the monolith.

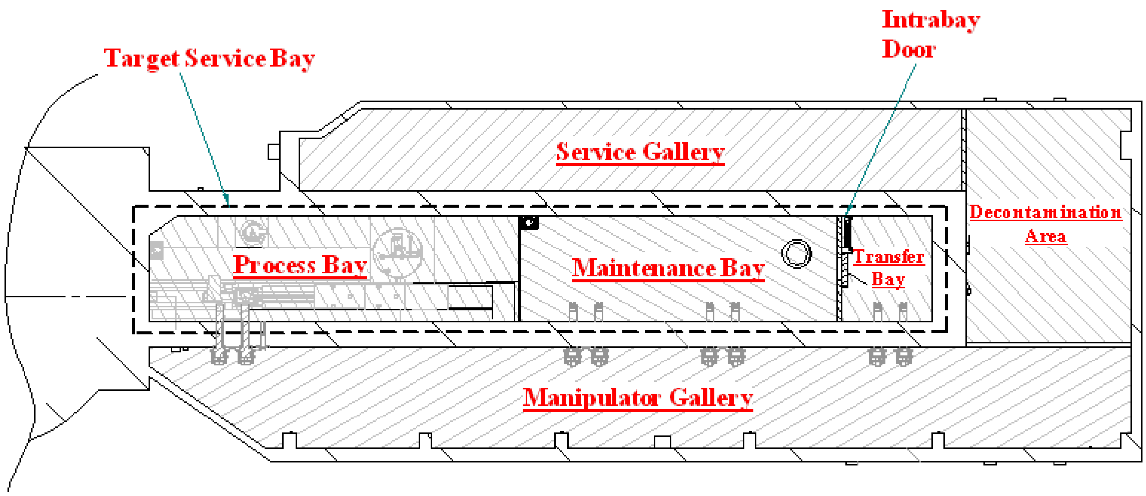


Figure 3.27. Location of functional areas of the service bay complex.

The maintenance bay contains remote handling equipment used to handle activated components. The area also provides space for holding activated components for decay before reuse or disposition.

The transfer bay is adjacent to the service bay but is separated by the two-part steel intrabay shielding door. The bottom part of the door slides horizontally to allow an access path between the service bay and the transfer bay. The upper part of the shielding door swings upward to allow the in-bay bridge crane and gantry servomanipulator to move to the transfer bay for maintenance and for general entry or exit of materials to or from the service bay. The intrabay doors are closed to provide shielding and physical separation between the transfer bay and remainder of the service bay to support personnel access via the transfer bay personnel door. The intrabay doors and transfer bay personnel door are monitored and interlocked by the transfer bay access control (TBAC) system (Section 3.3.8.4).

The service bay roof structure also serves as the high bay floor (Section 5 describes the high bay floor and interior service bay structure safety functions). Parts of the service bay roof are constructed of concrete T-beams that can be removed for major mercury loop component replacement or other vital activities.

Service bay penetrations for utilities (e.g., piping, electrical, helium, vacuum, nitrogen) include features such as remotely operable disconnect assemblies on the inside of the bay and flanged connections on the outside of the bay. Spare piping and electrical penetrations are installed through the shielded bulkheads to accommodate future needs. The service bay piping penetrations include remotely operable disconnect assemblies on the hot side and flanged connections on the cold side. Electrical feedthroughs include remotely operable disconnect assemblies on the hot side. In-bay lighting is remotely replaceable.

The bays have equipment transfer systems (referred to as pass-thru ports) that allow air lock transfers for small items, helping to keep worker exposure to radiation ALARA and to minimize the potential for spread of contamination. The bay manipulator workstations each have one lead glass shielding window that matches or exceeds the shielding provided by the bay shield walls and allows visual observation for remote operations while minimizing/eliminating exposure. The bay windows are designed for removal from the cold side for maintenance.

Three stainless-steel-lined floor sumps are provided to handle spillage, but none has a direct liquid-removal outlet from the service bay. Normally, capped lines in the service bay provide a connection to the LLLW system (Section 3.3.12). To remove liquid from the service bay, one of these drain lines must be remotely uncapped and connected to a sump pump. Liquid mercury and water could be spilled into one of the sumps (particularly the collection basin, which is the sump in the process bay). Therefore, the piping configuration and pump used are configured to prevent liquid mercury from being inadvertently discharged into the LLLW system. A continuous stainless-steel liner covers internal concrete surfaces of the service bay and is sealed to feedthroughs. The liner in the mercury process bay is sloped to direct spills toward the collection basin. Steel shielding plates cover the mercury components located in the process bay near the floor. These plates are sufficiently thick to provide radiation shielding. For example, a steel floor cover plate approximately 12 in. thick covers the heat exchanger pit.

3.3.5.2 Remote Handling and Material Transfer Systems

The service bay includes three specific areas, as illustrated in Figure 3.27: the process bay, the maintenance bay, and the transfer bay. Figure 3.28 shows a cut-away isometric view, and Figure 3.29 and Figure 3.30 depict cross-sectional views of the service bay from the side and the end.

The process bay holds the mercury process system, including related water cooling, instrument, and utility systems. The maintenance bay is designed to receive, size, package, and remove components from the service bay or monolith. This bay is also used for a variety of activities, including post-irradiation examination of components and packaging of waste. All operations in these two areas of the service bay are designed to be accomplished using remote handling equipment. Personnel will not enter these areas except under extenuating circumstances and only if the areas have been released for personnel entry under an approved radiological work permit (RWP) and job hazard analysis (JHA).

The transfer bay is separated from the higher radiation levels of the process and maintenance bays by the intrabay shielding door. Personnel may enter the transfer bay for contact maintenance or inspection of items such as the bridge crane or gantry servomanipulator. The sequence for such operations involves first opening the intrabay door, remotely moving the crane or other item into the transfer bay, closing the intrabay door, then opening the personnel access door for worker entry. An automatic interlock on the transfer bay personnel access door and intrabay doors ensures worker protection (Section 3.3.8.4).

The transfer bay is intended to be maintained as a relatively clean area for in-bay crane and servomanipulator hands-on maintenance. It is also a decontamination area for some of the materials (e.g., contact handled wastes, samples for analysis, tooling for repair) removed from the maintenance bay before they are removed from the bay environment. The flow of air is maintained from the transfer bay into the maintenance bay during all operational conditions to minimize airborne spread of contamination from the maintenance and process bays into the transfer bay.

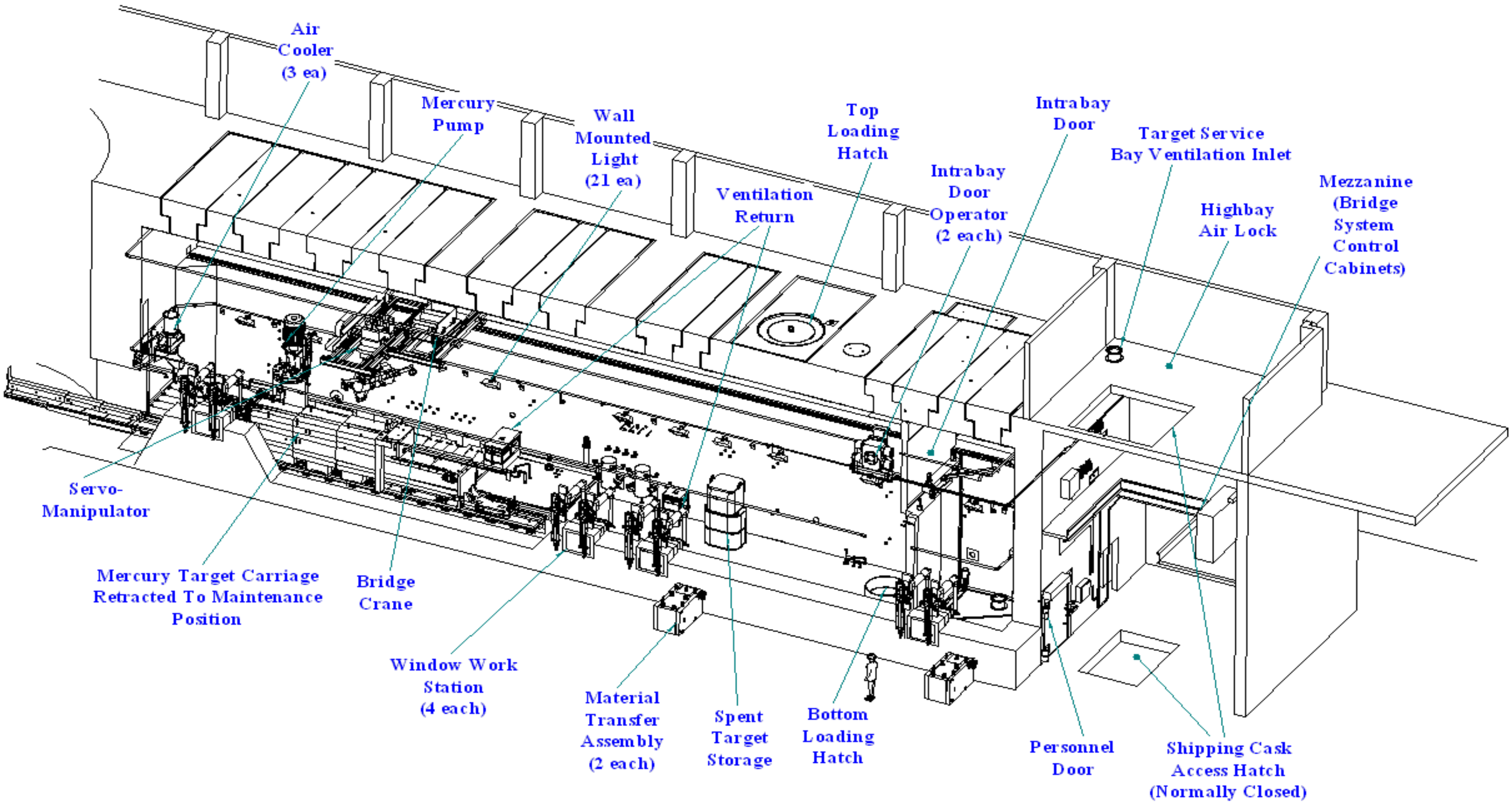


Figure 3.28. Cut-away view of target service bay from the southeast. The target carriage is shown in the withdrawn position.

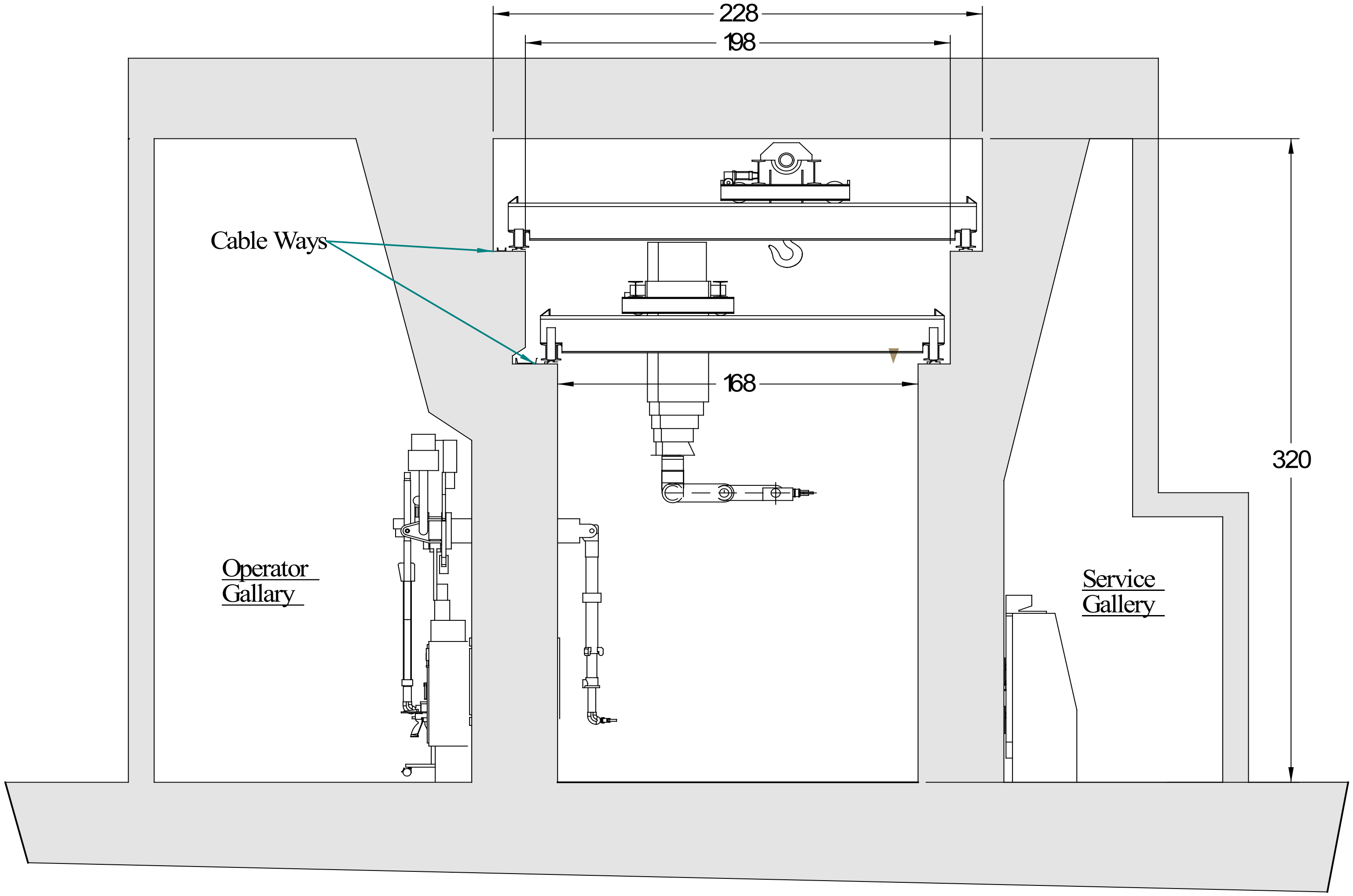


Figure 3.29. Cross-section view of target process bay and galleries.

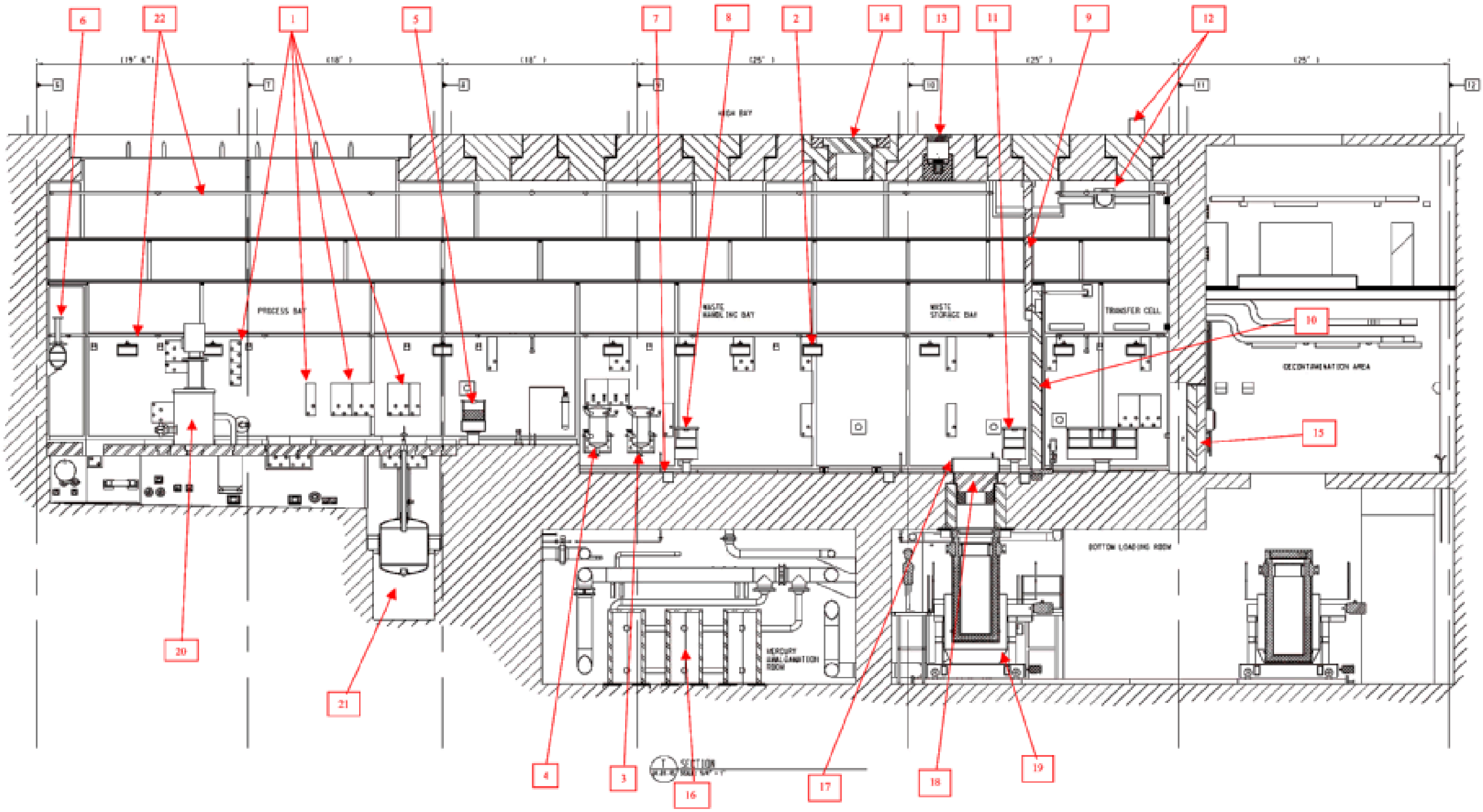


Figure 3.30. Target service bay cross-section view. Shielding beams above process bay shown removed, a very rare nonoperational configuration.

Key to numbered items in Figure 3.30:

The service bay is divided into the process bay and the maintenance bay. The transfer bay is part of the service bay, but it is labeled separately because of the intent to maintain it in a relatively contamination-free state to facilitate worker entry. The transfer bay is separated from the maintenance bay by movable steel shielding doors (Items 9 and 10 on the drawing and on the following list).

1. Penetration banks, typical of 50 within the service bay. Electrical and piping penetrations are both shown.
2. Light fixture, typical of multiple light fixtures within the target service bay.
3. Mercury condenser.
4. Not installed.
5. Process bay PCE system exhaust port (each exhaust port fixture holds a HEPA filter).
6. In-bay air cooler, typical of three within the service bay (service bay air recirculates through each water-cooled heat exchanger).
7. Floor sump, typical of three within the maintenance bay.
8. PCE system exhaust port, typical of two in maintenance bay.
9. Upper rotating intrabay shielding door (~8 in. thick steel).
10. Lower rolling intrabay shielding door (~11 in. thick steel).
11. PCE system exhaust port.
12. PCE system air intake for target service bay (air enters transfer bay first).
13. Upper intrabay shielding door latch.
14. Top-loading hatch.
15. Personnel door.
16. Ambient carbon adsorber.
17. Curb structure for bottom-loading port (prevents maximum credible water accumulation from leaking out of the service bay).
18. Bottom-loading port (shield plug is stored inside storage bay when removed for use of the port).
19. Shipping container cart for the bottom-loading port with TN-RAM cask.
20. Mercury pump.
21. Mercury storage tank and collection basin.
22. Water mist system spray distribution piping.

Remote Handling Systems

The service bay has two basic tooling systems: (1) four shield window work stations (WWSs), and (2) bridge-mounted tooling. Both are monitored and supported by a remote handling control room located outside the manipulator gallery.

The south wall of the service bay is equipped with four separate WWSs. Each WWS includes a leaded-glass shield window, a pair of through-the-wall manipulators, a video monitoring console, and a bank of utility services (compressed air, electrical, and high-pressure water). This wall is partially depicted in cutaway in Figure 3.28. The through-the-wall manipulators are operated by workers in the manipulator gallery. Two types of manipulators are installed: seven Central Research Laboratories (CRL) Model F (or equivalent) mechanically linked manipulator pairs and one CRL Model E. The manipulators are used for in-bay tasks requiring high dexterity such as handling wrenches or small fixtures, positioning bridge and servomanipulator-held components, and performing inspections with swipes or closed-circuit cameras. The maximum capacity of the manipulators is about 50 lb. The reach of the WWS manipulators is limited to the immediate vicinity of the stations.

Two overhead, in-bay, remote handling systems are provided: a 7.5 ton, in-bay bridge crane and a servomanipulator. The telerobotic servomanipulator system is mounted on the end of a telescopic boom mounted on a traversing bridge (gantry). The servomanipulator arms are rated for a maximum load of about 100 lb. The system is used throughout the bay to handle tools and to lift fixtures and other loads. The manipulator can be fitted with conventional parallel pinch grips, hooks, and tool-holding hands. The servomanipulator can travel vertically, allowing activities between floor level and approximately 13 ft above the bay floor throughout the full floor area of the bay.

The 7.5 ton overhead bridge crane is mounted above the servomanipulator to handle most loads inside the service bay. Generally, these components have lifting attachments designed to mate with the crane hook. Identified loads include shield blocks, used mercury process components, waste-handling containers with and without loads, spent target assemblies, proton beam window modules, and new and used filters. The vertical hook travel of the crane is approximately 27 ft. This range allows the crane to lower loads into a shielded cask docked at the bottom-loading hatch or to reach a load in the collection basin or storage tank pit. The crane is designed to reach below the service bay floor level for these required activities. The hook can approach to within about 12 in. of all the bay walls.

The remote handling control room houses the main control stations for the crane, servomanipulator, and associated video systems. Other systems operated from the control room include the intrabay door, air coolers, and lights. Because of the size of the service bay, video cameras are required to provide viewing for the operators. Video cameras are mounted on the walls and bridge systems throughout the target service bay. The cameras provide visibility throughout the bay and supplement direct viewing though the four shield windows. The video systems may also be operated and viewed from the four WWSs and the remote handling control room.

Material Transfer Systems

Four paths have been provided for loading materials into and out of the service bay. Each is designed to accommodate a specific range and type of component or tool.

Bottom-Loading Port: A bottom-loading port is mounted in the floor of the maintenance bay and is normally used to move wastes out of the bay via the cask cart room in the basement. Some contaminated and activated materials loaded out are packaged in liners before load-out into a waste liner located in the cask. Other waste materials too large to package are loaded directly into the waste liner. The bottom-loading port is designed for loading the TN-RAM (or equivalent) shielded shipping cask. The in-bay bridge crane is used to move items through the bottom-loading port into the cask.

Top-Loading Port: The top-loading port located in the ceiling of the maintenance bay is used to insert irradiated and potentially contaminated components such as a spent proton beam window or core vessel insert. These components are disassembled and packaged for loading into the TN-RAM shipping cask. The top-loading port is also used to insert some large, unirradiated items such as liners for target module storage and disposal.

Pass-Thru Ports: Two pass-thru ports—one at WWS 3 and one at WWS 4 (these are shown on Figure 3.28, labeled as “Material Transfer Assembly”)—allow small items to be transported into the service bay. Each pass-thru port is a shielded pass-through device mounted at floor level. A curb is built into the structure of the pass-thru port to make it impossible for the greatest water spill event to allow contaminated water to flow out of the service bay through the device.

Transfer Bay Personnel Door: New equipment enters the service bay primarily through the transfer bay. The transfer bay has a shielded personnel door at the instrument floor level that opens into the decontamination area, which functions as an air lock when the door is open. The ventilation system is designed to maintain a negative pressure in the service bay such that the air flows into the service bay with the personnel door open. New equipment to be loaded into the bay may be positioned inside the bay using a lift truck or transfer cart. A small sample cask may be positioned within the bay for loading out samples of the target module or other materials for analysis. Crane bridge and manipulator bridge maintenance occurs from a person-lift platform positioned in the transfer bay. Servomanipulator arm maintenance occurs from the transfer bay floor level. Operational procedures and a keyed interlock system prevent entry into the transfer bay when the intra-bay shielding door is open, and this process is backed up by a radiation monitor that is interlocked with the intra-bay door and with visual and audible alarms.

3.3.6 Cooling Water Loops, Vacuum, and Inert Gas Supply Systems

3.3.6.1 Water Cooling Systems

The target systems are cooled by four independent cooling loops. The cooling loops supply and control the distribution of cooling water to the various target components. The cooling loops remove approximately 2 MW of heat when the target is operating at 2 MW proton beam power. Three of the cooling loops use light water, and the fourth (loop 4, reflector cooling) may use light or heavy water. Heavy water is preferred because of its neutronics properties. Table 3.1 shows components and design heat loads for each loop. These values are intended for information only to provide context for the scope and scale of each of the four systems. The design requirements for the coolant loops are managed using SNS design processes.

The cooled components are in the service bay, core vessel, or monolith shielding area. Active components (e.g., pumps and motor operated valves) are generally located in the basement level utility vault. A similar design approach has been followed for each loop. Generic design information is presented to avoid repetition.

Table 3.1. Coolant loops and estimated 2 MW heat loads

Cooling water loop	Main component(s) served	Design basis heat load
1 (light water)	Mercury heat exchanger	1547 kW
2 (light water)	Proton beam window and target shroud	130 kW
3 (light water)	Moderators, shutters, and inserts	73 kW
4 (light or heavy water)	Reflector plugs	755 kW

A simplified block flow diagram representing the primary components in each cooling water loop is depicted in Figure 3.31. Components or features not included in or unique to individual loops are not identified. Light water loop 1 does not have a delay tank because the water is not activated.

Cooling loops 2, 3, and 4 each pass directly through intense neutron fields emanating from the target. Moreover, the full proton beam passes through loop 2 cooling water in the proton beam window and in the water-cooled shroud. The water and entrained impurities become significantly activated. These loops are equipped with delay tanks designed to provide the time needed to allow short-lived isotopes such as nitrogen-16 (7.1 s half-life) to decay. Cooling loop 1 is unique in that the water is not expected to be activated. Loop 1 circulates water through the mercury heat exchanger located in the service bay. Because the water of cooling loop 1 is removed from direct neutron exposure, it is not expected to have detectable activity.

During normal operation, water circulates in a closed loop. During shutdowns, the water may be drained to the drain tank. Each of the target cooling loops rejects heat to a secondary cooling water system through a heat exchanger. The loop 2 and 4 cooling systems are cooled by deionized water isolation loops, which are then cooled by the tower water system. Loop 3 is cooled by a deionized water isolation loop, which is cooled by the sensible chilled water system. This system is then cooled by the tower water system. The operating pressure of the cooling water loops 2, 3, and 4 is lower than the pressure in the deionized water isolation loops. At least two boundary failures would be required in loops 2, 3, and 4 to contaminate tower water with activated water. Loop 1 cooling water is not expected to be activated, and three boundary failures would be required to contaminate tower water with activated mercury. To reduce the potential for cross contamination during normal operations, differential operating pressures are maintained such that tower water is at a higher pressure in the heat exchangers where cross contamination could occur.

Delay tanks are employed in the return line of loops 2, 3, and 4 to facilitate localized decay of some of the short-lived water-activation products. The delay also reduces the potential for neutron activation of components located downstream in areas to which access must be provided for maintenance.

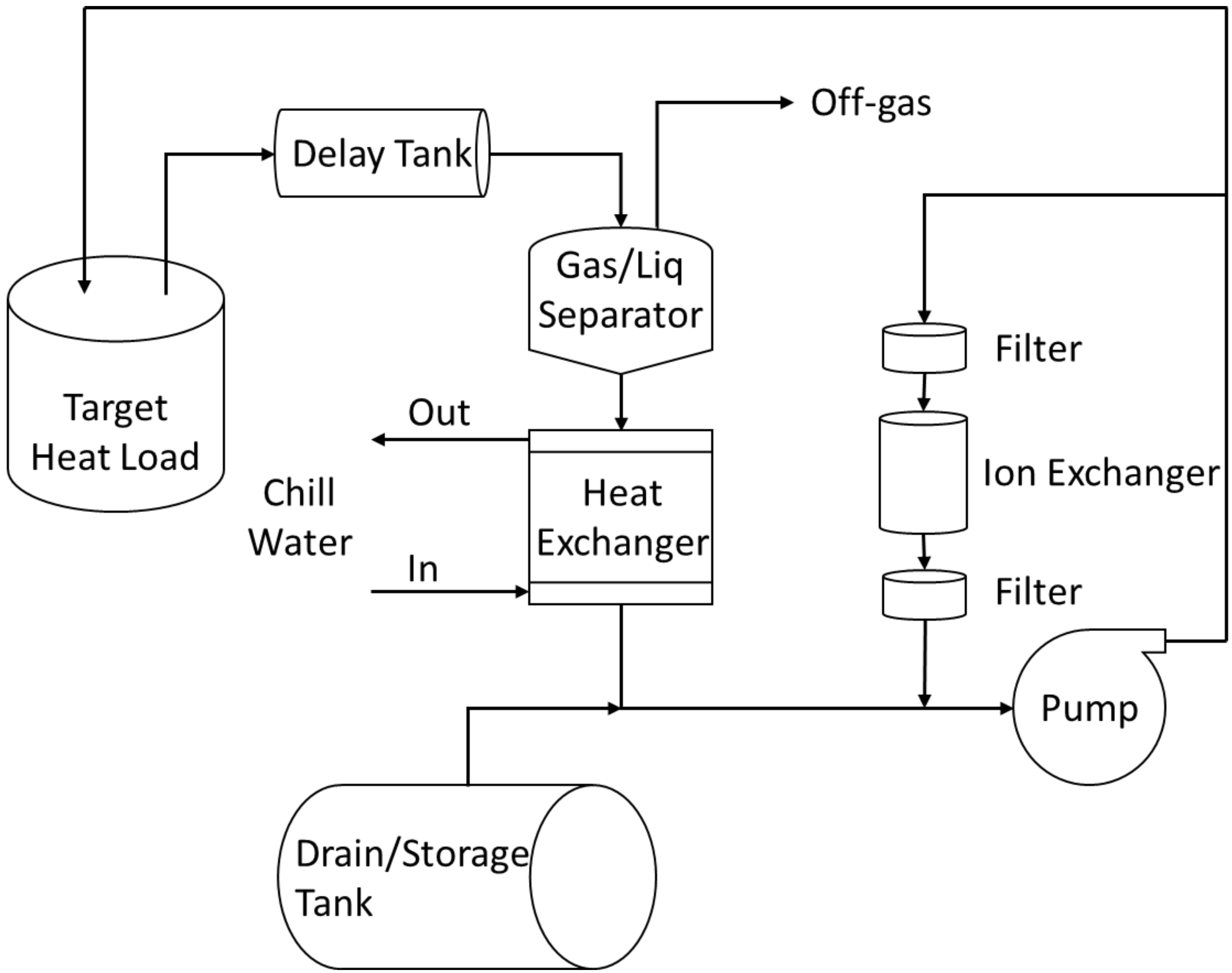


Figure 3.31. Generic schematic illustration of cooling loop components.

Localized shielding is provided, as required, to address the anticipated deposition of the longer-lived radionuclides (e.g., beryllium-7) in system components (e.g., heat exchangers, ion exchange units, filters).

Separation of gases generated in the water loops caused by spallation and the radiolytic decomposition of water is achieved in a gas/liquid separation tank that is located at the high point in the cooling loop. Inert purge gas is supplied as needed to maintain the long-term buildup of hydrogen or deuterium concentration in the gas/liquid separator tank headspace below the LFL. The separator tank head space vents to the hot off-gas (HOG) system. For loop 4, the purge gas may be recirculated to support recombination of deuterium into heavy water that can be recovered into loop 4.

Water quality is maintained by passing a slip stream from the total flow through particulate filters and ion-exchange columns. Based on periodic sample results, cooling loop water can be periodically discharged to the LLLW tanks to maintain loop tritium concentrations below desired levels. Spent ion-exchange column resin and filter subassemblies are replaced as needed based on differential pressure across the component, component dose rate, or water quality. Each cooling loop is instrumented to allow operators to monitor appropriate operational parameters.

The water in loop 1 is not activated by direct exposure to either protons or neutrons but could become contaminated with mercury if the heat exchanger leaks. To minimize the potential for cross contamination, the mercury/water heat exchanger design employs double-walled tubes (described in Section 3.3.1.3), and water loop 1 is normally maintained at a higher pressure than the mercury process loop.

Cooling loop 4 removes heat from the core vessel wall, proton beam window box, and the reflector plugs. Heavy water may be used to optimize neutron characteristics. Alternatively, light water may be used in cooling loop 4 without affecting safety.

Pipe leak and break accidents are considered in the hazard analysis (HA) for these systems (Section 4.3). Results indicate that cooling loops 2, 3, and 4 cannot threaten workers or exceed public evaluation guidelines for two primary reasons: (1) these systems operate at temperatures well below the boiling point of water, and (2) coolant radionuclide concentrations are kept relatively low by ion exchange and filtration. Results of the HA for cooling loop 1 indicate that unmitigated leakage of mercury into the loop 1 cooling water could threaten workers. Therefore, as discussed in Section 5.2.15, the robust double-walled design of the heat exchangers has been designated as a CEC.

3.3.6.2 Vacuum Systems

The vacuum systems serve numerous purposes. For example, the vacuum systems are used to remove air from target station components before they are backfilled with an inert gas and to activate seals employed between the core vessel and both the proton beam window and the target plug. Vacuum systems that evacuate the core vessel and mercury process equipment exhaust to the PCE system (Section 3.3.9).

3.3.6.3 Helium and Nitrogen Distribution

Helium is used as a cover gas in areas exposed to high-energy radiation to minimize the air activation (high-energy protons can also cause production of corrosive NO radicals in air) and for other purposes. Helium is also mixed into the flowing mercury to extend target lifetime. A gas distribution system is provided, as necessary, to facilitate its supply to its various uses.

Nitrogen is used to inert the cooling loop drain tank head space during loop fill operations, to maintain the gas concentrations in the cooling loop gas separator tanks below the LFLs, to perform seal leak checks, and to purge the core vessel vent line. A gas distribution system supplies the nitrogen for various uses.

3.3.7 Mercury Off-Gas Treatment System

Helium purge or other inert cover gas that contacts process mercury is routed through the MOTS, which is in the service bay and in the tritium removal room areas. It removes mercury, noble gases, iodine, and tritium from the target off-gas. The MOTS exhaust (i.e., gas not being recirculated) is routed directly to the HOG system, which is described in Section 3.3.9.3.

An elevated loop seal is provided at the inlet from the mercury process system to the MOTS to prevent liquid mercury from escaping into the MOTS as described in Section 5.2.15. This loop seal also provides protection in the case of mercury level transients resulting from gas expansion and venting from the mercury process loop as described in Section 5.2.20. Thus, the MOTS is designed only to cope with mercury vapor or aerosol in relatively small quantities because larger quantities of liquid mercury are not expected to reach the system.

The MOTS consists of the following elements (Figure 3.32 for schematic diagram):

1. A mercury vapor condenser,
2. Two gold amalgamation adsorbers in series,
3. Two molecular sieve trains in parallel (only one in service at a time),
4. Two charcoal delay beds (normally in series),
5. Two CuO tritium oxidation reactors in parallel (only one in service at a time),
6. Two molecular sieve trains in parallel (only one in service at a time),
7. Three cryogenically cooled charcoal adsorbers in parallel (only one in service at a time).

The mercury vapor condenser is located on the north wall in the service bay. The system includes two gold adsorbers, one located in the service bay and the other in the gold amalgamation room (GAR) (Room TA-B149, Figure 3.32). The first pair of molecular sieve trains and the two charcoal delay beds are also located in the GAR. The CuO reactors are located in the MOTS room with the second pair of molecular sieve trains and the three cryogenic charcoal adsorbers.

The in-line mercury vapor condenser reduces the amount of mercury vapor entrained in the target system off-gas stream. Refrigerant supplied by a chiller in the service gallery cools the gas flow to condense mercury vapors. Condensed mercury droplets deposit at the bottom of the condenser and are ultimately drained for return to the mercury system.

The gold adsorbers (Al_2O_3 pellets containing a gold impregnate) are sized to hold the quantity of mercury that would exit into the MOTS during the anticipated operational period of 5,000 h/year. The design assumption was 50 g of mercury per year, but experience has shown that with the mercury condenser in service actual loading is lower. These adsorbers capture any remaining mercury vapor or aerosol after the mercury condenser.

As part of the PPU project, a pair of molecular sieve trains has been incorporated into the MOTS flow path downstream of the gold adsorbers to ensure the effluent is dry before going into the ambient carbon adsorbers. The carbon media is highly hydrophilic, and water uptake into the media can dramatically reduce the delay time provided for noble gases. During initial operations, the mercury loop was dry, and the molecular sieves were included primarily to capture oxidized hydrogen isotopes. However, evidence of moisture in the effluent has been observed, presumed to originate from sources outside the loop, necessitating the additional molecular sieve trains. Two molecular sieve trains are provided with two molecular sieve beds in each train. One train is in service at a time. The molecular sieve beds are periodically regenerated using heated, dry nitrogen to transport the moisture from the sieve beds to a fifth bed, the iodine abatement adsorber, with activated carbon media to capture iodine produced by xenon decay.

Two room-temperature charcoal delay beds have been included in the system to reduce downstream radionuclide activity via decay. This capability was required to accommodate the increase in MOTS activity resulting from target gas injection. The beds delay the progress of noble gas isotopes within the heavily shielded GAR to allow short-lived isotope decay, reducing dose rates in less shielded, downstream areas. The carbon delay beds operate at room temperature and are designed to provide delay of noble gases, particularly krypton and xenon, with delay time varying according to the different sorption coefficients of the gas species and the flow rate. The delay beds are shielded to reduce area radiation levels in the GAR in support of ALARA considerations for personnel entering the GAR during or following operations.

The CuO beds are the next components in the system. Only one bed is in service at a time. It functions to oxidize tritium and other hydrogen isotopes in the gas stream to create water. It operates at around 195°C. The CuO supplies oxygen to react with any hydrogen present, including tritium, and becomes reduced to copper metal in the process. Therefore, it requires periodic regeneration, which is expected to be performed during shutdowns for target module maintenance, when the off-gas system is not operating. Because mercury is known to decrease the effectiveness of the CuO catalyst, monitoring the bed condition and periodically replacing the bed are required. The bed is designed for periodic catalyst replacement. Loss of catalyst activity should be detectable by gamma spectroscopy identification of mercury (or daughter isotopes) on the CuO bed. Elemental tritium that penetrates the CuO and molecular sieve bed system should be mostly trapped in the carbon bed. Because the quantity of hydrogen isotopes is expected to be small, capacity loss should not be an issue until the bed is completely deactivated.

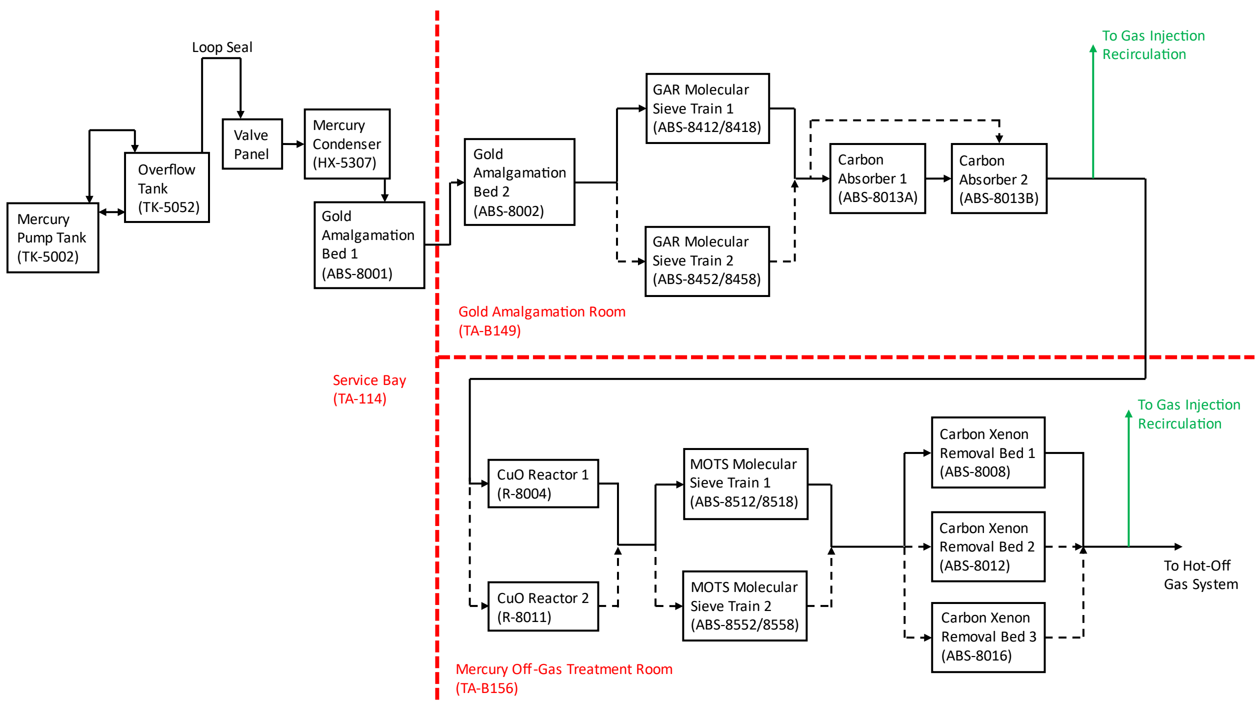


Figure 3.32. Mercury off-gas treatment system schematic.

Downstream of the CuO bed is a set of desiccant beds filled with a molecular sieve media. The hydrogen oxides are removed in this bed, and the bed is heated periodically to remove the moisture. The molecular sieve beds are regenerated using heated, dry nitrogen to transport the moisture from the sieve beds to a fifth bed, the iodine abatement adsorber, with activated carbon media to capture iodine produced by xenon decay. Neutronics calculations indicate as much as 2,000 Ci of tritium is expected to be produced by spallation of mercury during a 3-month period at 2 MW full beam power. However, experience has shown that significantly less tritium accumulates in MOTS. The source of discrepancy is unclear and may be associated with tritium retention within the loop or perhaps the conservatism within the calculation of the predicted values.

The last components in the treatment system are three cryogenically cooled charcoal beds in a parallel arrangement. Only one is in service at a time. The two units preferred for operations are cooled by helium compressor chillers. The backup unit is cooled by liquid nitrogen supplied by portable dewars. These components are present to remove noble gas spallation products (principally krypton and xenon) from the off-gas stream. The beds require shielding but should never require replacement. They are regenerated as needed by vacuum pumping with the exhaust directed to the iodine abatement adsorber. The charcoal bed also removes residual mercury and tritium from the gas stream.

Some of the components in the MOTS are designed to retain radionuclides, leading to elevated radiation. Each component is evaluated for a conservative radionuclide content and shielded appropriately to support ALARA goals. The design and review process for shielding combined with the work practices of the Radiological Protection program ensures these hazards are safely managed.

3.3.7.1 Gas Recirculation System

The gas recirculation system reduces helium usage for target gas injection by collecting gas from the MOTS flow, typically >99% helium, and recycling it back into the target gas injection supply. This system consists of four helium compressors and associated items installed in the carbon adsorber room (TA-B150). Two trains, each with one operating and one spare compressor, are used. One train provides helium to the bubbler flow supply, and the other provides the wall flow supply. Each train is designed to deliver a maximum flow rate of 10 SLPM. Two suction locations are provided for each train, one downstream of the ambient carbon adsorber beds in the GAR and one downstream of the cryogenic carbon adsorbers in the MOTS room.

3.3.8 Protection Systems and Integrated Control System

Monitoring and control of the mercury process system and related support systems are accomplished by three systems: the TPS, the target service bay differential pressure monitoring system (SBDPMS), and the target control system that is part of the integrated control system (ICS). Access to the transfer bay is controlled by the TBAC system. The PPS also fills protective roles in the target facility, which collectively make up the target segment of the PPS. Each neutron instrument also has a tailored PPS module that interfaces with the target PPS. These modules are collectively referred to as the instrument PPS.

The ICS is the non-safety system that provides normal controls and equipment protection functions for the target and is integrated with the SNS facility ICS. The facility ICS is based on the EPICS standard architecture. This system has a standards-based architecture that uses Linux, X-Windows, Ethernet, TCP/IP, and VME for building scalable control systems and integrating the control and display of the control and monitoring systems.

The TPS and SBDPMS, discussed in Section 3.3.8.2, and the TBAC, discussed in Section 3.3.8.4, are credited controls. The TPS is the CEC that trips the proton beam when necessary to prevent it from overheating the mercury. The SBDPMS provides a credited alarm on inadequate service bay negative pressure. The TBAC prevents personnel entry into the transfer bay unless the intrabay doors are closed. The target PPS and the instrument PPS are subsystems of the PPS that provide credited interlock and access control functions in the target and instrument areas.

3.3.8.1 Integrated Control System

The components of the ICS that are in the target controls include programmable logic controllers (PLCs), I/O modules that monitor and control the target processes, input/output controllers (IOCs), and equipment protection cards located in an IOC chassis and dedicated equipment-protection PLC. Networks accepted as standards for the SNS project connect this equipment. The PLCs and the associated I/O modules interface to the process instruments in the target. PLCs are highly reliable, industrial-quality equipment that provide direct control of the target systems. Remote I/O modules located in the field near the process instruments communicate over high-performance networks to the PLC processors located in the control room. The target controls are integrated into the ICS by a network that communicates from the PLCs to the IOCs. The IOCs place the target controls data into the EPICS database, which is available to the ICS in the control room, or into other locations where access to the database is granted. The EPICS database is a facility-wide database system that contains the control data from all the SNS control systems. The EPICS control system's capability to integrates large numbers of control systems and parameters has been proven by its performance at SNS and other accelerators. The ICS and EPICS perform a wide variety of accelerator information and control functions.

The IOCs contain the EPICS database that integrates the entire SNS control system. The IOCs in the target primarily interface between the PLCs, which control and interlock the target and the operator displays. The IOCs communicate data for operator display and setpoints for PLC control, but the target IOCs do not contain significant control algorithms or interlocks. Operators in the CCR, the TCR, or other locations where the EPICS network is available can access the parts of the database stored in the IOCs over a high-speed Ethernet network. The operator monitors and controls the target using graphical displays in the CCR or the TCR by receiving PLC data and sending setpoints to the target PLCs. Each IOC contains a processor, network interfaces, and some I/O modules.

The machine protection system (MPS) provides non-safety protection of equipment; however, the MPS contributes to overall safety by tripping the proton beam when systems are detected operating outside desired ranges. Target systems I&C variables dedicated to protection of target equipment are functionally a major arm of the overall accelerator MPS. They have a limited interface such that the target systems I&C detect conditions and decide when proton beam trip is needed, and the accelerator MPS actuates the trip. This process is illustrated schematically in Figure 3.33. All target equipment protection function inputs to both the accelerator MPS fast-protect system and selected mercury loop parameters input to the accelerator MPS PLC system. This approach provides redundancy and diversity for selected mercury loop parameters because both MPS systems can trip the proton beam.

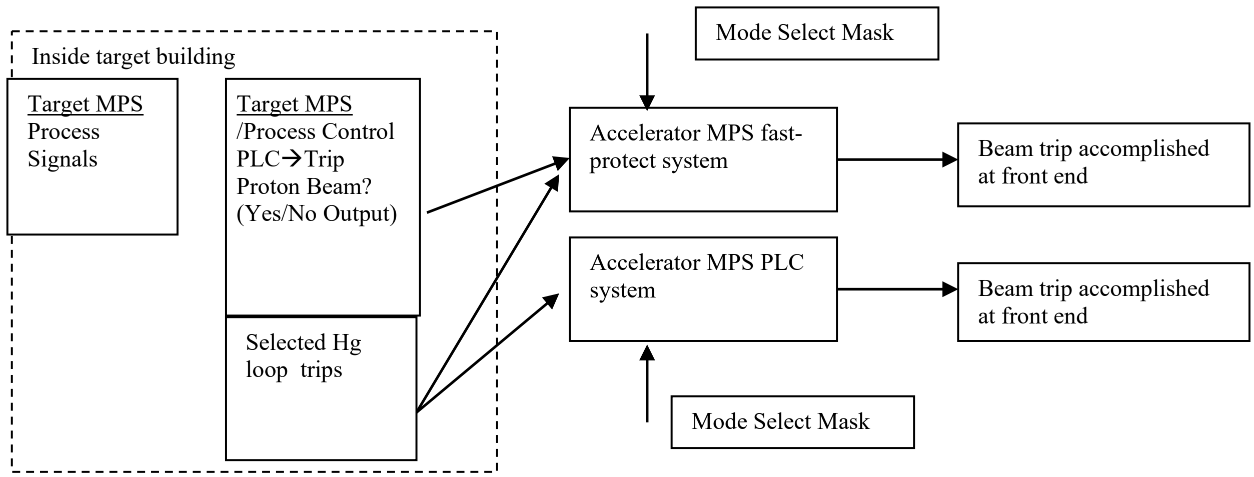


Figure 3.33. Machine protection system flow diagram.

The MPS fast-protect system (i.e., the overall accelerator MPS fast-protect function) protects equipment ranging from the ion source in the front end to the target equipment in the target building. Any one of the cards can trip the proton beam with a fail-safe signal (i.e., loss of signal from a card generates a beam trip). These cards provide a reliable, but non-safety, trip of the beam for conditions that could lead to an accident requiring safety system action. These utility cards include trip-masking capability that is used to bypass a card if its function is not required; for example, during beam testing in the linac when the target is not operating. The target system fast-protect system cards do not interface with the TPS, but the equipment protection function provides control system actuation of a beam trip to avoid conditions that could lead to an accident in the target. The accelerator PLC-based MPS function is independent of the fast-protect function but operates in an analogous manner to the above description for the fast-protect function.

EPICS provides alarm handling and data archiving. Alarms are displayed on the operator workstation monitors. Audible and visual alarms are used as needed to elicit the desired operator responses. EPICS receives the measured and computed parameters from the PLCs to process for alarms. Each database record includes alarm information that is used to display on an alarm screen. The alarm handler is organized in a hierarchical structure to simplify the display, and the database permits assigning alarm priority. Much of the data input to EPICS and the alarms generated by EPICS are recorded to file by a data archiver.

The target includes some instruments that are safety-related inputs to the PPS. These instruments, which include shutter position limit switches (input to instrument PPS) and target plug limit switches (input to target PPS), meet the design and qualification requirements of the PPS and are described in Section 3.3.8.3.

The CCR contains multiple workstations and consoles that can be used to control the target during normal operation, and it has hardwired TPS indicators and manual shutdown switches. The TCR is in the basement of the target building. The operators normally use the TCR, especially during startup of the target systems and during support activities such as target replacement, system maintenance, and scheduled activities for the target equipment.

Process indicators and TPS manual shutdown switches are in the CCR in the CLO and in the TCR. The operators in the CCR and the TCR can shut down the proton beam using EPICS or the TPS manual shutdown switches located there.

3.3.8.2 Target Protection System and Service Bay Differential Pressure Monitoring System

The TPS is a high-integrity system that employs highly reliable analog components to automatically initiate cutoff of the proton beam when any one of the following three predetermined conditions is met:

- High mercury temperature, based on sensing mercury temperature at the heat exchanger outlet.
- Low mercury flow, based on sensing pump differential pressure.
- Low mercury flow, based on low electrical power usage by mercury circulation pump. The power measurement is based on sensing current and voltage in the motor controller input and output cables.

The TPS employs two independent channels with 1-of-2 trip logic. Design features such as channel separation and the 1-of-2 logic render the TPS single-failure proof. Because the TPS is a CEC, Section 5 contains a more detailed description and evaluation.

The SBDPMS monitors confinement exhaust in the service bay and initiates visual and audible alarms in adjacent spaces if confinement exhaust is compromised. This system protects personnel in these protected spaces from the potentially hazardous atmosphere of the service bay. This alarm function is credited, as explained in Section 5.

3.3.8.3 Target and Instrument Personnel Protection Systems

The target PPS and instrument PPS are subsystems of the PPS associated with the target and the neutron instruments. These CECs are designed, procured, installed, and tested according to rigorous standards and procedures to provide a high level of system performance, as expected and achieved with the PPS in the SNS proton facilities. Essential parts of the PPS are designated quality assurance level 1 and are configuration controlled in accordance with SNS procedures. As shown in Figure 3.34, the scope of the PPS encompasses both the proton and neutron facilities. The FSAD-PF [1] contains further description of the entire PPS.

Target Personnel Protection System

Overview

The primary function of the target PPS is to prevent beam transport into the target building when the building is not ready to receive beam. The target PPS is a PLC-based control system similar in design to the proton facilities PPS segments. It monitors the following areas in the target building:

- PPS-controlled areas,
- Primary shutters,
- Interlocked radiation monitors (IRMs) located in the target building,
- PPS equipment installed on the individual instruments,
- Target cart position.

PPS-controlled areas are areas in the target building where personnel must be excluded prior to allowing beam operation. These include the basement utility vault, the shutter drive equipment room (target PPS-controlled areas) and certain areas associated with instruments (e.g., caves and detector enclosures). Target PPS-controlled areas are secured to allow beam to the target building.

The primary shutters are located within the monolith. When closed they confine the neutron beam within monolith. They are redundantly monitored by the PPS with open and closed limit switches. The PPS provides open and close commands to the shutter control system (a separate non-safety system) to allow staff and users to operate the shutters unless the shutter is placed in maintenance mode which allows the shutter to be controlled from a maintenance panel in the west (RTBT) side of the high bay. The secondary shutters are downstream, between the monolith and the instrument enclosure. When closed they prevent the neutron beam from reaching the instrument enclosure.

IRMs are used in the target building to measure radiation from prompt sources. If abnormal radiation levels are detected, then the IRM signal will trip the beam at the front end. IRMs may also be applied to selected instruments, based on the HE process for that instrument. The FSAD-PF [1] contains further description of an IRM.

The instrument PPS consists of individual PPS packages installed on each instrument. The instrument PPS monitors the status of PPS-controlled area(s) for each instrument. If an unsafe condition occurs, then the instrument PPS can directly control the secondary shutter when provided. If the instrument PPS cannot place the instrument in a safe state, then the instrument PPS will provide a fault signal to the target PPS that will close the primary shutter or terminate the proton beam if necessary.

Figure 3.34. Overall scope of the personnel protection system.

If beam were transported to the target building with the target cart withdrawn, extremely high radiation levels would be present in occupied areas of the target building. For this reason, the target PPS monitors the target cart position. Whenever the target cart is not in position, the PPS requires that two critical devices be used to prevent beam transport to the target building.

Safety Functions

The PPS is responsible for the following safety functions:

- Prevent beam operation in PPS-controlled areas not cleared of personnel (beam containment).
- Shut off beam if personnel enter a PPS-controlled area.
- Shut off beam if target plug is not in position to receive beam.
- Shut off beam if equipment faults cause radiation levels to increase over acceptable levels.
- Support administrative actions to clear personnel from target PPS-controlled areas before beam operation.
- Warn personnel located in PPS-controlled areas before beam operation.

The PPS is designed to require a manual reset any time the PPS takes an automatic action such as shutting off the beam. Administrative procedures specify steps to take following an automatic PPS action, including determining the reason for the trip and required approvals.

Operating Modes

The target PPS is designed to allow the target segment to be in one of three modes, as listed in Table 3.2.

Table 3.2. Target PPS operating modes

Mode	Features
Beam prohibited	No beam allowed to the target building. Personnel access is allowed to PPS-controlled areas in the target building.
Power permit	No beam allowed to the target building owing to Chipmunk trip or fault. Manual reset required to reestablish beam
Beam permit	Beam allowed to target building. Personnel access not allowed to PPS-controlled areas.

Beam Containment

The PPS uses several methods to prevent beam transport to the target building and beamlines. These methods are listed in Table 3.3.

Table 3.3. Beam-containment methods

Operating condition	Beam containment mechanisms
Beam prohibited	RTBT.DH13
Target cart rolled back	RTBT.DH13 and ring extraction septum
Instrument PPS-controlled areas not in beam permit	Primary and/or secondary shutters
All shielding normal Beam Permit mode Instrument PPS no faults	Mercury target

System Architecture

The PPS architecture is described in the FSAD-PF [1]. Signals are communicated between the target PPS equipment and the accelerator facility segments via hardwired I/O signals. These signals are designed to be fail-safe. In the event of a power loss, broken wire, or out-of-range signal, the equipment will go to a safe condition. The signals between the target PPS and instrument PPS are communicated in a similar fashion.

Control of safety-related keys (e.g., TPS and PPS) is the responsibility of the operations and instrument hall coordinator teams. These keys include those required to enter target PPS and instrument PPS controlled areas and keys for entry into the transfer bay. Key accountability, custody, and custody transfer are tracked via logbook or entries into the key control E-log. Keys not in use are placed in either a lock box controlled by the on-duty operations shift technician (OST) or in a lock box controlled by the instrument hall coordinator. The key codes for these spares are unique (not used by an existing key). If a trapped key is lost, the cylinder will be replaced with a uniquely coded spare. The old code will be marked as lost in the tracking database and will not be reused (the type of trapped key used by SNS has 625 unique codes).

Critical Devices/Beam Cutoff

When a fault condition is detected or when the target building is not ready to receive beam, the target PPS works in conjunction with the PPS to prevent beam transport to the building. Three methods prevent beam transport to the target building:

Beam Production

Beam production is inhibited by disabling the radio frequency to the radio frequency quadrupole and the 65 kV power supply or the plasma radio frequency supply (FSAD-PF [1], Section 3.2.4).

Ring Extraction Septum

The extraction septum in the ring beamline extracts beam from the ring beamline for transport to the RTBT beamline. When this magnet is disabled, beam cannot be extracted from the ring.

Ring-to-Beam Transport Dipole DH13

A dipole magnet in the RTBT directs the beam in the RTBT to the target building when enabled. When the magnet is disabled, beam is transported to the RTBT extraction dump.

Interlocked Area Radiation Monitors

IRMs, typically Fermilab-style Chipmunks or equivalent, are provided to monitor prompt radiation levels in occupied areas. This function is preventive and distinct from personal dosimetry. IRMs are used to automatically shut off the beam if significantly elevated radiation levels inconsistent with the area classification are detected. IRMs used for beam cutoff are part of the PPS; therefore, they are subject to the strict configuration control and other administrative procedures that govern the implementation and maintenance of the PPS.

IRMs are in the target building, as specified by the radiation safety officer (RSO). IRMs may be applied to detect prompt radiation caused by a proton beam control fault upstream of the target or to detect radiation from an improperly shielded beamline. In the case of a Fermilab-style Chipmunk, two digital outputs are used by the PPS as well as an internally generated trip. A 100 mrem/h fixed alarm output is used to stop beam production immediately when the radiation field exceeds 100 mrem/h. Chipmunk internal diagnostics monitor for a lack of pulse outputs and out-of-tolerance critical parameters (such as ionization chamber high voltage). If these diagnostics detect an internal failure of the Chipmunk, then a digital output stops beam production. The PPS also monitors the pulsed output of the Chipmunk to calculate a 15 min rolling average and will stop beam production if the 15 min rolling average exceeds 5 mrem/h.

The radiation levels measured by the IRMs are recorded by the main archive engine to allow operations personnel to trend radiation levels in occupied areas and retrieve data. A separate archive engine is maintained to back up IRM data in the event the main archiver malfunctions.

Target Personnel Protection System Controlled Areas

Two areas in the target building—the basement utility vault and the shutter drive equipment room—have PPS access controls. Shielding calculations and field measurements indicate that the radiation hazards in these areas are below those requiring credited controls (Section 4.3). Nevertheless, the basement utility vault and the shutter drive equipment room are equipped with PPS-controlled access systems. Any decision to change the PPS-access control features of these areas requires approval by the SNS Radiation Safety Committee.

<u>Personnel Protection System Access Control for the Basement Utility Vaults</u>

The basement utility vault contains equipment associated with cooling the mercury target and internals such as the target shroud, moderators, and core vessel internals. Cooling water in these systems becomes activated, leading to elevated radiation levels.

Access to the vault is gained via a single PPS entry door on the southeast side. This door is locked by the PPS. Access is controlled by a badge reader system. The door is only unlocked when an authorized proximity card is presented and when the vault is in restricted-access or sweep modes (provisions are made for emergency entry and exit through this door). The door is redundantly monitored by position switches. A local panel indicates status and facilitates a sweep of the vault. The vault has three modes: restricted access, sweep, and beam permit. A trapped key is used to drop the vault to restricted access. This key is obtained via key exchange with the controls for RTBT dipole magnet RTBT.DH13. The magnet must be off before entry is allowed into the vault (unless bypassed). Beam shutdown stations are located inside the vault area. These devices provide a local visual indication of the vault status and an audible warning before the vault goes into beam permit mode.

The vault has an emergency exit door on the northeast side. This door is locked using a conventional lock but is monitored by the PPS via redundant position switches. A tricolor stack light outside the door indicates the vault status.

A bypass function is provided via trapped key operation to allow access to the vault when the target is in beam permit mode. This function allows access during low-power operations when radiation levels from water activation are low. This bypass is controlled administratively.

Personnel Protection System Access Control for the Shutter Drive Equipment Room

The shutter drive equipment room contains equipment associated with the primary shutter hydraulic systems. Access to the room is gained via a single shielded door controlled by the PPS. The shielding door is designed so that the door is only locked in beam-permit mode. The door is redundantly monitored by position switches. A local panel is provided to indicate status and facilitate a sweep of the room. The room has three modes: access, sweep, and beam permit. A trapped key is used to drop the room to access mode. This key is obtained via key exchange with the controls for RTBT dipole magnet RTBT.DH13. The magnet must be off before entry is allowed into the room. A single beam shutdown station is located inside the room opposite the door. This device provides a local visual indication of the room status and an audible warning before the area is placed in beam permit mode.

Primary Shutters

Position Monitoring

The target PPS monitors the position of each primary shutter using redundant open and closed limit switches dedicated to the PPS (additional switches are provided for the shutter control system). These switches are actuated via diverse means. One set of switches is actuated by the hydraulic lift mechanism, and a redundant set is actuated by a metal rod tied directly to the top of the shutter.

Control cable from the limit switches to the PPS PLC interface cabinet is in troughs located in the shielding blocks (to allow the cabling to be moved when shutter maintenance removal or installation is required). Because this type of installation increases the probability of cable damage, the normally open and normally closed limit switch contacts are monitored. This process protects the PPS function from cable damage resulting in either a severed cable (open circuit) or crushed cable (short circuit).

The target PPS monitors these switches to ensure proper operation of the primary shutters. A shutter fault condition is declared upon detection of the following conditions, either of which could indicate a faulty limit switch:

- Shutter open and closed at the same time,
- Shutter neither open nor closed after a time limit.

Primary shutter position is used in conjunction with the instrument PPS to determine whether beam is allowed to the target building. If the instrument PPS for a specific instrument signals for the target PPS to close the primary shutter for that instrument and one of the two shutter position faults listed above occurred, then the target PPS would initiate proton beam trip.

Shutter Control

The PPS normally controls shutter position by providing open/closed signals to the non-safety shutter-control system. The PPS provides three commands for each shutter:

- Open-Momentary—the shutter should open. If the shutter is moving toward the closed position, then the shutter continues to the fully closed position and the command is ignored.
- Close-Momentary—the shutter should close. If the shutter is moving toward the open position, then the shutter stops immediately and proceeds toward the closed position.
- Absolute Close-Maintained—if the shutter is open, then it should immediately close. If the shutter is closed, then it should not open, regardless of other commands.

Normally, shutters are always open or closed or in transition (they do not stop at an intermediate location).

Normally, primary shutters are controlled from a user panel located at each instrument. This user panel allows personnel to open and close the shutter and indicates shutter position (open, closed, or transition). A trapped key switch is used for each shutter to allow operation when authorized. This trapped key is controlled administratively and is provided to the instrument staff member when instrument operation is permitted. An additional trapped key for each corresponding shutter is required to be in place on PPS CAB11 to allow shutter motion.

When shutter maintenance is required, this trapped key is provided to the maintenance staff. The trapped key is used at a maintenance panel near the shutter drive equipment room. A key switch located in this panel allows local control of the shutter when the trapped key is inserted (maintenance mode). This method ensures that the shutter is only operated when authorized and that instrument staff do not operate a shutter when maintenance is underway.

An emergency shutter-close pushbutton is provided in the TCR and the CCR. When this button is pressed, every shutter immediately closes, except for shutters in the maintenance mode. Beamlines with direct line of sight to the moderators close when the emergency shutter-close pushbutton is pressed in both operating and in maintenance mode.

Shutter Lockout

A shutter lockout panel (PPS CAB11) is provided in the TCR. This panel allows operations personnel to lock out the operation of a shutter. A trapped key panel is provided with one trapped key per shutter and one master trapped key that are used to lock out all shutters.

Each trapped key is locked in position until the corresponding shutter is closed. When the shutter is closed, the trapped key can be removed. When the key is removed, an absolute close signal is sent to the shutter control system for that shutter and the shutter will not open at this point until the trapped key is reinserted and an OPEN command is given. If the target PPS detects that the shutter is not closed (or is faulted), then it will drop the target to the beam prohibited mode.

Shutter Failure

The instruments are designed to be safe with the full beam on even if a primary shutter fails. Therefore, shutter failure is not a safety issue, but it is an operational issue because instrument PPS protection is provided for instrument enclosures. Despite preventive maintenance, occasional primary shutter failures may occur. In almost all such cases, the affected instrument would be taken out of operation until the next scheduled facility shutdown, at which time the problems with the shutter would be investigated and remedied if possible. If the remedy is not possible during that shutdown, then either the shutdown would be extended, or that instrument would remain out of operation until the shutter could be repaired during a subsequent facility shutdown.

Target Cart Position Monitoring

The target is mounted on a target carriage that allows the target module to be extracted from the target monolith for maintenance (Section 3.3.1). When the cart is rolled back, the monolith shielding is compromised, and extremely high levels of radiation would be possible in occupied areas should the beam be transported to the target building. Redundant limit switches inside the process bay monitor the cart position. When the target cart is not in position, the ring extraction septum and the RTBT dipole DH13 critical devices prevent beam transport to the target building.

Instrument Personnel Protection System

Each instrument installed at SNS has a dedicated instrument PPS package to protect workers from prompt radiation. Each package is designed to meet the requirements for each instrument. Because each instrument's requirements vary, the design of each instrument PPS is reviewed by the Instrument Systems Safety Committee (ISSC). Although design concepts vary, the following common elements are generally applicable.

Instrument PPS packages are provided for each instrument at SNS. To the greatest extent possible, each is designed to manage access control, area radiation monitoring, and beam containment for the associated instrument. If the instrument PPS (i.e., for a particular instrument) cannot correct an unsafe condition, then it will communicate with the target PPS to either close the primary shutter or shut off the beam to the target building if necessary.

Each instrument PPS package interfaces with the target PPS via a standard hardwired I/O interface. The standard interface consists of the following inputs and outputs:

- Target PPS inputs from the instrument PPS to operate the primary shutter,
- Target PPS outputs to the instrument PPS to provide primary shutter status (open, closed, transition, fault, or locked out),
- Target PPS inputs from the instrument PPS to indicate a fault condition (i.e., PPS-controlled area accessible and secondary shutter open).

The instrument PPS controls access to enclosed areas associated with each instrument that may experience hazardous radiation levels during beam operation. The access control feature of the instrument PPS may be used to protect workers from other hazards contained in the PPS-controlled area (e.g., prevent vacuum pump operation when the vacuum tank is accessible). These areas fall into two categories: PPS-controlled areas and restricted sample areas.

Instrument PPS-controlled areas consist of instrument caves, detector enclosures, vacuum tanks, and other areas that have radiation levels greater than 100 mrem/h. The instrument PPS controls access to these areas. These areas must be put into beam permit mode before beam is allowed at the instrument. A PPS monitored sweep function is provided when required. If the enclosure is small and free of obstructions such that the entire area can be observed from the entry door, then a PPS monitor sweep is not required. A user panel is provided at the entry to the controlled area. The worker uses the user panel to gain access to the enclosure, facilitate the sweep process if required, and place the enclosure in beam permit. PPS-controlled areas are totally enclosed; access is only available via interlocked doors or gates.

Restricted sample areas have elevated but not immediately hazardous prompt radiation levels during beam operation. These radiation levels are approximately 100 mrem/h inside the area. Access is restricted by the PPS during beam operation; these areas must be in beam permit mode to allow beam. Unlike PPS-controlled areas, access to restricted sample areas is limited by fences. For restricted sample areas, the PPS helps to maintain integrity of radiological areas and to prevent unnecessary radiation exposures but does not perform a credited safety function because the radiation levels are inherently limited.

Many instruments at SNS use a secondary shutter in conjunction with the primary shutter to control neutron flux to the sample. In some cases, the shutter acts as an on/off device. In other cases, the shutter has multiple open positions to provide different neutron beams. Secondary shutters that meet PPS requirements are tied to the instrument PPS and are used for beam containment, along with the primary shutter for that beamline. Secondary shutters are equipped with redundant open and closed limit switches dedicated to the instrument PPS. They also interface with the instrument PPS to allow it to control the shutter position. In some cases (such as pneumatically operated shutters) the instrument PPS directly controls the shutter. In other cases (e.g., multiposition stepping motor actuated shutters) the instrument PPS provides open/close commands to the motor controller. However, in these cases, the instrument PPS directly controls the power to the secondary shutter to ensure that the shutter does not open when the controlled area is accessible.

User–Staff Interfaces

Staff and users interact with the instrument PPS via interface panels provided at the instrument location. Panels are generally located next to the entry point to a PPS-controlled area or restricted sample area. In some cases, PPS-controlled areas such as detector enclosures are only accessed by SNS staff; in others, the interface is used by staff and users (e.g., in restricted sample areas or instrument caves). Each panel has the following features:

- Area Status: The panel displays the operating mode of the area (i.e., access, sweep [when provided], beam permit).
- Access Control: The modes (access, sweep, beam permit) of the PPS-controlled areas are controlled from the interface panel. The area cannot be dropped from beam permit to access until the secondary (or primary, if no secondary shutter is provided) shutter is closed.
- Secondary Shutter Control: Open/close pushbuttons and status lights are provided for the secondary shutter. The shutter cannot be opened until all PPS-controlled areas are in beam permit mode.
- Primary Shutter Control: Open/close pushbuttons and status lights are provided for the primary shutter. For instruments that do not have a PPS-controlled secondary shutter, the primary shutter cannot be opened until all PPS-controlled areas are in beam permit mode.

Instrument Area Radiation Monitors

Area radiation monitors may be provided for an instrument to detect prompt radiation in accessible areas during instrument operation. These monitors are installed in accordance with direction from the RSO. Detector locations are determined by the RSO based on neutronics calculations and surveys conducted during operations. Instrument area monitors can be used to indicate dose rate, provide a local alarm on high radiation, or automatically close the secondary or primary shutter if high radiation levels are detected. The instrument area radiation monitors are not credited controls and do not serve any credited

PPS function. The instrument area radiation monitors help ensure doses are maintained ALARA in accessible areas.

3.3.8.4 Transfer Bay Access Control System

Worker access is allowed into the transfer bay during normal beam operations but is subject to radiological controls enforced by Radiological Protection program requirements. The TBAC system enforces engineered controls required for access.

The TBAC system, which is independent from the PPS, provides automatic interlocks designed to protect workers by ensuring the intrabay doors are closed before the transfer bay personnel door is opened. This process prevents overexposure to radiation and reduces chemical hazards from mercury vapor associated with use of the transfer bay and/or the transfer bay access door. The maintenance bay portion of the target service bay contains equipment related to the mercury target. The adjoining transfer bay allows shielded personnel access for insertion of equipment or maintenance on the servomanipulator. Access to the transfer bay is via a massive shield door (personnel door). The service bay is separated from the transfer bay by two intrabay shield doors that are closed when personnel access is required. The upper intrabay shield door rotates on a horizontal axis to allow the crane to travel into the transfer bay. The lower intrabay door translates horizontally perpendicular to the long axis of the target service bay to facilitate equipment and personnel access into the service bay. The TBAC system ensures that the intrabay doors are closed when personnel access is allowed to the transfer bay via the personnel access door. The intrabay doors protect workers in the transfer bay in three ways. First, they prevent access to the maintenance bay and process bay of the service bay, which are both much higher hazard areas than the transfer bay. Second, they provide radiation shielding to reduce the radiation hazard inside the transfer bay to an acceptable level. Third, they support atmospheric confinement by reducing the open cross section between the relatively clean transfer bay and the relatively high-contamination areas in the maintenance and process bays, supporting the PCES in maintaining the maintenance and process bays at a negative pressure relative to the transfer bay.

The TBAC system is a CEC with the following two credited functions: (1) prevent the personnel access door from being opened when either intrabay shield door is not closed and (2) sound an alarm to warn workers if the access door is open and either intrabay shield door is not closed. The TBAC has dedicated limit switches on both intrabay doors and the personnel door. If the TBAC detects that the access door is open and either intrabay door is open, then an evacuation alarm is sounded inside the transfer bay informing personnel located in the bay to evacuate.

The intrabay shield doors are controlled from an operator interface located in the remote handling control room. A locked, trapped key is provided as a part of this interface. To open either intrabay door, the key must be present and trapped in the local key switch. While either door is open, the key cannot be removed from the switch. If entry into the transfer bay is desired, then the operator closes both intrabay doors and removes the trapped key. This key is then used at the TBAC panel located at the personnel access door to open the personnel access door. When the personnel access door is open, the trapped key is locked in the switch and cannot be removed.

An area radiation monitor is provided for the transfer bay. This unit has a local readout located outside the transfer bay, and the remote detector is located inside the bay. High radiation levels inside the bay when the personnel door is open activate the evacuation alarm inside the bay. Abnormally high radiation levels inside the bay prevent the personnel door from being opened. This function is provided for convenience and is not considered a credited function.

A bypass function is included with the TBAC to allow the personnel door to be opened when either intrabay door is open. This feature allows personnel access to the service bay during initial low-power operations or during major maintenance activities, such as repair of the intrabay door. The use of this key is administratively controlled in accordance with procedures specified in the Operations Procedures Manual (OPM). As described in Section 5.2.16, additional administrative measures are required when entering the transfer bay using the TBAC bypass key.

Operations will conduct administrative sweeps by procedure to assure the area is clear of personnel before the personnel door is closed for non-occupied use. The transfer bay is a small area, and operations can adequately assure no one is locked inside by procedure. Entry into the maintenance/process bay portion of the service bay is only practically envisioned for the early phase of SNS operations before significant activity is induced in the mercury.

3.3.9 Ventilation Systems

Ventilation systems complement physical barriers to minimize the spread of radioactive contamination and other hazardous materials during normal operation and off-normal conditions. Three separate exhaust systems are provided: (1) the PCE system, (2) the SCE system, and (3) the HOG system. The overall target building design provides a coordinated approach to confine hazardous materials, involving both passive structures and active ventilation systems. The building is divided into three ventilation zones, thereby offering a graduated scale of confinement (i.e., two confinement zones and one non-confinement zone). This arrangement helps limit the potential spread of contamination and helps ensure that exposure of workers to radiological hazards is ALARA. The innermost primary confinement zone—which includes the service bay—is serviced by the PCE system. It is maintained under a negative pressure with respect to the secondary confinement zone, which is, in turn, maintained by the SCE system at a negative pressure with respect to the balance of the building. The outermost part of the building, comprising the instrument halls and the north side of the basement area, has a standard conventional industrial HVAC system. The building layout channels typical personnel and equipment access first to this nonconfinement zone before entering a secondary confinement area. Some workers (e.g., users) do not need to enter the secondary confinement area of the building to complete their tasks. The SCE system connects ventilation to each neutron instrument station where local ventilation exhaust is required.

The HOG, PCE, and SCE are separate systems, but they share an exhaust stack with the beam dumps and accelerator tunnel exhaust systems. The stack, also referred to as the central exhaust facility (CEF), is designed to limit on-site doses and reduce offsite doses by enhancing atmospheric dispersion and is designed to accommodate isokinetic sampling and monitoring equipment.

3.3.9.1 Primary Confinement Exhaust System

Mercury and radioactivity are confined by the service bay configuration and by the PCE system. This system, shown in Figure 3.35, maintains negative pressure on the service bay and on the monolith; it also receives exhaust from the core vessel vacuum pumps during routine vacuum operation. It provides ventilation for the SDER and tank cavities for the water loops, both GLS and delay tanks. The system can also maintain a ventilation flow into the core vessel during maintenance activities when the core vessel upper head is removed. The PCE system removes mercury and particulates from the exhaust and has the credited safety functions described in Section 5.

ALARA concepts have been applied to the design of SNS ventilation systems for radiological confinement spaces. Recommended guides and practices, such as DOE-HDBK-1132-99, Section 1, have been followed to the extent practicable. Furthermore, per the ORNL Work Smart Standards for engineering design [4, 5], ASME N-509 was used in designing the confinement exhaust system, except for the charcoal adsorbers. Because ASME N-509 does not specifically address mercury adsorbers, the parts the designers determined to be applicable were used.

The PCE system exhausts the service bay and the transfer bay at flow rates adequate to accomplish the following:

- Assure that required negative pressure levels are maintained under normal operating conditions and defined accident conditions (Sections 4 and 5).
- Provide reliable means to achieve a minimum flow velocity of 100 ft/min across temporary openings in the service bay confinement barrier (e.g., plug openings, personnel access door, pass-thru ports).
- Ensure that airflow is from areas of lower potential contamination to areas of potentially higher contamination (e.g., from the transfer bay to the service bay).

The normal exhaust airflow through the service bay is optimized to minimize the flow of air being processed by the mercury removal system. The PCES maintains the service bay and transfer bay at a small negative pressure (approximately 1 in. water gauge) with respect to the surrounding areas. The desired hierarchy of negative pressures is as follows, from most negative to least negative: service bay, transfer bay, and manipulator/service galleries. This configuration is supported by interlocks in the SCE system. Exhaust airflow through the transfer bay is sufficient to achieve a minimum velocity of 100 ft/min through the largest transfer opening in communication with the decontamination room, thereby helping to prevent the spread of contamination during transfer activities (i.e., when the transfer bay personnel access door is open).

Air exhausted from the target service bay passes through a bank of manipulator-changeable, roughing HEPA filters mounted inside the service bay before entering the ductwork that conveys it downstream. These filters are an ALARA good practice to minimize the potential spread of contamination into ductwork and downstream components. Intake air drawn into the target service bay from the decontamination room (occupied area located outside the transfer bay) is filtered through a single bank of in-place, testable HEPA filters. Backdraft dampers upstream of the HEPA filters prevent flow reversal.

The PCE system has redundant, parallel-arranged blower and filter trains with isolation dampers configured in a manner that allows the use of either blower with either filter. The filter housings accommodate one bank of HEPA filters in series, upstream and downstream test sections, a set of pre-filters, and instrument test ports to accommodate measurement of filter pressure differential, inlet temperature, and inlet pressure differential. HEPA filter housings are constructed of stainless steel, as is the ductwork inside the building and the above-ground portions of the ductwork at the CEF. At the basement wall, the ductwork transitions to HDPE for the underground portion between the building and stack. Vacuum break protection is included to protect the HEPA filter housing from collapse due to excessive vacuum.

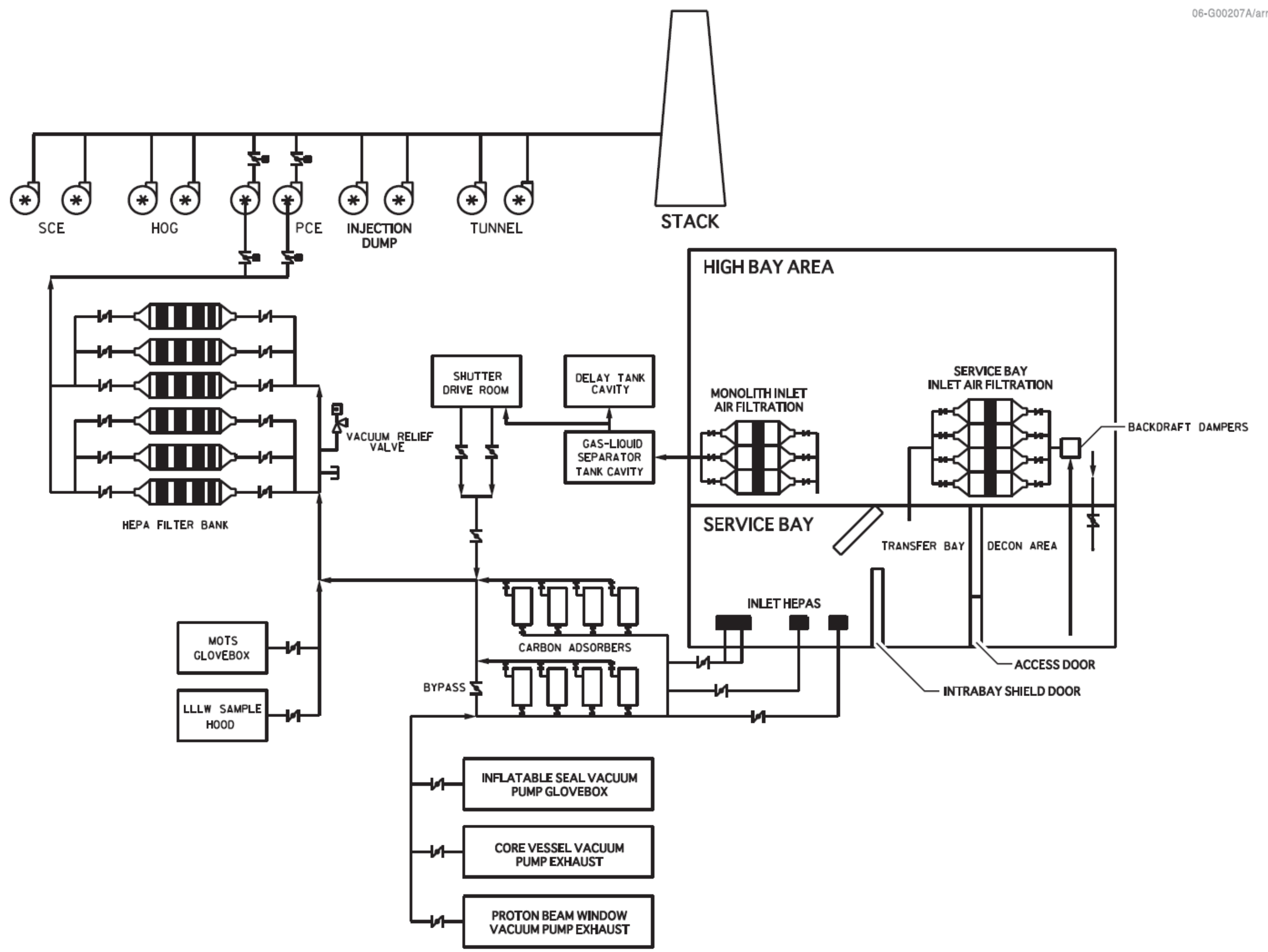


Figure 3.35. Schematic of primary confinement exhaust system.

The PCE system can remove mercury from the ventilation air exiting the service bay and selected other areas that could experience mercury contamination. This system consists of a sulfur-impregnated charcoal adsorber system comprising a set of eight cylindrical filtration beds manifolded together in a parallel flow arrangement. The adsorbers minimize the discharge of mercury vapor to the environment. Multiple beds facilitate safe handling and replacement of the charcoal and provide adequate bed residence time. The total quantity of charcoal is approximately 9,000 lb, and it originally had an expected lifetime on the order of 5 years, depending on the actual mercury release rate and the activity of the adsorbed mercury. Before operations, mercury accumulation on the adsorbers was predicted to be as high as approximately 2.2 kg/year. Measured accumulation after about 10 years of operating experience was less than 1 kg [21]. Plans are to change the charcoal before the surface dose of the adsorbent exceeds 200 mrem/h, which is the limit for contact-handled waste, for convenience in handling. During routine high-power operations, the activity was expected to increase to about 200 mrem/h well before reaching the limit on mercury inventory. This activity level has not occurred, primarily because the buildup of the long-lived mercury-194 has not reached levels of concern. High inventory levels of mercury would only be expected from an unanticipated major release in the service bay. The radiation level on the exterior of each individual adsorber is periodically measured. This dose rate has been less than 1–2 mrem/h measured at the surface of the measuring port through the adsorber shielding [21].

The adsorbent is activated charcoal impregnated with approximately 10 wt % sulfur, and nominal mercury removal capability is specified as follows: exit concentration of 0.1 μg/m^3 when inlet mercury vapor concentration is 50 μg/m^3. Given the chemical adsorption removal process and the amount of sulfur impregnate involved (about 10 wt %), a rough estimate is that more than 3,000 kg of mercury would be required to saturate (i.e., all sulfur reacted to form HgS) all eight filter units. The charcoal adsorbers are administratively required to be maintained with less than 155 kg of mercury total on all eight adsorbers during normal operation. The total inventory on all eight adsorbers was less than 1 kg after 10 years of operation.

The design volumetric airflow rate from the service bay through the filters is identified in the equipment data sheet for the charcoal adsorbers as between approximately 385 actual standard cubic feet per minute (SCFM) minimum and 440 actual SCFM maximum for each filter (eight filters in a parallel arrangement) with a maximum pressure differential of approximately 10 in. water gauge across the bank. Air is sampled upstream from the charcoal adsorbers to obtain a measure of mercury content and mercury mass flow rate. A mercury analyzer is installed in the service bay exhaust duct to give operators information on airborne mercury level in the service bay. This system collects data to quantify and track the performance of the charcoal adsorbers, including the accumulation of mercury on the adsorbers. A bounding mercury inventory may be calculated based on absorption efficiency and integrated mass flow.

Although combustion in the charcoal adsorber medium is considered highly unlikely, temperature monitors on the exhaust side of each charcoal adsorber unit detect elevated exhaust temperature. If elevated temperatures indicate the possibility of combustion, then operational actions could be taken, including isolation of individual charcoal adsorber units or manual initiation of flooding the affected units with water.

3.3.9.2 Secondary Confinement Exhaust System

The SCE system (Figure 3.36) serves the service bay support areas by maintaining desired air circulation and keeping them at a negative pressure with respect to the nonconfinement zones in the building such as the instrument halls and east end of the basement.

The SCE system also provides capacity for equipment and glove-boxes located in the neutron instrument laboratory areas where local ventilation exhaust is deemed desirable or necessary. The exhaust from the secondary confinement is drawn through HEPA filters located in the basement of the target building and ducted underground to the SCE system blowers and central exhaust stack.

The SCE system has redundant, parallel-arranged blower and filter trains with isolation dampers configured to allow the use of either blower with either filter. The filter housings accommodate one bank of HEPA filters in series, upstream and downstream test sections, a set of pre-filters, and instrument test ports to accommodate measuring the filter pressure differential, inlet temperature, and inlet pressure differential. HEPA filter housings are constructed of stainless steel, as is the ductwork inside the building and the above-ground portions of the ductwork at the CEF. At the basement wall, the ductwork transitions to high-density polyethylene for the underground portion between the building and stack. Filters in the SCE system were changed in 2011. These filters were smear clean and did not require disposal as radioactive waste.

The SCE system contains automatic control interlocks that turn off the SCE blowers in the event of low PCE flow. This noncredited action aids in confinement by preventing conditions that would cause SCE system spaces to be at a lower pressure than PCE system spaces, potentially promoting the spread of contamination from PCE areas. PCE system fan status and target service bay flow are monitored by the SCE system, and SCE fan operation is secured if parameters indicate the PCE system is not operating normally.

Another noncredited automatic control interlock designed to minimize the potential for spreading contamination is the personnel door–decontamination room SCE inlet damper interlock. The position of the transfer bay personnel door is monitored; if the door is open, then the SCE inlet damper in the decontamination room is automatically closed to minimize the potential of localized backflow from the transfer bay.

The SCE system is monitored to ensure flows, temperatures, and pressures are in the desired operational range.

3.3.9.3 Hot Off-Gas System

The HOG system removes radioactivity from gaseous waste streams produced by target and support systems, serving equipment items such as the cooling water head tanks, vacuum pump exhausts, and the MOTS. Components that may contain activated or gaseous radioactive materials are, in general, ventilated through the HOG system. A schematic diagram of the HOG system is shown in Figure 3.37.

The HOG system removes radioactivity primarily by decay and filtration. Atmospheric gas delay tanks are provided for gases that could have significant short-lived radionuclide content (e.g., purge gas from the activated cooling water loops). Off-gas from aqueous systems is routed through a mist removal stage to protect the HEPA filters from moisture. Helium purge gas from the target mercury system is processed through the MOTS (Section 3.3.7) before discharge to the HOG system. The other gaseous wastes go directly to the HOG system.

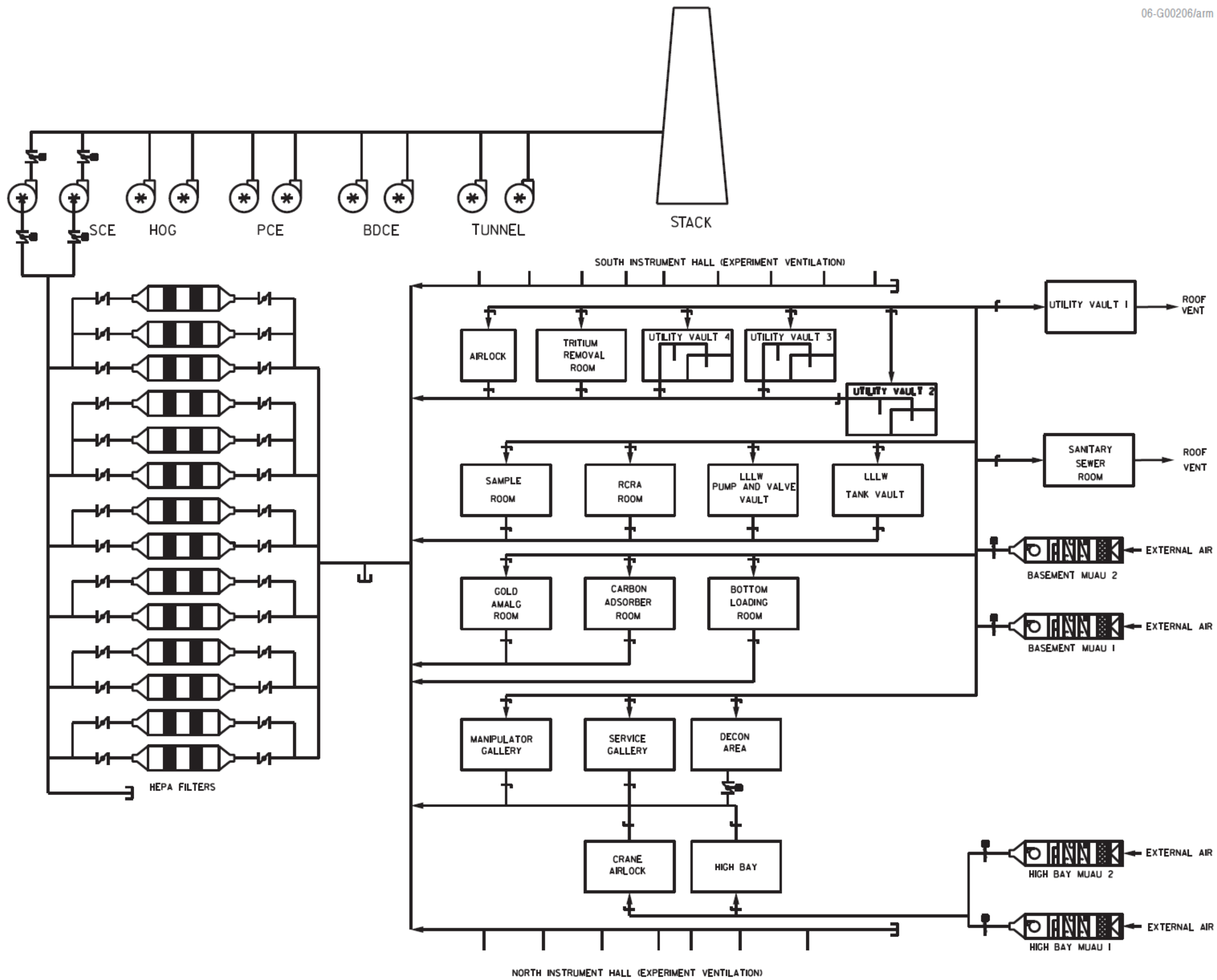


Figure 3.36. Schematic of the secondary confinement exhaust system.

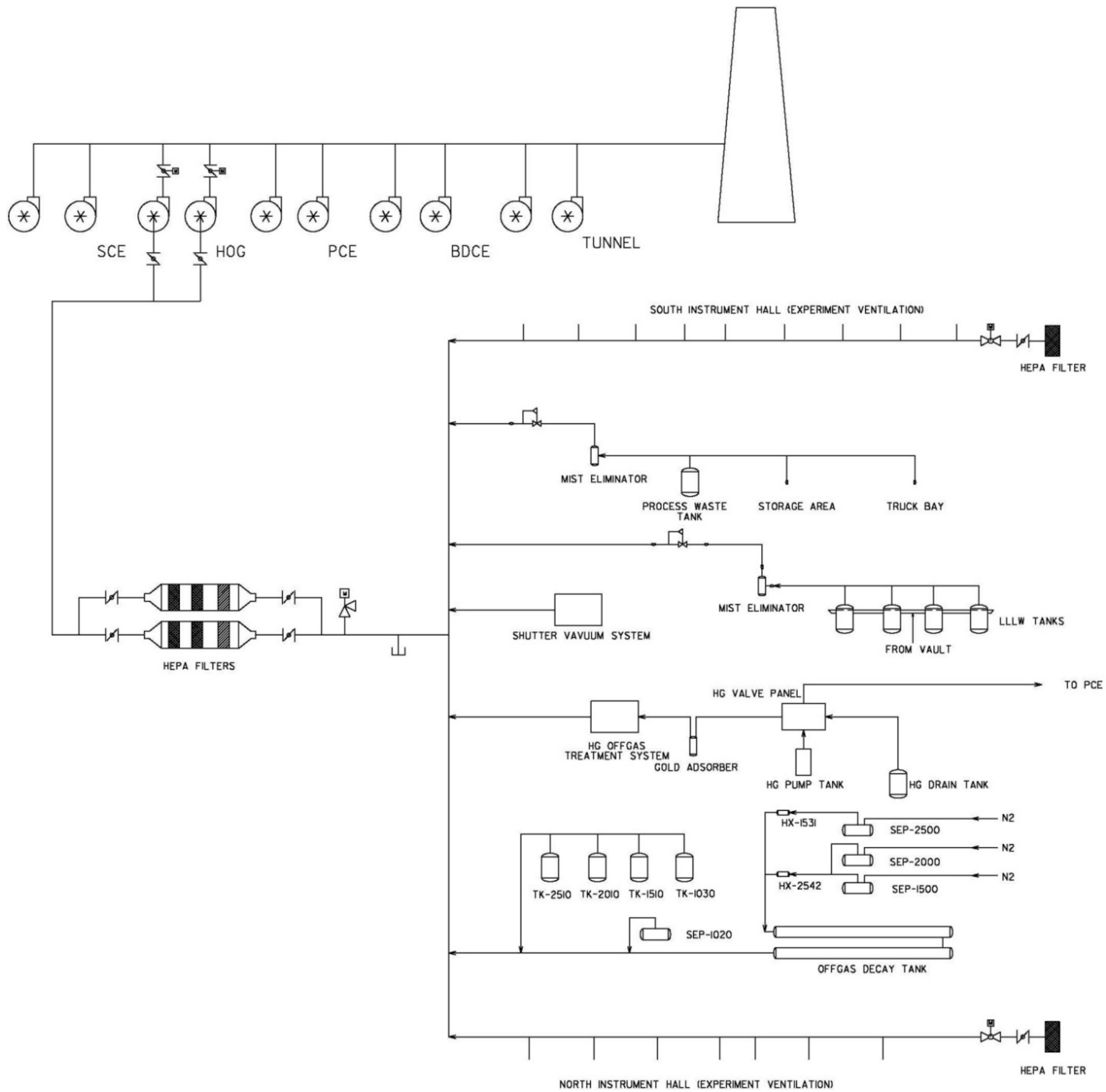


Figure 3.37. Schematic of the hot off-gas system.

Under normal conditions, off-gases from the target mercury/water cooling loop, target shroud and proton beam window cooling loop, cryogenic and ambient moderator cooling loop, and reflector heavy-water cooling loop are routed to the off-gas decay tank. This system delays the gases to allow short-lived isotopes to decay before venting to the HOG system. In addition to these sources, the shutter vacuum and neutron beamline and experiment vacuum systems exhaust to the HOG system as appropriate. Mist eliminators are provided from the process waste tank and LLLW tank off-gas lines. Trapped liquid droplets and backwash from the mist eliminators is transferred to the process and LLLW systems, respectively.

The HOG system has redundant, parallel-arranged blower and filter trains with isolation dampers configured to allow the use of either blower with either filter. The filter housings accommodate two banks of HEPA filters in series, upstream and downstream test sections, a set of prefilters, and instrument test ports to accommodate measurement of filter pressure differential, inlet temperature, and inlet pressure differential. HEPA filter housings are constructed of stainless steel, as is the ductwork inside the building and the aboveground portions of the ductwork at the CEF. At the basement wall, the ductwork transitions to high-density polyethylene for the underground portion between the building and stack. The HOG system is monitored to ensure flows, temperatures, and pressures are in the desired operational range. Vacuum breaker protection is provided to prevent HEPA filter housing from collapse due to excessive vacuum.

3.3.10 Safety Support Systems

3.3.10.1 Facility Radiation Monitoring System

The facility radiation monitoring system is made up of gamma area monitors installed at various locations throughout the target building. The area monitors provide a local readout of radiation level and are tied to an Ethernet network to allow the radiation levels to be remotely displayed and archived. Monitors are located inside the building in accordance with direction from the RSO. The monitors are strategically placed to provide coverage in areas that have frequent occupancy and/or are adjacent to locations that could have unexpectedly elevated radiation levels. These monitors also register and record ambient radiation levels in areas that are less frequently entered but are expected to accumulate radioactive materials (e.g., filter rooms). The monitors are periodically calibrated to ensure accurate reporting of radiation levels. In occupied areas of the target building, these radiation detectors are also used to track and detect elevated radiation levels, supporting efforts to maintain these levels ALARA.

The facility radiation monitoring system does not perform a credited function but rather monitors for changes in operations and maintains doses ALARA. The facility radiation monitoring system is not associated with the PPS system.

Portable constant air monitors are available and used when needed to characterize airborne radioactivity in the various potentially occupied areas of the facility or to monitor airborne radioactivity during nonroutine maintenance activities. Portable elemental mercury vapor monitors (e.g., Jerome meters) are also available and can help detect mercury vapor. Fixed air monitors are not used because the significant potential for airborne radioactivity exists only within the service bay, which is not routinely occupied. Moreover, the primary confinement exhaust system (Section 3.3.9.1) maintains normal airflow direction into the service bay, and a credited alarm—the SBDPMS (Section 5.2.14)—warns workers if the primary confinement exhaust system control of the service bay atmosphere is lost.

3.3.10.2 Gaseous Effluent Monitoring System

Radioactive emissions from the SNS facility are monitored at the CEF using an in-line radiation detector. The detector is a NaI scintillator fitted to a photomultiplier tube connected to appropriate electronics for pulse counting. Furthermore, the specific location of the monitoring has been qualified to meet 40 CFR 60 requirements using a tracer gas and the methods of ANSI/HPS N13.1-1999. The monitoring program implemented for the CEF meets or exceeds the requirements of 40 CFR 61, Subpart H—*National Emission Standards for Emissions of Radionuclides Other Than Radon from Department of Energy Facilities* (also incorporated in the Tennessee Air Pollution Control Regulation 1200-3-11-.08), and further defined in the US Environmental Protection Agency (EPA) approved Oak Ridge Reservation (ORR) National Emission Standards for Hazardous Air Pollution compliance plan, DOE/ORO/2196, Rev. 1, *Compliance Plan National Emission Standards for Hazardous Air Pollutants for Airborne Radionuclides on the Oak Ridge Reservation, Oak Ridge Tennessee*, April 4, 2013. Other detection equipment has been added to support characterization of the emitted radionuclides.

3.3.10.3 Fire Protection Systems

An FHA [15] has been completed. Fire protection design implements DOE-STD-1066-99 to the extent practicable. Where alternative design approaches were necessary, equivalent protection was documented and formal Equivalencies were granted by DOE. These equivalencies are referenced in the FHA.

Fire Barrier

Accident and hazard analyses have credited a fire barrier around the target service bay. Fire-rated walls around the target service bay are shown in Figure 3.38.

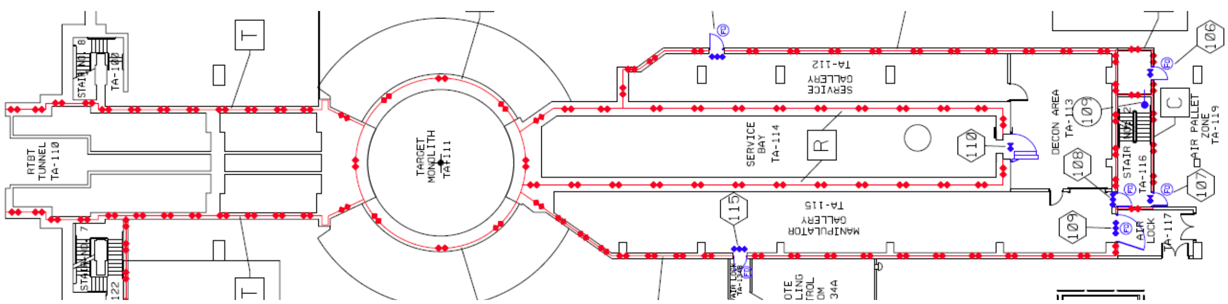


Figure 3.38. Fire-rated walls around the service bay.

Fire Suppression

The target building is protected throughout (except for the target service bay interior and the shutter drive area) with an automatic wet-pipe fire suppression system (FSS). Sprinklers are provided at the building ceiling levels, intermediate levels, and at/within enclosures, as required. Designs adhere to NFPA standards. The appropriate portable fire extinguishers are provided for manual firefighting efforts. SNS fire alarms are alarmed at the laboratory shift superintendent's office and the ORNL Fire Department, which responds to every fire alarm. This alarm puts professional firefighting resources into action within a short period of time.

An automatically initiated water mist FSS is used inside the service bay. The mist system is advantageous for the target service bay because it can extinguish a fire without using large quantities of water, thereby minimizing the volume of contaminated water that would be generated in the event of system actuation. A

Very Early Smoke Detection Apparatus (VESDA) smoke detection system is installed to provide early warning of a service bay fire. Section 5 for discusses the safety-related role of the target building FSSs.

The water mist system is required to be designed, installed, and tested in accordance with NFPA 750 [23]. The water mist FSS is driven by two similar gas-driven pump units (GPUs) located in the service gallery. Each GPU contains two banks of pressurized nitrogen cylinders, a dedicated water supply, and a gas-driven pump connected to a valve manifold that directs the water/nitrogen supply to the appropriate spray heads. The system is activated when a VESDA detects a fire. Upon system actuation, the high-pressure nitrogen provides driving force to operate the pump, pressurize the system, and produce water mist for the required duration. Pressurized cylinders allow the system to be replenished within 24 h of use so that the system can be restored to operation.

The water mist system is designed to address fires in the service bay and the transfer bay. The transfer bay is monitored by VESDA units #1 and #2, and the service bay is monitored by VESDA units #3 and #4. Two out of two logic is required to activate the water mist system. If this requirement is satisfied for the transfer bay, then GPU #1 will activate, and valves will align to supply the two spray heads in the transfer bay. If logic is satisfied for the service bay, then both GPU #1 and #2 will activate, and valves will align to supply the twelve spray heads in the service bay. Water mist fire suppression is a credited control for the service bay only. Water mist is secured in the transfer bay during personnel entry because water mist poses a life safety hazard caused by oxygen displacement and reduced visibility.

Fire Alarm System

An addressable, protected-premises, fire alarm system is installed throughout the facility. Fire alarm and supervisory devices report to a local fire alarm control panel at the protected premises. The fire alarm control panel sounds an alarm at the protected premises and transmits the fire alarm/supervisory signal to the supervising station at the ORNL Fire Department in Building 2500 and to the laboratory shift superintendent's office in Building 4512. Fire alarm/supervisory signals are also sent to a redundant fire alarm panel in the CCR.

The fire alarm system provides audible and visible evacuation signals throughout the facility. The standard ORNL audible fire alarm signal is a temporal horn.

Manual and automatic fire detection and alarm initiation devices are installed throughout the facility. Enhanced coverage is provided in critical or hazardous areas such as high-voltage centers, control rooms, and mercury removal systems.

Where required for specific hazard mitigation, smoke or heat detection devices are supplemented with pressure-sensitive sensors, combustion gas detectors, or other advanced detection devices.

Evacuation Lighting

Emergency lighting systems for egress lighting during power outages are provided per NFPA 101 [7].

3.3.11 Utility Systems

3.3.11.1 Electrical Power

The electrical power distribution system includes an alternating current (ac) power distribution system, an emergency on-site ac power supply system, and UPSs to power loads requiring a continuous source of ac power. The target building receives power from the SNS site power distribution system. The target building loads comprise a small percentage of the overall SNS power requirement.

3.3.11.2 Alternating Current Power Distribution System

The ac power distribution system supplies both neutron and proton facility loads.

Power is supplied from a TVA 161-kilovolt (kV) transmission line located about 0.5 mile from the SNS site and is routed to 13.8 kV transformers located in the SNS switchyard. The 13.8 kV feeders provide service from the primary plant service transformers and associated medium-voltage switchgear. The 161 kV and 13.8 kV circuit breakers simultaneously trip in the event of an electrical fault with the 161 kV switchyard bus and associated equipment.

On-site backup ac power supplies and UPS systems are provided to power loads that must remain operable in the event of the loss of off-site power. Where practical, separate electrical sources are provided for conventional building use and machine/experimental use. Copper conductors are used for interior electrical systems, and radiation-hardened/radiation-resistant electrical equipment, including wiring and cabling, is used where warranted by radiation levels.

3.3.11.3 Emergency On-Site Alternating Current Power Supply

The emergency on-site ac power supply consists of multiple diesel-powered generator units installed at various locations on the SNS site. Emergency power is supplied at 480 Vac to the access control system, the standby ventilation fans for the target service bay and the accelerator tunnels, the emergency lighting systems for tunnels, and standby lighting systems located throughout the plant.

Emergency on-site ac power is supplied at 480 Vac to UPS-supplied loads of normal/emergency distribution equipment that require additional power beyond the maximum backup period, including the safety interlock system, vacuum system I&C, CCR servers and network hardware, selected telecommunications equipment, and selected alarm systems.

Although needed for ensuring safe occupancy or evacuation conditions and for equipment protection, the emergency on-site ac power is not a CEC because the proton beam cannot be maintained without off-site power and active cooling is not needed for decay heat removal. When off-site power is lost, the on-site emergency ac power supply would help maintain safe working conditions within potentially occupied parts of the target building by helping to prevent the spread of contamination by maintaining target service bay negative pressure.

3.3.11.4 Uninterruptible Power Supply System

The UPS systems at the SNS invert direct current (dc) to ac and distribute this power to loads requiring a continuous source of power. The loads connected to the UPS system are necessary to provide safety to facility personnel and to prevent economic loss in the event of primary power supply failure. Loads connected to the UPS systems include the safety interlock system, the vacuum system I&C, the critical power supply controls and protection, the CCR servers and network hardware, selected telecommunications equipment, and selected alarm systems. The UPS systems are not safety credited.

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

3.3.11.5 Natural Gas Supply

Natural gas is not supplied to the target building. Building heat is supplied from the Central Utility Building hot water system. The boilers in that building are heated by natural gas, and they supply hot water to heaters in the target building.

3.3.12 Auxiliary Systems and Support Facilities

3.3.12.1 Waste Systems

The target building design and construction, as well as planned and phased-implemented programs, support compliant management of wastes produced at the facility. The facility will generate low-level waste (LLW), mixed low-level waste (MLLW), hazardous waste (HAZ), and standard sanitary/industrial waste. As described in the *SNS Waste Management Plan* (SNS 1020300000-TR002), all wastes have identified paths to treatment and/or disposal at existing commercial and/or DOE facilities, and these respective wastes are managed in compliance with state and federal regulations. Solid waste and liquid waste are packaged in approved containers for off-site disposal or treatment.

3.3.12.2 Solid Waste Systems

Typical examples of solid waste streams that may be generated in the neutron facilities include LLW, MLLW, HAZ, and sanitary/industrial waste. The programmatic management of these wastes is described in the *SNS Waste Management Plan* (SNS 102030000-TR0002).

In general, waste from the target service bay is packaged and decontaminated as needed and loaded into shipping containers and removed from the target service bay. A waste-handling (decontamination and packaging) area in the basement manages wastes such as ion-exchanger resins and other solid wastes.

Remotely handled LLW is volume reduced as necessary inside the target service bay for efficient packaging. The majority of the solid remotely handled LLW is used target components. Tools such as mechanical cutters, abrasive saws, and hydraulic shears may be used to size-reduce and load waste into packaging designed for off-site shipping casks. On-site storage of wastes may be periodically required depending upon the availability of off-site disposal sites.

Ion-exchange resins and particulate filters for the various contaminated target coolant loops are contained in a series of shielded beds. These ion-exchange resin beds are changed when spent and transferred to the target building decontamination area for resin replacement. Spent resin may be removed, de-watered and packaged for disposal. Alternatively, the beds may be shipped with the resins for vendor replacement. Particulate filters used in the contaminated target coolant loops are replaced periodically and handled as solid radioactive waste.

Solid waste is intended to be packaged for shipment according to appropriate regulations and then shipped off-site for disposal in approved repositories.

3.3.12.3 Liquid Waste Systems

No process waste or liquid radioactive waste is discharged to the environment at the SNS site. Radiological waste is transported to the central ORNL waste processing facilities for further treatment and eventual release in accordance with established ORNL procedures and limits.

The process waste collection system collects and samples potentially contaminated wastewater from clean and buffer area floor drains, cooling water system leakage, and some HVAC condensate from the target building.

The process waste system inside the target building consists of collection headers from cooling water systems and some of the HVAC condensate drains, sump pumps, and piping collection headers from floor drains. The building floor drains are generally routed to a central building sump that is pumped to a collection tank. Process waste from the target building is sampled before being discharged to the sanitary sewer in accordance with approved procedures. If the wastewater is contaminated, then it is transferred by tank truck to the ORNL LLLW system.

The LLLW system collects radioactively contaminated leakage and wastewater from the target cooling and support systems, wastewater discharged from the target service bay, and condensate from the target off-gas and HOG system. Components that may contain activated or radioactive liquid materials are connected to the LLLW systems via hot drains. The SNS LLLW system consists of four 1,000 gal storage tanks located in a storage vault. The system has a circulation pump, a set of filters, and a loading system to transfer LLLW from the storage tanks to a truck transport tank (used by the ORNL LLLW system). An ion-exchange bed for processing LLLW to remove mercury and other dissolved ions may be provided by contract if needed. LLLW may also be pumped to the process waste discharge to the sanitary sewer system if the discharge limits to that system can be met. The LLLW system piping is contained within the target facility building.

The SNS cooling water is managed to ensure applicable limits for tritium release to the ORNL LLLW system.

3.3.12.4 Gaseous Waste Systems

Gaseous waste treatment systems are described in Sections 3.3.7 and 3.3.9.

3.3.13 Instrument Systems

Neutron research motivates construction and operation of the SNS complex. Instrument systems include the facilities where the neutron research is done. In this section, the term *instrument* refers to any one of the several neutron instruments installed in the north or south instrument halls. Each instrument is a major research facility. Typical instrument features are described in the following subsections. Instrument systems hazards are addressed in Section 7.

Each neutron scattering instrument is shielded to protect workers or visitors from undue exposure to neutron or gamma radiation following the ALARA philosophy of 10 CFR 835 [2]. Shielding for the neutron scattering instruments conforms to the *Spallation Neutron Source Shielding Policy* [3]. Shielding design philosophy and shielding configuration control for the neutron scattering instruments are consistent with Section 4.2.1 of the FSAD-PF [1].

All instrumented neutron beamlines are equipped with advanced interlock systems to protect personnel. The instrument PPS is the engineered safety system intended to protect workers from gaining access to areas, such as instrument enclosures and sample irradiation areas, that could have hazardous levels of radiation. Additional safeguards prevent accidental or inadvertent modifications to critical beamline components (such as shielding blocks). The controls to be exercised in conjunction with these major beamline components include the following:

- Procedures and acceptance criteria.

- Configuration control of beamline shielding, including approved mechanical fastening or padlocking where necessary.
- Physical barriers as appropriate.
- Limited or controlled access areas interlocked to close the beamline shutter and/or shut down the accelerator if these areas are entered.

The PPS prevents access to areas where the potential exists for excessive radiological exposure (i.e., beamline shutter in the open position) and shuts down the accelerator if improper access is gained or if an instrument PPS system fault is detected that could potentially endanger personnel. Only authorized individuals are allowed to perform enclosure sweeping and/or instrument PPS resetting tasks. The training and qualification for personnel performing these tasks are commensurate with the degree of hazard present in their authorized tasks.

3.3.13.1 Introduction and Overview

The SNS instrument hall comprises 18 beam ports capable of providing neutron beamlines to more than 24 instruments when completely outfitted. Figure 3.39 shows a schematic of the overall arrangement of the instrument hall with the shielded beamlines radiating out to shielded instrument enclosures. Egress routes (not shown on the figure) are provided for personnel throughout the instrument hall per the guidelines of the *Life Safety Code* (NFPA 101) [7].

The neutron instruments include diffractometers, spectrometers, and reflectometers as well as basic neutron physics experiments. Some common components used in experiments include capabilities for high and low temperatures, high pressure, high magnetic fields, and various enclosed gaseous environments. Each beamline is unique and is generally used for a specific type of research. Although most instruments have some common and similar beamline components, each has differing mechanical, operational, and scientific characteristics.

Typical experiments involve placing small material samples, typically smaller than 1 mm^3 to several cubic centimeters, into the neutron beam path for a period of a few minutes to several days to gather neutron scattering data. Samples and their associated ancillary equipment are mounted either internal to an enclosure (sample chamber) or at a particular mounting location. All experiments must be approved through the SNS experiment review process, which involves screening and reviewing all proposed experiments.

3.3.13.2 Neutron Beamline Components

A typical neutron instrument includes an enclosed, shielded beamline extending from the core vessel insert (located within the target monolith beginning approximately 1 m from the associated moderator above or below the mercury target module) to a shielded beam stop some distance (typically 15–90 m) from the target. The beamline components include the following:

- Beam-modifying apparatus such as mirrored guides, choppers, apertures, and collimators.
- Beam-stopping equipment in the main shutter (located within the target monolith) and secondary shutters located outside of the monolith.
- Sample environment equipment such as furnaces, refrigerators, cryostats, high-pressure bays, magnets, and sample changers.
- Scattered beam flight paths often through a scattering chamber under vacuum or filled with a low-pressure gas (e.g., 1 atm) such as helium or argon.
- Neutron detectors, shielding, and a shielded beam transport tube leading unscattered neutrons to the beam stop.

- Beam monitors located at various positions along the beamline.
- Shielding required along the beamline and surrounding the scattering chamber to reduce radiation levels for workers and to lower background levels for adjoining instruments.
- Instrument PPS providing automatic access control interlocks.
- Control cabins/hutches.

3.3.13.3 Inserts

Replaceable inserts are installed in the primary shutter and in the core vessel in each beamline. These inserts contain neutron optical components specific to the requirements for experiments associated with each beamline. To ensure accurate alignment of the insert to the beamline, the inserts for the primary shutters have a clearance between the insert and the shutter opening so that the inserts rest on a solid support (external to the movable shutter) when the shutter is in the open position (Section 3.3.4). The inserts are constructed of a solid steel outer casing with an internal channel opening for the beamline optics. Typically, a helium-filled container is installed in the channel opening. Thin metal windows are installed at each end of the container to allow the neutrons to pass through. Inside the container, guides and benders may be mounted within the helium environment if required for that particular instrument. Helium supply and return lines are connected to the container to maintain the helium environment.

The core vessel inserts are located at the boundary between the core vessel environment and the primary shutter region environment; therefore, the neutron windows in the core vessel inserts form part of this boundary. This confinement function is a CEC. These windows are monitored for leakage. Because the core vessel inserts are near the moderators, the inserts require active water cooling to maintain the required design temperatures of their internal components. The primary shutter inserts are not part of a containment boundary. These shutter inserts do not require active cooling because they are in a lower heat load area.

The configuration of the core vessel inserts and shutter inserts is expected to change from time to time as new instruments are installed.

3.3.13.4 Shutters

The primary shutter for each beam port is within the target monolith bulk shielding. The shutters are remotely operated so that the neutron beamline can be opened or closed during target operation. Shutter inserts are provided in the shutters as described above. The principal function of the shutters is to provide adequate shielding in the closed position for downstream personnel access during active target operation. The shutters are interlocked with the instrument PPS. Shutter design is discussed in more detail in Section 3.3.4.1.

Secondary shutters are located on some instruments to provide an alternate method of stopping the neutron beam upstream of the sample area. Secondary shutters are typically included in instruments duplexed with additional instruments on a single beam port and for instruments requiring frequent access to the sample area. The design of these shutters meets shielding policy requirements (Section 4.2.1 of the FSAD-PF [1]) to allow personnel access to the beamline sample area when the shutters are closed. Additionally, the secondary shutters are interlocked with the instrument PPS.

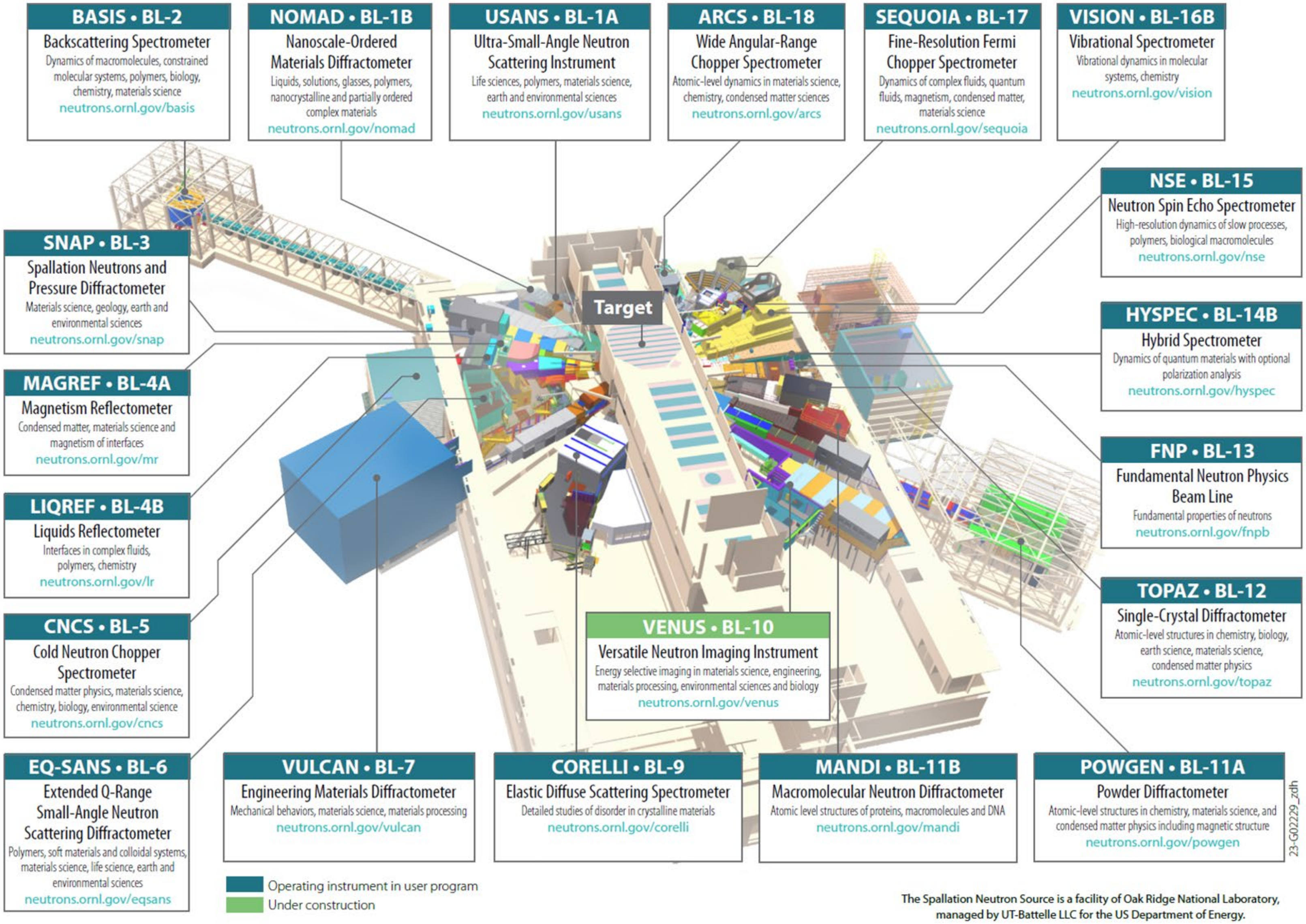


Figure 3.39. SNS instrument hall.

3.3.13.5 Optical Components

Optical components for the SNS neutron scattering instruments include neutron guides, beam benders, mirrors, spin flippers, spin polarizers, collimators, crystals/monochromators, and focusing devices. The neutron guides, beam benders, and mirrors are wide-bandwidth optical components, the main elements of which are substrates (usually silicate glass, sometimes borated) coated by single or multilayer metallic films up to 200 nm thick (the neutron mirror). The coating materials are typically nickel, titanium, cobalt, and iron. The neutron guides normally have a rectangular cross section. Internal surfaces are coated by the reflecting layer. Neutron guides can be very long (up to 100 m), thus the internal volume must be evacuated or helium filled to minimize air scattering. Most neutron guides have an external vacuum jacket to support the vacuum forces. Beam benders are multislit mirrors that are typically short (less than 15 m) and may not require vacuum conditions. Spin-flippers are usually equipped with electromagnets; therefore, appropriate safety rules that concern electrical shock and implanted medical devices are followed as necessary.

3.3.13.6 Neutron Beamline Vacuum Systems

Beamlines require components such as neutron guides and choppers to be operated in vacuum to minimize undesirable scattering of neutrons by air.

3.3.13.7 Neutron Beamline Shielding

The beamline shielding controls radiation to ALARA levels in the instrument hall in accordance with the SNS shielding policy. Fire hazards requirements must be met by the shielding design.

Hydrocarbon flammability hazard is minimized with instrument hall shielding. Simultaneously achieving ALARA radiation levels as well as minimizing fire hazard has resulted in retaining the potential use of some hydrocarbon-based shielding in the instrument hall, particularly in the shielding of instrument enclosures.

The neutron beamline shielding is constructed primarily of steel and concrete. The use of nonflammable beamline shielding reduces the fire hazard in the instrument hall by reducing the presence of hydrocarbon. Hydrocarbon neutron shielding is employed in various locations where the low density and neutron stopping power provide a significant advantage. The fire hazard is minimal in some cases because of the modest quantity of hydrocarbon involved (e.g., at the choppers). Larger amounts of hydrocarbon may be needed at the neutron instrument stations at the end of the beamlines. Design features are incorporated to minimize fire hazards. The beamline shielding provides a nonflammable buffer between the monolith/target service bay area and hydrocarbon shielding materials present at the instrument stations.

Because of the very desirable neutron shielding properties of paraffin and polyethylene, as well as the instrument station/enclosure requirements, some enclosure designs incorporate these materials even though (depending on quantity and material) significant mitigative features must be built into the designs.

The design intent for all instrument stations is to limit the amount or configuration of the hydrocarbon as needed to remain within the assumptions and requirements of the target building fire accident analysis, particularly to not exceed the size of the design basis instrument hall fire. As discussed in the target building FHA [15], the potentially destructive effects of instrument station/enclosure fires are limited by limiting the quantity and/or configuration of the hydrocarbon present.

The requirement for design mitigation of the fire hazard of hydrocarbon shielding varies with the size of the potential fire and its location, especially locations in the target building vs. locations in satellite buildings. Unmitigated fires in satellite buildings cannot transport significant heat into the monolith or target service bay; however, the hydrocarbon in them must still be encased to protect investments, and curbs or other design features are provided as needed to prevent molten hydrocarbon shielding from flowing into the target building proper. Encasing hydrocarbons such as paraffin in metal does not entirely eliminate all possibility of paraffin combustion but does limit the size and duration of potential fires, thereby allowing the use of significant quantities of hydrocarbon.

The following design requirements for the hydrocarbon configuration and encasement help to achieve the fire protection goals:

- Quantities of hydrocarbon exceeding 2,000 lb inside the instrument hall shall be encased in steel or other approved material.
- Individual encasements shall not exceed 4,000 lb of hydrocarbon.
- The steel-encased hydrocarbon will withstand heat flux from an adjacent fire without escaping from the steel, considering potential thermal expansion and phase change.
- The steel assembly shall have sufficient integrity to withstand anticipated mechanical challenges of installation and lifetime maintenance activities.
- The encasement is complete except for filling holes that may either be left open or provided with rupture disks, depending on the hydrocarbon being used and the overall configuration, orientation, and structural integrity of the encasement.

Instrument stations that contain more than 4,000 lb of hydrocarbon require a documented HE to ensure instrument hall fire protection goals are achieved. The evaluation considers the type and configuration of the hydrocarbon used in the instrument design and documents whether any additional measures must be taken to limit the size of potential fires.

The target building combustible material control program ensures that the above requirements are implemented into the instrument station designs or that alternative methods are identified and provided to achieve the same fire protection goals.

3.3.13.8 Neutron Choppers

SNS instruments incorporate neutron choppers to condition neutron beams enroute from the target/moderator to the instrument sample location. Three types of neutron choppers utilized are the T_0 neutron chopper, Fermi neutron chopper, and disk neutron chopper.

A T_0 neutron chopper contains a rotating mass that is inserted into the flight path of a neutron beam. The rotor assembly contains a metallic blade that blocks the prompt neutron pulses and the gamma flash created at the instant the proton pulse hits the target, while allowing the useful thermal, or subthermal, neutrons to pass when they arrive. Two major types of T_0 choppers are used, those rotating about an axis parallel to the neutron beam and those rotating about an axis perpendicular to the neutron beam.

A Fermi neutron chopper contains a rotating drum-like payload package inserted in the flight path of a neutron beam. The payload package contains slits that, when aligned with the neutron beam, allow transmission. When not precisely aligned, the slit package is opaque to neutron transmission. As the chopper window in the payload package rotates, it allows the beam to pass through the window, effectively chopping it in time.

A disk neutron chopper incorporates a rotating mass (i.e., rotor assembly) inserted in the flight path of a neutron beam. The rotor assembly contains a neutron-blocking disk that includes a neutron-transparent angular aperture that functions to control the bandwidth of the neutron pulses enroute to the sample.

All choppers incorporate a rotating mass supported by and contained in a vacuum-tight enclosure (i.e., the chopper housing). The choppers are driven by electric motor drive systems. The rotating mass can be significant (e.g., ~200 lb) for a typical T_0 chopper and can rotate at high speeds (e.g., 600 Hz for a typical Fermi chopper).

Although the choppers attenuate some of the beam and reduce the amount of radiation flowing into the instrument hall enclosures, this beneficial effect is not credited in shielding or safety analyses.

Neutron choppers may become moderately activated and emit ionizing radiation. The choppers are shielded. Radiation safety procedures implement 10 CFR 835 [2] to ensure radiation protection for handling during replacement. Chopper materials are selected with ALARA considerations in mind to minimize activation.

3.3.13.9 Neutron Beam Monitors

Beam monitors are low-efficiency neutron detectors placed within the neutron beamline to verify and monitor the beam. These monitors often require special access through beamline shielding for routine maintenance. Such access port designs must be consistent with shielding and access requirements to limit radiation streaming and total dose.

3.3.13.10 Sample Chambers

Most neutron scattering instruments require evacuated sample chambers to provide a vacuum or controlled atmosphere around the sample. The vacuum supports the cryogenic and furnace sample environments and reduces air scattering from the direct neutron beam. These chambers are small and have thin windows, so they typically are not designed to the ASME B&PV Code. These sample chamber designs are required to meet any additional requirements identified by the ISSC.

3.3.13.11 Scattering Chambers

Many neutron scattering instruments require evacuated scattering chambers to reduce air scattering between the sample and the neutron detectors. These chambers could enclose a volume of as much as 300 m^3; therefore, careful design planning is required to ensure worker safety. The pressure differential is less than 15 psi, so these chambers are not required to meet the ASME B&PV Code or to be code stamped. However, as a good practice, they are designed to meet the ASME B&PV Code's stress level requirement. These vacuum vessel designs must also meet any additional requirements identified by the ISSC.

Some instruments may have scattering chambers filled with argon or helium gas at atmospheric pressure instead of being evacuated. Such chambers need not be designed to meet the stress level requirements of the ASME B&PV Code, but any oxygen deficiency hazards they may present must be analyzed and mitigated if necessary.

3.3.13.12 Neutron Detectors

Every instrument has one or more neutron detectors to detect the neutrons scattered from the sample in particular directions. The two primary types of neutron detectors used at SNS are helium-3 gas proportional counters and scintillator detectors using lithium- or boron-containing scintillator materials coupled to commercial photomultiplier tubes. The gas detectors contain gases at pressures up to 150 psi or more, and both types of detectors employ high voltages.

3.3.13.13 Sample Environment Equipment

Equipment that provides a special sample environment for neutron scattering experiments is accessory (or ancillary) to the scattering instruments. This equipment may consist of furnaces, cryostats, closed-cycle refrigerators, pressure bays, magnets, sample changers, or orienters. Small cranes or hoists are often necessary to move and install the ancillary equipment on or into the sample chamber. Personnel are required to receive designated levels of training before operating sample environment equipment or associated cranes or hoists.

3.3.13.14 Instrument Enclosures

Several instruments may require shielded instrument enclosures to control worker access to beamline components, including sample chambers and equipment as well as scattering chambers and detectors. The enclosure's size varies depending on space constraints and enclosed component size. Radiation levels in these areas are expected to be significant even for brief exposures during the instrument operation with beam; therefore, personnel access to these areas is restricted during instrument operation. Consistent with the SNS shielding policy [3], the design goal for instrument enclosure shielding limits radiation levels to 0.25 mrem/h at accessible areas during instrument operation. A design goal for the maximum radiation level at normally accessible locations within the enclosure when the upstream beamline shutter is closed is 2.0 mrem/h. Access to the enclosures is interlocked with the instrument PPS. This system is designed to prevent personnel access unless the beamline shutter is blocking the beam and the enclosure ventilation system, if required, is fully operational. Openings for utilities, cabling, and ventilation are designed to minimize or prevent direct line of sight into the enclosure.

3.3.13.15 Neutron Beamline Utilities

Utilities include process water, chilled water, pressurized air, gaseous nitrogen, electric power, secondary confinement exhaust, and hot off-gas exhaust as needed. These utilities are distributed along the beamline via utility trenches in the instrument hall floor. Power utilities in the beamline include the utility power and clean power. Distribution of control, interlock, and instrumentation cabling is unique to each beamline, and design is based on location constraints. However, most utilities are distributed via utility trenches within the experimental floor or within cable trays along shield walls when utility trenches are inconveniently located.

3.3.13.16 Control Hutches and Sample Preparation and Staging Areas

Every instrument has computers and electronics to control the instrument and collect data. This equipment is typically located in a small modular hutch close to the instrument. Each hutch typically contains one or two desks and several chairs for instrument staff and users to use during an experiment.

Most instruments also typically need some space near the instrument sample location to prepare samples and stage equipment. In some cases, this space is in a second modular hutch, and in other cases it is a reserved area at the instrument's floor or mezzanine level. For some instruments, certain chemical supplies must be available for sample preparation. Chemical hazards are controlled according to ORNL SBMS requirements. Radiological hazards associated with activated samples and components are controlled in accordance with the ORNL Radiological Protection program. Individual instrument teams are responsible for controlling such hazards, and periodic inspections are held to ensure that appropriate controls are maintained.

3.4 OPERATIONS

3.4.1 Organization for Operations

This section addresses operation of the target systems and operation of the neutron instruments. The overall organization and management structure of the SNS is addressed in the *FSAD-PF* [1].

Operation of the Neutron Instruments: The Neutron Scattering Division (NSD) is responsible for the safe operation and maintenance of neutron instruments. The NSD organization includes the elements necessary for safe and efficient development and use of the neutron instruments, including groups for infrastructure support and a group for each major generic type of neutron research. Each of the existing or planned 24 instruments is assigned to a generic scattering group. Within each research group, a point-of-contact (POC) scientist is assigned to each of the instruments. The POC scientist is responsible for the operation of his or her designated instrument station, including operations, safety, and functionality of the station. The POC scientist has, as needed, an assistant scientist and a scientific associate to aid in achieving safe and efficient scientific operations of the instrument station. A local contact scientist is assigned to each neutron scattering experiment to provide the user with a staff member who assumes responsibility and accountability for the experiment. The SNS Beamline Operations group supports, oversees, and coordinates activities associated with maintaining operating instruments. The team of instrument hall coordinators within the SNS Beamline Operations group provides as-needed support to the instrument scientists and users to facilitate safe and efficient conduct of research activities. Radiological control technicians support users and staff during any radiological issues, including routine sample handling and response to potentially compromised samples. Procedures and processes exist to dictate sample receipt and disposition following an experiment.

Operation of Target System: The Research Accelerator Division is responsible for safe operation of the accelerator, target, and ancillary systems. The Target and Mechanical Systems (T&MS) section within the Research Accelerator Division has the primary responsibility for safely operating and maintaining the target, cooling, and vacuum systems. Operation of these systems is closely coordinated and integrated with accelerator and other site operations to ensure coordinated and safe operation of the entire SNS facility. The proton facilities and neutron facilities are both operated from the integrated CCR within the CLO building. Target systems may also be operated from the TCR. Only qualified personnel are allowed to operate target building equipment and systems.

The T&MS section includes the Target Operations group, Cooling Systems group, Target Systems group, and the Vacuum Systems group in addition to other administrative and professional staff. The responsibilities of this organization are described as follows.

The Section Head for T&MS is responsible for the safe and efficient operation and maintenance of the target and its support systems, cooling systems, and vacuum systems, in addition to functioning as the manager of the section. The Section Head is responsible for ensuring that individuals within the Target Operations group performing work are properly trained and equipped to accomplish the work safely and effectively. In this capacity, the Section Head establishes the level of training required for particular job assignments.

The Target Operations group is responsible for continuous operation of the target and support systems. The group leader is responsible for managing and coordinating activities of the shift operator team. The on-duty OST is responsible for operating, monitoring, and troubleshooting the target and support systems.

The OST functions as a member of the SNS integrated CCR staff. During target operations, the OST operates systems and monitors parameters from one of the control rooms. The OST is also responsible for conducting rounds and troubleshooting system problems. OSTs are properly trained to operate the integrated target systems and are certified to stand a shift alone.

The Target Systems group leader is responsible for managing and coordinating the activities of the team:

- Remote handling technicians perform the remote handling operations and maintenance required for the target and support systems.
- Facility technicians conduct maintenance, preventive maintenance, troubleshooting, repairs, and replacements of target and support systems.
- Bargaining unit personnel (matrixed or assigned) perform the craft work and maintenance activities.
- System engineers provide technical assistance to target operations, assisting in configuration management, evaluating ongoing system performance, recommending needed modifications and actions to correct operational issues, and providing engineering support associated with maintaining a system and improving performance and reliability. Some system engineering support is matrixed to the target systems group to ensure proper coverage.

The Cooling Systems group consists of a group leader responsible for managing of a team of engineers, designers, and technicians and coordinating their activities including:

- Operation and maintenance of accelerator cooling systems
- Operation and maintenance of the SNS Central Utilities Building providing heated water, chilled water, compressed air, and other utilities for the SNS site
- System engineering support providing technical assistance to operations, assisting in configuration management, evaluating ongoing system performance, recommending needed modifications and actions to correct operational issues, and providing engineering support associated with maintaining a system and improving performance and reliability.

The Vacuum Systems group consists of a group leader responsible for managing a team of engineers and technicians and coordinating their activities including:

- Operation and maintenance of accelerator, target and instrument vacuum systems
- System engineering support providing technical assistance to operations, assisting in configuration management, evaluating ongoing system performance, recommending needed modifications and actions to correct operational issues, and providing engineering support associated with vacuum system performance and reliability.

3.4.2 Procedures

Operation of the target and support systems (e.g., mercury loop, cooling water loops, moderator systems, PCE system) is performed in accordance with written operating procedures. Operating procedures are reviewed, approved, revised, and controlled according to approved policy.

Operating procedures provide instructions (required and/or suggested as warranted) to workers regarding the performance of activities, operation of equipment, or implementation of processes. In addition to the procedures specifically identified as CACs in Section 5, operating procedures include internal operating procedures (both technical and administrative), operator aids, and guidance from technical manuals and industry standards.

Site-wide procedures are included in the OPM, which can be accessed through a local website.

ORNL SBMS provides instructions for procedure and program development. Procedures are written and reviewed by technical and program experts. The level of review is tailored to ensure safety, technical accuracy, and program compliance. Once reviewed, approved, and issued for use, a controlled copy of the procedure is entered into the OPM. Procedures are controlled: revisions to an existing procedure will undergo appropriate review.

Emergency response procedures are used to assist the operations team to respond to unplanned events that could directly or indirectly affect personnel safety. The emergency response procedures provide an added margin of safety to target facility personnel and site personnel by ensuring prompt, decisive action is taken during abnormal events.

To supplement emergency response procedures, the *Target Facility Emergency Response Plan* has been developed using the ORNL SBMS guidelines. As directed by the SBMS, the *Emergency Response Manual* commissions a team to respond to emergency situations. The team coordinates event response activities to ensure personnel safety while mitigating any damage to the target facility and the environment. The manual also briefly describes the facility population, operational processes, facility equipment, and potential hazards. A list of key personnel to be notified and response team training requirements are also included.

3.4.3 Training and Qualification

NSD has jurisdiction over the operation of neutron scattering instruments. All personnel conducting experiments with and/or working on neutron scattering instruments and supporting equipment are appropriately trained and qualified to do the assigned work. Users (non-SNS employees) are trained for the activities they are allowed to perform and are supervised by assigned members of NSD (Section 3.4.7).

The Training and Qualification Program for the target OSTs is designed to ensure that they are qualified to perform their routine duties, respond to abnormal events, and mitigate any associated consequences.

The Training and Qualification Program is derived from industry standards, including conduct of operations, best management practices, and applying a tailored approach as appropriate.

The program is based on the “Systematic Approach to Training,” a recognized industry model that uses job requirements and performance-based criteria as the basis to ensure consistency, efficiency, and effectiveness. The training program ensures that OSTs are qualified to perform their job; are aware of relevant hazards, controls and work requirements; and understand the effect their activities may have on the facility. The program includes initial training and periodic retraining to maintain proficiency consistent with assigned duties.

The work control process described in Section 3.4.5 ensures that workers have required task-specific training or qualification prior to working on system/components designated as CECs (described in Section 5) and before working on systems/components with significant hazards.

The Training and Qualification Program specifically addresses the following required training topics specifically designated as CACs in Section 5:

- Emergency response procedures for a fire event while accessing the transfer bay with the personnel door open.

- Emergency response procedures for a fire event during maintenance activities when the target service bay, transfer bay, and high bay are open to a common air flow.
- Emergency response procedures for an external crane load drop on the target facility.

Qualification is a combination of education, experience, training, examination, and any special requirements necessary for individuals to perform their duties. Qualification requirements are based on industry standards and are determined by the organization and its needs. An individual's qualification is determined by comparing the individual's education and experience to the job requirements. When the deficiencies are identified, training is provided to meet those requirements.

Line management is responsible for training and qualifying operations personnel. Line managers review training material and participate in the final evaluation of shift operations personnel. Line management evaluates the training and qualification program to ensure it meets the organization's needs.

The training program defines the training requirements (e.g., classroom, demonstration of proficiency, knowledge objectives) and how the specific competencies are demonstrated (e.g., written test, performance demonstration, oral interview).

System-specific training combined with use of qualified personnel operating target systems and appropriately detailed and approved procedures minimize risks associated with operating potentially significantly hazardous systems, including the mercury loop, water cooling loops, service bay ventilation system, and the CMS. All operations activities involving such systems will be conducted by qualified operations personnel in accordance with approved procedures.

For example, activities such as startup, shutdown, CMS hydrogen filling, and hydrogen purging require verbatim compliance with approved procedures. Critical mode changes and transient conditions will be governed by approved procedures that set limits and describe sequential steps while allowing the shift technician the flexibility needed to make operational adjustments and optimize the CMS performance.

All OST team members will receive training during their initial qualification. Recurring training on the CMS will continue to ensure that OST team members receive refresher training to promote safe, efficient operation of key systems.

Area access training is provided to ensure all unescorted personnel in areas adjacent to the service bay are trained to respond appropriately to events and alarms such as the SBDPMS alarm. The target facility has badge-controlled access points arranged in layers around the service bay. Areas closer to the service bay are more likely to be affected by an accident scenario, so these areas have increased training requirements. These training programs are focused on hazard awareness, response to events and alarms, and CEC awareness.

A CEC system engineer is identified for each CEC in Section 5. They are trained and qualified to serve as the primary owner of the CEC under their purview, including familiarization with the FSADs and ASE with a focus on the basis and requirements for their CEC. The system engineers play a key role in the configuration control of CECs, as described in the following subsections.

3.4.4 Configuration Control Program

Each CEC has a designated CEC system engineer who is responsible for ensuring configuration control of the assigned CEC. These system engineers are intimately involved in every step of the process including design, fabrication, installation, operation, and maintenance. System engineers typically execute the administrative programs for configuration control and screen work and changes for potential unreviewed safety issues (USIs). They interface with quality assurance personnel to ensure the installed CEC and associated spares are appropriately controlled using the SNS quality program throughout procurement, fabrication, receipt, installation, and repair.

CEC configuration control is ensured by a combination of administrative programs appropriate to the type of change considered. Long-lead items are controlled by procedures that govern how engineering is conducted. Items of a more immediate nature and the installation phase of long-lead engineered modifications are managed as part of the work control process as described in the next subsection.

The administrative programs that accomplish configuration control examine proposed work that could affect CECs using a tailored approach that recognizes the safety function of the CEC and assigns a level of change control or approval that is commensurate with that safety function. Assessing for a USI is integral to the configuration control process.

This program assigns roles and responsibilities that involve the associated operations group and the systems engineer/design authority in a structured approach that clearly identifies the proposed work, evaluates it relative to change, identical replacement, or repair/replacement, and acquires approvals appropriate for that scope of work and safety function.

Design features are normally passive characteristics of the facility not subject to change by operations personnel (e.g., structural walls, relative locations of major components). Review of changes to these systems is controlled by the USI process in conjunction with the engineering and work control related processes that ensure configuration control. Evaluated changes or aspects of change include those that affect the required seismic qualification of CECs. This program ensures that the appropriate seismic protection remains in place following normal maintenance or facility modification and ensures that the seismic protection is not lost based on component degradation or failure.

The following passive design features require control under the Configuration Control Program:

- CMS hydrogen barrier (includes impact and seismic protection of CMS outside the core vessel),
- Core vessel and neutron beam windows,
- Service bay/core vessel fire barrier (isolation and 2 h equivalent fire barrier functions),
- Target service bay and monolith (confinement of mercury),
- Primary confinement exhaust ductwork from service bay to the sulfur-impregnated charcoal filter and associated backdraft dampers,
- CMS vacuum barrier,
- High bay crane design,
- High bay floor design,
- Mercury pump tank exhaust loop seal,
- Robust mercury heat exchanger,
- Mercury pump tank rupture disk and discharge path,
- Mercury pump tank exhaust line loop seal and orifice,
- Cryogenic moderator system catalytic converter retention elements.

Configuration control of active CECs is maintained under approved OPM procedures. The Target Operations group controls safety-related keys (e.g., TPS and target PPS), including keys required to enter target and instrument PPS–controlled areas and keys for entry into the transfer bay. Key accountability, custody, and custody transfer is be tracked via logbook. Keys not in use are placed in a lock box controlled by the on-duty OST and instrument hall coordinator. The key codes for these spares are unique (not used by any existing key). If a key is lost, then the cylinder will be replaced with a new uniquely coded spare. The old code will be marked as lost in the tracking database and will not be reused (the type of trapped key used by SNS has 625 unique codes).

3.4.5 Work Control

The work control program, described in the SNS work control document [24], ensures that jobs are planned and approved based on their importance to safety and their potential effect on CECs. Each individual task/system is screened, and work planning and control are administered using a tailored approach. The work control process follows the principles of ISM: (1) define the work and associated hazards, (2) develop and implement appropriate hazard controls, (3) perform the work within the controls, and (4) provide feedback on the work to improve the process. The work control process also ensures that individuals working on systems are properly trained to safely perform the required work.

Work on CECs requires a more rigorous routine than work on other components and systems, and this requirement is built into the work control process. Typically, the CEC system engineer owns work planning on this type of system. Operations, maintenance (including individuals directly involved in accomplishing the work), and engineering design are also involved, ensuring that safety functions and controls are recognized and maintained. Other disciplines are involved at the option of this core planning team based on the nature of the work. Furthermore, postmaintenance testing is specified as needed to confirm the proper operation of the serviced system/component.

Work control also involves the identification and control of potential hazards to both the worker and to the equipment being serviced. Work involving systems with significant hazard potential requires special considerations, including a more in-depth review and the identification of controls and work restrictions as needed. For example, potential hazards associated with work on the CMS include not only the release/ignition of hydrogen gas in the vicinity of the worker but also the purging of hydrogen from the entire system if the work requires opening the hydrogen boundary.

The rigor of maintenance procedure detail/usage and worker training requirements are also tailored depending on the safety and operational implications of the system being worked on and/or the task being performed. This approach ensures worker safety, proper work execution, and system acceptance.

3.4.6 Instrument Review Process

The ISSC reviews the initial design and proposed changes to instruments.

Each neutron beam instrument must satisfactorily undergo an instrument readiness review before the instrument operates with neutron beam. This review is conducted by an expert ISSC selected by and reporting to the SNS operations manager. Each instrument readiness review is intended to verify that the instrument is safe to operate and covers in detail the hazards specific to that instrument and the mitigation strategies used for that instrument. Particular emphasis is placed on review of radiation protection, including shielding design and configuration control, and the appropriate control measures such as the instrument-specific features of the PPS. However, other industrial hazards such as oxygen deficiency, vacuum, and cryogenic systems are also reviewed as appropriate to the specific instrument. The review also covers instrument operation and maintenance procedures along with staff and user training for instrument operation. Instrument reviews are repeated for a significant change to the beamline configuration or operations. Experiments to be performed on the instruments may involve chemical, cryogenic, high-pressure, and magnetic-field hazards. These experiments are not considered to be inherent parts of the instruments and are subject to a separate experiment review process.

Each instrument is used for a variety of scientific measurements or experiments. All experiments must be approved via the SNS experiment review process to ensure appropriate screening and review of all proposed experiments.

3.4.7 Scientific Instrument Users at Spallation Neutron Source

SNS is a user facility: most of the time available on individual neutron scattering instruments is assigned to researchers (users) via a peer-reviewed proposal system. Proposals are reviewed internally for experimental feasibility. These evaluations combined with the recommendations of a panel assessing the scientific impact are used to award beam time to investigators. All approved proposals are reviewed internally for safety.

SNS is expected to ensure the safety of these researchers while enabling them to control their measurements as fully as possible. Use of SNS instruments by ORNL or external scientific investigators is governed by SNS policies and procedures. An appropriate level of training is a key element to safe operation of a user facility. The NScD User Office oversees the general training required of users for unescorted access into the target building and is the central repository for user training records. Training specific to the operation of individual neutron scattering instruments is organized by the relevant instrument team and is tracked in the user training records. Additional training may be needed to handle samples and to operate sample environment equipment. This training is also organized by the instrument team and similarly tracked. The training program is reviewed and approved at the appropriate division level.

As a user facility, SNS receives or prepares many experimental samples in a variety of forms. All experiments are screened and receive appropriate safety review. Samples are handled and stored appropriately. Radiological and hazardous material requirements are followed. Before a sample is placed into a neutron beam, a plan must be developed to address the final disposition of the sample, which is usually discarded as waste or shipped to the user. Shipment of such samples follows established SBMS procedures.

Once a sample or other equipment has been exposed to a flux of neutrons, it must be assumed to have some residual radioactivity. Before a sample is placed into a neutron beamline, its expected neutron activation should be evaluated. If this evaluation yields an acceptably low level, confirmed by radiation detectors (process instrumentation) upon withdrawal from the sample location in the neutron beamline, then handling of the sample or its container can be accomplished by the user (with appropriate training) near the neutron scattering instrument. Minimal sample storage is maintained in a properly posted and controlled area near each neutron scattering instrument. Upon completion of a series of measurements, samples are expected to be transferred to a central storage area in the target building.

SNS staff are responsible for ensuring that samples or equipment have been appropriately cleared before they leave the target building. *Appropriately cleared* means surveyed and/or smeared and tagged by the radiological control technicians and either cleared for normal handling (following established procedures and guidelines) or arrangements made for shipping as a radioactive material. Furthermore, users are allowed to move uncleared irradiated samples only in the immediate vicinity of the instrument they are using. Any other movement of irradiated samples within the target building (e.g., to a central locked area for short-term decay) must be done by trained SNS staff. Handling unencapsulated radioactive samples capable of spreading loose contamination (e.g., liquids or powders) requires appropriate equipment and a higher level of training. Once a sample has been cleared for residual activity, it can be handled in a fashion appropriate to its other possible hazards.

3.5 REFERENCES

1. *Spallation Neutron Source Final Safety Assessment Document for Proton Facilities*, SNS 102030103-ES0018-R02, Oak Ridge National Laboratory, Oak Ridge, Tennessee, December 2010.
2. 10 CFR 835, "Occupational Radiation Protection," *Code of Federal Regulations*, US Government Printing Office, Washington, D.C.
3. *Spallation Neutron Source Shielding Policy*, SNS 102030000-ES0008, Oak Ridge National Laboratory, Oak Ridge, Tennessee, November 2005.
4. *ORNL Necessary and Sufficient Standards for Environment, Safety, and Health, Summary Report of the Identification Team for Engineering Design of Standard Industrial, Radiological, Non-Reactor Category 2 and 3 Nuclear, and Accelerator Facilities, Oak Ridge National Laboratory*, Oak Ridge National Laboratory, Oak Ridge, Tennessee, March 1998.
5. *Final Report: ORNL Necessary and Sufficient Process Work Smart Standards for Environment, Safety, and Health, Report of the Identification Team for Construction and Construction-Like Activities*, Oak Ridge National Laboratory, Oak Ridge, Tennessee, March 1997.
6. *SNS Standards for Design and Construction of the Target Facility,* SNS 102030102-ES0012-R2, Oak Ridge National Laboratory, Oak Ridge, Tennessee, October 2002.
7. *Life Safety Code*, NFPA-101, National Fire Protection Association, 1997.
8. *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities*, DOE-STD-1020-94, US Department of Energy, Washington, D.C., Change Notice 1, January 1996.
9. *Natural Phenomena Hazards Performance Categorization Guidelines for Structures, Systems, and Components,* DOE-STD-1021-93, US Department of Energy, Washington, D.C.
10. *Natural Phenomena Hazards Characterization Criteria,* DOE-STD-1022-94, US Department of Energy, Washington, D.C., Change Notice 1, January 1996.
11. *Natural Phenomena Hazards Assessment Criteria*, DOE-STD-1023-95, US Department of Energy, Washington, D.C., Change Notice 1, January 1996.
12. *SNS Seismic Basis of Design, Volume I Target Facility and Equipment*, SNS 10203010-ES0004-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, March 2004.
13. Deleted.
14. K. W. Childs, *Thermal Calculations of Mercury Process System Collection Basin*, SNS Design Analysis Calculation SNS-106010202-CA0005-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, October 2001.
15. *Fire Hazards Analysis, Target Building, Buildings 8700, 8702, 8711, and 8760 at SNS, Rev 0*, SNS 108030700-ES0008-R00, December 31, 2008.
16. *Boiler and Pressure Vessel Code*, ASME, Section VIII, American Society of Mechanical Engineers.
17. *Facilities Handling Radioactive Materials*, NFPA 801, National Fire Protection Association 1998.
18. *Standard Building Code (SBC)*, Southern Building Code Congress 1997.
19. *Volume Capacity of the Core Vessel Drain Line*, SNS Design Analysis Calculation, SNS 106040100-DA0014-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, June 2002.
20. *Mercury Process System Mercury Operational Parameters Final Design*, SNS Design Analysis Calculation, SNS 106010202-DA0018-R01, Oak Ridge National Laboratory, Oak Ridge, Tennessee, March 2006.

21. Mercury Inventory Control Sheet, May 2016.
22. *Two-Dimensional Shielding Analysis of the SNS Target Station Shutters, Shutter Beam Stops, Un-instrumented Neutron Beamlines, and Biological Shielding Monolith*, 106100200-DA0001-R01.
23. Standard on Water Mist Fire Protection Systems, NFPA-750, National Fire Protection Association, 1996.
24. *Spallation Neutron Source Site Work* Control, SNS 108000000-PR0061, R01, Oak Ridge National Laboratory, Oak Ridge, Tennessee, March 2006.

4. HAZARD AND ACCIDENT ANALYSES

4.1 INTRODUCTION

This section describes the process used to systematically identify hazards associated with the operation of the SNS neutron facilities and the controls needed to mitigate risks to workers, the public, and the environment. A tailored approach has been used for the hazard and accident analysis commensurate with the magnitude and types of hazards present and with the complexity of the facility.

The HA assesses process-related, external, and NPH events. Potential hazards have been identified and categorized as either standard laboratory and industrial hazards (also referred to in this section as “common” hazards) that can be safely managed by the existing ORNL Integrated Safety Management (ISM) programs or as accelerator specific hazards that warrant additional analysis and controls to mitigate adequately. Standard laboratory and industrial hazards are evaluated for the potential to serve as initiators or contributors to accelerator accidents.

The process for the identification and evaluation of potential hazards is presented in Section 4.2. Section 4.3 focuses on hazards associated with a wide range of postulated events and identifies credited controls required to protect workers. The analyses also identify postulated events with the potential for offsite impacts. Section 4.4 presents the offsite impact analyses, and Section 4.5 summarizes the credited controls. Environmental protection is addressed in Section 4.6.

Credited controls selected to mitigate specific hazards are not the only layer of protection. The facility design, structured operational practices, and ORNL ISM programs are also key elements in providing extra layers of safety. Much of the initial hazard and accident analysis for SNS was completed before the more recent versions of the DOE accelerator safety order and implementation guide were issued [2,3]. During the SNS design phase, the decision was made to develop the initial safety documentation in accordance with DOE-STD-3009-94 [1], which also influenced safety-related design decisions. A comprehensive hazard identification and evaluation document was developed [18], and this document served as the basis for the initial analyses. Since that time, revisions have been issued to maintain this document up to date.

The analyses show that SNS can be operated without undue risk to the workers, the public, or the environment. The information contained in this section supports the conclusion that the facility can be operated safely in conjunction with the identified controls.

<u>Requirements, Guidance and Standards</u>

Requirements for performing the analyses presented in this section are contained in DOE Order 420.2D [2]. DOE Guide 420.2-1A [3] presents guidance that has been followed for the HA. Although not required for an accelerator facility, methodology presented in DOE-STD-3009 [1] was used as a basis for much of the analysis for SNS.

Chemical screening was performed by identifying the chemicals present in amounts exceeding the threshold planning quantity listed in the *Emergency Planning and Notification*, 40 CFR 355 [5]; the threshold quantity listed in *Risk Management Programs for Chemical Accidental Release Prevention*, 40 CFR 68 [6]; the reportable quantity listed in the *List of Hazardous Substances and Reportable Quantities*, 40 CFR 302.4 [7]; or the threshold quantity listed in *Process Safety Management (PSM) of Highly Hazardous Chemicals*, 29 CFR 1910 [8]. Neither [6] nor [8] apply to metallic mercury. However, SNS has target mercury is in excess of the [5] threshold quantity (1 lb or 0.453 kg). Early in the project lifetime, it was deemed appropriate to consider target mercury vapor as a special hazard because the target system involves a significant quantity of mercury (~1.4 m^3) undergoing significant energy deposition (~2 MW). Beryllium is present as a reflector material; however, it is encapsulated in an aluminum case, and no credible accidents were identified that could disperse the beryllium, so it is not addressed further in the HA. ORNL ISM programs as promulgated through the SBMS directly address chemical safety and are more than adequate to control risk associated with on-site chemical usage.

The design basis criteria for natural phenomena are based on DOE Order 420.1A [9]; DOE-STD-1020-94, *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities* [10]; DOE-STD-1021-93, *Natural Phenomena Hazards Performance Categorization Guidelines for Structures, Systems, and Components* [11]; and DOE-STD-1022-94, *Natural Phenomena Hazards Characterization Criteria* [12]; DOE-STD-1023-95, *Natural Phenomena Hazards Assessment Criteria* [13]; and DOE-STD-1024-92, *Guidelines for Use of Probabilistic Seismic Hazard Curves at Department of Energy Sites for Department of Energy Facilities* [14].

The NPH design requirements were applied to the structures, systems, and components required to meet PC-2 demand loads to ensure the safety function was provided (i.e., PC-2 demand load analyzed with PC-3 technique or full PC-3 qualification).

Design codes, building standards, and regulations are discussed in Section 3. The governing design codes and standards applicable to SNS are specified in *Spallation Neutron Source Standards for Design and Construction of the Target Facility* [15].

4.2 HAZARD ANALYSIS METHODOLOGY

This section presents the methodology used to perform the hazard and accident analysis for the SNS target facility excluding instrument beamlines. The approach involves the systematic analysis of potential process-related natural phenomena, and external hazards that could affect the public, site workers, and the environment owing to single or multiple failures. The analysis considers the potential for equipment failure and human error.

The HA includes a thorough, predominantly qualitative evaluation of the spectrum of risks to site workers, the public, and the environment caused by accidents involving identified hazards. The HA comprehensively addresses the following:

- Identification of hazards associated with potential events, event initiators, and dominant scenarios.
- Estimation of the risk associated with the hazards.
- Identification of necessary preventive and mitigative controls.

Informed, qualitative estimates of consequences and frequencies are performed in the HA such that attention can be focused on the highest-risk scenarios. Section 4.2.1 describes the comprehensive process used to identify potential hazards, and Section 4.2.2 discusses the evaluation process used to identify potential events that could affect workers, the public, or the environment. Criteria for determining whether an event requires mitigative credited controls are also addressed in Section 4.2. Section 4.3 presents the HA for each potential event determined to have significant risk potential.

Details of the hazard identification and evaluation performed for SNS are presented in the report, *SNS Target Facility Hazard Identification and Evaluation* [18].

4.2.1 Hazard Identification

The SNS HA team included representatives from the following disciplines:

- Hazard and accident analysis,
- Selection of credited controls,
- Facilities and systems engineering,
- Design,
- Operations.

The hazards associated with the target facility were systematically identified by listing hazardous materials, energy sources, and their locations in tables. This screening was based on DOE-STD-1027, *Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23* [17], which states that "The Hazard Analysis process consists of the identification of the relative and absolute hazards of the materials in a facility. The objective is to focus the safety assessment effort on those hazards which have the potential to present significant, non-routine concerns to the worker, the public, and the environment." Hazard identification tables provide a rigorous method of identifying hazards. The tables list hazardous energy sources and include the information listed in Table 4.1 used to evaluate each system.

Except for hazards that could cause a worker to experience breathing air with oxygen concentration below 12.5 vol %, screening was performed to eliminate material/energy types and quantities considered standard industrial or common hazards. Common hazards must be addressed in facility design and operational practices and are not specifically addressed in the hazard or accident analysis. Common hazards, although screened out for further study, were evaluated as possible mercury release event initiators.

Hazard identification was divided into three steps: (1) division of the facility into sections, (2) facility/information walkdowns, and (3) identification of common hazards. The hazard identification tables list identified hazards and corresponding locations for each section identified for the target facility. These hazard identification tables are provided as a key basis document supporting the HA presented in this section. The hazard identification tables guide event definition and affected-system evaluation. The historical initial hazard identification and evaluation document developed during early project HA efforts is documented in the *Hazard Analysis for the Spallation Neutron Source Target System* [17].

Division of the Target Facility

To facilitate hazard identification, the SNS target building was divided into five sections. These sections were based on the physical locations of the various rooms or areas, their contents, flow of material in the building, and, in some cases, equipment functions. The sections for the SNS target facility are as follows:

- Target assembly,
- Service bay,
- Basement utility vault,
- High bay,
- Target building balance of plant.

Table 4.1. Screening list for hazard analysis

Electrical • Battery banks • Cable runs • Diesel generators • Electrical equipment • Hot plates • Heaters • High voltage • Locomotive, electrical • Motors • Pumps • Power tools • Switchgear • Service outlets, fittings • Transformers • Transmission lines • Underground wiring • Wiring *Open Flame* • Bunsen burners • Torches • Pilot lights • Gas welding *Firearm Discharge* *Explosion* *Power Outage* *Aircraft Crash* *Transportation* *Fire*	*Thermal* • Bunsen burner, hot plate • Electrical equipment • Furnaces • Boilers • Lasers • Electrical wiring • Welding surfaces • Engine exhaust • Heaters • Steam lines • Welding torch • Exothermic reactions *Combustible Materials/ Flammable Materials* • Flammable gases • Natural gas • Spray paint • Compressed flammable bases • Propane • Paint solvent • Cleaning/decontam-ination solvents • Gasoline • Flammable liquids • Flammable mixtures	• Explosive/pyrophoric • Explosive gas • Dynamite • Sodium • Hydrogen (batteries) • Primer cord • Electric squibbs • Nitrates • Dusts • Peroxides • Caps • Plutonium/uranium • Potassium • Superoxides • Hydrogen/tritium • Propane • Explosive chemicals • Radiological material • Ionizing radiation • Fissile material • Radiography equipment • Electron beams • X-ray machines • Critical masses • Contamination • Radioactive materials • Radioactive sources	*Hazardous Materials* • Alkali metals • Asphyxiants • Acetone • Fluorides • Lead • Drowning • Asphyxiation • Ammonia and compounds • Beryllium and compounds • Chlorine and compounds • Trichloroethylene • Decontamination solutions • Dusts and particles • Sandblasting particles • Metal plating • Herbicides • Insecticides • Bacteria • Viruses • Biological • Carcinogens • Oxidizers • Corrosives • Other toxics
Kinetic – Linear and Rotational (Friction) • Belts • Bearings • Presses • Grinders • Crane loads (in motion) • Vehicles • Rail cars • Forklifts • Carts • Dollies • Centrifuges • Drills • Saws • Shears • Fans • Gears • Motors • Power tools	*Natural Phenomena* • Earthquake • Flood • Lightning • Rain • Snow, ice • Freezing weather • Straight wind • Tornado *Vehicles in Motion* • Airplane • Helicopter • Train • Heavy construction equipment • Truck/car • Forklift/lift truck	*Potential (Pressure)* • Gas bottles • Gas receivers • Pressure vessels • Coiled springs • Boilers • Heated surge tanks • Autoclaves • Furnaces • Stressed members • Steam headers/lines *Potential (Height/Mass)* • Stairs • Lifts • Cranes • Elevated doors • Loading docks • Hoists • Elevators • Trucks • Jacks	*Potential (Height/Mass) continued* • Scaffolds and ladders • Pits • Elevated work surfaces • Mezzanines

Facility Walkdowns

A conceptual walkdown of the facility, with the support of subject matter experts, was used as an aid in identifying potential hazards. Documents associated with the proposed design and operations functions of SNS were reviewed with the HA team. The initial conceptual walkdown included review of facility-related documents listed in the reference section of [18], which is provided as a historical reference only.

As a part of the hazard identification process, the team compiled a preliminary inventory of all known radiological and chemical hazards as presented in Appendix C of [18]. Because the initial HA was performed during the preliminary design phase, numerous assumptions and engineering judgments were made in approximating some of the hazardous material inventory information.

Screening of Common Hazards

The HA team examined each identified hazard for each section to determine its potential contribution to events resulting in release of radiological material or hazardous energy. If the identified hazard did not meet the screening criteria for identification as a common hazard, then the hazard was carried forward through the complete HE process.

Initial Conditions

Initial conditions within the HA were based on the *National Spallation Neutron Source Conceptual Design Report* [19], the *Construction and Operation of the Spallation Neutron Source—Final Environmental Impact Statement* [20], the *Spallation Neutron Source Design Manual* [21], interviews with system designers, and analyst judgment. These initial conditions were maintained current within the inputs and assumptions document that has been the basis for the SNS hazard and accident analyses and with subsequent updates. Updated inputs and assumptions are detailed elsewhere [22]. The initial conditions used in the HA are listed in the scenario summary for each system.

4.2.2 Hazard Evaluation

HE ensures a comprehensive assessment of facility hazards and focuses attention on those events that pose the greatest risk to the workers, the public, and the environment.

The HE is presented in tabular form elsewhere [18] and includes the following information:

- Event number and event category,
- Event description, cause, and unmitigated initiating event frequency,
- Unmitigated impact on systems,
- Unmitigated consequences (and risk bin),
- Preventive features (design and administrative),
- Method of detection,
- Mitigative features (design and administrative),
- Planned accident analysis,
- Credited engineered and administrative controls,
- Mitigated consequences.

4.2.2.1 Event Categories and System/Area Groupings

Events are numbered to provide each with a unique reference. The numbering system mnemonically identifies each facility section, system, or area. For example, the service bay (formerly identified as the target cell) is abbreviated as TC in the HE table. Following the two-letter designation, events are then numbered according to the event category followed by a sequence number. For example, event TC2-3 indicates the service bay, event category 2 (explosion), event number 3.

Events are categorized according to the nature of the postulated release mechanism. A standard list of event categories, based on those given in Appendix C of DOE/TIC-11603 [23], is used. The event category number is also included in the third alphanumeric position of the event number. This categorization scheme labels the various types of postulated events and plays no part in the subsequent identification of preventive or mitigative controls. The event categories are listed in Table 4.2.

Table 4.2. Event categories

Event category	Event category description
E-1	Fire
E-2	Explosion
E-3	Loss of containment or confinement
E-4	Direct radiological/chemical exposure
E-5	Nuclear criticality (not applicable to SNS)
E-6	External hazards
E-7	Natural phenomena

The systems presented in the HE tables were defined as groups based primarily on the specific system and its function. Once each system or area grouping was established, it was given a two-letter mnemonic for use as part of the event identification. The system/area groupings are listed below:

- Target system (TS),
- Cryogenic moderator system (CM),
- Cooling water loops 2, 3, and 4 (CW),
- MOTS and core vessel vacuum and helium systems (GW),
- Process waste and sanitary waste systems (PW),
- Contact waste handling and decontamination area (WH),
- Confinement ventilation systems (HV),
- Core vessel general area, including shielding, reflectors, and shutters (SH),
- Service bay general area (TC),
- Beam dumps (BD) (addressed in FSAD-PF),
- High bay area (HB),
- Compressed air system (CA),
- Fire detection and suppression system (FS),
- Truck bay and utility vault general area (UV),
- Target building general (BG).

4.2.2.2 Unmitigated Initiating Event Frequency

The frequency level is recorded in the HE tables according to the DOE-STD-3009-94 [1]–based lettering scheme given in Table 4.3. Sources of frequency information, including generic initiator databases were used, including judgment by experts. The basis for the table is derived from “Rates of Initiating Events at U.S. Nuclear Power Plants: 1987–1995” [24].

Table 4.3. Initiating event frequency evaluation level

Event frequency code	Description	Estimated annual frequency of occurrence (year^{-1})
Anticipated (A)	Accidents that may occur several times during the life cycle of the facility (accidents that commonly occur).	$\geq 10^{-2}$
Unlikely (U)	Accidents that are not anticipated to occur during the life cycle of the facility. Natural phenomena of this probability class include Uniform Building Code–level earthquake, 100-year flood, maximum wind gust.	10^{-4}–10^{-2}
Extremely unlikely (EU)	Accidents that will probably not occur during the life cycle of the facility. This class includes the design-basis accidents.	10^{-6}–10^{-4}
Beyond extremely unlikely (BEU)	All other accidents.	$<10^{-6}$

4.2.2.3 Unmitigated Consequences (and Risk Bin)

Unmitigated consequences are categorized in accordance with Table 4.4 for offsite and on-site receptor locations to assess health effects associated with the postulated event. On-site receptors include workers inside of the facility (Onsite-1) and workers outside of the facility (Onsite-2).

Table 4.4. Radiological consequence evaluation levels for hazard receptors

Consequence level	Off-site receptor	On-site receptor
High (H)	≥25 rem	≥100 rem
Moderate (M)	$5 \leq C < 25$ rem	$25 \leq C < 100$ rem
Low (L)	$0.5 \leq C < 5$ rem	$5 \leq C < 25$ rem
Negligible (N)	<0.5 rem*	<5 rem

*Note: At the time of this analysis, the applicable Accelerator Facility Safety Implementation Guide [3] used a value of 1 rem. The analysis presented here has retained the lower value.

Offsite Offsite receptors are individuals outside the reservation boundary and members of the public.

Onsite-1 Onsite-1 receptors are workers inside the facility. This category of receptors includes those workers in the immediate area of the hazard and those workers in the same room or building who may not be aware of the hazardous condition.

Onsite-2 Onsite-2 receptors are workers outside the facility but within the site boundary. For evaluation purposes, these workers are located outside the last possible barrier from the hazard and at the worst possible location. Doses are calculated for the Onsite-2 receptor 100 m from the hazard and are used to guide the evaluation of worker consequences depending on the location, consistent with the policy for selection of credited controls [4].

Anyone within the site boundary is evaluated as a worker. Travelers on Bethel Valley Road are an exception and, as discussed in Section 4.4 of this document, are treated as public. This special treatment provides the analysis necessary should DOE determine that it is acceptable to reopen Bethel Valley Road to uncontrolled access by the public.

Risk Bins

Figure 4.1 and Figure 4.2 are risk bin matrices for the three receptor locations (i.e., off-site and both Onsite-1, and Onsite-2) for radiological risk. They define bins in frequency–consequence space. Those events that were binned for further consideration and control selection were evaluated against the requirements for safety controls established in an early version of the *SNS Policy for Selection of Safety Related Credited Controls* [4]. The figures were historically used to guide design and analysis decisions.

<table>
<tr><th>Frequency→
consequence
↓</th><th>Beyond extremely unlikely
$<10^{-6}$/y</th><th>Extremely unlikely
10^{-6}–10^{-4}/year</th><th>Unlikely
10^{-4}–10^{-2}/year</th><th>Anticipated
$\geq 10^{-2}$/year</th></tr>
<tr><td>High</td><td>10</td><td>7</td><td>4</td><td>1</td></tr>
<tr><td>Moderate</td><td rowspan="2">11</td><td>8</td><td>5</td><td>2</td></tr>
<tr><td>Low</td><td>9</td><td>6</td><td>3</td></tr>
<tr><td>Negligible</td><td colspan="4">11</td></tr>
</table>

Figure 4.1. Unmitigated risk binning matrix—off-site receptors (radiological).

<table>
<tr><th>Frequency→
consequence
↓</th><th>Beyond extremely unlikely
$<10^{-6}$/y</th><th>Extremely unlikely
10^{-6}–10^{-4}/year</th><th>Unlikely
10^{-4}–10^{-2}/year</th><th>Anticipated
$\geq 10^{-2}$/year</th></tr>
<tr><td>High</td><td>10</td><td>7</td><td>4</td><td>1</td></tr>
<tr><td>Moderate</td><td rowspan="2">11</td><td>8</td><td>5</td><td>2</td></tr>
<tr><td>Low</td><td>9</td><td>6</td><td>3</td></tr>
<tr><td>Negligible</td><td colspan="4">11</td></tr>
</table>

Figure 4.2. Unmitigated risk binning matrix—on-site receptors (inside and outside facility) (radiological).

The current selection criteria for credited controls (Section 4.2.2.4-1) do not require a frequency component for selection of the first level of control. The criteria require a second level of control for workers outside the target building for events that require control and are in the anticipated and unlikely frequency categories. This requirement for an additional layer of control for workers outside the facility recognizes the potentially greater number of workers who could be present outside.

Figure 4.1 presents the unmitigated risk bin matrix for offsite receptors. The cross-hatched bins (i.e., 1, 4, 7, and 10) represent risk that exceeded the unmitigated HA screening criteria. Unmitigated events falling into these bins, along with bins 2 and 5, were evaluated further.

The four dark cross-hatched bins in Figure 4.1 (i.e., 3, 6, 8, and 9) fell below the offsite unmitigated HA screening criteria; however, these events were considered situations of concern and were evaluated for possible identification as a subset of representative events needing further examination. Representative events bound several similar events of lesser risk (i.e., the worst fire among several similar fires). At least one event from each of the event types (i.e., fires, explosions) was considered representative; however, representative events were examined only to the extent that they were not bounded by unique events. Hazard event scenarios analyzed for on-site disruptions are addressed in Section 4.3.16.

Figure 4.2 is the risk bin matrix for the on-site receptors. The cross-hatched bins (i.e., 1, 2, 4, 5, and 7) represent risk that exceeded the on-site HA screening criteria. Unmitigated events falling into these bins typically require further evaluation as candidates for worker protection functions.

Chemical Risk

The chemical criteria used for credited controls (Section 4.2.2.4) are frequency independent. Credible events that exceed the chemical criteria are evaluated for appropriate controls that protect the public and workers. The HE tables report "Exceeds" or "Meets" rather than using a binning scheme for chemical evaluation.

4.2.2.4 Selection of Credited Controls

A credited control is determined via safety analysis to be essential for safe operation directly related to the protection of workers, the public, and the environment. The number of credited controls should be a limited subset of the total number of controls employed for overall facility operation [1]. Credited controls are assigned a higher degree of operational assurance than other controls.

The following criteria for selection of controls were adopted from [4] to ensure that unacceptable risks have been mitigated to acceptable levels via controls and/or limits on facility operation:

1. If the unmitigated dose exceeds 25 rem to an off-site receptor, then two levels of control are required:
   (a) A primary level of control shall be identified to prevent or mitigate the accident.
   (b) A second level of control shall be credited as a backup.

2. If the unmitigated dose is between 5 and 25 rem to an off-site receptor with an estimated frequency above 10^{-4}/year, then at least one level of control shall be identified.

3. If the unmitigated offsite airborne toxic chemical vapor concentrations exceed ERPG-2 (2 mg/m^3 for 1 h for mercury vapor), then a level of control shall be identified.

   Note: Either of the two levels of control required by criterion 1 above may be used to satisfy requirements for criteria 2 and 3. The level of control required by criterion 2 may be used to satisfy the criterion 3, and vice versa.

4. If the unmitigated radiation dose to a worker exceeds 25 rem, or exposure to airborne chemical concentrations is above the defined ERPG-3 level (4 mg/m^3 for mercury vapor), then a level of control shall be identified.

5. If the unmitigated radiation dose to a worker outside the building[1] exceeds 25 rem and occurs at an estimated frequency exceeding 10^{-4}/year, then at least two separate levels of control shall be identified.

6. For each unmitigated event that could cause a worker to experience breathing air with oxygen concentration below 12.5 vol % and for which existing SBMS procedures do not provide adequate design or operational requirements adequate to assure worker safety, a LOC shall be identified.

ERPG levels listed in the criteria above apply to irradiated target mercury. Chemical hazards associated with other ancillary activities, should they arise, are safely managed under the provisions of the ORNL SBMS program for chemical safety. For scenarios in which unmitigated consequences meet the control selection criteria, the controls are grouped into levels of control. A level of control, as defined in the *Spallation Neutron Source Policy for Selection of Safety Related Credited Controls* [4], is “one or more structures, systems, components, administrative controls, or inherent features (e.g., chemical properties, gravity, physical constants, underground location) which can be readily expected to act to prevent or mitigate the release of hazardous material to an unwanted location.” The administrative and/or engineered items necessary for each level of controls are classified as credited controls. Credited controls are grouped together by level of control for applicable events in the controls matrix presented in Appendix A.

Credited controls are identified as needed based on the analyses presented in Section 4.3 and Section 4.4.

4.3 HAZARD ANALYSIS—POTENTIAL ON-SITE IMPACTS AND CONTROLS

This section discusses identified hazards determined to pose significant risk to on-site workers at ORNL. This evaluation process identified 180 potential events involving credible hazards to the public, workers, and the environment. The results are based on the analyses presented elsewhere [18]. Of the 180 events evaluated during the preconstruction phase, 53 were identified as potentially exceeding the criteria requiring credited controls. Evaluations of those events are presented in the following subsections. Those events judged as potentially challenging the public radiological or hazardous chemical criteria were carried forward for a more detailed quantitative analysis of potential off-site effects (Section 4.4). The remaining events did not challenge the criteria for any of the receptors; therefore, they required no further analysis.

The following subsections present the analysis of unmitigated event scenarios and the credited controls selected for worker protection. The controls matrix, provided in Appendix A, summarizes the postulated events that require credited controls and identifies the credited controls for each of these events.

4.3.1 Target Systems Event Scenario Summary

In evaluating the target systems, several fire events, an explosion event, numerous loss-of-confinement events, and several events involving direct radiological exposure were postulated. The primary concern in the evaluation of the target systems is the release of radioactive and toxic mercury. Several of the events were revisited during HA for the PPU project [64]. Except as noted below, the PPU modifications were determined to have no significant effect on the HE and, thus, the conclusions of the HA.

[1] The dose criteria for on-site workers located outside the building during atmospheric releases are applied at a 100 m distance downwind from the point of release.

TS Initial Conditions and Assumptions

- The design proton beam power is 2 MW.
- Normal mercury operating temperature is less than or equal to 125°C.
- The total volume of mercury in the mercury circulation loop and storage tank is 1.6 m^3 at nominal temperatures (during operations 1.4 m^3 is in the loop, and 0.2 m^3 remains in the storage tank) and is contained within the service bay and core vessel.
- The radionuclide inventory assumes the mercury is not replaced during the life of the facility.
- Target mercury in excess of 19.4 kg is not stored in the target building outside the target service bay. This assumption applies to mercury that has been introduced into the mercury loop and not to unirradiated mercury. Mercury that is not irradiated is handled and stored per requirements of the ORNL SBMS and SNS procedures.
- The mercury loop doghouse shielding is normally in place when mercury is in the process loop. The shielding reduces radiation levels surrounding the loop to less than 250 rem/h to minimize radiation damage to electrical equipment.
- The walls surrounding the service bay are designed to PC-3 seismic requirements and would provide a barrier after a seismic event to separate combustibles outside the service bay from mercury inside the service bay.
- For purposes of the unmitigated analysis, automatic proton beam cutoff interlocks are not credited.
- Mercury is drained from the mercury circulation loop to the mercury storage tank before the target module is removed from the core vessel or target carriage.
- The accumulation rate of spallation product hydrogen in the mercury process loop has been determined to be insufficient for accumulation of a concentration greater than the LFL for hydrogen gas in air [25].
- Loop 1 cooling water is cooled directly by the tower water cooling system.
- Interstitial mercury in the mercury heat exchanger is at a higher pressure than loop 1 cooling water pressure and the mercury circulation loop pressure in the mercury heat exchanger.
- Activation of loop 1 cooling water is negligible.
- The mercury heat exchanger is a robust double-walled heat exchanger design.
- An interstitial gap (normally filled with stagnant helium gas) exists between the mercury containment and loop 2 cooling water containment within the target module.
- Leakage of mercury into the core vessel would not cause a hydrogen release owing to rapid corrosion of the aluminum moderator vessels because liquid mercury would collect at the bottom of the core vessel and not contact the moderator vessels. Tests conducted for SNS indicate that liquid mercury corrodes aluminum rapidly, whereas mercury vapor does not [71].

- The helium and nitrogen supplies for the mercury process loop, including target gas injection, enter the service bay at a sufficiently high elevation to prevent target mercury from escaping the service bay under normal and credible off-normal conditions.

TS1 Fire Events

Target systems fire events are evaluated to cover a full range of postulated bounding events. The postulated fire events are focused on the evaluation of fires with the potential to create significant quantities of airborne mercury. By design, target mercury is confined within the mercury circulation loop and storage tank, which is housed in the process bay portion of the service bay. Because of the mercury's high radiation levels, the circulation loop and storage tank are normally covered by heavy steel shielding to protect electronics within the service bay. This shielding protects the mercury system from damage from a service bay fire.

When the target cart is inserted into the core vessel, the target module extends into the core vessel such that the mercury circulation loop boundary crosses into the core vessel. A fire large enough to affect the target mercury is not likely to occur within or to propagate into the core vessel owing to the design location of the heavily shielded internals. Core vessel events are addressed in Section 4.3.8.

Mercury vapor released to the service bay atmosphere is collected on the PCES sulfur-impregnated charcoal adsorbers located in the target building basement. The potential for a fire in the basement that affects the mercury collected on the charcoal adsorbers is also evaluated.

A small fire is postulated that originates in the service bay and damages equipment but does not cause a mercury release (TS1-1). Therefore, no further analysis is necessary.

A medium fire is postulated that originates outside of the service bay (e.g., the high bay) and propagates into the service bay (TS1-2a). A fire in the vicinity of the mercury circulation loop is conservatively assumed to vaporize a significant amount of the target mercury such that two levels of control are provided to protect workers outside the target building. The following credited controls either suppress/extinguish the fire or prevent it from spreading into the target service bay:

- FSS Outside the Service Bay: provides a means to suppress/extinguish the maximum fire anticipated outside the service bay to ensure the service bay and core vessel 2 h equivalent fire barrier is not challenged.

- Service Bay and Core Vessel 2-Hour Equivalent Fire Barrier: ensures fires outside the core vessel and service bay cannot propagate into either the core vessel or service bay (fire barrier function).

- Combustible Material Control Program Outside the Service Bay: ensures combustibles outside of the service bay are maintained below prescribed loading limits to prevent challenges to the service bay and core vessel 2-hour equivalent fire barrier.

- PCES Air Intake Location: the design feature of locating the PCES air intake just above the floor level of the decontamination room discourages fire propagation into the service bay by minimizing the intake of hot gasses produced by a fire outside the service bay.

The medium fire that starts outside the service bay is also evaluated for its potential to involve the PCES charcoal filter room in the target building basement (TS1-2b). The mercury from the service bay atmosphere is deposited on the PCES sulfur-impregnated charcoal adsorbers. This fire is postulated to vaporize the mercury accumulated on the charcoal adsorber. The potential consequences for this event are limited by the credited controls listed for TS1-2a with the addition of the following administrative credited control:

- Procedures and Training to Control Mercury Inventory on PCES Charcoal Adsorbers: used to ensure the mercury accumulated on each charcoal adsorber is maintained less than 19.4 kg.

A medium fire is postulated that originates inside the service bay while mercury is present in the circulation loop (TS1-3). The following credited controls are applied to this event.

- FSS Inside the Service Bay: provides a means of detecting and suppressing a fire inside the service bay. Alternatively, if the mercury loop steel shielding is in place, the FSS Inside the Service Bay is not required because the steel shielding protects the mercury circulation loop from fire.

- Combustible Material Control Program Inside the Service Bay: ensures combustibles inside the service bay are maintained to ensure the size of a fire in the process bay cannot exceed the maximum analyzed 1 MWh locally intense fire.

- Service Bay and Core Vessel 2-Hour Equivalent Fire Barrier: prevents combustibles from outside of the service bay from migrating into the service bay (isolation function).

- PCES flame Retardant Exhaust Filters: mounted in the service bay stainless steel housings and discourage transmission of fire to charcoal adsorbers.

- SBDPMS: provides detection and alarm upon loss of negative pressure between the service bay and adjacent areas.

- Procedures and Training for Evacuation of Adjacent Areas from SBDPMS Alarm: ensures workers evacuate areas adjacent to the service bay upon loss-of-negative-pressure alarm and subsequently evacuate the building and area outside the building if required.

- PCES Backdraft Dampers: close upon loss of negative pressure in the service bay to prevent backflow from the service bay through the PCES ductwork.

- TBAC: prevents inadvertent worker access to the interior of the service bay.

A medium fire is postulated that is similar in scope to TS1-3, but additionally assumes a worker is in the transfer bay with the personnel door open (TS1-6). In addition to the credited controls required for TS1-3, the following control is needed:

- Emergency Response Procedures and Training to Close the Personnel Door Upon Evacuation from Service Bay Fire: ensures workers close the personnel door when it is safe to do so upon evacuation of the transfer bay from a loss-of-negative-pressure alarm.

A fire is postulated to occur in the service bay during maintenance activities when mercury is drained from the mercury circulation loop to the storage tank (TS1-4). Because the mercury is drained to the storage tank, controls are not needed to protect the mercury circulation loop. TS1-4 further postulates that the service bay, transfer bay, and high bay are open to a common air flow (e.g., removal of one or more service bay ceiling T-beams). The following credited controls are needed to protect workers from the potentially contaminated atmosphere of the service bay:

- TBAC: prevents inadvertent worker access to the interior of the service bay.

- SBDPMS: provides detection and alarm upon loss of negative pressure between the service bay and adjacent areas.

- Procedures and Training for Evacuation of Adjacent Areas from SBDPMS Alarm: ensures workers evacuate areas adjacent to the service bay upon loss-of-negative-pressure alarm and subsequently evacuate the building and area outside the building if required.

- Emergency Response Procedures and Training for Evacuation from Service Bay Fire with Common Air Flow: ensures workers evacuate in event of fire during maintenance activities when the service bay, transfer bay, and high bay are open to common air flow.

The last fire that is postulated is a full-facility fire that causes major structural damage that damages the target mercury circulation loop (TS1-5). This event is evaluated in Section 4.3.14 as event BG1-1.

TS2 Explosion Events

Other than postulated explosions for cryogenic moderator hydrogen release (CM events), one explosion event (TS2-1) was postulated for the target systems. This event involved ignition of spallation product hydrogen that was assumed to accumulate in the mercury pump tank. Further investigation [25] of this event determined that only trace amounts of hydrogen were involved, so the event did not require further analysis.

TS3 Loss of Confinement Events

TS loss of confinement events evaluate a breach of the target mercury system or a breach of an activated cooling water system for the target module shroud and the proton beam window.

Several loss-of-confinement events involve damage to the target module or proton beam window but do not exceed any exposure criteria. Thus, no further analysis is necessary. These events include a proton beam misalignment that damages the proton beam window and releases activated cooling water (TS3-1), a malfunction of the proton beam expander mechanism that leads to additional activation in the RTBT tunnel (TS3-3), a failure of the target module that leads to a release of mercury into the helium-filled interstitial region of the target module (TS3-5), and a breach of the loop 1 cooling water system that releases activated water in the target building basement utility vault (TS3-20).

Two loss-of-confinement events that are postulated are a release of MOTS inventory into the service bay (TS3-17) and a release of mercury and shroud cooling water into the service bay from a high bay crane heavy load drop (TS3-19). These events are respectively addressed as event GW3-2 in Section 4.3.4 and event HB3-3 in Section 4.3.10.

Three loss-of-confinement events are postulated that involve a failure of the target module that leads to a release of mercury and/or activated cooling water into the core vessel. Two postulated events are initiated by a loss of material integrity within the target module (TS3-4 and TS3-8). Another postulated event involves the release of loop 2 cooling water into the helium-filled interstitial region between the target module and target module shroud (TS3-6). Instruments are provided to detect this condition and trip the proton beam before damage to the target shroud can occur. However, TS3-6 assumes the water boils and causes failure of both the target shroud and module. The following credited control is applied to these events to confine the releases.

- Confinement Function of Core Vessel and Neutron Beam Windows: retains liquid mercury in a confined location, mitigates mercury vapor release inside the building, and delays cooling water spills to allow for delay of short-lived activation products.

Four loss-of-confinement events are postulated that are loss of heat sink events that lead to overheating and failure of the target module and release of mercury and activated cooling water into the core vessel. A postulated event involves a loss of pumping power in the loop 1 cooling water system that services the mercury heat exchanger (TS3-13). Another postulated event involves a flow blockage in the loop 1 cooling water system (TS3-14). Another postulated event involves a leak or break in the loop 1 cooling water system (TS3-15). The last postulated event involves a loss of the tower water heat sink for the loop 1 cooling water system (TS3-16). The following credited control is applied to these four events to prevent the loss of heat sink from damaging the target module.

- TPS Beam Trip on High Mercury Loop Temperature: prevents excessive overheating of the mercury circulation loop by tripping the proton beam upon high mercury temperature.

Five loss-of-confinement events are postulated that are loss of mercury circulation loop flow events that lead to failure of the target module and a release of mercury and activated cooling water into the core vessel. The postulated events are caused by both a gradual and sudden partial loss of flow from a mercury pump failure (TS3-22 and TS3-24), both partial and complete loss of flow from a loss in electrical power to the mercury pump (TS3-23 and TS3-12), and a partial loss of flow from a mercury pump motor speed controller failure (TS3-25). The following credited control is applied to these five events to prevent the loss of mercury process loop flow from damaging the target module.

- TPS Beam Trip on Low Mercury Loop Flow: prevents excessive overheating of the mercury circulation loop by tripping the proton beam upon out-of-limits differential pressure across the mercury pump.

Three additional postulated loss-of-confinement events are also loss of mercury circulation loop flow events. These events are all partial loss-of-flow events that are caused by blockages in the mercury circulation loop. The loss of flow leads to overheating and failure of the target module and a release of both mercury and activated cooling water into the core vessel. The postulated events are caused by objects being dislodged from their normal position (TS3-11 and TS3-26) and foreign material being left in the mercury circulation loop piping during maintenance (TS3-27). The following credited control is applied to these three events to confine the releases.

- Confinement Function of Core Vessel and Neutron Beam Windows: retains liquid mercury in a confined location, mitigates mercury vapor release inside the building, and delays cooling water spills to allow for decay of short-lived activation products.

Two postulated loss of confinement events are associated with leakage across the mercury heat exchanger. A postulated event involves a release of loop 1 cooling water into the mercury circulation loop caused by a breach in the mercury heat exchanger (TS3-9). The cooling water is boiled by the proton beam, and the associated pressure pulses cause a breach in the target module that leads to a release of both target mercury and activated cooling water into the core vessel. Another postulated event (TS3-21) leads to a release of target mercury to the cooling tower water through an existing breach in the loop 1 cooling water to tower water heat exchanger. The following credited control is applied to these two events to prevent leakage across the mercury heat exchanger.

- Mercury Heat Exchanger Double-Wall Design: the design of the double-walled mercury heat exchanger prevents a single wall failure from allowing radioactive mercury to be released to the loop 1 cooling water.

Three postulated loss of confinement events involve a release of mercury and loop 1 cooling water into the service bay. Two events are a small and a large break in the mercury circulation loop that led to a release of mercury into the service bay (TS3-7 and TS3-10). Another event is a release of both mercury and loop 1 cooling water into the service bay from a heavy load drop from the service bay crane (TS3-18). The credited controls that are applied to these three events are designed to confine the spilled mercury, to keep workers out of the service bay, and to protect workers if there is a loss of differential pressure that indicates insufficient confinement ventilation of the service bay.

- Service Bay Confinement of Mercury: the service bay stainless steel liner is configured and sloped to promote spilled mercury to travel to the collection basin.
- PCES Ductwork: confines mercury vapor within the service bay following a spill.
- TBAC: prevents inadvertent worker access to the service bay.
- SBDPMS: provides a means of detecting and alarming upon loss of negative pressure between the service bay and adjacent areas.
- Procedures and Training for Evacuation of Adjacent Areas from SBDPMS Alarm: ensures workers evacuate areas adjacent to the service bay upon loss-of-negative-pressure alarm and subsequently evacuate the building and area outside the building if required.

Another postulated loss-of-confinement event is a release of mercury into the MOTS during routine filling of the mercury pump tank (TS3-28). This event is sometimes referred to as a loop overfill. This scenario postulates that the mercury circulation loop is overfilled such that the mercury pump tank overflows, leading to excessive radiation levels outside of the service bay. Section 5.2.15 provides additional detail for the basis of this evaluation. The credited control that is applied to this event serves to prevent the accident from occurring.

- Mercury Pump Tank Exhaust Line Loop Seal: the height of the loop seal is sufficient to prevent mercury from escaping the service bay as a result of overfilling the loop.

Event TS3-29 was identified during target gas injection initial implementation [66] and postulates that injected gas accumulates in the mercury process loop, displacing the target mercury in sufficient volume to force mercury over the loop seal and into the MOTS, leading to a “High” consequence to worker group 1. At the time [66] was issued, credited controls were identified and implemented to mitigate this accident. Later, as part of the PPU project [64], passive design features, specifically the overflow tank, were incorporated to ensure that an overflow of the mercury pump tank caused by gas accumulation is not credible. Thus, credited controls are no longer required for TS3-29.

Other potential new accidents from target gas injection [66] were also evaluated. The possibility of helium accumulation degrading the performance of the heat exchanger (TS3-30) or causing excessive mercury flow reduction (TS3-32) were evaluated. The possibility of target gas injection equipment malfunction was also considered for the possibility of causing partial flow blockages (TS3-33), transient helium flow rate into the loop (TS3-34), or excessive gas flow that leads to mercury in MOTS (TS3-35). All these events were determined elsewhere [66] to be bounded by existing accident analysis.

Event TS3-36 was added to evaluate the consequences of an event that was observed during operational fill of the mercury circulation loop in 2019 [67]. In this event, the mercury in the storage tank was depleted, leading to a rapid injection of pressurized helium gas into the mercury process loop. If pressurized helium gas is rapidly injected into the mercury circulation loop from the storage tank during filling operations, then target mercury could be pushed out of the pump tank and into the MOTS, resulting in "High" consequences to worker group 1. The credited controls selected to mitigate the radiological consequences of this event are as follows.

- Mercury Pump Tank Rupture Disk and Discharge Path: the rupture disk actuates before mercury reaches the top of the loop seal, while the discharge path provides sufficient capacity to prevent liquid mercury from overflowing the loop seal such that it escapes the service bay.

- Mercury Pump Tank Exhaust Line Loop Seal and Orifice: the loop seal is fixed at a sufficient elevation to ensure the mercury pump tank rupture disk actuates before mercury reaches the top of the loop seal, while the orifice provides sufficient flow resistance to ensure the discharge capacity of the rupture disk and discharge path is sufficient to prevent liquid mercury from escaping the service bay.

The mercury fill transient in 2019 [67] also prompted evaluation considering the potential for the fill transient (TS3-38), static loop overfill (TS3-37), or gas injection helium accumulation (TS3-39) to force mercury into gas supply lines to the mercury process system. All three of these events led to the installation of the credited service gallery radiation alarm system to ensure protection from direct exposure to the radiation emitted by the displaced target mercury. However, as described elsewhere [68], design changes were implemented to replace the at-risk gas supplies from the service gallery into the service bay with supplies provided from the high bay via the shielded GLS cavity. This change ensures that the gas supply lines for the mercury process loop do not provide a potential path for mercury to escape the service bay.

TS4 Direct Exposure Events

Three events involving direct radiological exposure to personnel were postulated. These include personnel exposure to residual mercury in the system during target changeout activities (TS4-1 and TS4-2) and direct exposure to loop 1 cooling water (TS4-3). Event TS4-3 resulted in negligible consequences; therefore, no further analysis was performed.

Event TS4-1 is an inadvertent actuation of the beam to the service bay when the target carriage has been withdrawn from the core vessel for maintenance or target changeout. Evaluation of this event indicates that extremely high radiation levels could be produced in various areas in the target building [70]. The unmitigated consequences for this event are high to the Onsite-1 worker. The following credited controls prevent this accident.

- PPS Prevents Beam to Target if Target Cart is Not Inserted: PPS monitors the target cart position and will prevent beam to target if the target cart is not fully inserted (Section 5.2.1 of the FSAD-PF [26]).

- TPS Prevents Beam to Target if Target Cart is Not Inserted: TPS monitors the differential pressure across the mercury pump and will prevent beam to target if the differential pressure is too low, which will occur if the target is not inserted and connected to the mercury circulation loop.

Measured dose rates in the manipulator gallery during target changeout confirms that the service bay's thick shield walls and windows are adequate. Thus, direct radiation hazards are confined to the service bay during target changeout activities (TS4-2). The credited control selected for event TS4-2 is needed to protect the Onsite-1 worker:

- TBAC: prevents inadvertent worker access to the service bay, initiates alarm if intrabay shielding doors are not closed when transfer bay access door is open.

4.3.2 Cryogenic Moderator System Event Scenario Summary

Because the CMS uses hydrogen and spans multiple areas of the facility, fire (i.e., rapid deflagration) and explosion events from the ignition of released hydrogen can be postulated. In the CMS design phase, nonmechanistic fires and explosions were postulated that result from breaches in the CMS piping in the core vessel, HUR, high bay, and shutter drive equipment room (the space just above the core vessel under the shielding blocks).

Hydrogen combustion caused by oxygen leakage into the CMS was determined to be noncredible because of the 13 bar normal pressure of the hydrogen in the CMS, the use of high-purity hydrogen for charging the system, and the routine warm-ups of the CMS accompanied by replacement of the hydrogen inventory (following helium fill and vacuum purge cycles; Section 3.3.3).

Following an inadvertent failure of the hydrogen boundary outside the core vessel, air could diffuse into the hydrogen moderator after depressurization. Combustion would be unlikely because of the lack of an ignition source. Nevertheless, the hydrogen boundary would be able to withstand combustion of atmospheric-pressure hydrogen/air mixture in such a scenario. Scenarios involving combustion of hydrogen inside the CMS were either noncredible or would not have consequences severe enough to warrant further evaluation.

CM Initial Conditions and Assumptions

- The cryogenic hydrogen system contains trace quantities of tritium and activated particulates.
- All layers of the moderator vessels are aluminum.
- Per normal procedures (Section 3.3.3), hydrogen is vented from the CMS to the hydrogen-safe vent system before cryogenic hydrogen system maintenance or IRP removal from the core vessel.
- The IRP design prevents direct proton beam view into the area of the moderator vessels.
- The CMS aluminum vessels are not significantly corroded by mercury in accidents because no accident scenarios result in their submersion in liquid mercury (Section 5.2.8.4).
- The hydrogen boundary is designed for a maximum pressure of 19 bar absolute.

CM1 Fire Events

In the postulated fire events (CM1-1 through CM1-4), the hydrogen leak is assumed to be small, such that the events are limited to rapid deflagrations with limited damage to the surrounding equipment. Therefore, these events required no further analysis.

CM2 Explosion Events

Event CM2-1a is an explosion with a follow-on fire caused by a breach (large leak) in a cryogenic moderator vessel that flows into the core vessel and is inadvertently ignited, releasing mercury and activated cooling water. Event CM2-1b is an explosion event like CM2-1a, but with no follow-on fire.

The unmitigated radiological consequences for events CM2-1a and CM2-1b are high to the Onsite-1 worker and moderate to the Onsite-2 worker. The chemical consequences exceed the criteria for all receptors. One issue involving the possibility of masking the existence of a leak in the system was resolved by recognizing the design of the transfer lines. The size and hydraulic impedance of the lines are such that no matter how hard the vacuum pumps pull, a leak that would allow significant hydrogen into the core vessel would spoil the vacuum layer and vent the system [27]. The credited controls needed to reduce the frequency of these two events and to mitigate the radiological and chemical consequences consist of the following:

- CMS Hydrogen Boundary: design prevents failures resulting in hydrogen leakage into the core vessel. The credited design includes its relief path and the seismically qualified (PC-3), restrained and externally protected hydrogen equipment that provides protection against impact and ensures the relief path remains unobstructed.

- CMS Vacuum Boundary: design prevents hydrogen from flowing into the core vessel following hydrogen leakage. The credited design includes its relief path and the seismically qualified (PC-3), restrained and externally protected vacuum equipment that provides protection against impact and ensures the relief path remains unobstructed.

The explosion events resulting from a breach in the CMS piping outside the core vessel (CM2-2 through CM2-4) are assumed to result from a large leak of hydrogen and cause significant damage to the surrounding equipment. The radiological/toxicological consequences for these events are either negligible or low to all receptors; therefore, no further analysis was performed. An additional postulated explosion event (CM2-7) involves a breach in the CMS piping in the core vessel (slow leak) that allows hydrogen to escape to the vacuum vent system (followed by ignition). The unmitigated consequences for this event are either negligible or low to all receptors; therefore, no further analysis was performed.

CM3 Loss-of-Confinement Events

Several loss-of-confinement events are postulated. These events involve a breach in the cryogenic moderator vessel or associated piping such that hydrogen (and/or pre-moderator water, depending on the event) is released without causing a fire or explosion. The postulated events cause releases to areas such as the core vessel, core vessel vent system stack (through the rupture disk), high bay, and HUR. These events consider such occurrences as failure of the moderator vessel (CM3-1), impacts (CM3-2 and CM3-3), loss of vacuum (CM3-4), system overpressurization or high temperature (CM3-5), and loss of power (CM3-6 through CM3-8).

A loss of confinement releasing hydrogen outside the core vessel could allow air to diffuse into the CMS inside the core vessel after the escape of hydrogen depressurizes the CMS. Subsequently, an explosion inside the CMS would not be capable of vaporizing mercury because the robust hydrogen boundary would contain the explosion without failure.

As part of the PPU project, iron oxide catalyst modules were added to each CMS loop. A scenario was identified in which the iron oxide catalyst media escapes confinement in its module, circulates through the CMS loop, and becomes activated in the moderator vessel [69]. This condition could lead to direct exposure of workers near the hydrogen transfer lines (CM4-1), or airborne release of the activated catalyst media caused by an overpressure event in the CMS loop causing the rupture disk to open and vent the hydrogen inventory out of the hydrogen-safe vent stack (CM3-9). CM3-9 was determined to have negligible consequences, so no further analysis was performed. CM4-1 has the potential for moderate radiological consequences to worker group 1, so the following controls were identified to mitigate the hazard:

- Catalytic Converter Retention Elements: the robust design and fabrication of the retention elements confines the iron oxide catalyst media to its designed canister and prevent transport into the CMS loop.

Although the hydrogen and premoderator water in the CMS could contain trace quantities of tritium or other activation products or activated corrosion and erosion products, the unmitigated radiological consequences resulting from release of hydrogen from the system would be small. The doses resulting directly from a release of hydrogen or premoderator water are well below criteria for all receptors and require no further analysis.

Oxygen deficiency caused by hydrogen or helium leakage was considered. The worst location (smallest volume) would be in the HUR. However, the quantities of helium or hydrogen and buoyancy of both gases prevent excessive oxygen displacement in breathable room air.

4.3.3 Loops 2, 3, and 4 Cooling Water Event Scenario Summary

Hazards identified for loops 2, 3, and 4 cooling water include a potential for fires, explosions, loss-of-confinement events, and events involving direct radiological exposure.

CW Events Initial Conditions and Assumptions

- Beryllium-7 is assumed to be present as an activation product in water cooling systems exposed to direct proton beam radiation (loops 2 and 3 cooling water).

- Cooling water loops 2 and 4 are cooled by the deionized water isolation loops, which are, in turn, cooled by the tower water system. Loop 3 is cooled by a deionized water isolation loop that is cooled by the sensible chilled water system, which is, in turn, cooled by the tower water system.

- Pumps for the deionized water isolation loops are in the target building basement.

- Gas generated by radiolysis in the water cooling systems accumulates in the system gas/liquid separators or other high points of the system. The gas is assumed to include hydrogen and tritium. Tritium is in oxide form. Elemental tritium exists only to the extent of the tritium/hydrogen ratio in the cooling water loops.

- The operating pressure of the loops 2, 3, and 4 cooling water is lower than the pressure in the deionized water isolation loops.

- Cooling water systems are operated at a pressure less than or equal to 150 psig.

- Cooling water systems have no automatic makeup water feed capability from the storage tanks into the system.

- All four cooling water loops include a gas/liquid separator or other vessel providing surge-tank capability to the system.
- The source term resulting from a release of loop 3 cooling water is conservatively represented by the source term from a release of loop 2 shroud cooling water.

CW1 Fire Events

The postulated fires include one small fire (CW1-1) and one more substantial fire (CW1-2), both originating in the basement utility vault. Based on the radionuclide inventory in the cooling water systems, the consequences for these events are either negligible or low to all receptors; therefore, no further analysis was performed.

CW2 Explosion Events

The postulated explosion events (CW2-1 and CW2-2) consider the possibility of hydrogen explosions in the gas/liquid separators located in a cavity the high bay area. The unmitigated consequences for these events are either negligible or low to all receptors; therefore, no further analysis was performed.

CW3 Loss-of-Confinement Events

The postulated loss-of-confinement events (CW3-1 through CW3-16) include a breach in cooling water system components resulting in a release of loop 2 shroud cooling water to either the service bay, the core vessel, the bulk shielding liner and drain line, the high bay, the basement utility vault, the central deionized water loop (through a breach in a heat exchanger), or the manipulator gallery (by seepage through the building structure). Based on the radionuclide content of the loop 2 cooling water at end of facility life, the radiological consequences for all the loss-of-confinement events would not pose consequences to a worker that would require credited controls.

CW4 Direct Exposure Events

Acutely hazardous radiation levels are not expected in the basement utility vault or in the shutter drive equipment room. Radiation measurements [60] indicate dose rates during full-power operations in these areas do not rise to the level of requiring a credited control. Operational measurements indicate 2 MW dose rates in the basement utility vault general area would be about 0.3 to 2 R/h and up to about 10 R/h at a location (ceiling area where pipe chase enters room) that requires a ladder to access. TLD measurements in the shutter drive equipment room indicate that 2 MW dose rates would be well below 1 R/h. Unless future radiation measurements indicate that acutely hazardous radiation levels can occur, the target PPS control interlock for the basement utility vault and shutter drive equipment room need not be credited. Routine access control provided by the Radiological Protection program is more than sufficient.

One direct radiological exposure event was postulated (CW4-1). The initial analysis for this event assumed that an individual remained in an assumed radiation field of 100 R/h adjacent to an activated cooling water system in the basement utility vault or high bay (with shield blocks removed) during beam operation, or immediately after beam shutdown, for 30 min. Measured dose rates in the basement utility vault and shutter drive equipment room are much lower than the initial assumption of 100 R/h. Measured dose rates [60] indicate 2 MW dose rates on the order 60 R/h in the delay tank pit and 20 R/h in the gas–liquid separator pit. The unmitigated radiological consequences for a worker entering the delay tank pit during high power beam operations are moderate to the Onsite-1 worker; therefore, controls must be evaluated. The selected control to reduce the consequences to an acceptable level is provided by the following:

- Radiological Protection Program: provides a means of controlling the radiological exposure received by facility workers by controlling access to radiological areas and the placement of shielding.

4.3.4 Mercury Off-Gas Treatment System and Core Vessel Vacuum and Helium Systems Event Scenario Summary

The postulated events identified during the evaluation of the mercury off-gas treatment, vacuum, and helium systems include fires, explosions, loss-of-confinement events, and an event involving direct radiological exposure.

GW Initial Conditions and Assumptions

- The MOTS contains a mercury vapor condenser, two gold adsorber beds, an ambient charcoal delay bed, a CuO/molecular sieve system, and a cryogenic charcoal bed to trap residual mercury, xenon, iodine, and tritium.
- The MOTS is operated near atmospheric pressure.
- The helium system pressurization equipment and storage tank are located outside the target building.
- The vacuum system and the MOTS are assumed to have no more than loose internal surface contamination.
- The helium and nitrogen supplies for the mercury process system, including target gas injection, enter the service bay at a sufficiently high elevation to prevent target mercury from escaping the service bay under normal and credible off-normal conditions.

GW1 Fire Events

The postulated fire events include one involving overheating of the CuO molecular sieve, resulting in combustion and release of tritium oxide (GW1-1). The other fire event (GW1-2) assumes that a fire originates within the HOG system and burns HEPA filters, releasing trapped radiological material. Unmitigated consequences for this event were determined to be negligible or low to all receptors and required no further analysis.

GW2 Explosion Events

One postulated explosion event assumes hydrogen from a variety of sources is drawn into the vacuum system and is ignited (GW2-2). The explosion does not affect the mercury because it is too far away from the core vessel or service bay. Consequences for this event were determined to be negligible to all receptors and required no further analysis.

GW3 Loss-of-Confinement Events

Several loss-of-confinement events associated with the mercury off-gas treatment, vacuum, helium, and nitrogen systems were postulated. These events include internal failures, leaks, or ruptures of MOTS components, releasing tritium, mercury vapor, or other radioactive gases (GW3-1 through GW3-5, GW3-8, GW3-11, GW3-14, GW3-16). Other postulated loss-of-confinement events include releases of radioactive material from leaks or failure of nitrogen purge gas (GW3-17 and GW3-18), off-gas system exhaust fans (GW3-12), delay line (GW3-10), vacuum booster pumps (GW3-9 and GW3-14), and HEPA filters (GW3-13). Target gas injection introduced two additional scenarios, GW3-19 and GW3-20, that postulate helium supply ruptures in the high bay and service bay [66]. These events were revisited with consideration for gas injection recirculation operation and target nose area gas injection during the PPU project [64]. All these events have negligible unmitigated radiological consequences to the public and low consequences to the facility worker and meet hazardous chemical criteria. Therefore, no further analysis was performed.

GW3-2 is a leak or breach of the MOTS within the service bay, resulting in a release of mercury vapor and off-gas into the service bay atmosphere. The unmitigated consequences for this event are negligible to the public; however, airborne mercury levels within the service bay could build up to ERPG-3 levels should the PCES fail during the event. The following controls are credited to protect the facility worker:

- TBAC: prevents inadvertent worker access to the service bay.
- SBDPMS: provides a means of detecting and alarming upon loss of negative pressure between the service bay and adjacent areas.
- Procedures and Training for Evacuation of Adjacent Areas from SBDPMS Alarm: ensures workers evacuate areas adjacent to the service bay upon loss-of-negative-pressure alarm and subsequently evacuate the building and area outside the building if required.

Another loss-of-confinement event was postulated during the safety evaluation of target gas injection for the PPU project. The event (GW3-2a) postulates a release of MOTS flow into the GAR owing to a system leak [64]. The event assumes an extended leak from the MOTS piping in the GAR upstream of the ambient charcoal adsorbers, allowing radioactive gases to accumulate in the GAR, followed by an uncontrolled entry into the GAR. The unmitigated consequences for this event are moderate to the Onsite-1 worker and negligible to all other receptors. The following control is credited to protect the facility worker:

- Radiological Protection Program: provides a means of controlling the radiological exposure received by facility workers by controlling access to radiological areas and the placement of shielding.

Releases downstream of the ambient charcoal adsorbers (GW3-2b and GW3-2c) were evaluated and determined to have low consequences, so no credited controls were required.

GW4 Direct Exposure Events

Two direct radiological exposure events were postulated.

Event GW4-2 involves direct worker exposure in the vicinity of the MOTS. GW4-3 postulates excessive backflow of mercury and spallation gases into the target gas injection helium supply lines from gas panels in the high bay. The unmitigated consequences for these events were negligible to the off-site public and low to the facility workers; therefore, no further analysis was performed.

4.3.5 Process Waste and Sanitary Waste Systems Event Scenario Summary

Process liquid waste for the target building drains to the process waste collection tank in the basement that is subsequently pumped to the sanitary sewer system. Samples removed from the process waste tank allow contaminated waste to be diverted from the normal drain path to the LLLW storage tank in the basement utility vault of the target building.

Postulated events that could occur in the process waste and sanitary waste systems include a fire (PW1-1), an explosion (PW2-1), and a loss-of-confinement event (PW3-1). Event PW1-1 involves flammable laboratory chemicals that may have been inadvertently drained to the process waste system and are ignited. The initiation of the explosion (PW2-1) occurs similarly to the fire except that the incompatible chemicals drained to the process waste system form explosive vapors that are subsequently ignited. The loss-of-confinement event (PW3-1) involves a leak from the process waste collection tank to the surrounding area.

The process waste system normally contains little radioactive material since it must be discharged to the sanitary sewer. The unmitigated consequences resulting from the above events involving process waste do not result in doses that challenge offsite or on-site hazardous material criteria. Therefore, no further analysis was performed, and no credited controls were required.

4.3.6 Contact Waste Handling and Decontamination Area Event Scenario Summary

During the evaluation of the contact waste handling and decontamination area, fires, explosions, loss-of-confinement events, and an event involving direct radiological exposure were postulated.

WH Initial Conditions and Assumptions

- As many as 20 spent ion-exchanger resin columns may be stored in the contact waste handling and decontamination area awaiting processing [22].
- The contact waste handling and decontamination area has no more than loose surface contamination.
- The contact waste handling and decontamination area can have radioactive system components.
- Ion-exchanger resin regeneration and replacement activities occur in the contact waste handling area.
- Drains in the decontamination area drain to the process waste system.
- Spent ion-exchange resins are not a fire or explosion hazard even if allowed to dry. Resins of low flammability are used, and strong chemicals that would promote flammability upon drying are not used.

WH1 Fire Events

Several ignition sources were identified elsewhere [18] along with the potential for combustibles to accumulate. On that basis, a fire in the general contact waste handling and decontamination area was postulated (WH1-1). Several ion exchange columns containing spent resin could be stored within the area at any given time. Furthermore, the room is assumed to have surface contamination. In addition to the general area fire (WH1-1), a localized fire involving the LR-56 LLLW shipping trailer was postulated (WH1-2). This event is assumed to occur during transfer of LLLW from the hold tanks to the trailer for shipment and is assumed to be confined to the immediate area of the truck bay. The unmitigated consequences for these events were negligible to the off-site public and low or negligible to the facility workers; therefore, no further analysis was performed.

WH2 Explosion Events

Potential explosion event scenarios include explosions involving hydrogen released from forklift batteries (WH2-1), spent ion-exchange resin that has been allowed to dry (WH2-2), and fuel on the tractor removing the LR-56 waste shipping trailer (WH2-3). The unmitigated consequences for events WH2-1 and WH2-3 were negligible to the off-site public and low to the facility workers; therefore, no further analysis was performed.

The unmitigated consequences for WH2-2 are negligible to the Onsite-1 worker because combustion or explosion is not a credible outcome for the types of resin and ion-exchange chemicals used by SNS. SNS has no current plans to regenerate resin on-site.

WH3 Loss-of-Confinement Events

Several loss-of-confinement events were postulated. These events include spread of radiological material (general contamination) from the decontamination area via ventilation system failure (WH3-1) or internal flooding (WH3-3), release of ion-exchange resin within the decontamination area (WH3-2), and release of waste liquid through leaks in the process waste tank (WH3-4) or the LLLW tanks (WH3-5). The unmitigated consequences resulting from these events do not result in doses that challenge off-site or worker radiological or toxicological criteria. Therefore, no further analysis was performed.

WH4 Direct Exposure Events

One event involving direct radiological exposure to personnel was postulated. This event (WH4-1) involves excessive exposure to unshielded ion-exchange resin (e.g., as the result of shielding failure or leaks). Based on the inventory of radiological material expected to be present in the LLLW, the unmitigated consequences are small, including those for the facility worker. The unmitigated consequences resulting from this event are negligible to the off-site public and low or negligible to the worker groups. Therefore, no further analysis was performed; however, although not required to be credited, the ALARA and Radiological Protection programs in place ensure that exposures from this event are low.

4.3.7 Confinement Ventilation Systems Event Scenario Summary

During the evaluation of the primary and secondary confinement ventilation systems, fires, loss-of-confinement events, and an event involving direct radiological exposure were postulated.

Initial Conditions and Assumptions

- Primary confinement ventilated spaces are maintained with more negative pressure than secondary confinement ventilated spaces under normal operating conditions.
- Exhaust fans for the primary and secondary confinement ventilation systems are located outside of the target building.
- The confinement ventilation system air flow passes once through before discharge from the CEF.

HV1 Fire Events

One fire event (HV1-1) was postulated that resulted in negligible consequences to the off-site public and low consequences to facility workers; therefore, no further analysis was performed.

HV3 Loss-of-Confinement Events

The loss-of-confinement events include a breach in a HEPA filter housing (HV3-1), exhaust fan failure (HV3-2), failure of a HEPA filter (from breakthrough or plugging) (HV3-3 and HV3-4), a mishandling or confinement failure during replacement (HV3-5), and a failure of the gold adsorber beds (HV3-6). Except for HV3-5, the unmitigated consequences were negligible to the off-site public and low or negligible to the facility workers; therefore, no further analysis was performed.

The unmitigated consequence from the postulated inhalation of radioactive material for event HV3-5 was moderate to the Onsite-1 worker, requiring evaluation of controls to reduce the consequences. The following credited control was selected:

- Radiological Protection Program: provides a means of controlling the radiological exposure received by facility workers.

HV4 Direct Exposure Events

Two direct radiological exposure events were postulated. One event (HV4-1) assumes that an excessive amount of radiological material collects on the HEPA filter and that an individual is exposed to that material. The other event (HV4-2) involves a facility worker who receives excessive exposure near the gold adsorber beds. The unmitigated consequences for both events are negligible to the public and low or negligible to the facility workers; therefore, no further analysis was performed.

4.3.8 Core Vessel General Area including Shielding, Reflectors, and Shutters Event Scenario Summary

Fire events, explosion events, loss-of-confinement events, and an event involving direct radiological exposure were postulated during the evaluation of the core vessel general area including shielding, reflectors, and shutters.

SH Initial Conditions and Assumptions

- The IRP is clad in stainless steel, and the lower aluminum section contains stainless steel and beryllium pieces. All beryllium is encapsulated in aluminum so that no credible accidents render the beryllium airborne. The reflector plug is cooled by heavy or light water.

- The core vessel and bulk shielding liner and drain line area have no more than loose surface contamination.

- The core vessel and bulk shielding liner and drain line areas have highly activated system components.

- Shielding material outside the core vessel is steel or concrete and is sufficient to prevent excessive radiation exposure to workers in adjacent occupied spaces.

- The core vessel atmosphere may be a helium blanket or a rough vacuum.

- The core vessel pressure is protected by a rupture disk to the hydrogen safe vent stack. The rupture disk ruptures at approximately 7 psig.

- The core vessel and monolith drain lines are normally closed.

- The shutter drive equipment room is accessible from the high bay and is exhausted by the PCES.

SH1 Fire and SH2 Explosion Events

The potential exists for a fire involving the hydraulic shutter drives (in the shutter drive equipment room above the core vessel). The unmitigated consequences for this event (SH1-2) are negligible to the off-site public and low or negligible to the facility workers; therefore, no further analysis was performed. Other fire and explosion events that can occur within the core vessel were identified but are specifically associated with the CMS and are discussed in Section 4.3.2.

SH3 Loss-of-Confinement Events

Several loss-of-confinement events were postulated involving a release of radioactive gases and liquid caused by a breach in the core vessel (SH3-1), a neutron beam window (SH3-2), or target module and core vessel seals (SH3-3). The unmitigated consequences for these events are negligible to the off-site public and low or negligible to the facility workers; therefore, no further analysis was performed.

SH4 Direct Exposure Events

The postulated direct radiological exposure events result from misalignment of the target module (SH4-1), cracks in the concrete shielding (SH4-2), inadvertent opening of a shutter (SH4-3), or inadvertent exposure to an unshielded shutter during shutter replacement (SH4-4). The unmitigated consequences for all events were negligible to the off-site public.

For completed instruments with chopper, beamline, and instrument enclosure shielding in place, instrument PPS interlocks will shut off the beam in the event of inadvertent shutter opening that would expose workers to excessive radiation levels (Section 7). Worker 1 could be exposed to high radiation for operations when chopper, beamline, or enclosure shielding is not installed and the primary shutter is open (SH4-3). Measures implemented by the Radiological Protection program, such as requiring the primary or secondary shutter to be locked into place with a radiation safety hold in accordance with the approved operations procedures, adequately prevents this scenario. Radiation safety holds are described in the *Movable Shielding* subsection of Section 4.2.1.1 of the FSAD-PF [26]. For event SH4-3 with shielding not installed, the following credited control protects workers:

- Radiological Protection Program: provides a means of controlling the radiological exposure received by facility workers when shielding is not in place by ensuring that appropriate measures are in place (e.g., primary or secondary shutter is locked in place with approved radiation safety hold).

PPS-interlocked area radiation monitors (Chipmunks or approved equivalent) placed near the monolith and choppers in locations specified by the RSO provide an extra level of safety for event SH4-3 by automatically tripping the proton beam in the event of unusual radiation levels.

Event SH4-1 is a direct radiological exposure event involving misalignment of the target module, proton beam window plug assembly, or core vessel inner plug assembly (with moderator vessels), allowing radiation to stream into the high bay area. This event was postulated before beam operations. Operational surveys at high power have confirmed adequate shielding performance. This event is retained to cover situations that involve significant changes in the placement of shielding associated with these components. The consequences of this event are assumed high to the Onsite-1 worker and require evaluation of controls. The following credited control was selected for the Onsite-1 worker:

- Radiological Protection Program: provides a means of controlling the radiological exposure received by facility workers by ensuring that radiation surveys take place as appropriate after replacement of shielding.

Event SH4-2 is a direct radiological exposure event that assumes a worker, unaware of breaches or cracks in the concrete shielding, receives prolonged exposure over time. This event was postulated before operations. Operational surveys at high power have verified facility shielding performance. The event involving direct exposure to an unshielded shutter (SH4-4) (or other highly activated component) assumes the worker is exposed to a 1,000 rad/h field for 5 min. Both SH4-2 and SH4-4 resulted in moderate unmitigated consequences for the Onsite-1 worker, which requires evaluation of controls to reduce the consequences. The following credited control was selected credited control for the Onsite-1 worker:

- Radiological Protection Program: provides a means of controlling the radiological exposure received by facility workers by ensuring that periodic radiation surveys take place. Enforces the use of RWPs with required approvals commensurate with potential hazard.

4.3.9 Service Bay General Area Event Scenario Summary

The service bay houses the mercury circulation loop and portions of its supporting equipment (e.g., heat exchanger cooling water loop), as described in Section 3. The service bay fire events and some of the explosion events postulated to occur in the service bay are discussed in Section 4.3.1. Several other explosion events, loss-of-confinement events, and direct radiological events related to the service bay were postulated and are discussed herein.

TC Initial Conditions and Assumptions

- The service bay and transfer bay can withstand a surface vehicle impact originating from outside the building, small external fires and explosions, or a tornadic missile without a significant release of radiological materials.
- Service bay shielding material is concrete and steel and is sufficient to prevent excessive radiation exposure to workers in adjacent occupied spaces.
- The shield door separating the service bay from the transfer bay is normally closed. Personnel are not allowed in the transfer bay during beam-on conditions unless the intrabay doors are closed.
- Normal operations in the service bay are accomplished remotely.
- The loop 2 shroud cooling water delay tanks for the target shroud are contained within the service bay, whereas the delay tank for the proton beam window cooling water and the gas/liquid separators are contained in a high bay cavity.
- The service bay and transfer bay have loose surface contamination.
- The service bay contains highly activated system components.

TC1 Fire Events

Section 4.3.1 discusses TS1 events.

TC2 Explosion Events

Event TC2-2 involves a breach of the CMS hydrogen piping, allowing hydrogen to escape to the high bay. The hydrogen is drawn into the PCES ventilation ductwork via the air intake, is ignited in the service bay, and explodes, releasing mercury. A similar event (TC2-3) postulates that an explosive gas external to the target building is drawn into the high bay area through the building air supply system. The gas is then drawn into the air intake and eventually into the service bay where it explodes like the previous event. Both explosion events would be expected to result in radiological doses that would challenge the off-site public exposure guidelines and on-site hazardous material criteria for all receptors. However, these events have both been determined to be noncredible based on the assumption that any hydrogen leaked into the atmosphere of the high bay would become sufficiently diluted to less than the LFL for hydrogen in air before being drawn into the PCES ventilation supply intake [29] and because the target building does not have natural gas service [28]. Therefore, no further analysis is required.

TC3 Loss-of-Confinement Events

One of the loss-of-confinement events involves a breach in the service bay confinement barrier that releases contamination and mercury vapor (TC3-1). The radiological consequences for TC3-1 were originally postulated to be moderate to the Onsite-1 worker with a risk rank of 2, which required evaluation of controls. Projected end-of-life mercury concentrations based on measured airborne mercury in the service bay indicate that the consequences associated with a loss of confinement in the service bay would not rise to the level of requiring credited controls [43]. Nonetheless, controls associated with the original analysis are retained. The need for a credited control is based on an assumption that PCE ventilation is lost. The following controls were selected to reduce the consequences for the Onsite-1 worker:

- SBDPMS: detects and alarms on loss of negative differential pressure between the service bay and adjacent locations.

- Procedures and Training for Evacuation of Adjacent Areas from SBDPMS Alarm: ensures workers evacuate areas adjacent to the service bay upon loss-of-negative-pressure alarm.

Event TC3-2 involves over-travel of the target carriage drive mechanism that damages core vessel or service bay components and releases residual quantities of mercury. The unmitigated radiological consequences to the Onsite-1 worker are high, and the chemical consequences exceed hazardous chemical criteria. Therefore, the following controls were selected to protect the workers within the occupied area:

- TBAC: prevents inadvertent worker access to the service bay.

- SBDPMS: detects and alarms on loss of negative differential pressure between the service bay and adjacent occupied areas.

- Procedures and Training for Evacuation of Adjacent Areas from SBDPMS Alarm: ensures workers evacuate areas adjacent to the service bay upon loss-of-negative-pressure alarm.

Event TC3-3 involves inadvertent movement of the target module while mercury is still being circulated, thereby releasing significant quantities of mercury. The unmitigated radiological consequences of TC3-3 are high for the Onsite-1 worker and moderate for the Onsite-2 worker, requiring evaluation of controls to ensure protection of the worker outside the occupied area as well as those within the occupied area. The following controls were selected:

- TBAC: prevents inadvertent worker access to the service bay.

- Service bay Confinement of Mercury: the service bay stainless steel liner is configured and sloped to route spilled mercury to the collection basin.

- PCES Ductwork: confines mercury vapor within the service bay after a spill.

- SBDPMS: detects and alarms on loss of negative differential pressure between the service bay and adjacent occupied areas.

- Procedures and Training for Evacuation of Adjacent Areas from SBDPMS Alarm: ensures workers evacuate areas adjacent to the service bay upon loss-of-negative-pressure alarm.

TC4 Direct Exposure Events

Event TC4-1 is a direct radiological exposure event that occurs when the intrabay doors are opened while workers are in the transfer bay. The unmitigated consequences to the Onsite-1 worker are high and require evaluation of controls. The following controls were selected to reduce the consequences of this event:

- TBAC: prevents opening of the transfer bay personnel door if the intrabay doors are not closed and sounds an alarm if the intrabay doors are not closed when the personnel access door is open.

Event TC4-2 involves exposure to personnel from a large breach in a manipulator gallery shielding window caused by crane load impact. The unmitigated consequences for this event to the Onsite-1 worker are high and require evaluation of controls. The following controls were selected:

- TBAC: prevents inadvertent worker access to the service bay.

- Radiological Protection Program: provides a means of controlling the radiological exposure received by facility workers. Radiation worker training enables workers to understand shielding provided by thick windows and to evacuate if they break.

- Hoisting and Rigging Program: ensures safe operation and proper certification and preventive maintenance of the service bay crane and gantry servomanipulator.

Event TC4-3 is an exposure to personnel resulting from a breach in the mercury heat exchanger. The unmitigated consequences for event TC4-3 to the Onsite-1 worker are high and require evaluation of controls. The following control was selected to reduce the consequences of this event:

- Mercury Heat Exchanger Double-Wall Design: the robust design prevents failure of a single wall from allowing radioactive mercury to escape from the service bay via the mercury loop cooling water system.

Event TC4-4 is an exposure to personnel resulting from a loss of the PCES ventilation during maintenance activities while the personnel door is in the open position and a worker is in the transfer bay. The number designator for this event indicates a direct radiation exposure, but the actual hazard would involve inhalation of mercury present in the service bay atmosphere. The number has been left intact for traceability to the historical hazard analyses. The unmitigated consequences for event TC4-4 to the Onsite-1 worker in the transfer bay are moderate and require evaluation of controls. The following controls were selected:

- SBDPMS: detects and alarms on loss of negative differential pressure between the service bay and adjacent occupied areas.

- Procedures and Training for Evacuation of Adjacent Areas from SBDPMS Alarm: ensures workers evacuate areas adjacent to the service bay in response to loss-of-negative-pressure alarm.

4.3.10 High Bay Area Event Scenario Summary

Fire events, explosion events, loss-of-confinement events, and an event involving direct radiological exposure were postulated during the evaluation of the high bay area.

HB Initial Conditions and Assumptions

- The Combustible Material Control Program Outside the Service Bay regulates the use of forklifts in the high bay.

- Electric–hydraulic robots may operate in the high bay.

- The loop 2, 3, and 4 gas/liquid separators are contained within a shielded pit in the high bay floor directly above the manipulator gallery and are covered by shielding during operations.

- The high bay area may have no more than loose surface contamination.

- The steel biological shielding assembly surrounding the core vessel and the inner and outer reflector plugs are in place during operations. This shielding includes the “birthday cake” shielding of carbon steel above the core vessel, as shown in Figure 3.17.

HB1 Fire Events

In the high bay area, a small (localized or incipient) fire (HB1-1) and a more substantial fire (HB1-2) were postulated. The two fires have identical initiators, but the larger fire is assumed to progress beyond the incipient stage. In these events, it is assumed that the high bay area has surface contamination throughout the area and that both fires release of that contamination. Also, it is assumed that these fires do not breach a transfer cask and do not propagate to the entire facility. The full-facility fire is evaluated in event BG1-1 in Section 4.3.14. The unmitigated consequences for events HB1-1 and HB1-2 do not challenge the radiological guidelines or criteria for any receptor group; therefore, no further analysis was performed.

HB2 Explosion Events

Event HB2-1 is an explosion that involves a breach of cryogenic moderator piping in the high bay or in the HUR. This explosion scenario is evaluated as part of the CMS in events CM2-2 and CM2-3 in Section 4.3.2.

Event HB2-2 involves a crane load dropping onto the core vessel. During the SNS project design phase, the postulated impact was assumed to cause sufficient displacement of the IRP assembly to breach the cryogenic moderator vessels and the mercury target, spilling hydrogen and mercury into the core vessel. Released hydrogen was assumed to ignite and explode within the core vessel, thus dispersing the spilled mercury. In reality, the core vessel, and thus the IRP, is protected from significant deflection by the massive steel biological shielding installed above and around the core vessel. The core vessel internals would experience acceleration but not significant deflection. The cryogenic moderator system inside the core vessel would remain intact for small deflections; however, the transfer line outside the core vessel could be crushed, trapping hydrogen in the core vessel. The trapped hydrogen could be released inside the core vessel: bounding consequences would be similar to the CM explosion events (Section 4.3.2). The unmitigated radiological consequences of HB2-2 to the on-site receptors are high and require evaluation of controls. The radiological consequences to the off-site receptor are low based on the operational requirement to have bulk radiation shielding during operating conditions. Additionally, physical access within the core vessel is not credible during operating conditions, so consequences to the worker immediately adjacent to the hazard are not possible (except through direct mechanical bodily injury, a standard industrial hazard). The following controls were selected to prevent the explosion:

- CMS Hydrogen Boundary: protects against impact and ensures the relief path remains unobstructed.

- High Bay Crane Design: ensures features are provided to prevent mechanical or electronic control failure of the crane. Single-failure-proof features are included so that any credible failure of a single component would not result in the loss of capability to stop and hold the critical load.

- Hoisting and Rigging Program: provides regular inspection and maintenance of equipment. Crane lifts are performed by trained personnel in accordance with approved lift plans and procedures. The program restricts crane lifts over the core vessel and mercury process system unless beam to target is terminated and mercury is drained to the mercury storage tank.

- High Bay Floor Design: the high bay floor is designed to withstand load drops permitted by Hoisting and Rigging Program to pass above the core vessel when the target mercury is not drained to the storage tank.

HB3 Loss-of-Confinement Events

Several loss-of-confinement events were postulated for the high bay area that resulted in unmitigated consequences that do not challenge public or worker criteria; therefore, no further evaluation was performed. These events included release of radiological material as the result of a leak in a transfer cask containing contaminated equipment (e.g., cask lid gasket failure) (HB3-1), a release of radiological material resulting from failure of confinement capability affecting personnel located in the high bay (HB3-4), and an air reversal at the inlet ductwork to the transfer bay (HB3-5).

Event HB3-2 postulates that the high bay crane drops a transfer cask, causing the cask to leak and release radiological material. The crane drop is caused by crane failure or operator error. The unmitigated consequences for event HB3-2 to the Onsite-1 worker are moderate and require evaluation of controls. The following controls were selected to reduce the frequency of this event and to protect the Onsite-1 worker:

- High Bay Crane Design: ensures that features are provided to prevent mechanical or electronic control failure of the crane. Single-failure-proof features are included so that any credible failure of a single component would not result in the loss of capability to stop and hold the critical load.

- Hoisting and Rigging Program: provides inspection, certification, crane operator training, crane maintenance procedure and maintenance personnel training.

Event HB3-3 involves a crane load drop on the service bay that penetrates the high bay floor, which serves as the service bay roof, and damages the mercury loop, releasing mercury. The unmitigated consequences for event HB3-3 are negligible to the off-site public and high to the Onsite-1 and Onsite-2 workers and require evaluation of controls to protect the on-site workers. The following controls were selected to reduce the frequency and consequences of this event:

- TBAC: prevents inadvertent worker access to the service bay.

- High Bay Crane Design: ensures that features are provided to prevent mechanical or electronic control failure of the crane. Single-failure-proof features are included so that any credible failure of a single component would not result in the loss of capability to stop and hold the critical load.

- Hoisting and Rigging Program: provides regular inspection and maintenance of equipment. Crane lifts are performed by trained personnel in accordance with approved lift plans and procedures.

Event HB3-6 involves damage caused by dropping the upper intrabay shield door. Dropping the upper intrabay shield door could significantly damage the adjacent transfer bay and remote waste handling area in the service bay. The unmitigated consequences for event HB3-6 are negligible for the off-site public and low to the Onsite-2 worker but high for the Onsite-1 worker and require evaluation of controls. The following control was selected to reduce the consequence to the Onsite-1 worker:

- TBAC: prevents opening of the transfer bay personnel door if the steel intrabay shielding doors are not closed.

Event HB3-7 is similar to HB3-2, but the load is assumed to be dropped on the core vessel. If the steel shielding above and surrounding the core vessel were not in place, then this event could cause an impact sufficient to displace the IRP and breach the cryogenic moderator vessels and the mercury target, spilling hydrogen and mercury within the core vessel. However, the steel shielding is in place for all beam-on-target operations. The steel shielding would prevent significant displacement of the IRP and thus prevent significant leakage. Nonetheless, it is conservatively assumed that damage to the target module does occur. The target module mercury boundary and the water-cooled shroud are assumed to fail and release mercury into the core vessel (equivalent to the TS3 loss of confinement of mercury inside the core vessel). The unmitigated radiological consequences for event HB3-7 are negligible to the off-site receptor, low to the Onsite-2 worker, and high to the Onsite-1 worker. The unmitigated chemical consequences are below off-site criteria but exceed on-site criteria. The following controls were selected:

- High Bay Crane Design: ensures that features are provided to prevent mechanical or electronic control failure of the crane. Single-failure-proof features are included so that any credible failure of a single component would not result in the loss of capability to stop and hold the critical load.

- Hoisting and Rigging Program: provides regular inspection and maintenance of equipment. Crane lifts are performed by trained personnel in accordance with approved lift plans and procedures.

HB4 Direct Exposure Events

Based on the types of material that could be present in various locations in the high bay, it was postulated that a worker could receive excessive direct radiological exposure. This exposure could occur near the transfer bay enclosure during equipment repairs. Event HB4-1 was postulated for this direct exposure, resulting in consequences that did not challenge either public or worker criteria; therefore, no further evaluation was performed.

Event HB4-3 postulates excessive exposure caused by inappropriate removal of movable shielding in the high bay area. For example, elevated radiation levels could occur in the high bay if the 50-ton crane were used for unauthorized removal of concrete shielding T-beams that provide access to normally unoccupied spaces such as the RTBT beam tunnel, the shutter drive equipment room, the service bay, the cooling water delay tank, and gas–liquid separation pits. Prevention of potential direct radiation exposure owing to inappropriate movement of shielding is discussed in the *Moveable Shielding* subsection of Section 4.2.1.1 of the FSAD-PF [26]. Following the approach described therein, the Radiological Protection program controls access to radiological areas and controls placement of shielding that mitigates dose and prevents worker access.

- Radiological Protection Program: provides a means of controlling the radiological exposure received by facility workers by controlling access to radiological areas and the placement of shielding.

4.3.11 Compressed Air System Event Scenario Summary

Fire, explosion, and loss-of-confinement events were postulated during the evaluation of the compressed air system (CAS).

CA Initial Conditions and Assumptions

The configuration of the compressed air lines makes significant back-leakage of air out of the service bay unlikely. When the air is not connected to the devices it powers, installed quick disconnects act like a cutoff valve. When connected, the air-powered devices would prevent or restrict backflow.

Instruments, valves, or other components controlled by compressed air are a fail-safe design on a loss of compressed air.

CA1 Fire Events

Considering the ignition sources associated with the CAS and the potential for combustibles to be present in the compressor located outside the target building, a fire could be initiated in the system. Because the CAS is located outside the target building, no radiological material is involved, and the event (CA1-1) is considered a common hazardous event.

CA2 Explosion Events

Event CA2-1 is an overpressure event. This event describes physical injuries to a facility worker resulting from rupture of an air receiver or other pressurized component. Because of the location of the compressor and supporting components, the rupture is not assumed to directly impact processing equipment. The event does not involve release of any radiological material, and the event is considered a common hazardous event.

CA3 Loss-of-Confinement Events

Event CA3-1 involves a breach in the cooling water supply piping to the compressor. This breach progresses to an overheating and ultimate failure of the compressor, causing loss of compressed air supply to the facility. This event assumes that the loss of compressed air does not affect processing equipment such that radiological material is released. It assumes any equipment that relies on compressed air for control is designed to fail safely and is not adversely affected. The event does not release any radiological material, and the event is considered a common hazardous event.

4.3.12 Fire Detection and Suppression System Event Scenario Summary

Fire events, an explosion event, and a loss-of-confinement event were postulated during the evaluation of the fire detection and suppression system.

FS Initial Conditions and Assumptions

The fire detection and suppression system inside the target service bay employs a UL Solutions (formerly Underwriters Laboratories, Inc.; UL)-listed or FM Global (formerly Factory Mutual; FM)-approved water mist system with pressurized cylinders to develop system pressure.

FS1 Fire Events

Event FS1-1 is a fire initiated in the fire detection and suppression system. Considering the ignition sources associated with the fire detection and suppression system and the potential for combustibles to be on or immediately adjacent to the system, a fire could be initiated in the system. Assuming that the fire involves only the electrical wiring or components on the fire suppression and detection system, it can be considered a common hazardous event because the system is not likely to contain any contamination. If the fire is left unattended, then it could ultimately propagate to areas of the facility that contain radiological material, although this event is unlikely to occur because of the limited quantity of combustible material available. Fires that occur in these areas are evaluated as part of other systems.

FS2 Explosion Events

Event FS2-1 involves an energetic rupture event. This event describes physical injuries to a facility worker resulting from rupture of pressurized cylinders. This event assumes the fire detection and suppression system could include cylinders containing CO_2 or nitrogen. Also, it is assumed that the cylinder rupture does not result in any impact to processing equipment and that no radiological material is released. Therefore, the event is considered a common hazardous event.

FS3 Loss-of-Confinement Events

Event FS3-1 involves a breach in the sprinkler water supply piping. This event assumes that the breach could cause internal flooding. The flooding is then assumed to flush surface contamination from a confinement area to a normally occupied area or to the environment. The release of radiological material in this case is determined to be negligible to the off-site public and low to the on-site workers; therefore, no further evaluation was performed.

4.3.13 Truck Bay and Utility Vault General Area Event Scenario Summary

Fire events, an explosion event, and a loss-of-confinement event were postulated during the evaluation of the truck bay and basement utility vault general area.

UV Initial Conditions and Assumptions

- The basement utility vault has no more than loose surface contamination.
- The cooling system components in the basement utility vault have highly activated cooling water during operations and some long-lived particulates following shutdown.
- Road vehicles have access to the truck bay in the target building basement.

- Sumps in the basement utility vault drain to the LLLW tank or process waste system depending on radioactivity content.
- Electric forklifts may operate in the basement utility vault.
- The utility vault may be fitted with an overhead monorail system for hoisting and moving loads.

UV1 Fire Events

Event UV1-1 is a general-area fire in the truck bay and basement utility vault. The designation as a general-area fire is based on the identification of several ignition sources along with the potential for combustibles to accumulate. The area may have surface contamination that is released during the general-area fire; therefore, only low levels of radiological material are involved, and no further analysis was performed.

Event UV1-2 is a localized fire involving a vehicle in the truck bay. This event is assumed to occur during delivery of supplies, for example. Furthermore, this event is assumed to be confined to the immediate area of the truck bay. The material released is assumed to be general surface contamination; therefore, no further evaluation was performed.

UV2 Explosion Events

Event UV2-1 is a small explosion likely from hydrogen released from forklift batteries or a battery-charging station or is a more substantial explosion involving fuel on the vehicle. The consequences of the explosion event involving the forklift battery or charging station are assumed to be limited to the release of surface contamination from the basement utility vault general area. Event UV2-2 is an explosion involving vehicle fuel assumed to damage the LLLW tanks and ion-exchange columns in the decontamination area, releasing their contents. It is assumed that neither of these events adversely impacts mercury processing equipment, so large quantities of highly radioactive material are not released. In both events, the unmitigated consequences are negligible or low to all receptors; therefore, no further evaluation was performed.

UV3 Loss-of-Confinement Events

Several loss-of-confinement events were postulated for the basement utility vault general area and truck bay. These events include release of general contamination from the basement utility vault general area or truck bay caused by ventilation system failure or worker error (UV3-1), release of nitric acid within the basement utility vault area (UV3-2), or as the result of a truck impact in the truck bay (UV3-3). The event involving leaking nitric acid (UV3-2) is evaluated in event CW3-7 in Section 4.3.3. The event involving the truck impact (UV3-3) assumes that no fire or explosion occurs after the impact. Although the vehicle is assumed to penetrate the wall at the end of the truck bay, the radiological effect is small. The unmitigated consequences for both UV3-1 and UV3-3 are negligible or low to all receptors; therefore, no further evaluation was performed.

UV4 Direct Exposure Events

Event UV4-1 recognizes the possibility that radiation exposure higher than background could exist in some areas of the basement utility vault general area and truck bay. The unmitigated consequences for UV4-1 are negligible to all receptors; therefore, no further evaluation was performed.

4.3.14 Target Building General Event Scenario Summary

The target building general event evaluations focus on scenarios that affect the entire target facility or multiple systems contained within the facility, including events that occur within the target building, external events that damage the target building, and natural phenomena.

BG Initial Conditions and Assumptions

- Electric forklifts and associated charging stations are used on the experiment floor of the target building.
- Facility workers can react to obvious hazardous conditions and evacuate unless injured because of the hazardous event.
- No fissionable material, which could cause an inadvertent criticality, is available in the target building.
- The SNS facility is located 1.5 km from the nearest uncontrolled public access.
- Surface vehicles can access roadways or parking lots in areas immediately adjacent to the target building.
- Hazards associated with chemicals (not related to the irradiated target system mercury) used at the facility are safely managed in accordance with the provisions of the ORNL SBMS Chemical Safety Management Program. Any beryllium in the reflector is encapsulated in aluminum.
- Target mercury in excess of 19.4 kg is not stored in the target building outside the service bay. This assumption only applies to mercury that has been introduced into the mercury loop and not to unirradiated mercury. Unirradiated mercury is handled and stored in accordance with the ORNL SBMS Chemical Safety Management Program and SNS procedures.
- The walls surrounding the service bay are designed to PC-3 seismic requirements and will provide a barrier after a seismic event to separate combustibles outside the service bay from mercury inside the service bay.
- Mercury loop steel shielding is normally in place when mercury is in the mercury circulation loop. This condition is operationally required only when mercury is activated to 250 rem/h (design goal to protect electronics within the service bay). Mercury loop shielding is designed to PC-2 seismic requirements.
- Combustible material is available in each section of the building.

BG1 Fire Events

Event BG1-1 is a full-facility fire. The fire is assumed to cause major structural damage that results in a mercury spill from the impact of falling structural components. The spilled mercury is then exposed to heat from the fire. Like event TS1-2 (Section 4.3.1), the fire is also postulated to propagate into the service bay. This event is assumed to involve the entire target building and to affect all the charcoal adsorbers in the basement PCES charcoal adsorber room. The release of significant quantities of mercury is assumed. The unmitigated radiological consequences for BG1-1 are high to on-site receptors, and the unmitigated chemical consequences exceed hazardous chemical criteria. This event requires evaluation of controls for radiological and chemical protection for all worker groups. The following controls were selected to reduce the event frequency and consequences:

- Service Bay and Core Vessel 2-Hour Equivalent Fire Barrier: encloses the service bay and core vessel and (1) ensures fires outside the core vessel and service bay cannot propagate into the core vessel or service bay (fire barrier function) and (2) prevents combustibles outside of the service bay from migrating into the service bay (isolation function).

- Combustible Material Control Program Outside the Service Bay: ensures combustibles outside of the service bay are maintained such that (1) the fire barrier is not challenged and (2) the gross building structure is protected from failure.

- PCES Air Intake Location: locating the PCES air intake just above floor level in the decontamination room discourages propagation of a fire into the service bay by minimizing the intake of hot gases produced by a fire outside the service bay.

- FSS Outside the Service Bay: provides a means to suppress or extinguish the maximum fire anticipated outside the service bay (1) to ensure the service bay and core vessel 2 h equivalent fire barrier is not challenged and (2) to protect the building structure.

- TBAC: prevents inadvertent worker access to the service bay.

- Procedures and Training to Control Mercury Inventory on PCES Charcoal Adsorbers: used to ensure the mercury accumulated on each charcoal adsorbers is maintained less than 19.4 kg and less than 155.2 kg on all adsorbers.

BG3 Loss-of-Confinement Events

Event BG3-1 involves a leak in the helium or liquid nitrogen supply piping. This event could occur at essentially any location in the building. The event assumes a potential for asphyxiation and does not involve a release of radiological material. Subsequent design changes removed liquid nitrogen supply piping in the target building, but gaseous nitrogen supplies remain. Liquid nitrogen piping only supplies dewar fill stations external to the building. The liquid nitrogen supply to the MOTS charcoal bed is also provided by dewars. This event is considered a common industrial hazardous event; therefore, no further evaluation was performed.

BG6 External Events

The postulated external events include a major loss of power (BG6-1), a small fire in the experiment hall (BG6-2), a fire that originates outside the target building (e.g., a forest fire) (BG6-3), a laboratory explosion (BG6-4), a natural gas explosion from a furnace (BG6-5), a natural gas explosion from piping outside the target building (BG6-6), an explosion from a vehicle carrying explosive material (BG6-7), a large aircraft impact (BG6-8), a small aircraft impact (BG6-9), a vehicle impacting the target building (BG6-10), and an external crane drop on the target building (BG6-11).

Event BG6-5 is not considered credible because natural gas is not piped into the target building. Moreover, any natural gas released into the atmosphere external to the target building (event BG6-6) would become sufficiently diluted to less than the LFL for natural gas in air before being drawn into the service bay ventilation supply intake [28].

The unmitigated consequences for events BG6-1, BG6-2, BG6-3, BG6-4, BG6-6, BG6-7, and BG6-10 are negligible or low for all receptors; therefore, no further evaluation was performed for these events.

Events BG6-8 and BG6-9 both are external aircraft impact events. An evaluation [32] of aircraft impact risk was performed for the target building using the methodology of DOE-STD-3014-96, *Accident Analysis for Aircraft Crash into Hazardous Facilities* [31]. The results of that evaluation indicate that, despite conservative assumptions, the frequency of potentially damaging aircraft impact is less than 10^{-6}/year. Therefore, aircraft impacts are not considered credible external man-made hazards to the target building and were not evaluated further.

Event BG6-11 postulates an external crane drop over the target building resulting in a release of radiological material. The unmitigated radiological consequences are low to the off-site public, high to the Onsite-1 worker, and moderate to the Onsite-2 worker, and the chemical criteria are exceeded for both worker groups and the off-site public. The following controls were selected to reduce the frequency and consequences of this event:

- Hoisting and Rigging Program: controls external crane lifts over the target building.

- Emergency Response Procedures and Training for Evacuation from External Crane Drop on Target Building: ensures notification and evacuation of target building in the event of an external crane drop.

BG7 Natural Phenomena Events

The postulated natural phenomena events that do not challenge public or worker evaluation criteria and require no further analysis include tornado or high straight winds that cause other structures (such as a stack) to collapse onto the target building (BG7-5), lightning (BG7-6), flooding (BG7-7), and roof collapse from heavy snow (BG7-8).

Event BG7-1 is an earthquake with a subsequent fire or explosion. Fire and explosion are assumed to be credible post-earthquake phenomena because of the CMS hydrogen that could be released in a seismic event. The unmitigated radiological consequences for event BG7-1 are high to on-site receptors and low to the off-site receptor. The hazardous chemical criteria are exceeded for all receptors. Therefore, an evaluation of controls is required for public (chemical only) and worker protection. The following controls were selected:

- Service Bay and Core Vessel 2-Hour Equivalent Fire Barrier: encloses the service bay and core vessel and (1) ensures fires outside the core vessel and service bay cannot propagate into the core vessel or service bay (fire barrier function) and (2) prevents combustibles outside of the service bay from migrating into the service bay (isolation function).

- Procedures and Training to Control Mercury Inventory on PCES Charcoal Adsorbers: used to ensure the mercury accumulated on each charcoal adsorber is maintained less than19.4 kg and less than155.2 kg on all adsorbers.

- CMS Hydrogen Boundary: prevents failures resulting in hydrogen leakage into the core vessel. The credited design includes its relief path and the seismically qualified (PC-3), restrained and externally protected hydrogen equipment that provides protection against impact and ensures the relief path remains unobstructed.

- Combustible Material Control Program Outside the Service Bay: ensures the fire barrier is not challenged and precludes gross building structural failure.

- Combustible Material Control Program Inside the Service Bay: limits the allowable combustibles, fixed or transient, consistent with the maximum 1 MW/hour locally intense fire analyzed in the safety basis inside the service bay to ensure a fire in the service bay could not challenge the primary mercury containment.

- Service Bay Confinement of Mercury: consists of seismically qualified (PC-2) stainless steel liner configured and sloped to promote spilled mercury travel to the collection basin.

- Ignition Control Program: limits ignition sources outside of the service bay and monolith.

Event BG7-2 is an earthquake without an explosion or fire. The unmitigated consequences for event BG7-2 are high radiologically to the Onsite-1 worker and exceed hazardous chemical criteria for the Onsite-1 and -2 workers and require evaluation of controls. The following controls were selected to reduce the consequences to the on-site workers:

- Service Bay and Monolith Confinement of Mercury: ensures confinement of mercury following a PC-2 seismic event.

Event BG7-3 is an earthquake followed by a hydrogen explosion with no follow-on fire. The unmitigated consequences for event BG7-3 are bounded by event BG7-1. Further analysis of radiological consequences to the off-site receptor is not required based on the assumed initial condition that radiation shielding is required to be in place during normal operating conditions for equipment protection and worker ALARA considerations. The following controls were selected to reduce the consequences of this event:

- CMS Hydrogen Boundary: prevents failures resulting in hydrogen leakage into the core vessel. The credited design includes its relief path and the seismically qualified (PC-3), restrained, and externally protected hydrogen equipment that protects against impact and ensures the relief path remains unobstructed.

- CMS Vacuum Boundary: prevents hydrogen from flowing into the core vessel following hydrogen leakage. The credited design includes its relief path and the seismically qualified (PC-3), restrained, and externally protected vacuum equipment that protects against impact and ensures the relief path remains unobstructed.

- Service Bay and Monolith Confinement of Mercury: ensures confinement of mercury following a PC-2 seismic event.

Event BG7-4 is a tornado or high winds with missiles that damage the target building, which subsequently releases radiological material. Further analysis of the radiological consequences to the off-site receptor is not required based on the assumed initial condition that radiation shielding is required to be in place during normal operating conditions for equipment protection and worker ALARA considerations. The unmitigated radiological consequences for event BG7-4 are negligible to the off-site receptor, moderate to the Onsite-1 worker, and low to the Onsite-2 receptor. Although moderate to the Onsite-1 worker, mitigation of consequences was not required per the policy for selection of credited controls [4] because the initiating frequency of this event is extremely unlikely (below 10^{-4}/year).

4.3.15 Summary of Hazard Analyses and Required Credited Controls

Of the 180 hazard events initially identified, the HA indicates that 53 require credited controls for worker protection. Analyses for these events are summarized in the controls matrix presented in Appendix A. CECs identified in the HA for worker protection are listed in Table 4.5. CACs are listed in Table 4.6. The analysis of effects to the off-site public (presented in Section 4.4) indicates that credited controls identified for worker protection are sufficient to protect the public. Therefore, the credited controls listed in the following tables represent the comprehensive set of credited controls for SNS.

Table 4.5. Summary of credited engineered controls

Credited engineered control	Applicable events
CMS Hydrogen Boundary	CM2-1a, CM2-1b, HB2-2, BG7-1, BG7-3
CMS Vacuum Boundary	CM2-1a, CM2-1b, BG7-3
Catalytic Converter Retention Elements	CM4-1
Service Bay and Core Vessel 2-Hour Equivalent Fire Barrier	TS1-2a, TS1-2b, TS1-3, TS1-6, BG1-1, BG7-1
TPS Beam Trip on Low Mercury Loop Flow	TS3-12, TS3-22, TS3-23, TS3-24, TS3-25
TPS Beam Trip on High Mercury Loop Temperature	TS3-13, TS3-14, TS3-15, TS3-16
TPS Prevents Beam to Target if Target Cart is Not Inserted	TS4-1
PPS Prevents Beam to Target if Target Cart is Not Inserted	TS4-1
FSS Inside the Service Bay	TS1-3, TS1-6
FSS Outside the Service Bay	TS1-2a, TS1-2b, BG1-1
Confinement Function of Core Vessel and Neutron Beam Windows	TS3-4, TS3-6, TS3-8, TS3-11, TS3-26, TS3-27
Service Bay and Monolith Confinement of Mercury	TS3-7, TS3-10, TS3-18, TC3-3, BG7-1, BG7-2, BG7-3
PCES Ductwork	TS3-7, TS3-10, TS3-18, TC3-3
PCES Air Intake Location	TS1-2a, TS1-2b, BG1-1
PCES Backdraft Dampers	TS1-3, TS1-6
PCES Flame Retardant Exhaust Filters	TS1-3, TS1-6
High Bay Crane Design	HB2-2, HB3-2, HB3-3, HB3-7
High Bay Floor Design	HB2-2
SBDPMS	TS1-3, TS1-4, TS1-6, TS3-7, TS3-10, TS3-18, GW3-2, TC3-1, TC3-2, TC3-3, TC4-4
TBAC	TS1-3, TS1-4, TS1-6, TS3-7, TS3-10, TS3-18, TS4-2, GW3-2, TC3-2, TC3-3, TC4-1, TC4-2, HB3-3, HB3-6, BG1-1
Mercury Heat Exchanger Double-Wall Design	TS3-9, TS3-21, TC4-3
Mercury Pump Tank Exhaust Line Loop Seal	TS3-28
Mercury Pump Tank Exhaust Line Loop Seal and Orifice	TS3-36
Mercury Pump Tank Rupture Disk and Discharge Path	TS3-36

Table 4.6. Summary of credited administrative controls

Credited administrative control	Applicable events
Radiological Protection Program	CW4-1, GW3-2a, HV3-5, SH4-1, SH4-2, SH4-3, SH4-4, TC4-2, HB4-3
Chemical Safety Management Program	No longer applicable
Combustible Material Control Program Outside the Service Bay	TS1-2a, TS1-2b, BG1-1, BG7-1
Combustible Material Control Program Inside the Service Bay	TS1-3, TS1-6, BG7-1
Ignition Control Program	BG7-1
Hoisting and Rigging Program	TC4-2, HB2-2, HB3-2, HB3-3, HB3-7, BG6-11
Procedures and Training for Evacuation of Adjacent Areas from SBDPMS Alarm	TS1-3, TS1-4, TS1-6, TS3-7, TS3-10, TS3-18, GW3-2, TC3-1, TC3-2, TC3-3, TC4-4
Procedures and Training to Control Mercury Inventory on PCES Charcoal Adsorbers	TS1-2b, BG1-1, BG7-1
Emergency Response Procedures and Training to Close the Personnel Door upon Evacuation from Service Bay Fire	TS1-6
Emergency Response Procedures and Training for Evacuation from External Crane Drop on Target Building	BG6-11
Emergency Response Procedures and Training for Evacuation from Service Bay Fire with Common Air Flow	TS1-4

4.3.16 Identification of Events with Potential Offsite Impacts

Hazard event scenarios analyzed for on-site impacts were reviewed to identify accidents that may affect the off-site public. Events initially placed in off-site public risk bins 1 through 9 during qualitative HA were selected for off-site impact analysis. Based on the approach taken in DOE-STD-3009-94 [1], events in risk bins 1, 2, 3, 4, 5, and 7 are strongly suggested for inclusion in the accident analysis process. SNS also chose to evaluate events in risk bins 6, 8, and 9 as situations of concern, yielding a subset of representative events for further examination.

The number of events needing accident analyses was reduced by grouping similar events that could be bounded conservatively by a single source term. For example, the bounding consequence analysis for large- and small-break releases of mercury into the target service bay is identical. This sort of grouping is possible because the quantitative accident analysis determines bounding consequences rather than characterizes small differences between similar accidents. As the chemical consequence analysis followed the radiological analysis, accident selection for chemical evaluation employed the existing radiological analysis.

The following events were selected for off-site impact accident analysis:

1. Service bay fire (TS1-3, TS1-6),
2. Medium fire (TS1-2a, TS1-2b),
3. Full-facility fire (BG1-1),
4. Hydrogen explosion with follow-on fire (CM2-1a),
5. Hydrogen explosion without follow-on fire (CM2-1b),
6. Service bay loss of confinement (TS3-7, TS3-10),
7. Core vessel (helium) loss of confinement (TS3-4, TS3-6, TS3-8, TS3-11),
8. Core vessel (vacuum) loss of confinement,
9. Partial loss of mercury flow (TS3-22, TS3-23, TS3-24, TS3-25),
10. Complete loss of mercury flow (TS3-22),
11. Loss of heat sink (TS3-13, TS3-14, TS3-15, TS3-16),
12. Service bay crane load drop (TS3-18),
13. High bay crane load drop onto service bay (HB3-3),
14. High bay crane load drop onto core vessel with no hydrogen explosion (HB3-7),
15. High bay crane load drop onto core vessel with hydrogen explosion (HB2-2),
16. External load crane drop (BG6-11),
17. Seismic event including follow-on hydrogen explosion and fire (BG7-1),
18. Seismic event including follow-on fire (BG7-2),
19. Seismic event including follow-on hydrogen explosion (BG7-3).

Accident analyses for impacts to the off-site public are presented in Section 4.4.

4.4 ANALYSIS OF EVENTS WITH POTENTIAL OFF-SITE IMPACTS

This section presents the quantitative assessment of accident scenarios that have a postulated radiological or toxicological effect on the public. The basis for selection of these scenarios is presented in Section 4.3.

Accident analyses were performed based on guidance provided in DOE-STD-3009-94 [1]. An overview of methodology, including source term, meteorological dispersion, and dose calculations, is provided in Section 4.4.1.

Bounding consequences to the off-site public calculated for the various postulated accident scenarios are presented in Section 4.4.2. Bounding consequences are presented for the unmitigated scenarios and for accident scenarios associated with the as-constructed facility. The results of the bounding consequence analyses are summarized in Section 4.4.2.10.

Unmitigated analyses, calculated before SNS operations began, served to identify certain design features and other controls needed to ensure protection of the off-site public. The unmitigated analyses assumed no benefit of the credited controls specifically designed to eliminate or diminish accident consequences. Thus, in the unmitigated analysis, analysts intentionally ignored credited structures/components and normally present conditions that they provide, such as the seismically qualified steel and concrete monolith. This strategy highlighted the important safety role of these features and provided input into the design process. For instance, the important safety role of the service bay walls (e.g., confinement of airborne mercury and protecting the mercury loop from fire events) led to their PC-3 seismic design level. Passive structures were not assumed to provide any protection in unmitigated analyses except as noted otherwise.

The as-constructed analyses considered passive robust structures and design features but not active controls or administrative controls. The as-constructed analysis incorporates updated information based on operational experience that was not available during the project's pre-operational phase. Assumptions associated with the as-constructed analyses are described with the various accident scenarios in Section 4.4.2. In several instances, the unmitigated analysis consequences were well below crediting thresholds, so no as-constructed analysis was performed, and consequences were assumed equal to the unmitigated consequences.

The functions provided by passive structures with no credible failure mode may be accounted for when determining unmitigated consequences. The *SNS Policy for Selection of Safety Related Credited Controls* [4] defines unmitigated consequences as follows:

> *The unmitigated consequences of an event are generally taken to be the consequences without the benefit of human actions and without the benefit of structures, systems, or components that would prevent or mitigate the event. Passive structures that do not have credible failure modes for the event under evaluation are allowed to provide mitigation in determining unmitigated consequences.*

The unmitigated consequences were analyzed before SNS operations began to determine the need for credited controls to protect the off-site public. Results for unmitigated consequences were compared with the criteria for the selection of credited controls (Section 4.2.2.4) to determine whether credited controls were needed for public protection.

Accident analyses are typically carried out only to the point at which the conservative assessment confirms that the calculated consequences of the event satisfy the *SNS Policy for Selection of Safety Related Credited Controls* [4] for radiological and chemical exposures. The mitigation strategies have been analyzed [33] as necessary to demonstrate the effectiveness of controls. A tailored approach has been applied for accident evaluation based on the following concepts:

- Accident analyses are carried out only to the point at which the conservative assessment confirms that the calculated consequences of the event satisfy the selection of credited controls criteria (Section 4.2.2.4).

- Analyses use the bounding maximum radionuclide inventory associated with end-of-facility life when radioactivity content is highest.

- The analyses credit only the minimum number of systems and physical phenomena needed to ensure that the selection of credited controls criteria is satisfied.

The unmitigated consequence analyses were based on very conservative simplifying assumptions. If the resulting consequences exceeded criteria, then follow-up analyses were performed by employing more realistic modeling and assumptions and/or by crediting prevention and mitigation control functions until the appropriate level of mitigation was reached. If the resulting consequences were below the criteria requiring credited controls, then no further analyses were performed, and the results presented to demonstrate that criteria were not challenged.

This approach is considered cost effective, but the degree of conservatism in the analysis varies from event to event. Therefore, the calculated consequences are not intended to be representative of expected doses if the accident were to occur. Furthermore, the calculated consequences are of limited value when comparing the relative hazards of various events or for comparisons with consequences at other facilities.

As part of the analysis, events were grouped by type (e.g., fire, tornado, seismic) and examined to identify the bounding event for each specific type. This examination concludes that, in many instances, the bounding hazardous material release consequences for events listed in Section 4.3.16 are bounded by similar events (e.g., events of the same type occurring in a different location). This inspection process reduces the number of events for which detailed analyses are performed.

The results show that none of the bounding off-site consequences exceed radiological thresholds, but some of the associated bounding consequences for unmitigated accidents exceed the toxicological consequence threshold (EPRG-2) for mercury vapor. In such instances, a single level of credited control is required per the selection criteria presented in Section 4.2.2.4. In all cases, the credited controls designated in Section 4.3 for worker protection were found to be more than adequate to mitigate consequences to the public [33]. Off-site consequences associated with the as-constructed analysis were all below crediting thresholds.

Engineering calculations describing processes employed to develop the accident source term and consequence analysis are provided in the literature [43, 49–51]. The results of the engineering calculations have been updated based upon changes to the base assumptions for radionuclide inventory resulting from the PPU project [64]. The changes include the nominal proton beam energy, facility lifetime (including actual power history), and CMS hydrogen inventory. Updated radionuclide inventory of the target mercury owing to increased proton beam energy and extended facility life is documented elsewhere [62].

4.4.1 Methodology for Off-site Impact Analysis

This section describes the basic methodology used for the accident analysis of the SNS target facility.

4.4.1.1 Assumptions and Input

The assumptions and inputs used for hazard and accident analyses are documented elsewhere [22]. This subsection provides an overview of the topic and discusses some of the more significant assumptions and inputs used in the accident analyses. These assumptions and inputs address the following:

- Facility operations,
- Facility physical characteristics,
- Facility physical configuration,
- Physical phenomena under accident conditions.

The assumptions and inputs related to the facility operations, facility physical characteristics, and facility configuration involve items that facility personnel can control or change. Those critical assumptions and inputs that preserve the validity of the safety analyses and ensure the facility is operated within the analyzed operating safety envelope must be protected by controls and limits on facility operations.

The following facility-related assumptions are employed for all analyses:

- The maximum temperature of the mercury in the hot leg of the target system during normal operations is 125°C.
- The maximum mercury system pressure during normal operations is 105 psig (at the pump outlet).
- The arrangement of the facility equipment and the system internal pressures are such that the maximum drop height for liquid mercury escaping from the system is 8.08 m.
- The maximum ambient temperature in the target service bay is 50°C, and the maximum ambient temperature in the core vessel is 60°C.
- Radioactive inventories are based on those that would exist after the facility's full operational lifetime [62] with an uncertainty multiplier of 1.5 for calculation uncertainty and 1.05 for proton beam power uncertainty, yielding a net uncertainty factor of 1.575 to account for calculation uncertainties in predicted activity levels.
- The total hydrogen mass in the cryogenic moderator system is 9.4 kg [63].
- The target building has no natural gas service.
- In unmitigated consequence assessments, it is usually assumed that the beam cutoff function does not stop the beam from continuing to transfer energy to the mercury system. An exception is the analyses of seismic events that account for the inherent physics-based characteristics of accelerators to shut down when the beam's alignment is disturbed. Analyses performed by the SNS project indicate that ground accelerations equivalent to or more severe than PC-1 create a disturbance that would upset the crucial alignment necessary for the approximately 300 m long accelerator to provide the proton beam [44, 45].

To allow for instrument uncertainty and operational variability, input values used in the analyses, such as those cited in the first six items above, are generally more conservative than design—or expected operational—values. For example, the 125°C, initial hot-leg temperature is well above the 90°C nominal hot-leg temperature expected at 2 MW proton beam power. These assumed parameter values were used in the quantitative accident analyses.

The work control process protects features of the facility configuration and operating conditions credited in the analyses against function-altering modification.

Controls on the facility inventory of hazardous material and the basic facility configuration are needed to meaningfully define the facility. The hazard and accident analyses are based on these assumptions for those specific events that were carried forward for both control selection and those that did not require credited controls because even unmitigated consequence assessments assume certain basic control functions. For example, if no upper bound is placed on the quantity of material that can be present in the facility at any one time, then, in principle, no upper bound can be placed on the consequences of certain postulated scenarios. Thus, a control on the inventory, or material at risk (MAR), is always required. This control is accomplished by limiting the power of the proton beam impacting the target module and by maintaining the same basic target module and reflector configuration. Specifically, the radiological inventory assumed in the accident analysis was initially based on 5,000 h/year operation for 40 years at the maximum beam power of 2 MW. As part of the PPU project, the inventory was revisited to account for increased beam energy to an assumed 1.3 GeV. The assumed operational period was also extended, incorporating the known power history of the facility plus an additional 40 years of operation following completion of the project [62]. An uncertainty factor of 1.575 was applied to the predicted activity levels to account for uncertainty in the predicted values [33].

In addition to these facility-related assumptions, the following physical phenomena assumptions are employed for all analyses:

- Radioactive decay during plume transport has been ignored for simplicity.
- The unmitigated receptor exposure is assumed to end in 8 h [4].
- Passive cooling is adequate to remove decay heat from stagnant mercury in the primary loop after the proton beam is shut off [46].
- All non-condensable gases are assumed to escape.

Additional specific event assumptions used are described in the following subsections.

4.4.1.2 Source Term

The basic methodology used to quantitatively determine the amount of respirable radioactive or other hazardous material released from the facility to the atmosphere is based on techniques described in DOE Handbook 3010 [47].

The source term (*ST*) is the quantity (in curies or kilograms) of hazardous material that is released airborne in respirable form. It is determined using Eq. (1) or (2).

For a short-duration (or instantaneous) release:

$$ST = (MAR)(DR)(RF)(LPF) \tag{1}$$

For a constant release rate:

$$ST = (MAR)(DR)(ARR \times t)(RF)(LPF) \tag{2}$$

where

MAR = material at risk—the radioactive material (in curies) or hazardous material (in kilograms of mercury) available to be acted upon by a given physical stress.
DR = damage ratio—the fraction of *MAR* affected by accident-generated conditions (unitless).
ARF = airborne release fraction—the fraction of *MAR* affected by accident conditions that is suspended in air as an aerosol owing to the physical stresses from a given accident and thus available for airborne transport (unitless).
ARR = airborne release rate—the coefficient used to estimate the amount of a radioactive or hazardous material that can be suspended in air by continuously acting mechanisms such as aerodynamic entrainment/resuspension (units are per time increment, normally per hour for SNS).
RF = respirable fraction—the fraction of airborne radionuclides as particles that can be transported through air and inhaled into the human respiratory system—generally assumed to include particles less than 10 µm aerodynamic equivalent diameter (AED) (unitless).
LPF = leak path factor—the fraction of radionuclides in air that is not removed by confinement, deposition, or filtration mechanisms during transport to the exterior of the facility (unitless).

t = release duration time (normally 8 h for radiological analysis).

Radionuclide source terms are calculated for two general phases: (1) a short-duration phase, where the direct effects of the event cause material to become airborne (possibly including vapor formation from heated mercury) and (2) a longer-duration evaporation phase, where spilled (or otherwise affected) material emits vapor at a slower rate after it has cooled (or continues to cool). This longer-duration phase extends to 8 h, consistent with the guidance in the *SNS Policy for Selection of Safety Related Credited Controls* [4].

Several analytical steps are necessary to select the parameters used in the source term equations: (1) developing postulated event scenarios to be quantitatively analyzed; (2) identifying the physical processes caused by the initiating event that can directly affect the facility's MAR; (3) identifying any normally operating systems that can affect the progression of the scenario; and (4) identifying secondary events that can be triggered by the initiating event, so they can be included in the source term analysis.

The MAR comprises the process mercury and the radionuclide inventory generated by the spallation process. For the process mercury, the MAR is expressed in terms of mercury mass (in kilograms) so that toxicological health effects can be addressed. A few spallation products, such as osmium, have chemical toxicity comparable to that of mercury, but the amount that accumulates in the mercury is very small relative to the amount of mercury present. Therefore, mitigating the chemical toxicity effects of the mercury adequately protects against the other toxic spallation products. For the radionuclide inventory generated by the spallation process, the MAR consists of an extensive table of radionuclides [62] calculated to be present in the process mercury and activated cooling water. The source term analysis determines releases of mercury as a vapor and as an aerosol and tracks these releases separately because the radiological composition of each release form is different.

For some scenarios, the analysis conservatively assumes that the entire radioactive inventory can be subjected to the accident stresses. For these events, a DR value of 1.0 is specified. In other scenarios, physical considerations limit the amount of radioactive inventory exposed to the accident stresses.

The ARF, ARR, and RF values are generally based on results from experiments and tests such as the generic data summarized elsewhere [47] combined with results of the precursor engineering analysis.

In general, the primary methods of preventing respirable material that has become airborne within a facility from escaping are (1) remove the material from air and other gases exiting the facility (such as by filtration for particles and condensation for vapor) and/or (2) prevent the atmosphere in the building from exiting (such as by use of confinement structures without forced exhaust). Because the analysis does not credit such systems, an LPF of 1.0 is used.

Equations (1) and (2) can be simplified by introducing the respirable release fraction (RRF), which is defined as the ratio (*ST*)/(*MAR*). Equations (1) and (2) can then be expressed as Eq. (3):

$$ST_i = (MAR)_i \times (RRF)_i \tag{3}$$

where i denotes a particular radionuclide or group of radionuclides, and

$RRF_i = [(DR)(ARF)(RF)(LPF)]_i$ for the short-duration release, and
$RRF_i = [(DR)(ARR \times t)(RF)(LPF)]_i$ for a constant-rate release.

The RRF term will be used for the remainder of the source-term discussion.

Source terms for the accident analysis are summarized in a preliminary safety report [34] and are based on analyses from ORNL and WSMS [41, 42]. Unmitigated RRFs for the various events are presented in Table 4.7. For the hydrogen explosion (no fire) event, source terms are given separately for the detonation case and deflagration case.

Material at Risk

The total mercury inventory of 18,000 kg (from Table 1 of [22]) and the radionuclide inventory contained within represent the MAR. This value represents the minimum mass of mercury in the mercury loop and is calculated by taking 95% of the nominal mass of mercury in the system (i.e., 18,950 kg from Table 1 of [22]). Use of the minimum mercury mass results in a more concentrated radionuclide inventory (i.e., more activity per unit mass). The conservatism of this approach is apparent when a fixed amount of mercury is exposed to the accident stress (i.e., DR less than 1.0) or when the analysis determines only a fixed amount of mercury can be released by the accident stress (e.g., amount of mercury vaporized is proportional to the amount of thermal energy present). The radiological inventory is based on the entire facility lifetime at 2 MW beam power. An uncertainty factor of 1.575 is applied to these values to account for uncertainty in the predicted activity levels.

Respirable Release Fractions

Inventory radionuclides are grouped according to volatility characteristics. The radionuclides released to the atmosphere during a postulated accident consist of the following three main components:

- Group I—volatile radioactive products,
- Group II—radioactive mercury vapor,
- Group III—radioactive liquid mercury containing dissolved nonvolatile radioactive spallation products.

Group I is divided into two primary subgroups: Group IA consists of volatile materials in the mercury, and Group IB consists of volatile materials in the activated cooling water. Group IA is further subdivided into four second-level subgroups based on volatility characteristics.

The nature of these inventory groups is discussed below. The discussion is largely a summary of the evaluation documented elsewhere [48].

Group I—Volatile Radioactive Spallation Products

- Group IA-1 (highly volatile) consists of radioactive products that are gaseous at ambient temperature. Specifically, gaseous tritium and noble gas (e.g., xenon) isotopes make up this group. These radionuclides are assumed to be released in their entirety during an accident (i.e., $RRF = 1$).

- Group IA-2 (moderately volatile) consists of volatile halogen isotopes (e.g., iodine, chlorine, bromine, fluorine). The volatility of the halogens is similar to that of mercury. Thus, the same RRF is applied to these radionuclides as is applied to the Group II and Group III mercury isotopes.

- Group IA-3 (moderately volatile oxides) consists of arsenic isotopes, which form As_2O_3. As_2O_3 is less volatile than mercury. The same RRF is conservatively applied to arsenic isotopes as is applied to the Group II and Group III mercury isotopes.

- Group IA-4 (conditionally formed volatile oxides) consists of osmium, ruthenium, technetium, and rhenium isotopes that form oxides only at temperatures above the boiling point of mercury with oxygen present. Thus, releases of these radionuclides as volatile oxides occur in accident scenarios in which a heat flux is present to completely boil/evaporate exposed mercury, leaving behind the initially nonvolatile Group IA-4 elements, which are heated so that the potentially volatile oxides can begin forming. If this condition is met, then the same RRF is applied to these radionuclides as is applied to mercury isotopes. If this condition is not met, then the same RRF is applied to these radionuclides as is applied to the nonvolatile spallation products (i.e., the Group III).

- Group IB (gaseous nuclides in cooling water) consists of gaseous nitrogen and oxygen isotopes that are present in the activated cooling water as well as tritium. If the accident scenario involves a breach of radioactive cooling water loops, then the entire inventory is assumed to be released ($RRF = 1$). Otherwise, the RRF is assumed to be zero.

Group II

- Group II consists of mercury isotopes. The nonvolatile spallation products contained within the mercury are assumed to stay with the portion of the mercury that remains in the liquid state. This group represents mercury released in vapor form owing to accident conditions that promote evaporation or boiling of the liquid mercury. Mercury boiling can be caused by fires, deflagrations, or excessive heating by the proton beam. The RRF for mercury vapor for each accident scenario represents the response of exposed mercury to thermal stresses as determined by accident analysis [50,51].

Group III

- Group III consists of mercury isotopes and the nonvolatile spallation products contained within the mercury. This group represents mercury released in aerosol form owing to accident conditions that promote droplet formation. The RRF for these radionuclides for each accident scenario represents the response of liquid mercury to mechanical stresses as determined by accident analysis [50, 51].

Table 4.7 summarizes the RRF specifications for the various inventory groups. The accident analyses documented elsewhere [41, 42] provide the basis for the Group II RRF (RRF_{II}) and the Group III RRF (RRF_{III}) specifications, and the RRF specifications for the other inventory volatility groups are then determined as indicated in the Table 4.7.

Table 4.7. Summary of respirable release fraction specifications

Volatility group	Vapor RRF	Aerosol RRF	Total RRF
IA-1	1.0	0	$RRF_{IA\text{-}1} = 1.0$
IA-2	RRF_{II}	RRF_{III}	$RRF_{IA\text{-}2} = RRF_{II} + RRF_{III}$
IA-3	RRF_{II}	RRF_{III}	$RRF_{IA\text{-}3} = RRF_{II} + RRF_{III}$
IA-4	RRF_{II} if mercury boiled dry 0 if mercury not boiled dry	RRF_{III}	$RRF_{IA\text{-}4}$ = (RRF_{II} or 0) + RRF_{III}
II	RRF_{II}	N/A	RRF_{II} {from analysis [50, 51]}
III	N/A	RRF_{III}	RRF_{III} {from analysis [50, 51]}
IB	0 if cooling water loop not breached or 1.0 if cooling water loop breached	0	RRF_{IB} = 0 or 1.0

The total RRF values represent those used in the source-term calculations for the RRF_i term of Eq. (3). The subscript i in Eq. (3) denotes a particular radionuclide, and each radionuclide belongs to a volatility group. Mercury isotopes are a special case in that mercury isotopes are part of both Groups II and III. The total fractional mercury release is equal to the sum of RRF_{II} and RRF_{III}. Group II consists of mercury isotopes released in vapor form (the aerosol RRF component for Group II is not applicable by definition). Group III includes mercury isotopes released in droplet form together with nonvolatile spallation products (the vapor RRF component for Group III is thus not applicable by definition). The key elements associated with determining RRF_{II} and RRF_{III} values for the various accident scenarios include the physical processes involved in the event (e.g., mechanical shock, vibration, and explosion blast forces) and, when applicable, the quantity of kinetic and thermal energy involved in the scenario.

Mercury has a small vapor pressure at temperatures associated with normal SNS operation. The vapor pressure increases essentially exponentially with temperature. The accident analysis assumes a mercury temperature of 125°C for event scenarios that do not involve a temperature excursion. This 125°C conservatively represents the hot-leg temperature of the mercury process system. The vapor pressure is only about 1.3×10^{-3} atm at 125°C and is 1 atm at 357°C.

Because of the vapor pressure of mercury, any accidental release of mercury from the target module or associated mercury loop piping will yield airborne (and respirable) mercury vapor. Mercury vapor formation is assumed to continue until the accident stabilizes. In most scenarios, the liquid mercury cools after it is released from the mercury process system. The rate of vaporization decreases as the temperature decreases. Mercury vapor does not contain nonvolatile spallation products (those with vapor pressures well below the ambient atmospheric pressure at the location of the release).

Airborne respirable mercury droplets (Group III) may form during certain accidents. Droplets can be formed from a pressurized spray release and by forces exerted on the fluid during events in which the mercury falls from an elevated pipe break and then impacts a solid surface. Airborne droplets formed in this way would contain dissolved spallation products in addition to radioactive liquid mercury. Airborne respirable mercury droplets may also be formed by condensation of mercury vapor as the vapor cools when it mixes with air. Droplets formed by condensation would have the same radioactive inventory as mercury vapor (i.e., would not contain nonvolatile spallation products). Because the source term and consequence analysis model the transport and dispersion of mercury vapor and droplets in the same way, the condensation process is effectively ignored. Specifically, respirable droplets of mercury, such as those that might be formed by condensation, are modeled to be transported of the facility on air currents and without removal by deposition mechanisms. This treatment is unrealistic but conservative for the hazardous material release in droplet form.

ARF and RF values from thermal-hydraulic analysis of the SNS mercury target [46] generally serve as the starting point for determining the non-vapor components of the releases (i.e., RRF_{III} values). Most of the ARF and RF values were developed for aqueous solutions and slurries containing radioactive uranium and plutonium. Additional evaluations were performed to identify factors to adjust the airborne respirable aerosol values based on aqueous solutions to correspond to mercury properties and SNS accident conditions.

For several types of postulated events, the accident analysis employs detailed calculations of heat-transfer and fluid-flow effects to determine a bounding value for the fraction of the mercury inventory vaporized during the event (i.e., the $\mathrm{RRF_{II}}$ value).

The following subsections briefly describe the basic techniques used to determine RRF_{II} and RRF_{III} values for various types of events.

RRFs for Low-Temperature Mercury Vaporization

For mercury evaporative releases, the RRF_{II} value is equal to the fractional amount of mercury that evaporates during the event. This quantity is, in turn, related to the temperature of the mercury and of the ambient air, the surface area of the mercury exposed to air, and the airflow rate across the exposed liquid surface.

The accident analysis determines RRF_{II} by employing a calculation method, for use in events other than fires, based on the analogy between mass transport by convection and heat transport by convection. This method is based on information found in standard textbooks such as *Heat and Mass Transfer* [50].

This method treats mass transfer by evaporation. The liquid is treated as having formed a 1 cm deep circular pool (unless a structure, such as a sump, dike, or berm, is credited to limit its spreading), and the evaporation is driven by airflow over the pool. If no structure is credited to retain the liquid, then the pool area (A) is calculated by dividing the liquid volume by the 1 cm pool depth, and the diameter (d) is calculated from the calculated area for the pool.

The mass transfer rate ($\dot{m}$), defined as the rate of mass transfer from liquid state to vapor state, is determined by the following equation:

$$\dot{m} = hA\left(\frac{M\Delta p}{\mathrm{R_u}T}\right) \tag{4}$$

where

$\dot{m}$ = mass transfer rate (kg/s)
h = mass transfer coefficient (m/s)
A = pool surface area (m^2)
M = molecular weight of the volatile compound (g/g·mol)
Δp = difference between liquid-phase vapor pressure and gas-phase partial pressure (bar)
$\mathrm{R_u}$ = universal gas constant (0.08314 [bar·m^3]/[kg·mol·K])
T = air temperature (K)

The mass transfer rate can be positive or negative depending upon the sign of the pressure-difference term. A value of zero for the pressure-difference term denotes equilibrium conditions in which no net mass transfers from the liquid phase to the vapor phase.

For simplicity, the gas-phase partial pressure is taken to be zero, which provides the maximum evaporation rate, which is conservative. The pressure difference (Δp) then reduces to the liquid-phase vapor pressure.

The transitional Reynolds number between laminar and turbulent air flow past a floor spill is 500,000. The calculated Reynolds numbers for SNS mercury spill events are above this value. The mass transfer coefficient (h) is determined from the following relationship for turbulent flow:

$$h = \frac{D}{d}(0.037 Re^{0.8}) Sc^{1/3} \text{ for } Re \geq 5 \times 10^5 \tag{5}$$

where

d = pool diameter (m)
D = diffusion coefficient of the volatile compound in air (m^2/s)
Re = Reynolds number (unitless)
Sc = Schmidt number (unitless)

The Reynolds and Schmidt numbers are defined as follows:

$$Re = \frac{d\, u\, \rho_a}{\mu_a} \tag{6}$$

$$Sc = \frac{\mu_a}{D\rho_a} \tag{7}$$

where

u = wind speed (m/s)
ρ_a = air density (kg/m^3)
μ_a = air viscosity (kg/[m·s])

The spilled material is assumed to fall 3 m, which bounds the maximum possible fall from a leak at any piping location. For scenarios involving a release from a pressurized pipe, a geyser effect that increases the effective release height is postulated. The basic spill scenario is intended to address a leak or break at any location in the mercury process system (i.e., a spill in the core vessel or in the target service bay) and to involve the entire primary loop inventory.

Conservative assumptions used for spill events that include significant mercury evaporation include the following:

1. Mercury spills cool only by evaporation and forced convection from the airflow across the upper surface of the spilled material. Conduction to the facility floor is neglected.

2. Air velocity across the spill is 2.5 m/s. This value is greater than the air velocities associated with normal ventilation in the target service bay by about two orders of magnitude.

In addition to evaporation releases, most spill scenarios include mechanical or kinetic energy stresses on the liquid mercury that promote the formation of respirable-sized droplets of liquid mercury. The response of the liquid mercury to these stresses is the basis for the RRF_{III} value. Mercury falling and possibly being expelled under pressure from a leaking pipe (or other type of process vessel) generates droplets. Moreover, once the spilled mercury forms a pool, aerodynamic entrainment over the surface of the spilled mercury pool by air currents can drive small amounts of respirable-sized droplets. The RRF_{III} value to represent the droplet formation from these stresses is derived from the *ARF*, *ARR*, and *RF* values summarized in the thermal-hydraulic analysis of the SNS mercury target [46].

RRFs for Mercury Vaporization during Fire Accidents

Three scenarios are considered with a fire starting in one of three locations: (1) inside the service bay, (2) in the target building with propagation into the service bay (referred to as a medium fire), and (3) outside the target building with propagation into the target building (i.e., full-facility fire).

Mercury loop piping and components are normally covered in shielding at least 4 in. thick (12 in. thick in places) when mercury is in the mercury loop. The shielding extends the life of nearby electronic components. The analyzed fire event is a localized, intense fire with a heat release rate of 1 MW and duration of 1 h. The analysis assumes that routine housekeeping programs to support facility operation and specific combustible controls on liquid combustibles limit transient combustibles that would support a fire that exceeds these conditions [51]. The analysis indicates that the steel shielding temperature remains below the atmospheric boiling point of mercury and concludes that the fire does not cause failure of the steel panels that surround the mercury loop. With the steel panels in place, the boundary of the mercury loop is maintained, and no mercury spills or vents. Although the source term is nominally zero, a fire could vaporize minor quantities of residual mercury that could accumulate in the target service bay. The analysis assumes 19.4 kg of mercury immediately adjacent to the fire to demonstrate the potential for mercury vaporization owing to miscellaneous mercury accumulation outside the shielding panels.

During the commissioning of the target loop and early operations before mercury becomes radioactive enough to warrant protective shielding, part of the steel shielding may be left temporarily uninstalled to support loop integrity checks. Therefore, the analysis of the fire in the target service bay was performed to address potential consequences under these conditions. This analysis conservatively assumes that the fire causes a mercury spill and that the spilled mercury is exposed to the heat flux from the fire. A similar approach is used in the analysis of the full-facility fire and post-seismic fires in which mercury spills either because of the impact of falling structural components or from the fire itself. In the analyses of the fire events that involve a mercury spill, mercury vaporization is calculated from the amount of heat from the fire deposited in the mercury, the specific heat capacity of liquid mercury (while heating the mercury to saturation), and the latent heat of evaporation of mercury. The release of nonvolatile spallation products is based on a mercury aerosol release equivalent to 10% of the mercury vaporized to represent respirable droplets of mercury entrained in the vapor leaving the liquid surface during boiling (i.e., $RRF_{III} = RRF_{II}/10$ from the literature [50]).

The mitigated consequence analysis for the post-seismic fire takes credit for the carriage tracks associated with the target cart and steel shielding that surrounds the mercury process system for shielding much of the spilled mercury from the radiant energy of the fire. These design features do not have credible failure modes for a PC-2 seismic event that would block the spill drainage flow path. The worst-case mercury leak and fire locations are assumed to be near any leaking mercury exposed during part of its drainage path. The amount of mercury vapor formed during such a mitigated fire is based on only the heat from the fire absorbed by the mercury as it exits from a postulated pipe break and flows (toward the collection basin) over the relatively small fraction of the sloped floor not shielded from thermal radiation.

For the medium fire (i.e., fire outside the target service bay), the bounding fire is one that propagates to the target service bay. Another scenario considers a fire that occurs in the basement room housing the charcoal adsorbers and conceivably vaporizes radioactive mercury residing on the sulfur-impregnated charcoal. To bound this release, 19.4 kg of mercury (inventory limit per adsorber) is released in vapor form from a medium fire, and 155 kg of mercury (inventory of all eight filters) is released in vapor form from a full-facility fire. Measured accumulation on the adsorbers after 5 years of operations indicates that a maximum total of 7.6 kg mercury would accumulate on all adsorbers throughout the life of the facility [60]. The mercury on the filters would have been transported there as a vapor that formed under low-temperature conditions in the target service bay (before the fire) and became trapped in the filter. This mercury is not expected to contain more than negligible quantities of spallation products (i.e., RRF_{IA-1} = RRF_{IA-2} = RRF_{IA-3} = RRF_{IA-4} = 0 and RRF_{III} = 0).

RRFs for Flammable Gas Explosions

The accident analysis postulates situations in which a hydrogen leak from the CMS mixes with air to form a flammable hydrogen/air mixture. This mixture is assumed to explode (by detonation or deflagration), causing aerosolization (and vaporization from deflagrations) of mercury assumed to have spilled before the hydrogen ignited. Detonations and deflagrations have both been considered to determine which type of explosion produces the bounding release, and both evaluation methods are presented here and are maintained in the supporting documentation for completeness. During the accident analysis process, the deflagration mechanism was chosen as the bounding model for consequences. The deflagration tends to produce a larger quantity of mercury vapor (RRF_{II}), whereas the detonation tends to produce a larger quantity of aerosol (RRF_{III}). Because one of the radionuclides with the strongest contribution to committed dose is gadolinium-148, which is nonvolatile (RRF_{III}), the detonation produces a higher radiological consequence, whereas the deflagration produces a higher chemical consequence. Because the results of the two mechanisms were similar (different by less than a factor of two), and the TNT-equivalent model estimates the respirable mass of all affected materials, including other components in the core vessel or service bay besides mercury, the deflagration mechanism was selected as the bounding mechanism. This decision is documented in the Master Engineering Calculation published in 2003 [65].

For a detonation, the mass of mercury made airborne as an aerosol at the point of the explosion is calculated using the TNT-equivalent model [47]. This value is then converted into an equivalent RRF_{III} value. In the implementation of the TNT-equivalent model, (1) the energy from the explosion is calculated, (2) the mass of TNT that would generate the same total energy is determined, and (3) the mass of liquid (i.e., mercury for SNS) in respirable form made airborne by the explosion is assumed to be equal to the equivalent mass of TNT based on empirical correlation to experimental data.

For a deflagration, only mercury exposed to the combustion (not inside a pipe or vessel) will be subject to an airborne release from the thermal energy of the deflagration. The mass of mercury vapor made airborne by the deflagration is estimated based on thermal energy transfer considerations. This value is then converted into an equivalent RRF_{II} value. Respirable droplets of mercury may be entrained in the vapor that leaves the liquid surface during boiling. To account for this phenomenon, a release of liquid mercury droplets containing nonvolatile spallation products is based on a mercury aerosol release equivalent to 10% of the mercury vaporized (i.e., $RRF_{III} = RRF_{II}/10$) [50, 57].

The energy output of a hydrogen explosion in terms of the equivalent mass of TNT (M_{TNT}) is given by Eq. (8):

$$M_{\mathrm{TNT}} = \frac{M_{\mathrm{H_2}} E}{E_{\mathrm{TNT}}} \tag{8}$$

where

M_{TNT} = mass of TNT (kg)
M_{H_2} = mass of liquid hydrogen (kg)
E = heat of combustion of hydrogen (1.2×10^5 kJ/kg)
E_{TNT} = specific energy of TNT (4,520 kJ/kg)

The hydrogen assumed to be involved in the explosion is the mass of liquid hydrogen in the moderator systems. During pre-PPU operations, this mass was assumed to be 7 kg [37], except for events in which the hydrogen is assumed to escape the core vessel, leading to a stoichiometric mixture of hydrogen and air at atmospheric pressure [29]. The PPU project adds components to the CMS as described in Section 3.3.3, increasing the assumed mass to 9.4 kg [63]. In the assessment of the quantity of mercury released, the resultant mercury release is directly proportional to the mass of hydrogen assumed for both detonation and deflagration. Thus, the updated consequences arising from the increase in hydrogen inventory can be conservatively estimated by multiplying the existing value by the ratio of the new inventory to the original inventory (9.4/7 = 1.343). This estimate unrealistically but conservatively amplifies the contributions of groups that have an RRF value of 1.0 (typically Groups IA-1 and 1B) and groups that have contributions not dependent on hydrogen inventory, such as the contribution of mercury evaporation to RRF_{II}.

Unmitigated hydrogen explosion scenarios are modeled in two phases: (1) an initial explosion inside the core vessel and (2) a second explosion inside the target service bay. The initial explosion is postulated to damage seals, allowing hydrogen not consumed in the first explosion to migrate into the target service bay. The possibility that the initial explosion could allow unconsumed hydrogen to migrate to portions of the building where radioactive material is not present is conservatively ignored, as is the possibility that the unconsumed hydrogen could be diluted below the LFL without encountering an ignition source. The analysis conservatively postulates that mercury has spilled to the bottom of the core vessel and the bottom of the target service bay before the explosions. This analytical approach ensures that the analysis bounds a situation in which the force of explosion can both damage the mercury-containing process vessels and vaporize or aerosolize the mercury released from the damaged vessel.

In the unmitigated consequence assessments of detonations and deflagrations in the core vessel (the initial explosion), the mercury is assumed to be in a pool at the bottom of the core vessel, and the remainder of the free volume of the core vessel is assumed to be filled with a stoichiometric hydrogen/air mixture that contacts the pooled mercury. No credit is taken for the nonflammable atmosphere inside the core vessel. Hydrogen released after the initial explosion is assumed to migrate to the target service bay and form a stoichiometric hydrogen/air mixture that contacts the pooled mercury there.

For deflagrations, the fraction of the radiant energy deposited in the mercury pool is determined from geometric considerations. The exposed mercury is assumed to be pooled at the bottom of the core vessel in the ullage volume. Because the ullage volume is about 2.5 m^3 and the total core vessel free volume is about 7.5 m^3, only one-third of hydrogen combusting inside the core vessel would be able to vaporize the exposed mercury [51]. Moreover, the fraction of the cloud energy that is deposited in the pool is equal to the fraction of the surface area occupied by the pool relative to the total surface area in the ullage. Similarly, in the target service bay, the pre-burn flammable gas configuration is conservatively taken to be a stoichiometric mixture that fills the internal volume of the target service bay, and the fraction of the cloud energy deposited in the spilled mercury pool is equal to the fraction of the surface area occupied by the pool relative to the total surface area of the floor, walls, and ceiling of the target service bay conservatively modeled.

The quantity of radiant thermal energy incident upon each mercury pool because of the hydrogen deflagration is assumed to be absorbed in the upper surface of the mercury pool. The mass of mercury that vaporizes is determined by dividing the radiant energy by the sum of the energy required to heat the surface layer of the spilled mercury from ambient temperature to boiling and the latent heat of vaporization of the mercury. This approach assumes that the deflagration is so rapid that only the top surface of the puddle is heated. Thus 100% of the thermal energy is assumed to be used to create mercury vapor.

RRFs for Loss-of-Heat-Sink Accidents

In the loss-of-heat-sink accidents, the mercury in the target module boils, and the violent pressure surges that accompany two-phase mercury flow cause failure of the front face of the target module and water-cooled shroud boundaries. Failure of the target module and water-cooled shroud allows mercury to depressurize into the core vessel. Mercury flashes during the depressurization, forming the dominant portion of the source term for this event. The remaining liquid mercury discharged out of the failed target module forms a pool. Steam forms from water that contacts this hot mercury.

Equation (9) is used to calculate the flash fraction (F_f) of a mass of pressurized mercury for an adiabatic expansion process in which the energy to vaporize mercury is supplied by cooling the mercury liquid.

$$F_f = \frac{C_p(T_0 - T_b)}{H_{fg}} \tag{9}$$

where

F_f = flash fraction (unitless)
C_p =specific heat of liquid mercury (135.6 J/[kg·K])
T_0 = initial saturation temperature of pressurized mercury in target module (°C)
T_b = boiling point of mercury at atmospheric pressure (357°C)
H_{fg} =heat of vaporization (295 J/g)

The flash fraction from Eq. (9) represents the amount of mercury vapor released by flashing into the core vessel. Mercury vapor that does not condense on the massive metallic structures inside the core vessel represents the dominant contribution to the RRF_{II} value for this event. An additional contribution to the RRF_{II} term is calculated for the evaporation from the liquid mercury pool.

Respirable aerosol droplets are also formed and carried away with the mercury vapor and steam flows. The sudden expansion of the flashed mercury vapor fragments the surrounding liquid mercury (flash atomization). The contribution to the RRF_{III} term is based on experimental data summarized in the thermal-hydraulic analysis of the SNS mercury target [46] for flashing sprays modified as explained by WSMS[42] to account for the properties of mercury. As steam is generated from contact with hot liquid mercury, additional mercury droplets are generated and entrained into the steam flow. As explained in the literature [53], this entrainment is modeled assuming conservatively that steam bubbles through mercury before escaping from the core vessel.

RRFs for Loss-of-Mercury-Flow Accidents

Analysis is performed for scenarios in which mercury flow completely stops and for scenarios in which the mercury flow decreases to a very low level. These accidents involve similar types of failure of the target module caused by boiling phenomena as the loss-of-heat-sink accidents. Thus the same methodology is used to calculate the mercury vapor and aerosol releases from flashing, flash atomization, steam-flow entrainment, and pool evaporation. However, less mercury is released compared with the loss-of-heat-sink accidents. A greater percentage of the mercury is heated to boiling or near boiling conditions in the loss-of-heat-sink accidents because the mercury continues to flow through the system to be heated by the proton beam but without heat removal from the heat exchanger. With complete loss of mercury flow, only mercury in the target module would be subjected to boiling conditions. With reduced mercury flow, the heat exchanger continues to remove heat from the still-circulating mercury, so the cold-leg temperature of the mercury remains well below boiling conditions.

RRFs for Crane-Drop Accidents

Crane-drop accidents that result only in a loss of confinement (e.g., the crane load is dropped onto a mercury-bearing pipe) are treated as a loss-of-confinement accident with an additional source-term component related to the kinetic energy of the dropped crane load. Source terms for loss-of-confinement accidents include a small component to account for the possible formation of mercury droplets from splashing associated with the kinetic energy of falling or expelled liquid mercury. The additional source-term component for crane-drop accidents is that the postulated droplet component is increased by the ratio of the maximum kinetic energy of a dropped load relative to the maximum kinetic energy of falling mercury [42].

Summary of RRFs

Table 4.8 summarizes the RRFs calculated for the preconstruction design phase unmitigated accident scenarios evaluated in this analysis.

4.4.1.3 Consequence Analysis

Radiological consequence is expressed in terms of the total effective dose equivalent (TEDE). The TEDE includes the 50 year committed effective dose commitment (CEDE) from inhalation and the external exposure owing to the receptor being immersed in a semi-infinite cloud of the radionuclide at the plume ground-level concentration.

The CEDE from inhalation is calculated using Eq. (10):

$$CEDE = \sum_{i} ST_i \cdot DCF_i \cdot (\chi/\mathrm{Q}) \cdot BR \qquad (10)$$

where

$CEDE$ = 50 year CEDE from inhalation (rem)
ST_i = source term for airborne radiological release for radionuclide i (Ci)
DCF_i = inhalation dose conversion factor for radionuclide i (rem/Ci)
χ/Q = atmospheric dispersion factor (s/m^3)
BR = breathing rate (m^3/s)

Source term determination is discussed in Section 4.4.1.2. At a given downwind distance, the ratio of the time-integrated centerline concentration (units of kilogram-seconds per cubic meter or curie-seconds per cubic meter) to the source term release quantity (kilograms) or activity (curies) defines the parameter χ/Q (units of seconds per cubic meter). This parameter is a measure of the dilution of the plume during atmospheric transport. The calculations to determine values for this parameter are detailed in the next subsection.

External dose from immersion in a semi-infinite cloud has been determined to be a small fraction (0.75%) of the internal dose, as documented in previous SNS accident consequence studies [51]. Therefore, the TEDE is calculated as follows:

$$TEDE = CEDE \times 1.075 \tag{11}$$

Table 4.8. Summary of unmitigated respirable release fractions for accident scenarios

Event	RRFs for volatility groups (defined in Section 4.4.1.2.2)						
	IA-1	**IA-2**	**IA-3**	**IA-4**	**IB**	**II**	**III**
1. Service bay fire (with shields)	1.0	1.2E-3	1.2E-3	1.2E-3	0	1.1E-3	1.1E-4
1. Service bay fire (without shields)	1.0	2.7E-2	2.7E-2	2.7E-2	0	2.5E-2	2.5E-3
2a. Medium fire that spreads into the service bay	See event 1						
2b. Medium fire in the charcoal filter room	0	0	0	0	0	1.1E-3	0
3. Full-facility fire	1.0	3.4E-2	3.4E-2	3.4E-2	1.0	4.0E-2	3.1E-3
4. Hydrogen explosion without follow-on fire (detonation)	1.0	1.5E-2	1.5E-2	1.4E-2	1.0	9.4E-4	1.4E-2
4. Hydrogen explosion without follow-on fire (deflagration)	1.0	3.5E-2	3.5E-2	3.5E-2	1.0	3.1E-2	3.1E-3
5. Hydrogen explosion with follow-on fire	Bounded by event 17						
6. Service bay loss of confinement	1.0	5.4E-4	5.4E-4	3.6E-5	0	5.0E-4	3.6E-5
7. Core vessel (helium) loss of confinement	1.0	7.4E-4	7.4E-4	3.6E-5	1.0	7.0E-4	3.6E-5
8. Core vessel (vacuum) loss of confinement	1.0	3.5E-3	3.5E-3	3.6E-5	0	3.5E-3	3.6E-5
9. Partial loss of mercury flow	1.0	3.6E-3	3.6E-3	1.1E-3	1.0	2.5E-3	1.1E-3
10. Complete loss of mercury flow	1.0	1.3E-3	1.3E-3	1.1E-3	1.0	1.1E-3	1.7E-4
11. Loss of heat sink	1.0	4.9E-3	4.9E-3	2.2E-3	1.0	2.7E-3	2.2E-3
12. Service bay crane load drop	1.0	5.6E-4	5.6E-4	6.3E-5	1.0	5.0E-4	6.3E-5
13. High bay crane load drop onto service bay	1.0	8.7E-4	8.7E-4	3.7E-4	1.0	5.0E-4	3.7E-4
14. High bay crane load drop onto core vessel with no explosion	1.0	1.1E-3	1.1E-3	3.7E-4	1.0	7.0E-4	3.7E-4
15. High bay crane load drop onto core vessel with hydrogen explosion	Bounded by event 17						
16. External crane load drop	1.0	6.8E-3	6.8E-3	6.3E-3	1.0	5.0E-4	6.3E-3
17. Seismic event including follow-on hydrogen explosion and fire[a]	1.0	4.9E-2	4.9E-2	4.9E-2	1.0	3.2E-2	1.7E-2
18. Seismic event including follow-on fire	Bounded by event 17						
19. Seismic event including follow-on hydrogen explosion	Bounded by event 17						

[a] The RRF values for event 17 reflect an increase only in the contributions of the hydrogen detonation owing to the increased system hydrogen inventory. The consequences presented in Section 4.4.2.10 apply the increased inventory factor (1.343) to the entire accident consequence.

For toxicological consequence analysis, the chemical exposure consequence is simply expressed in terms of centerline concentrations of the plume. The following equation is used to calculate the centerline concentration of mercury in the plume at a given downwind location for an accidental release of mercury over an assumed duration.

$$[\mathrm{Hg}] = \frac{ST_{\mathrm{Hg}}\ \chi/Q}{\Delta t} \tag{12}$$

where

[Hg] = centerline concentration of mercury in the plume (mg/m^3)
Δt = assumed duration of the mercury release (s)
$ST_{\mathrm{Hg}} = MAR_{\mathrm{Hg}} \times 10^6 \times (RRF_{\mathrm{II}} + RRF_{\mathrm{III}})$

where

MAR_{Hg} = 18,000 kg

Meteorological Dispersion

EPA recommended Industrial Source Complex Short-Term (ISCST3) air dispersion model [52] was used to estimate χ/Q values for the on-site worker at 100 m and for the maximally exposed offsite individual (MOI). ISCST3 uses the steady-state Gaussian plume algorithm. Key elements of the χ/Q calculations [53, 54] are summarized as follows:

- Per DOE guidance, the statistical treatment of calculated χ/Q values as described in regulatory position 3 of US Nuclear Regulatory Commission Regulatory Guide 1.145 was followed to determine the χ/Q value representative of 95th percentile of the distribution of doses to the MOI. The location of the MOI is the site boundary, considering variations in distances to the site boundary as a function of direction.

- Meteorological data recorded for each hour during a 5 year period from the ORNL Tower C, located in the valley immediately southeast of Chestnut Ridge, was used in the analysis. ORNL Tower C is the closest site with meteorological data at a height approximating the SNS facility's elevation (i.e., elevation above mean sea level). Initially, 6 years of data (1996–2001) were analyzed. Because the year 2000 contained the most missing or invalid hours, that year was eliminated from the analysis. The resulting dataset included a total of 40,939 hours of valid data.

- Many receptors—including receptors at locations along or outside the ORR boundary and on Bethel Valley Road—were carried in the calculation to allow positive identification of the MOI receptor. A radial receptor grid was created centered on the SNS facility. Terrain elevations, obtained from the US Geological Survey Digital Elevation Model 10 m database, were included for the source and receptors (modeled locations). The ISCST3 model does not incorporate the effects of intervening terrain between the source and receptors. For each hour, the calculations were performed for receptors along a single radial corresponding to the direction toward which the wind was blowing during that hour. The receptors extend outward from the ORR boundary at 50 m intervals for at least 2 km in each direction. In addition, locations inside the reservation on Bethel Valley Road and Highway 95 were included as receptors in the appropriate radials. A total of 77,691 public receptor locations were used. The meteorological data and the receptors were divided into 360 sets, one for each of the 360 integer directions. For each hour, the maximum χ/Q value was selected among all receptors along that direction. The 95th-percentile χ/Q value was determined using an aggregated, sorted list of the hourly maximum χ/Q values.

- The 95th-percentile χ/Q value predicted for a 1 hour duration ground-level release at the SNS site is 3.62×10^{-5} s/m^3 for the public receptor (Case 2g from Table 3 of [52]). For the worker at 100 m, the 95th-percentile χ/Q value is 7.4×10^{-4} s/m^3 [60].

- Building wake effects were not included. Ignoring building wake effects is conservative because building wake effects increase dispersion.

- The dispersion calculation assumes no mercury deposition from the plume. Calculations have shown that a high fraction of mercury released in the form of a pure vapor would condense within 300 m of the release point. Ignoring the removal of mercury from the plume owing to condensation deposition leads to conservatively higher downwind mercury concentrations.

Inhalation Dose Conversion Factors

Of the 768 radionuclides identified for the SNS inventory, the inhalation DCFs for 500 radionuclides are taken from the International Commission on Radiological Protection (ICRP) Publication 68 [55]. Different methods were used to derive the DCFs for the other radionuclides, depending mainly on the type and quality of available nuclear decay data. An improved methodology was used elsewhere [56] to estimate the inhalation DCFs for radionuclides not addressed by ICRP publications. Even though ICRP publications document inhalation DCFs for mercury vapor, revised DCFs were developed elsewhere [56] to be more consistent with published experimental data.

4.4.2 Accident Scenarios

This section provides a detailed description of the various postulated accident scenarios and presents bounding off-site consequences. Bounding consequences are presented for the unmitigated and for the as-constructed facility accident scenarios as described in Section 4.4.

In all cases, the credited controls identified to protect the workers also protect the public. The list of accidents that potentially affect the off-site public were identified in the accident selection process (Section 4.3.16).

Details of the unmitigated radiological and toxicological consequences analysis and the bounding consequence analysis for the as-constructed facility are presented elsewhere [33, 60]. Toxicological consequences are presented in terms of the ratio of the MOI airborne mercury concentration to the ERPG-2. ERPG-2 (2 mg/m^3) represents the threshold value for requiring a credited control based on mercury toxicity.

For the events involving hydrogen explosions, the higher of the two consequence values between the detonation case and deflagration case are given. The analysis of [33] showed that higher toxicological consequences occur with deflagrations (higher total mercury release) and higher radiological consequences occur with detonations (higher aerosol release that includes the nonvolatile spallation products).

None of the off-site radiological consequences associated with the unmitigated consequence analysis exceed levels that would require credited controls; however, some of the events had associated off-site mercury concentrations that exceed the ERPG-2 criteria. In such instances, a single level of credited control is required per the criteria of Section 4.2.2.4. No credited controls beyond those already identified in Section 4.3 for worker protection are required to mitigate effects to the public. Off-site consequences associated with the as-constructed facility analyses were all below crediting thresholds.

Accident scenarios with unmitigated radiological and toxicological consequences well below the off-site credited control criteria are not discussed here, although their results are presented in the summary table of Section 4.4.2.10. Detailed information on these scenarios and the analyses performed on them can be found in the literature [33, 60].

4.4.2.1 Seismic Event Including Follow-On Explosion and Follow-On Fire

This section addresses the natural phenomena (seismic) event including a follow-on explosion and follow-on fire. The results of this analysis serve as input into the design process by indicating the need for robust seismically qualified structures. The specific scenario assessed is event BG7-1 described in Section 4.3.14.

The analysis assumes that the process mercury system fails because of a seismic event so that (1) mercury is released from the primary loop; (2) water is released from loops that serve the lower moderator systems and that cool the target shroud (cooling loop 2), reflectors, and other components within the core vessel (cooling loop 3); and (3) hydrogen is released from piping associated with the moderator systems.

The proton beam is assumed to shut down because of the seismic event, stopping the transfer of energy from the beam to the mercury. No engineered protective device function is relied upon to generate a trip signal for this interruption because this assumption reflects an inherent physics-based feature of accelerators to shut down when the alignment of the beam is disturbed causing the beam to come to ground. Analyses performed by the SNS project indicate that ground accelerations equivalent to, or more severe than, PC-1 create a disturbance that would upset the crucial alignment necessary for the approximately 300 m long accelerator to provide the proton beam and thus automatically shut down the beam [44, 45].

The unmitigated consequence analysis considers the possibility of deflagrations and detonations involving the hydrogen/air mixture. The key features of the detailed analysis of the explosion phase of the event are the same as described in Section 4.4.1.2.2.

<u>Scenario for Seismic Event with Explosion and Fire</u>

The unmitigated scenario for this event is as follows:

- The system is running normally, with the mercury in the target module and mercury process system at the upper normal operating limits for pressure, temperature, and inventory.
- A seismic event occurs, causing damage that leads to breaks in (1) the hydrogen-filled moderator vessels (and associated piping), (2) the water-filled moderator vessel (and associated piping of cooling loop 3); (3) the shroud (and associated piping of cooling loop 2); (4) the target module (and associated piping and target carriage); and (5) the core vessel. These breaks cause (1) leakage of liquid mercury, (2) leakage of hydrogen into the region above the spilled mercury (and formation of a flammable hydrogen and air mixture in this region), and (3) leakage of water (coolant).
- The proton beam shuts down because the accelerator components are displaced during a seismic disturbance, stopping the transfer of energy from the beam to the mercury.
- Airborne droplets of mercury (and dissolved spallation products) are formed by splashing and (possibly) pressurized release.

- Mercury vapor is formed by evaporation of spilled hot mercury.
- Mercury droplets are formed by metal/water reactions as hot mercury falls into the colder water.
- Airborne water droplets (containing spallation activation products) are formed from cooling water spilling from coolant piping.
- An ignition source causes the flammable hydrogen/air mixture to explode (deflagrate or detonate).
- The explosion in the core vessel creates a blast wave that (1) provides stresses to the spilled liquid and (2) damages seals separating the core vessel from the service bay.
- Hydrogen not consumed in the initial explosion migrates into the target service bay via the damaged seals.
- The hydrogen mixes with the air inside the target service bay to form a second flammable hydrogen/air mixture.
- An ignition source causes the flammable hydrogen/air mixture to explode (deflagrate or detonate).
- The explosion in the service bay creates a blast wave that (1) damages piping and other process vessels inside the service bay (causing liquid mercury to spill) and (2) provides stresses to the spilled liquid.
- Several mechanisms associated with the explosion lead to airborne radioactive material. For the detonation case, the primary release mechanism is aerosolization by the impact of the shock wave with the pool. For the deflagration case, the following release mechanisms contribute to the source term: (1) evaporation (boiling) of some liquid mercury at the upper surface of the liquid caused by heat from the explosion over the gas/liquid interface, which leads to mercury vapor and formation of particles from spallation products formerly dissolved in the upper "skin" of the original liquid surface; (2) entrainment of liquid droplets as the blast wave passes over the liquid surface; and (3) splashing owing to liquid surface motion caused by blast effects.
- A fire starts in the target building (or spreads into the target building from some source external to the building).
- The heat from the fire increases the temperature of the mercury. This heat can be transferred to the spilled mercury pool via (1) direct radiative heat transfer from the flame and (2) convective heat transfer from the heated air from a fire.
- The heat from the fire causes failures of the process equipment owing to reduced piping integrity at the high temperatures or to failures of seals, gaskets, and/or O-rings at high temperatures (assumes steel shields covering mercury system are not in place).
- Mercury evaporates because of the heat of the fire until combustibles are consumed.
- The mercury vapor, airborne mercury droplets, and airborne water droplets are transported away from the building by natural air currents.

Unmitigated Source Term for Seismic Event with Explosion and Fire

The source term for this event is calculated using the RRFs presented in Table 4.9.

Table 4.9. Summary of respirable release fractions for seismic event with follow-on fire and explosion

Volatility group	Vapor RRF	Aerosol RRF	Total RRF
IA-1: highly volatile	1.0	0	1.0
IA-2: moderately volatile	3.2E-3	1.7E-2	4.9E-2
IA-3: moderately volatile oxides	3.2E-3	1.7E-2	4.9E-2
IA-4: conditionally formed volatile oxides	3.2E-3	1.7E-2	4.9E-2
II: mercury vapor	3.2E-3	N/A	3.2E-2
III: mercury droplets with nonvolatile solids	N/A	1.7E-2	1.7E-2
IB: activation products in cooling water	1.0	N/A	1.0

Note: The RRF_{II} and RRF_{III} values are based on the primary safety analysis [33], which combines the contributions from the explosion and fire release mechanisms [43] with the contributions from the mercury spill release mechanisms [42]. The RRF_{III} values have been updated from these source documents to reflect changes to the CMS increasing its inventory to 9.4 kg. This change was accomplished by increasing the source term produced by the hydrogen explosion proportionately with the increase in hydrogen inventory (9.4 kg/7 kg = 1.343 increase factor). The other RRF specifications are derived from the RRF_{II} and RRF_{III} values using the scheme outlined in Table 4.8. WSMS's accident analysis [42] shows that the bounding consequences occur with the detonation instead of the deflagration for the follow-on explosion. Because the mercury may boil dry in this scenario, the vapor component of $RRF_{\mathrm{IA\text{-}4}}$ is set to the RRF_{II} value. This scenario can involve a breach of the cooling water system, so RRF_{IB} is equal to 1.0.

The RRF_{II} value of 3.2E-2 corresponds to approximately 569 kg of mercury vapor release that is the result of the following components:

- Direct radiative heat transfer from the fire (556 kg),
- Evaporation for 8 hours (13 kg).

The RRF_{III} value of 1.7E-2, equivalent to approximately 306 kg of mercury, represents aerosol formation and entrainment from the combination of the following components:

- Aerosolization from pressurized venting, free-fall spill and splashing, and pool aerodynamic entrainment (<1 kg),
- Aerosolization from the impact of the detonation shock wave with the pool (250 kg),
- Aerosolization from agitation of the pool surface from bubbling phenomena during the fire (56 kg).

The total respirable mercury release fraction is calculated by adding RRF_{II} and RRF_{III} (Table 4.9) to obtain 4.9E-2 for this event.

Consequence for Seismic Event with Explosion and Fire

In the absence of seismically qualified components and structures, the unmitigated consequences associated with this event were calculated to be 7.5 rem with an associated toxicological consequence at 6.6× ERPG-2. Because EPRG-2 is exceeded, a single level of control is required per the selection of credited controls criteria presented in Section 4.2.2.4. This event is considered the maximum credible incident (MCI) for the unmitigated consequence analysis.

These consequences were conservatively updated to reflect facility modifications from the PPU project. The mercury radionuclide inventory was updated for increased beam energy and facility life. The updated radionuclide inventory was then used to calculate updated radiological consequences using the existing RRFs [62]. The radiological and toxicological consequences were then conservatively updated for the increased hydrogen inventory [63] by multiplying each result by the proportionate increase in hydrogen inventory. This update is conservative because the hydrogen explosion only contributes to the aerosol (RRF_{III}) and not the vapor (RRF_{II}) component of the consequences.

The mitigation strategy for this event is to (1) prevent hydrogen from escaping from the cryogenic moderator system into the core vessel through robust design, (2) channel spilled mercury to a location where a fire cannot affect significant quantities of mercury such as the collection basin or under the floor shielding, and (3) mitigate the size of the fires, both inside and outside the service bay, via combustible material control programs and a 2 h equivalent fire barrier enclosing the service bay and core vessel.

The as-constructed facility analysis accounts for the following passive design features:

(1) Radiation shielding covering piping and other process vessels that are required for normal operation,

(2) Service bay features that confine mercury,

  (i) The target service bay's sloped floor,

  (ii) Drainage channels in the slopped target tunnel floor that route spilled mercury under the target carriage track to the collection basin such that the carriage track structure supporting the target cart prevents heat transfer by thermal radiation to all but a small area of the flow path for any spilled mercury to the collection basin,

(3) Seismically qualified (PC-3) CMS hydrogen boundary.

In addition, the steel shielding panels surrounding the mercury loop are qualified for a PC-2 seismic event. The off-site consequences associated with the as-constructed facility are bounded at 0.14 rem with an associated toxicological consequence at 0.18 × ERPG-2 [60, 70].

Credited Controls for Seismic Event with Explosion and Fire

Credited controls established for worker protection as described in Section 4.3.14 for this event (BG7-1) also protect the public by ensuring atmospheric releases associated with such an event are minimized. No new credited controls are required to protect the public.

4.4.2.2 Loss-of-Heat-Sink Event

This section addresses the loss-of-mercury heat sink events TS3-13, TS3-14, TS3-15, and TS3-16.

In addition to serving as the spallation target, mercury cools the target vessel structure and transports heat to the mercury heat exchanger. The bulk of the mercury enters the target module through two side channels and returns through a passage in the middle of the module. A small amount of mercury passes at the bottom into an annular passage at the front of the target module to cool the walls of the target mercury vessel window (portion of the vessel structure within the proton beam). The walls of the target water-cooled shroud window are cooled by water. The mercury used to cool the mercury vessel walls of the target window merges with the main mercury flow inside the target module for return to the cooling loop. The heat is removed from the mercury by loop 1 cooling water flowing through the secondary side of the heat exchanger.

The loss-of-heat-sink event can be caused by initiating events such as loss of cooling water flow to the mercury heat exchanger that may result from pump failures, valve failures, leaks in the water loop, loss of cooling water provided by the cooling tower, or loss of power to secondary side equipment. The analysis scenario assumes that the proton beam continues to operate and heat the circulating mercury to boiling conditions in the target module. Substantial flow instabilities are assumed to result from the large differences in liquid and vapor densities. Boiling two-phase flow conditions marked by violent pressure surges lead to failure of the front face of the target module and water-cooled shroud boundaries through which the proton beam passes to reach the mercury in the target module. Mercury vapor and entrained droplets are released to the air, and mercury liquid and water spill into the core vessel.

<u>Scenario for Loss Heat Sink</u>

The unmitigated scenario for this event is as follows:

- The system is running normally with the mercury in the target module and mercury process system at the upper normal operating limits for pressure, temperature, and inventory.
- No heat is transferred through the heat exchanger.
- The proton beam continues to heat the target. The mercury continues to circulate, and the mercury in the annulus and bulk flow region of the target module continues to heat until the mercury reaches boiling conditions. After several circuits of the mercury process system, the mercury in the loop approaches its boiling point. At this elevated temperature, the pump in the mercury process system may cavitate, reducing its effectiveness in circulating the mercury, thereby increasing the rate at which the temperature of the mercury in the nose of the target module increases.
- The violent pressure surges accompanying boiling two-phase mercury flow conditions cause failure of the front face of the target module and water-cooled shroud boundaries through which the proton beam passes to reach the mercury in the target module.
- The outer annulus (window) wall of the target module and the water-cooled shroud boundary fail at the elevation of the lowest point where the beam enters the target module.
- Failure of the target module allows mercury, together with cooling loop 2 water, to depressurize and discharge into the core vessel.
- Mercury flashing occurs during the depressurization, forming radioactive mercury vapor and aerosol. Much of this mercury vapor condenses on the surface of core vessel internals.
- The mercury vapor, mercury aerosol, and airborne water droplets are transported away from the building via natural air currents.
- The depressurization rapidly empties the mercury loop to a level below that of the target module breach, and then the proton beam would pass through the emptied target module and dissipate its

energy into the massive shielding steel of the target cart. This condition does not generate a significant source term because the heat is going into steel shielding and not into mercury.

Unmitigated Source Term for Loss of Heat Sink

The source term for this event is calculated using the RRFs presented in Table 4.10.

Table 4.10. Summary of respirable release fractions for loss-of-heat-sink accidents

Volatility group	Vapor RRF	Aerosol RRF	Total RRF
IA-1: highly volatile	1.0	0	1.0
IA-2: moderately volatile	2.7E-3	2.2E-3	4.9E-3
IA-3: moderately volatile oxides	2.7E-3	2.2E-3	4.9E-3
IA-4: conditionally formed volatile oxides	0	2.2E-3	2.2E-3
II: mercury vapor	2.7E-3	N/A	2.7E-3
III: mercury droplets with nonvolatile solids	N/A	2.2E-3	2.2E-3
IB: activation products in cooling water	1.0	0	1.0

Note: The RRF_{II} and RRF_{III} values are from the analysis [33], which combines the contributions from the flashing and steam-entrainment mechanisms [43] with the contributions from the mercury spill release mechanisms [42]. The other RRF specifications are derived from the RRF_{II} and RRF_{III} values using the scheme outlined in Table 4.8. Because the mercury does not boil dry in this scenario, the vapor component of RRF_{IA-4} is zero. This scenario can involve a breach of the cooling water system, so RRF_{IB} is equal to 1.0.

The RRF_{II} value of 2.7E-3 corresponds to approximately 49 kg of mercury vapor release that is the result of the following components:

- Flashing (36 kg),
- Evaporation for 8 hours (13 kg).

The RRF_{III} value of 2.2E-3, equivalent to approximately 40 kg of mercury, represents aerosol formation and entrainment from the combination of the following components:

- Aerosolization from pressurized venting, free-fall spill and splashing, and pool aerodynamic entrainment (<1 kg),
- Flash atomization (38 kg),
- Steam flow entrainment (1.5 kg).

The total respirable mercury release fraction is calculated by adding RRF_{II} and RRF_{III} to obtain 4.9E-3.

Consequence of Loss of Heat Sink

The unmitigated radiological consequence to the public is calculated to be 0.81 rem for this event, and the unmitigated toxicological consequence to the public is calculated to be 0.53 × ERPG-2. The radiological consequences have been adjusted to account for the increased beam energy and facility lifetime associated with the PPU project [62]. Unmitigated radiological and toxicological consequences are below thresholds that would require credited controls to protect the public.

In the mitigated accident analysis, credit is taken for the TPS proton beam cutoff on high mercury temperature. The TPS was designated as a credited control for worker protection for this event (Section 4.3.1). The proton beam would be cut off upon detection of a high mercury temperature in the mercury cold leg before the mercury temperature increases to a value at which boiling could occur. The mitigated scenario is terminated by the beam cutoff with no damage to the facility. Therefore, no mercury is released for the mitigated loss-of-heat-sink event.

The as-constructed analysis takes no credit for the TPS because it is an active system and therefore simply assumes the same consequences as with the unmitigated consequence analysis.

Required Controls for Loss of Heat Sink

No credited controls are required to protect the public. Credited controls established for worker protection as described in Section 4.3.1 for this event also protect the public, although selection criteria do not require any controls to be credited to protect the public.

4.4.2.3 Hydrogen Explosion with Follow-On Fire

This section addresses the hydrogen explosion accident in the target facility with a follow-on fire. The specific scenario assessed is event CM2-1a. Cryogenic moderator events are described in Section 4.3.2.

During the preconstruction design process, the analysis assumed non-mechanistically that spontaneous failure of the CMS hydrogen boundary released hydrogen directly to a large volume where it then exploded directly over a large puddle of spilled mercury. The analysis highlighted the importance of the hydrogen barrier and led to the passive seismically qualified design features that make up the robust hydrogen barrier, which includes a separate seismically qualified vacuum barrier (Section 5.2).

The analysis for the unmitigated scenario focuses on a postulated situation in which a hydrogen leak (from the cryogenic moderator vessels or associated piping) mixes with air to form a flammable hydrogen and air mixture in the core vessel. This mixture then explodes (either detonates or deflagrates), causing aerosolization (and vaporization with deflagrations) of radioactive mercury and other radioactive material in the core vessel. Evaporative mercury releases also occur until the event is stabilized. Detonations and deflagrations are both considered. Detonation is less likely than deflagration because it can occur under more limited circumstances. A detonation creates a mercury aerosol release. A deflagration creates a release that is primarily mercury vapor.

The free volume of the core vessel is not large enough to hold a flammable hydrogen and air mixture involving the entire hydrogen inventory. To provide a bounding unmitigated scenario, the initial explosion in the core vessel is postulated to damage the target seal, allowing hydrogen not consumed in the initial core vessel explosion to migrate into the service bay, where a second explosion occurs.

The analysis postulates that mercury has spilled into the bottom of the core vessel or service bay at the time of each explosion. This analytical approach ensures that the analysis bounds a situation in which the force of explosion can damage the mercury-containing process vessels and cause aerosolization or vaporization of mercury released from the damaged vessel.

The analysis treats the unmitigated scenario of the fire phase of the event as being identical to a post-seismic fire.

Scenario for Hydrogen Explosion with Fire

The unmitigated scenario for this event is as follows:

- The system is running normally, with the mercury in the mercury circulation loop at the upper normal operating limits for pressure, temperature, and inventory.

- A catastrophic hydrogen leak develops in a cryogenic hydrogen moderator system inside the core vessel.

- The hydrogen mixes with the air to fill the open space inside the core vessel to form a flammable hydrogen–air mixture. This assumption was conceived for a vacuum-inerted core vessel with a pre-accident vacuum leak. It is not credible for the present operational regime in which the core vessel atmosphere is filled with helium gas at approximately 1 atm.

- An ignition source causes the flammable hydrogen and air mixture to explode (deflagrate or detonate).

- The explosion in the core vessel creates a blast wave that (1) damages the target module, spilling liquid mercury; (2) provides stresses to the spilled liquid; and (3) damages seals separating the core vessel from the service bay.

- Hydrogen not consumed in the initial explosion migrates into the service bay via the damaged seals. No credit was taken for venting through the core vessel rupture disk and vent line.

- The hydrogen mixes with the air inside the service bay to form a second flammable hydrogen and air mixture.

- An ignition source causes the flammable hydrogen and air mixture to explode (deflagrate or detonate).

- The explosion in the target service bay creates a blast wave that (1) damages piping and other process vessels inside the service bay, spilling liquid mercury, and (2) provides stresses to the spilled liquid.

- Several mechanisms associated with the explosion lead to airborne radioactive material. For the detonation case, the primary release mechanism is aerosolization by the impact of the shock wave with the pool. For the deflagration case, the following release mechanisms contribute to the source term: (1) evaporation (boiling) of some liquid mercury at the upper surface of the liquid owing to heat from the explosion over the gas/liquid interface, leading to mercury vapor and formation of particles from spallation products formerly dissolved in the upper "skin" of the original liquid surface; (2) entrainment of liquid droplets as the blast wave passes over the liquid surface; and (3) splashing owing to liquid surface motion caused by blast effects. These mechanisms are in addition to releases (like those described in Section 4.4.1.2.2 for a loss-of-mercury confinement event) that are associated with the spill portion of the event.

- A fire, which is initiated by one or both explosions, starts in the target building.

- The heat from the fire increases the mercury's temperature. This heat can be transferred to the spilled mercury pool via (1) direct radiative heat transfer from the flame and (2) convective heat transfer from the heated air from a fire.

- The heat from the fire causes failures of the process equipment owing to reduced piping integrity at the high temperatures or to failures of seals, gaskets, and/or O-rings at high temperatures.
- Mercury evaporates because of the heat of the fire until combustibles are consumed.
- The mercury vapor and airborne mercury droplets are transported away from the building by natural air currents.

Unmitigated Source Term for Hydrogen Explosion with Fire

The source term for this event is bounded by that calculated for the seismic event with follow-on explosion and follow-on fire (Section 4.4.2.1); no further analysis was performed.

Consequence of Hydrogen Explosion with Fire

The consequences to the public for this event are assumed bounded by that calculated for the seismic event with follow-on explosion and follow-on fire (Section 4.4.2.1). No further analyses have been performed. The unmitigated toxicological consequence exceeds the credited control threshold of 2 mg/m^3 and therefore requires one level of control.

This scenario provided input that led to the credited robust seismically qualified design of the double-walled hydrogen barrier. As built, the passive design provides credited protection to ensure that spontaneous failure of the boundaries is beyond credible. Therefore, the as-built design of the system prevents hydrogen from escaping from the cryogenic moderator system into the core vessel. Because the explosion is the initiator for the follow-on fire, preventing the explosion also prevents the fire. The entire scenario is prevented by the passive credited design, so no consequences are associated with the as-constructed analysis.

Although spontaneous failure of the hydrogen barriers in the as-constructed facility analysis is considered unrealistic, other scenarios do consider effects of simultaneously breaching both hydrogen barriers, including seismic (Section 4.4.2.1) and impact by a heavy crane load drop over the core vessel (Section 4.4.2.6).

Credited Controls for Hydrogen Explosion with Fire

Credited controls established for worker protection (robust hydrogen and vacuum barrier design) as described in Section 4.3.2 for this event also protect the public by ensuring hydrogen is contained. No new credited controls are required to protect the public.

4.4.2.4 Hydrogen Explosion (No Fire)

This section addresses the hydrogen explosion accident in the target facility. The specific scenario assessed is event CM2-1b. Cryogenic moderator events are described in Section 4.3.2. The analysis for the unmitigated scenario is the same as the hydrogen explosion with fire event, except that no follow-on fire occurs.

Scenario for Hydrogen Explosion

The unmitigated scenario for this event is the same as the hydrogen explosion with fire event, except that no follow-on fire occurs.

Unmitigated Source Term for Hydrogen Explosion

The total respirable mercury release is calculated by adding RRF_{II} and RRF_{III}, yielding 3.5E-02, as shown in Table 4.9 (Section 4.4.1.2.2) for this event. A higher total respirable mercury release occurs with the deflagration case in comparison with the detonation case.

Consequence of Hydrogen Explosion

The completely unmitigated bounding toxicological consequence to the public calculated for this event, assuming that a spontaneous leak of hydrogen into a large volume explodes over a large puddle of mercury, exceeds ERPG-2 by a factor of 3.8. Because EPRG-2 is exceeded, a single level of control is required per the selection of credited controls criteria presented in Section 4.2.2.4. The unmitigated radiological consequence is conservatively bounded at 2.3 rem. The radiological consequence was updated to reflect increased radionuclide inventory in the mercury resulting from increased beam energy and facility lifetime from the PPU project [62]. Both consequences were then conservatively updated by multiplying each result by the proportionate increase in hydrogen inventory [63].

This scenario provided input that led to the credited robust seismically qualified design of the double-walled hydrogen and vacuum barrier. As built, the passive design provides credited protection to ensure that spontaneous failure of the boundaries is beyond credible. Therefore, the as-constructed design of the system prevents hydrogen from escaping from the CMS into the core vessel. The entire scenario is prevented by the passive credited design, so this event has no credible toxicological or radiological consequences.

Although spontaneous failure of the hydrogen barriers of the as-built system is considered unrealistic, other scenarios do consider effects of simultaneously breaching both hydrogen barriers, including seismic (Section 4.4.2.1) and impact by a heavy crane load drop over the core vessel (Section 4.4.2.6).

Credited Controls for Hydrogen Explosion

Credited controls established for worker protection (robust hydrogen and vacuum barrier design), as described in Section 4.3.2, for this event also protect the public by ensuring hydrogen is contained. No new credited controls are required to protect the public.

4.4.2.5 Partial Loss of Mercury Flow

This section addresses the partial loss-of-mercury flow accident in the SNS target facility. The specific scenarios assessed are events TS3-22, TS3-23, TS3-24, TS3-25, TS3-26, and TS3-27. TS events are described in Section 4.3.1.

A partial loss-of-flow could range from slight to a near-total loss of mercury flow. If the loss reduces flow from the normal range (about 380 gpm for 2 MW beam power) to below 31 gpm, then bulk boiling could occur. Events TS3-22 through TS3-25 could credibly reduce total loop flow to below 31 gpm. Flow-blockage events TS3-26 and TS3-27 are not addressed in the analysis because occurrence of credible blockage would reduce total loop flow only to about 100 gpm [58]. A partial loss-of-flow event involves a less severe flow reduction than a complete loss-of-flow event, as discussed elsewhere [42]. However, the consequences are not necessarily less severe than a complete loss of flow for an unmitigated scenario because the bounding partial loss-of-flow accident is defined as allowing essentially the entire hot-leg temperature to reach the saturation temperature before boiling occurs, resulting in a mercury vapor generation source term midway between that of a loss-of-heat-sink accident (Section 4.4.2.2) and a complete loss of mercury flow.

A partial loss-of-flow accident can be caused by problems such as a pump motor failure (e.g., a worn bearing), a failure of a pump motor speed-control device, a damaged pump impeller, or a disturbance to the pump electrical power (e.g., power brownout or low frequency), such as events TS3-23, TS3-24, and TS3-25. A localized or partial flow blockage is also possible, such as from a foreign object in the piping or a system component that becomes loose within the piping system, like events TS3-26 and TS3-27. In most cases, flow blockage accidents would involve blockage of one flow path, whereas parallel flow paths are not directly affected.

Forced circulation of the mercury is required to transport the heat deposited by the beam. The reduced flow means the mercury temperature in the target module (and in the system's hot leg) increases relative to its normal value. This temperature increases because the beam deposits the same amount of heat into the target per unit time. However, the amount of mercury passing through the target module per unit time decreases (relative to normal conditions). Therefore, each unit of mercury mass absorbs proportionately more heat, increasing mercury temperature in the target module and in the hot leg of the mercury system. This increase is somewhat offset by the reduction in cold leg temperature as the mercury heat exchanger approaches the inlet cooling water temperature.

A key issue in the event scenario is whether the increased temperature is sufficient to boil the mercury in the target module. If the mercury in the target module boils, then flow resistance increases, further reducing the system flow. Therefore, the unmitigated event scenario for a very large sudden decrease in flow is expected to result in a temperature excursion and loss of integrity of the target module at the beam elevation, like the complete loss-of-flow event. The analysis scenario assumes that the proton beam continues to operate and heat the mercury in the target module to boiling conditions. Failure of the front face of the target module and water-cooled shroud boundaries through which the proton beam passes to reach the mercury in the target module occurs when enough vapor is produced at the target module face that it restricts the supply of mercury to the hot face to below what is necessary to adequately cool it. Mercury vapor and entrained droplets are released to the core vessel, and mercury liquid and water spill into the core vessel.

Scenario for Partial Loss of Mercury Flow

The unmitigated accident consists of the following sequence of events:

- The system is running normally with the mercury in the target module and mercury process system at the upper normal operating limits for pressure, temperature, and inventory.
- The system's bulk mercury flow decreases to a very low level (less than 10% of normal mercury flow but not all the way to zero flow).
- The rate at which mercury moves through the target module decreases, resulting in more heat deposition from the proton beam per unit of mercury mass flow, thereby increasing the temperature of the mercury in the target module and in the hot leg of the mercury system.
- The proton beam continues to heat the target.
- The mercury in the target module begins to boil, reducing heat transfer from the metal body of the target module to the mercury, which normally cools this metal.
- The mercury in the annulus and bulk flow region of the target mercury vessel continues to heat until enough vapor is produced at the outer annulus (window) wall of the target module mercury

vessel that it restricts the supply of mercury to the hot wall to below what is necessary to adequately cool it.

- The outer annulus (window) wall of the target module mercury vessel and the water-cooled shroud boundary fail at the elevation of the lowest point where the beam enters the target module.

- Failure of the target module allows radioactive mercury vapor and aerosol to escape into the core vessel through the failure location together with cooling loop 2 water.

- The mercury vapor and aerosol are transported away from the building via natural air currents.

Unmitigated Source Term for Partial Loss of Mercury Flow

The total respirable mercury release is calculated by adding RRF_{II} and RRF_{III}, yielding 3.6E-03, as shown in Table 4.9 (Section 4.4.1.2.2) for this event.

Consequence of Partial Loss of Mercury Flow

The unmitigated off-site radiological consequence is conservatively bounded at 0.45 rem with an associated toxicological consequence at 0.39 × ERPG-2. This consequence was updated to reflect facility changes from the PPU project [62].

In the mitigated accident analysis, credit is taken for the TPS proton beam cutoff on out-of-limits differential pressure across the mercury pump. The proton beam would be cut off on a TPS signal from differential pressure across the mercury pump. This feature would prevent overheating of the target wall from prolonged operation of the proton beam. Decay heat would be removed by passive cooling. Therefore, no mercury is released for the mitigated partial loss-of-mercury flow event.

The as-constructed facility analysis takes no credit for the TPS because it is an active CEC. Because the original unmitigated consequences were well under thresholds for requiring credited controls, no further analyses were performed, and as-constructed consequences are simply assumed to equal the unmitigated consequences.

Credited Controls for Partial Loss of Mercury Flow

No credited controls are required to protect the public.

4.4.2.6 High Bay Crane Load Drop Accident with Follow-On Hydrogen Explosion

This section addresses mercury and hydrogen releases caused by a load drop from the high bay crane onto the monolith. The initiator for this accident is a malfunction of the high bay crane that results in a drop of its maximum load. The original design input accident analysis did not account for the massive steel shielding of the monolith that surrounds core vessel. Previous analysis of crane drop events [42] showed that only the scenario involving a follow-on hydrogen explosion may potentially challenge off-site criteria (specifically, the toxicological criteria).

The specific scenario assessed in this section is event HB2-2. As discussed in Section 4.3.10, the core vessel and CMS inside the core vessel are protected by massive monolith steel shielding in place above and around the core vessel. Nevertheless, the CMS transfer lines (all three) could be crushed by the dropped load, resulting in a release of hydrogen into the core vessel. Consequences of the load drop are bounded by assuming that the mercury drains from the target module into the core vessel and that the hydrogen within the core vessel explodes, releasing mercury vapor.

Scenario for High Bay Crane Drop with Hydrogen Explosion

The unmitigated scenario assumed in the pre-construction design phase for this event is as follows:

- The system is running normally, with the mercury in the mercury process system at the upper normal operating limits for pressure, temperature, and inventory.
- A lift is in progress. The high bay crane carries the load over the core vessel, or any portion of the CMS hydrogen lines (e.g., an operator error or malfunction causes the load to pass over this location).
- The lifted load is 50% heavier than the nameplate rating of the crane.
- When the load is over the core vessel, the load is assumed to fall and strike process equipment that contains radioactive mercury and hydrogen (or the falling load strikes other objects, which are then displaced, and these other objects strike process equipment that contains radioactive mercury and other process equipment that contains hydrogen).
- Liquid mercury is ejected from the mercury circulation loop through the failed component because of the pressure difference between the interior and exterior of the mercury process system. This leak continues until the level (elevation) of mercury remaining in the system drops below the elevation of the leak location.
- Droplets of mercury are formed by aerosolization as the pressurized liquid mercury moves through the orifice in the target module or mercury process system.
- Hydrogen leaks from the CMS or the associated piping.
- The hydrogen mixes with the air to fill the open space inside the core vessel to form a flammable hydrogen and air mixture.
- An ignition source causes the flammable hydrogen and air mixture to explode (deflagrate or detonate).
- The explosion in the core vessel creates a blast wave that (1) damages the target module, spilling liquid mercury; (2) provides stresses to the spilled liquid; and (3) damages seals separating the core vessel from the target service bay.
- Hydrogen not consumed in the initial explosion migrates into the service bay via the damaged seals.
- The hydrogen mixes with the air inside the service bay to form a second flammable hydrogen and air mixture.
- An ignition source causes the flammable hydrogen and air mixture to explode (deflagrate or detonate).

- The explosion in the service bay creates a blast wave that (1) damages piping and other process vessels inside the target service bay, spilling liquid mercury, and (2) provides stresses to the spilled liquid.

- Several mechanisms are associated with the explosion lead to airborne radioactive material. For the detonation case, the primary release mechanism is aerosolization by the impact of the shock wave with the pool. In the deflagration case heat from the explosion over the gas/liquid interface evaporates (boils) some liquid mercury at the upper surface of the liquid, leading to mercury vapor and formation of particles from spallation products formerly dissolved in the upper "skin" of the original liquid surface. Additionally, entrainment of liquid droplets occurs as the blast wave passes over the liquid surface, and motion from blast effects causes splashing.

- The mercury vapor and airborne mercury droplets are transported away from the building by natural air currents.

Unmitigated Source Term for High Bay Crane Drop with Hydrogen Explosion

The unmitigated source term for this event was assumed to be bounded by that calculated for the seismic event with follow-on explosion and follow-on fire presented in Section 4.4.2.1.

Consequence for High Bay Crane Drop with Hydrogen Explosion

The unmitigated consequences to the public for this event are bounded by those calculated for the seismic event with follow-on explosion and follow-on fire presented in Section 4.4.2.1. The unmitigated toxicological consequence exceeds the credited control threshold of 2 mg/m^3; therefore, one level of control is required.

The credited control set for the high bay crane drop scenario includes the high bay crane design and the protective barrier features that protect the CMS from external impact. As a second layer of safety, the Hoisting and Rigging program includes provisions to allow only those combinations of crane loads, lift heights, and load paths to ensure the high bay floor can withstand the impact of the dropped load, thereby preventing damage that could lead to the hydrogen explosion (this layer of safety does not apply if the mercury is drained from the core vessel). With this control, the mercury release scenario is prevented, and no consequences occur.

Because the high bay crane loads and lift heights bound those for the pedestal manipulator, in principle, the Hoisting and Rigging Program also applies to the pedestal manipulator. However, because the pedestal manipulator has a much lower load capacity and can provide lifts over a smaller fraction of the high bay floor area, the Hoisting and Rigging Program is expected to only rarely (if ever) restrict operations with the pedestal manipulator.

The as-constructed facility analysis [60] considers the massive steel shielding that surrounds the core vessel. This shielding would prevent a dropped load from directly crushing the core vessel. A dropped load falling from directly above the core vessel would first strike the massive 36 in. thick steel plug that sits above the core vessel and is supported by the monolith's stacked steel shielding. The kinetic energy of the load's impact would be absorbed by the steel load path of the monolith rather than being directly transferred to the mercury and hydrogen process components. Because the core vessel is protected from being crushed, none of the process components are likely to be damaged by such a load drop. Nonetheless, the as-constructed facility analysis conservatively assumes the load drop leads to breaches of both the CMS and mercury systems.

Additionally, the as-constructed facility analysis accounts for the fact that the core vessel interior is operated in a helium atmosphere by design (pre-operations analysis assumed a core vessel design that could operate in vacuum). The helium atmosphere prevents hydrogen from combusting inside the core vessel until air can diffuse into the core vessel after the event, eventually assumed to result in combustion. The analysis accounts for mercury vaporization by this delayed hydrogen combustion. The off-site consequences [60] associated with the as-constructed facility are bounded at 0.12 rem with an associated toxicological consequence at 0.14 × ERPG-2. These consequences were updated to reflect changes to the facility from the PPU project [62].

Credited Controls

Credited controls established for worker protection as described in Section 4.3.10 for this event also serve to protect the public by ensuring crane load drops do not breach the mercury or hydrogen systems. No new credited controls are required to protect the public.

4.4.2.7 External Crane Load Drop Accident

This section addresses mercury release from damage to the mercury piping system caused by a load drop from the external crane. The initiator for this accident is a malfunction of an external crane located outside of the facility that results in a drop of its maximum load. The specific scenario assessed in this section is event BG6-11. BG events are described in Section 4.3.14.

Scenario for External Crane Load Drop

The unmitigated scenario for this event is as follows:

- The system is running normally, with the mercury in the mercury circulation loop at the upper normal operating limits for pressure, temperature, and inventory.
- A lift is in progress. The external crane carries the load over the service bay (e.g., an operator error or malfunction causes the load to pass over this location).
- The lift is of a load that is 50% heavier than the rating of the crane.
- When the load is over the service bay, the load is assumed to fall and strike process equipment that contains radioactive mercury (or the falling load strikes other objects, which are then displaced, and these other objects strike process equipment that contains radioactive mercury).
- Liquid mercury is ejected from the mercury circulation loop through the failed component because of the pressure difference between the interior and exterior of the mercury circulation loop. This leak continues until the level (elevation) of mercury remaining in the system drops below the elevation of the leak location.
- Droplets of mercury are formed via aerosolization as the pressurized liquid mercury moves through the orifice in the target module or mercury circulation loop.
- The liquid mercury falls to the floor of the service bay, forming a pool of hot liquid mercury (droplets are assumed to be formed at this step owing to entrainment because a jet or stream of liquid breaks up while falling and splashing).

- Vapor is formed as the hot liquid mercury evaporates. This evaporation continues until facility conditions are stabilized. However, the rate of vaporization decreases significantly as the mercury cools to near ambient (some internal heat is generated in the spilled mercury via decay heating from the radioactive atoms in the mercury).

- The mercury vapor and airborne mercury droplets are transported away from the building by natural air currents.

Unmitigated Source Term for External Crane Load Drop

The total respirable mercury release for this event is calculated by adding RRF_{II} and RRF_{III}, yielding 6.8E-03 as shown in Table 4.1 (Section 4.4.2).

Consequence of External Crane Load Drop

The unmitigated consequences to the public calculated for this event were 2.1 rem and 0.74 × ERPG-2. The unmitigated consequences are below thresholds for requiring credited controls.

In the pre-operations analysis, a load drop of 450 tons was assumed. Experience gained during the construction of the SNS facility indicated maximum external crane lift loads did not exceed 50 tons. Therefore, the as-constructed facility consequence analysis assumes a more credible load drop of 150 tons rather than the 450 tons assumed during pre-construction, under the assumption that a 100 ton crane may be used in the vicinity when the Second Target Station is constructed. The resulting as-constructed facility consequences are 0.7 rem and 0.25× ERPG-2.

The mitigation strategy for this event is to prevent the load drop by using the Hoisting and Rigging Program credited for worker protection (Section 4.3.14). An external crane lift over the central portion of the facility, which houses the mercury systems, is considered very unlikely. With this control, the scenario is prevented, and no consequences occur.

Credited Controls for External Crane Load Drop

Credited controls established for worker protection as described in Section 4.3.14 for this event also protect the public by preventing the external crane load from being dropped on the target system. No new credited controls are required to protect the public.

4.4.2.8 Service Bay Fire

This section addresses the fire event that originates in the service bay of the SNS target facility. The specific scenario assessed in this section is event TS1-3, but it also bounds event TS1-2, which is a medium fire that migrates into service bay. The primary concerns from a service bay fire were the consequences that could result if the fire occurred during commissioning or early operations before the mercury became significantly radioactive. It was thought that part of the steel shielding that covers the loop might be left uninstalled. To protect electronic equipment within the service bay, the steel shielding is required once significant radioactivity builds up in the mercury circulation loop. This scenario was developed before initial operations when schedule delays threatened to delay the delivery of the shielding until after commissioning. The shielding was in fact delivered and installed before the first beam on target. When in place, the loop shielding serves as an effective barrier, protecting the loop from damage associated with a service bay fire. Because the steel shielding serves an essential role in protecting in-cell electronics, the amount of time that the shielding might be removed with mercury in the loop is expected to be insignificant with respect to the assumed lifetime of the facility. When the loop is drained to the storage tank, it is considered protected from fire events regardless of the presence of the steel shielding. Nonetheless, this event is retained because it illustrates the importance of the loop shielding.

Scenario for Service Bay Fire

The unmitigated scenario for this event is as follows:

- The system is running in the pre-activation phase with the mercury in the mercury process system at the upper normal operating limits for pressure, temperature, and mercury inventory. Portions of the steel shielding that are to be present as protective radiation shielding during the activation phase are left uninstalled, exposing sections of the mercury circulation loop.
- A fire starts in the service bay.
- The heat from the fire causes failure of the exposed portion of the mercury circulation loop because of (1) reduced piping integrity (or reduced piping support integrity) at the high temperatures or (2) failures of seals, gaskets, and/or O-rings at high temperatures. These postulated failures lead to some mercury being initially released from the system in liquid form.
- A portion of the spilled liquid mercury is directly exposed to radiant heat from the fire and vaporizes.
- Respirable droplets of mercury form and are entrained in the vapor leaving the liquid surface during boiling.
- The mercury vapor and airborne mercury droplets are transported away from the building by natural air currents.

Unmitigated Source Term for Service Bay Fire

The total respirable mercury release for the unmitigated service bay fire without mercury loop shielding in place is calculated by adding RRF_{II} and RRF_{III} as documented in [33] for this event. This sum is equal to 2.7E-02 and is equivalent to approximately 486 kg.

Consequence of Target Service Bay Fire

The unmitigated radiological consequence to the public with mercury loop shielding assumed not to be in place is conservatively bounded at 1.75 rem with an associated bounding toxicological consequence at 2.4 × ERPG-2. The unmitigated toxicological consequence to the public exceeds the credited control threshold, so a single level of control is required per the selection of credited controls criteria presented in Section 4.2.2.4. This consequence was updated to reflect facility changes from the PPU project [62].

Because the steel shielding serves an essential role in protecting in-cell electronics, the amount of time that the shielding might be removed in the future with mercury in the loop is expected to be insignificant with respect to the assumed lifetime of the facility. When the loop is drained to the storage tank, it is considered protected from fire events regardless of the presence of the steel shielding. The as-constructed facility analysis assumes the mercury loop shielding to be in place with associated consequences bounded at 0.08 rem and 0.1× ERPG-2.

In the mitigated accident analysis, credit is taken for fire detection and suppression system inside the service bay that would suppress a fire consistent with the combustible material program for inside the service bay and the 2 h equivalent fire barrier. Thus, no mercury would be released, and no radiological or toxicological consequences would occur on-site or off-site.

Credited Controls for Service Bay Fire

Credited controls established for worker protection as described in Section 4.3.1 for this event also serve to protect the public. No new credited controls are required to protect the public.

4.4.2.9 Full-Facility Fire

This section addresses the full-facility fire event of the SNS target facility. The specific scenario assessed is event BG1-1, as discussed in Section 4.3.14. The primary concerns to an off-site receptor from a full-facility fire are the toxicological consequences that result if this fire causes a mercury spill from the impact of falling structural components followed by exposure of the spilled mercury to the heat flux from the fire both in the building and in the service bay.

Scenario for Full-Facility Fire

The unmitigated scenario for this event is as follows:

- The system is running normally, with the mercury in the mercury circulation loop at the upper normal operating limits for pressure, temperature, and inventory.
- A fire external to the building propagates to the target building and into the service bay.
- Falling structural components damage a portion of the mercury circulation loop, leading to breaks that spill liquid mercury.
- A portion of the spilled liquid mercury is directly exposed to radiant heat from the fire (both inside and outside the service bay) and vaporizes.
- Respirable droplets of mercury form and are entrained in the vapor leaving the liquid surface during boiling.
- The mercury vapor and airborne mercury droplets are transported away from the building by natural air currents.

Unmitigated Source Term for Full-Facility Fire

The total respirable mercury release is calculated using the sum of RRF_{II} and RRF_{III} as shown in Table 4.2 (Section 4.4.1.2.2) for this event. This sum is equal to 4.3E-02 and is equivalent to approximately 780 kg, which is a result of the following components:

The RRF_{II} value of 4.0E-2 corresponds to a release of approximately 724 kg of mercury vapor associated with the following components:

- Direct radiative heat transfer from the fire inside the service bay (433 kg) and outside the service bay (123 kg),
- Evaporation for 8 h (13 kg) from spilled mercury in the service bay,
- Release of mercury from the eight PCES carbon adsorbers (155 kg).

The RRF_{III} value of 3.1E-3, equivalent to approximately 56 kg of mercury, represents aerosol formation and entrainment from the combination of the following components:

- Aerosolization from pressurized venting, free-fall spill and splashing, and pool aerodynamic entrainment (<1 kg),
- Aerosolization from agitation of the pool surface from bubbling phenomena during the fire (56 kg).

Consequence of Full-Facility Fire

The unmitigated full-facility fire assumes that an extensive fire occurs throughout the facility, including the service bay, and that the steel shielding that surrounds the mercury target loop is not installed. This scenario was thought to credible during commissioning and early operations as was discussed for the service bay fire (Section 4.4.2.8). The resulting unmitigated radiological consequence to the public is conservatively bounded at 2.5 rem with an associated toxicological consequence at 1.2× ERPG-2. Because EPRG-2 is exceeded, a single level of control is required per the selection of credited controls criteria presented in Section 4.2.2.4. This consequence was updated to reflect facility changes from the PPU project [62].

The as-constructed analysis assumes that the fire spreads into the service bay despite the seismically qualified 2 h equivalent fire barrier of the service bay but assumes the mercury loop steel shielding is in place when mercury is in the target loop (Section 4.4.2.8). No credit was taken for the active fire detection and suppression system. Approximately 19 kg of mercury is assumed to be vaporized by the fire in the service bay. Because no credit was taken for the fire detection and suppression system, the as-constructed facility analysis assumes the full-facility fire also leads to a release of all the mercury contained in the PCES charcoal adsorbers (conservatively estimated at 80 kg based on measured accumulation [70]) located in the basement of the facility. The associated bounding consequences are 0.23 rem with an associated toxicological consequence at 0.51× ERPG-2.

Consequences are mitigated by crediting the NFPA-13–compliant building fire detection and suppression system and a combustible material program for outside the service bay to ensure that the fire barrier is not challenged. These systems prevent the fire from progressing into the service bay and from releasing mercury on the PCES carbon adsorbers.

Credited Controls for Full-Facility Fire

Credited controls established for worker protection as described in Section 4.3.14 for this event also protect the public. No new credited controls are required to protect the public.

4.4.2.10 Accident Analysis Summary

A summary of off-site bounding consequences for credible postulated accidents associated with both the unmitigated and as-constructed analyses is provided in Table 4.11.

Unmitigated off-site radiological consequences were all found to be below the threshold for requiring credited controls. Associated unmitigated toxicological consequences for the following events exceeded the toxicological threshold (ERPG-2) and thus required credited controls:

- Service bay fire (TS1-3, TS1-6, TS1-2a),
- Full facility fire (BG1-1),
- Hydrogen explosion with and without follow-on fire (CM2-1a, CM2-1b),

- Seismic event with follow-on hydrogen explosion and/or fire (BG7-1, BG7-2, BG7-3),
- High bay crane load drop onto core vessel with hydrogen explosion (HB2-2).

In all cases, credited controls established for worker protection in Section 4.3 also effectively protect the public. As noted in Section 4.4.1.3.1, fourth bullet, the bounding exposure to workers located on-site 100 m from the target building is a factor of about 20.4 greater than the bounding off-site exposures discussed in this section. No new credited controls beyond those identified for worker protection are needed.

The unmitigated consequence analyses served as design input and were used to highlight the importance and need of certain design features (e.g., seismically qualified structures). Now that these passive design features have been incorporated into the facility, their effect on accident progression has been assessed. A summary of the post-construction bounding for credible postulated off-site consequences assuming all active controls and administrative controls fail is presented in Table 4.11.

In several instances, the unmitigated consequences were well below thresholds for requiring credited controls. In these instances, no additional analyses were performed, and the as-constructed analysis simply assumes the same value as the unmitigated analysis.

Table 4.11. Bounding Offsite Consequences for Postulated Accidents

Event (HE Designation)	Unmitigated (input for design)		As-constructed facility[b]	
	Radiation dose (rem)	ERPG-2 ratio	Radiation dose (rem)	ERPG-2 ratio
1. Service bay fire (TS1-3, TS1-6)	1.75	2.4	0.08	0.1
2a. Medium fire that spreads into the service bay (TS1-2a)	1.75	2.4	0	0
2b. Medium fire in the charcoal filter room (TS1-2b)	0.037	0.1	0.019	0.052
3. Full-facility fire (BG1-1)	2.5	1.2	0.23	0.51
4. Hydrogen explosion without follow-on fire (CM2-1b)[c]	2.3	3.8	0	0
5. Hydrogen explosion with follow-on fire (CM2-1a)[a]	≤7.5	≤6.6	0	0
6. Service bay loss of confinement (TS3-7, TS3-10)	0.032	0.05	0.032	0.05
7. Core vessel (helium) loss of confinement (TS3-4, TS3-6, TS3-8, TS3-11)	0.04	0.07	0.04	0.07
8. Core vessel (vacuum) loss of confinement	0.135	0.08	0.135	0.08
9. Partial loss of mercury flow (TS3-22, TS3-23, TS3-24, TS3-25)	0.45	0.39	0.45	0.39
10. Complete loss of mercury flow (TS3-22)	0.1	0.14	0.1	0.14
11. Loss of heat sink (TS3-13, TS3-14, TS3-15, TS3-16)	0.81	0.53	0.81	0.53
12. Service bay crane load drop (TS3-18)	0.042	0.05	0.042	0.05
13. High bay crane load drop onto service bay (HB3-3)	0.14	0.08	0.14	0.08
14. High bay crane load drop onto core vessel with no explosion (HB3-7)	0.16	0.1	0.04	0.07
15. High bay crane load drop onto core vessel with hydrogen explosion (HB2-2)[a]	≤7.5	≤6.6	0.12	0.14
16. External crane load drop (BG6-11)	2.1	0.74	0.7	0.25
17. Seismic event including follow-on hydrogen explosion and fire (BG7-1)[c]	7.5	6.6	0.14	0.18
18. Seismic event including follow-on fire (BG7-2)[a]	≤7.5	≤6.6	≤0.14	≤0.18
19. Seismic event including follow-on hydrogen explosion (BG7-3)[a]	≤7.5	≤6.6	≤0.14	≤0.18

[a] Consequences conservatively assumed to be bounded by BG7-1.

[b] The as-constructed facility analyses take into account passive robust structures and design features but take no credit for active or administrative controls.

[c] The consequences of CM2-1b and BG7-1 were adjusted to account for increased hydrogen inventory by increasing the dose in direct proportion to the increase in hydrogen inventory (9.4 kg/7 kg = 1.343), which is conservative because portions of the total consequence are not directly linked to the hydrogen inventory.

4.5 SUMMARY OF CREDITED CONTROLS

The SNS criteria for selection of safety-related credited controls as summarized in Section 4.2.2.4 requires credited mitigative controls be in place when postulated unmitigated accident scenarios lead to unacceptable on-site or off-site consequences. The credited controls identified for SNS are listed in the summary tables of Section 4.3.15.

Section 4.3 focuses on potential hazards to workers. Several postulated accident scenarios resulted in worker exposures high enough to warrant credited controls to mitigate consequences. Credited controls selected to protect the worker are summarized in the tables provided in Section 4.3.15.

Section 4.4 focuses on the analysis of potential offsite hazards to the public. In all instances, credited controls identified in Section 4.3 to protect workers from the same events were effective in protecting the off-site public. Therefore, no new credited controls were identified for public protection.

The credited controls identified in Section 4.3 mitigate the release of hazardous materials from the facility. As such, the credited controls protect not only the on-site workers but also the off-site public and the environment.

Appendix A presents the SNS controls matrix, which summarizes credited controls identified for each event. Each column listing credited controls makes up one level of control (discussion in Section 4.2.2.4).

Section 5 provides information about the design and functional requirements for each designated credited control and serves as the basis for the ASE.

4.6 ENVIRONMENTAL PROTECTION

The potential for large radioactive or toxic material releases is minimized by the CECs and CACs identified in this section. These controls protect the worker outside the facility and the public by mitigating atmospheric releases from the facility. Those CECs and CACs that protect either the on-site workers or the public also inherently protect the environment. The current evaluation of the protection for the environment is provided in the *Construction and Operation of the SNS—Final Environmental Impact Statement* [20].

4.7 REFERENCES

1. Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Safety Analysis Reports, DOE-STD-3009-94, Change Notice 2, US Department of Energy, Washington, D.C., April, 2002.
2. Safety of Accelerators, DOE Order 420.2D, US Department of Energy, Washington, D.C., September 2022.
3. Accelerator Facility Safety Implementation Guide for DOE O 420.2C, Safety of Accelerator Facilities, DOE Guide 420.2-1A, US Department of Energy, Washington DC, August, 2014.
4. Spallation Neutron Source Policy for Selection of Safety Related Credited Controls, SNS 102030100-ES0005-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, March 2005.
5. Emergency Planning and Notification (TPQ), 40 CFR 355, Appendices A and B, US Environmental Protection Agency, Washington, D.C., revised June 1993.

6. Chemical Accident Prevention Provisions, 40 CFR 68, Risk Management Programs for Chemical Accidental Release Prevention, Environmental Protection Agency, Washington, D.C., revised January 1999.
7. List of Hazardous Substances and Reportable Quantities, 40 CFR 302.4, Environmental Protection Agency, Washington, D.C., revised July 1997.
8. Process Safety Management (PSM) of Highly Hazardous Chemicals, 29 CFR 1910.119, Labor, US Occupational Safety and Health Administration, Washington, D.C., revised July 1992.
9. Facility Safety, DOE Order 420.1A, US Department of Energy, Washington, D.C., May 2002.
10. Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities, DOE-STD-1020-94, US Department of Energy, Washington, D.C., Change Notice 1, January 1996.
11. Natural Phenomena Hazards Performance Categorization Guidelines for Structures, Systems, and Components, DOE-STD-1021-93, US Department of Energy, Washington, D.C., Change Notice 1, January 1996.
12. Natural Phenomena Hazards Characterization Criteria, DOE-STD-1022-94, US Department of Energy, Washington, D.C., Change Notice 1, January 1996.
13. Natural Phenomena Hazards Assessment Criteria, DOE-STD-1023-95, US Department of Energy, Washington, D.C., Change Notice 1, January 1996.
14. Guidelines for Use of Probabilistic Seismic Hazard Curves at Department of Energy Sites for Department of Energy Facilities, DOE-STD-1024-92, US Department of Energy, Washington, D.C., Change Notice 1, January 1996.
15. Spallation Neutron Source Standards for Design and Construction of the Target Facility, SNS 102030102-ES0012-R02, Oak Ridge National Laboratory, Oak Ridge, Tennessee, September 2001.
16. Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23, Nuclear Safety Analysis Reports, DOE-STD-1027-92, US Department of Energy, Washington, D.C., Change 1, September 1997.
17. K. R. B. Menger, M. D. Lowman, and I. K. Paik, Hazard Analysis for the Spallation Neutron Source Target System, WSMS-OR-99-0008, Draft Rev. B, Westinghouse Safety Management Solutions LLC, Aiken SC, December 1999 (Historical Reference Only).
18. SNS Target Facility Hazard Identification and Evaluation, SNS 102030102-ES0017-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, October 2005.
19. National Spallation Neutron Source Conceptual Design Report, NSNS/CDR-2/V1 and V2, Oak Ridge National Laboratory, Oak Ridge, Tennessee, May 1997.
20. Construction and Operation of the Spallation Neutron Source—Final Environmental Impact Statement, DOE/EIS-0247, US Department of Energy, Office of Science, Washington, D.C., April 1999.
21. Spallation Neutron Source Design Manual, Oak Ridge National Laboratory, Oak Ridge, Tennessee, September 1998.
22. Request for Formal Verification of Information For Use in the 2005 Spallation Neutron Source Safety Assessment Report for Neutron Utilization (SAD-NU), WSMS-LIC-05-0067, Washington Safety Management Solutions LLC, Aiken South Carolina, August 2005.
23. C. H. Blanton and S. A. Eide, "Nonreactor Nuclear Facilities: Standards and Criteria Guide," DOE/TIC-11603, Rev. 1, Science Applications International Corp., LaJolla, California, September 1986.

24. J. P. Poloski, D. G. Marksberry, C. L. Atwood, and W. J. Galyean, “Rates of Initiating Events at U.S. Nuclear Power Plants: 1987–1995,” NUREG/CR-5750, US Nuclear Regulatory Commission, February 1999.

25. M. D. Lowman, “Hydrogen Generation Rate in the SNS Target Mercury Process System,” WSMS-SAE-M-0079, Memo-to-File, Westinghouse Safety Management Solutions LLC, Aiken, South Carolina, October 11, 1999.

26. Spallation Neutron Source Final Safety Assessment Document for Proton Facilities, SNS 102030103-ES0018-R03, Oak Ridge National Laboratory, Oak Ridge, Tennessee, July 2022.

27. J. A. Crabtree personal communication of Calculation of Hydraulic Impedance of CM Transfer Lines, August 2005.

28. Calculation of Atmospheric Dispersion of Natural Gas Releases, SNS 102030102-ES0004 R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, February 2000.

29. Hydrogen Concentration after Release to the High Bay, SNS 102030102-ES0009 R01, Oak Ridge National Laboratory, Oak Ridge, Tennessee, March 2002.

30. Rules for Construction of Overhead and Gantry Crane, ASME NOG-1-2002.

31. Accident Analysis for Aircraft Crash into Hazardous Facilities, DOE-STD-3014-96, US Department of Energy, Washington, D.C., October 1996.

32. R. Lux, Aircraft Impact Risk for the Spallation Neutron Source Target Facility, WSMS-OR-0000015, August 24, 2000.

33. R. M. Harrington and D. C. Thoman, Master Engineering Calculation for SNS Target Facility Accident Analyses Supporting the Final SAD for Neutron Facilities, SNS 102030103-CA0005-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, August 2005.

34. Spallation Neutron Source Preliminary Safety Analysis Report, SNS 102030102-ES0001-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, December 1999.

35. Spallation Neutron Source Preliminary Safety Analysis Report Update Report, SNS 102030102-ES0008-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, March 2001.

36. Spallation Neutron Source Preliminary Safety Analysis Report Update Report, SNS 102030102-ES0008-R02, Oak Ridge National Laboratory, Oak Ridge, Tennessee, May 2002.

37. Spallation Neutron Source Preliminary Safety Analysis Report Update Report, SNS 102030102-ES0008-R03, Oak Ridge National Laboratory, Oak Ridge, Tennessee, August 2003.

38. Spallation Neutron Source Preliminary Safety Analysis Report, SNS 102030102-ES0001-R02, Oak Ridge National Laboratory, Oak Ridge, Tennessee, December 2003.

39. Spallation Neutron Source Preliminary Safety Analysis Report, SNS 102030102-ES0001-R01, Oak Ridge National Laboratory, Oak Ridge, Tennessee, August 2000.

40. Spallation Neutron Source Final Safety Assessment Document for Neutron Facilities, SNS 102030102-ES0016-R02, Oak Ridge National Laboratory, Oak Ridge, Tennessee, April 2007.

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

42. C. C. Fields, Master Engineering Calculation for Accident Analyses Supporting Revised PSAR, WSMS-OR-03-0006, Rev. A, Westinghouse Safety Management Solutions LLC, Aiken, South Carolina, December 2003.

43. R. M. Harrington, Airborne Mercury Accident Source Terms for the Target Building Safety Assessment Document, SNS 102030102-CA0020-R01, Oak Ridge National Laboratory, Oak Ridge, Tennessee, August 2006.

44. T. L. Grimm and J. Popielarski, Microphonic Measurements of β=0.81 Elliptical Cryomodules in the Spallation Neutron Source Tunnel, SNS 102030102-TR0008-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, July 2005.

45. K. Davis and J. Delayen, SNS SRF LINAC Earthquake Response Testing at 4K, SNS 102030102-TR0009-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, July 2005.

46. M. W. Wendel, Thermal-Hydraulic Analysis of the SNS Mercury Target, SNS 106010101-DA-0005-R01, February 2006.

47. Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities, Volume 1 — Analysis of Experimental Data, DOE-HDBK-3010-94, Change Notice 1, US Department of Energy, Washington, D.C., March 2000.

48. P. Ferguson, Radionuclide Inventory of the SNS Mercury Target, SNS 106100200-DA0014-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, July 2005.

49. C. F. Weber and R. M. Harrington, Spallation Product Volatility and Accident Release Transport Groups, SNS 102030102-TR0005-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, March 2005.

50. E. R. G. Eckert and R. M. Drake, Heat and Mass Transfer, McGraw-Hill, New York, 1959.

51. R. M. Harrington, Fire Accident Source Terms and Consequences, SNS 102030102-CA0001-R01, Oak Ridge National Laboratory, Oak Ridge, Tennessee, September 26, 2003.

52. USEPA, User's Guide for the Industrial Source Complex (ISC3) Dispersion Models, EPA-454/B-95/003a, Research Triangle Park, North Carolina.

53. A. L. Sjoreen and R. L. Miller, Atmospheric Dispersion Analysis of Mercury Releases for Postulated Fire Accidents at the SNS Facility, SNS 102030102-CA0003-R01, Oak Ridge National Laboratory, Oak Ridge, Tennessee, August 2003.

54. A. L. Sjoreen and R. L. Miller, Onsite Dispersion Coefficient, SNS 102030102-CA0013-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, September 2003.

55. ICRP, Dose Coefficients for Intakes of Radionuclides by Workers, ICRP Publication 68, International Commission on Radiological Protection, Pergamon Press, Oxford, 1994.

56. R. W. Leggett, Determination of Inhalation Dose Coefficients for SNS Accident Analysis, SNS 102030102-TR0006-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, May 2005.

57. C. F. Weber, Mercury Aerosol Production in a Postulated SNS Loss of Heat Sink Accident, SNS 102030102-TR0070-R00, March 2006.

58. Setpoint Definition for Low-Speed Mercury Pump Operations, SNS-106010200-DA0003-R05, September 2005.

59. American Industrial Hygiene Association, Emergency Response Planning Guidelines for Mercury Vapor, December 2003.

60. Addendum to Master Engineering Calculation in Support of the FSAD-NF Rev 3 Update, SNS 102030102-CA0024-R00, July 2011.

61. Safety of Accelerator Facilities, DOE Order 420.2C, US Department of Energy, Washington, D.C., July 2011.

62. R. M. Harrington, Effect of PPU Increased End-of-Life Spallation Product Inventory on Radiological Consequences of Hypothetical SNS Accidents, PPUP-103-ES0002-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, January 2023.
63. B. DeGraff, Cryogenic Moderator System (CMS) Maximum Hydrogen Inventory Assessment, 106020200-DAC10001-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, September 2022.
64. Proton Power Upgrade Project Hazard Analysis Report, PPUP-103-ES0004-R01, June 2020.
65. Master Engineering Calculation for SNS Target Facility Accident Analyses Supporting Revised PSAR, WSMS-OR-03-0006, Rev A, December 2003.
66. Safety Assessment Supplement for Target Gas Injection Initial Implementation (GI3), 102030102-ES0094-R00, September 2017.
67. Safety Evaluation of Mercury Loop Operations Following Fill Transient Events, 102030102-ES0104-R00, June 2019.
68. USI Evaluation for Supplying Mercury Process Loop Gas from the High Bay, 102030102-ES0114-R00, August 2020.
69. Hazard Analysis for Loss of Confinement of o-p Catalyst in Cryogenic Hydrogen Loop, PPUP-103-TR0002-R00, June 2020.
70. Addendum #2 to the Master Engineering Calculation in Support of Revision 4 of the FSAD-NF, 102030102-CA0025-R00, August 2023.
71. S. J. Pawel and E. T. Manneschmidt, Corrosion of Type 6061-T6 Aluminum in Mercury and Mercury Vapor, Fifth International Workshop on Spallation Materials Technology, Charleston, South Carolina, May 19–24, 2002.

5. CREDITED CONTROLS AND BASIS FOR THE ACCELERATOR SAFETY ENVELOPE

5.1 INTRODUCTION

Credited controls were identified in accordance with the criteria specified in Section 4.2.2.4, *Selection of Credited Controls*, for the accident events analyzed in Section 4. Identified CECs and CACs are described in detail below. For each control, the means for maintaining the control's safety function is given. The continued operability or safety function of credited controls is assured by various means, including ASE Coverage, operational envelope coverage, configuration management, and operating procedures. ASE coverage constitutes the most rigorous control and forms the basis for the ASE. The ASE is a separate DOE-approved document that establishes requirements to be strictly adhered to. The ASE specifically addresses conditions under which controls are strictly required and the limiting operational restrictions (e.g., prohibition of operation, appropriate compensatory controls, etc.) that must be adhered to when a particular control is not operational or available.

5.2 CREDITED ENGINEERED CONTROLS

This section addresses relevant information to elucidate the safety function of CECs that prevent or mitigate the consequences of potential accidents. The CECs are listed in Table 4.15-1 (Section 4.3.15). This section provides the safety functions, system description, functional requirements, system evaluation, and ASE bases, where applicable, for each CEC.

Safe operation requires that CECs perform their credited safety mission in the event of a challenge unless specified otherwise. For CECs that perform an active safety function, the ASE specifies conditions under which each CEC must be operable and specifies requirements for periodic testing to ensure that reliability is maintained. Passive CECs are generally more appropriately covered by the configuration control program or in the operations envelope because they are generally design features that provide the credited function unless an intentional effort has been undertaken to change the structure from its initially installed configuration. When an existing ORNL SBMS policy provides sufficient requirements to assure operability, no further coverage of that control is required. For example, the operability and surveillance requirements for the fire suppression systems in the service bay and for the target building in general (outside of the service bay) are covered in SBMS. Therefore, no additional requirements are needed to ensure operability. The configuration control program ensures that all CECs remain as described in this section.

NPH qualification requirements are listed only where the CEC is specifically credited in performing its safety function for an NPH event. Therefore, only the PCs relevant to performing the identified safety functions are listed. Consistent with DOE-STD-1020, *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities* [2], and DOE-STD-1021-93, *Natural Phenomena Hazards Performance Categorization Guidelines for Structures, Systems, and Components* [3], other criteria, such as good practice or facility mission, have dictated higher NPH requirements in many cases. PCs for CECs have been defined as part of the design process consistent with the aforementioned DOE standards [2, 3]. Configuration control of the environment surrounding credited, NPH-qualified CECs is maintained to ensure that interaction with other items does not defeat the credited NPH mission of the credited CEC [3].

Design codes and standards applicable to SNS are referenced in *Spallation Neutron Source Standards for Design and Construction of the Target Facility* [4].

It is sometimes necessary, for maintenance or other purposes, to take a credited control out of service. When bypassed, a system does not provide the designated protective function; therefore, compensatory measures must be invoked to provide an acceptable degree of safety during the bypass period. The system engineer for a protective system is responsible for deciding when a bypass is warranted and for establishing/documenting the rationale for the bypass that should include the following items: (1) compensatory measures that must be instituted during the bypass, (2) hold tags or other cautionary postings to be placed, and (3) the administrative approvals that must be secured before the bypass is executed. Bypass approvers include not only the system engineer but also operations management responsible for ensuring that the compensatory measures are in place before the bypass is executed.

5.2.1 Cryogenic Moderator System Hydrogen Boundary

5.2.1.1 Safety Function

The CMS hydrogen boundary prevents hydrogen leakage into the core vessel caused by system breaches. The adjacent CMS vacuum boundary provides the credited backup to the hydrogen boundary (Section 5.2.2).

5.2.1.2 System Description

Section 3.3.3 provides a general description and operational summary of the CMS. The CMS uses supercritical hydrogen as a neutron moderator within the core vessel. The system cools the supercritical hydrogen using circulators and a helium-cooled heat exchanger located in the HUR on the truss level of the target building. Some of the piping is inside the core vessel, and some is outside the core vessel. The boundaries that confine the hydrogen are (1) the walls of the moderator vessels inside the core vessel, (2) the pipe walls for the piping that carries hydrogen from the HUR to the moderator vessels and back again, and (3) the walls of components inside the common vacuum space in the HUR. The hydrogen boundary inside the pump and heat exchanger modules is not included because no flow path is available for the escaped hydrogen to flow to the core vessel. The vacuum system for the pump and heat exchanger modules is separate from the vacuum system for the balance of the cryogenic system.

Three highly similar, but not identical, subsystems—also called loops—are included in the CMS. Each of these subsystems contains a moderator vessel inside the core vessel adjacent to the mercury target, and piping—also called cryogenic transfer line—to supply cryogenic hydrogen from the HUR to the moderator vessel and to return it to the helium heat exchanger in the HUR.

The CMS uses a multilayer barrier system consisting of concentric boundaries to insulate the cryogenic hydrogen. The multiple boundaries necessary to provide for a functional cryogenic system also provide layers of confinement of the hydrogen. In general, the hydrogen is confined by the innermost hydrogen boundary that is then enveloped by a vacuum layer and boundary. The vacuum boundary serves as a credited second barrier in preventing hydrogen from reaching the core vessel.

The hydrogen boundary of each of the three CMS subsystems is protected by a rupture disk in the HUR that relieves to an inert gas-purged line that discharges above the roof level. If the cryogenic hydrogen temperature inside the core vessel begins to increase, then hydrogen pressure would increase, and the rupture disk would actuate when the pressure reaches 19 bar (275.5 psia). No hydrogen would escape to the vacuum layer unless the hydrogen boundary failed. The rupture disk is part of the credited relief path. The design also includes a spring-loaded relief valve that actuates at 18 bar (261 psia) and discharges to the atmosphere through the same inerted relief path. This spring-loaded relief valve would be expected to relieve most overpressure upsets without actuation of the rupture disc.

The relief path for hydrogen expanding inside the moderator vessel is as follows:

> Moderator vessel ⇨ Transfer line ⇨ Hydrogen line inside pump module (in HUR**)** ⇨ Pigtails leading to relief header ⇨ Relief header in HUR ⇨ Rupture disk ⇨ Discharge line ascending to above roof level ⇨ Environment.

Two hydrogen relief connections are provided inside the pump module to ensure that a blockage inside the heat exchanger cannot defeat the relief function.

5.2.1.3 Functional Requirements

The following functional requirements support the safety function of the hydrogen barrier:

1. The hydrogen confinement boundary shall maintain design integrity for internal pressures up to the overpressure protection limit.

2. Rupture discs (nominal rupture pressure 19 bar [275.5 psia]) shall provide overpressure protection for the hydrogen confinement boundary.

3. Hydrogen piping and moderator vessels inside the core vessel shall be protected against damage by the core vessel internals (inner and outer reflector plugs) by being routed/mounted in recessed channels/chambers. The physical protection provided within the core vessel for the CMS provides protection up to the PC-3 seismic requirements.

4. Hydrogen piping outside the core vessel shall be protected from impact that may result in crimping or crushing that would block the normal flow path (relief path) between the rupture disk and the core vessel. Protection is provided for issues such as internally generated missiles, operator error, and equipment failure and is qualified to perform this function during and after a PC-3 seismic event.

Operability

The CMS hydrogen boundary is required to be operable when the possibility exists for a hydrogen explosion in the core vessel to impact the target mercury. If the hydrogen is purged from the CMS, then the energetic source is removed, ensuring that a hydrogen explosion cannot occur, so the CMS hydrogen boundary is not needed to prevent hydrogen release.

- The CMS hydrogen rupture disks and vent path must be operable unless hydrogen is purged from the CMS.

5.2.1.4 System Evaluation

The design and fabrication of all piping meets the requirements of ASME B31.3 [5]. The design and fabrication of the pressure vessels is performed in accordance with an equivalent protection plan [6]. This plan's requirements [6] are largely derived from the ASME Section VIII B&PV Code [7], the approach is tailored to better fit the unique design, material, and fabrication needs of the moderator vessels. Design to these standards provides a high degree of confidence that the hydrogen boundary maintains integrity throughout its design range, up to and including the rupture disc's actuation pressure.

The hydrogen must be continuously cooled, circulated, and insulated to maintain a cryogenic operating state. Any condition that leads to loss of hydrogen flow, hydrogen cooling, or vacuum insulation requires that the hydrogen be vented outside the core vessel. Unless the hydrogen is vented, the resulting system overpressure could cause the inner hydrogen barrier to fail in the core vessel. The venting occurs automatically upon actuation of the hydrogen rupture disc. The rupture disk actuation pressure and flow capacity are certified per ASME by the vendor and ensure adequate relief to maintain the hydrogen boundary within acceptable stress levels during heating events, including loss of vacuum. If cryogenic conditions are not maintained, then beam-on-target power level is restricted per approved design analysis calculations to maintain the hydrogen and vacuum boundary temperatures within their design range.

A leak past the hydrogen barrier of a CMS subsystem would spoil the vacuum region inside the core vessel regardless of the leak's location. Because the vacuum regions are interconnected, this leak could result in hydrogen entering the core vessel if failure of the vacuum barrier inside the core vessel is assumed. As discussed in Section 5.2.2, the vacuum barrier provides a secondary credited barrier between the hydrogen and the core vessel.

Each hydrogen transfer line has been evaluated to demonstrate the PC-3 seismic capability of the hydrogen barrier [8, 9, 10]. The hydrogen barrier components and lines are supported in accordance with criteria developed for a PC-3 level seismic event with respect to the functional requirements to specify horizontal and vertical acceleration and maximum unsupported length. Seismic interaction is evaluated to determine seismic requirements for adjacent components, as needed, to prevent their failure from causing failure of the hydrogen barrier system boundary.

5.2.1.5 Assurance of Continued Operability

The robust hydrogen barrier is considered a passive design feature; therefore, it does not require ASE coverage. The configuration control program ensures safety features of the design are maintained. These features and their requirements have been included in Appendix A of the ASE.

Operations envelope coverage ensures operability of the rupture discs by requiring periodic inspections for deformation or other visual damage and replacement whenever the CMS pressure at the inlet to a rupture disk rises to the rupture disk deformation pressure, whenever the rupture disk safety head is disassembled, or at least once every 5 years. Furthermore, the relief path requires periodic surveillance to ensure the rupture disk discharge path remains open downstream of the rupture disk. The integrity and configuration of the vent paths from the rupture disks to atmosphere shall be visually verified at least annually (not to exceed 15 months). This check should include the piping and exhaust cover.

Operations envelope coverage is required to specify a limit for the beam-on-target power level when cryogenic conditions cannot be maintained in one or more of the CMS units to prevent overheating from damaging the vessels. The limiting proton beam power for noncryogenic conditions is preestablished in an approved design analysis calculation [11].

5.2.2 Cryogenic Moderator System Vacuum Boundary

5.2.2.1 Safety Function

The CMS vacuum boundary (vessel and piping) shall provide a robust barrier as a second level of protection to the hydrogen boundary that prevents hydrogen from escaping into the core vessel.

5.2.2.2 System Description

Section 3.3.3 provides a general description and operational summary of the CMS. The cryogenic moderator vacuum boundary is adjacent to the hydrogen boundary discussed in Section 5.2.1. The cryogenic moderator vacuum barrier consists of the metal walls in direct contact with the hydrogen barrier and the metal walls separating the vacuum (thermal insulation) from an outer annular region. The normal operating pressure of the vacuum region is expected to be between about 10^{-6} torr and 10^{-9} torr.

A leak past the hydrogen barrier in the moderator vessel or transfer line would spoil the CMS vacuum inside the core vessel regardless of the leak's location. Because the vacuum regions for the moderator vessel and transfer line are interconnected, this leak could result in hydrogen entering the core vessel were it not for the vacuum boundary.

The vacuum boundary does not include the vacuum boundary of the CMS pump and heat exchanger modules. The vacuum for the pump and heat exchanger modules (which are interconnected) is separate from the transfer line vacuum. Leakage of hydrogen from hydrogen lines into the pump or heat exchanger module would not be able to flow into the core vessel.

5.2.2.3 Functional Requirements

The vacuum barrier shall perform the following to prevent hydrogen from flowing into the core vessel as credited in the safety analysis:

1. The vacuum barrier shall prevent hydrogen from leaking into the core vessel following hydrogen leakage caused by random or seismically initiated failure of a hydrogen boundary.

2. Overpressure protection shall be provided by rupture discs (i.e., one for each of the three CMS subsystems with nominal actuation pressure to ensure the relief-protected maximum pressure of the vacuum barrier 2 bar [29 psia]).

3. Vacuum piping and moderator vessels inside the core vessel shall be protected against damage by the core vessel internals (inner and outer reflector plugs) by being routed/mounted in recessed channels/chambers. The physical protection provided within the core vessel for the CMS provides protection to PC-2 seismic requirements.

4. Vacuum piping outside of the core vessel shall be protected from impact that may result in crimping or crushing that would block the normal flow path (relief path) between the rupture discs and the core vessel. Protection is provided for issues such as internally generated missiles, operator error, and equipment failure and is qualified to perform this function during and following a PC-2 seismic event.

Operability

The CMS vacuum boundary must be operable when the possibility exists for a hydrogen explosion in the core vessel to impact the target mercury. If the hydrogen is purged from the CMS, then the energetic source is removed, ensuring that a hydrogen explosion cannot occur, so the CMS vacuum boundary is not needed to prevent hydrogen release.

- The CMS vacuum rupture disks and vent path must be operable unless hydrogen is purged from the CMS.

5.2.2.4 System Evaluation

The design and fabrication of all piping meet the requirements of ASME B31.3 [5]. The design and fabrication of the pressure vessels is performed in accordance with an equivalent protection plan [6]. The requirements of [6] are largely derived from the ASME Section VIII B&PV Code [7], but it tailors the approach to better fit the unique design, material, and fabrication needs of the moderator vacuum vessels. Design to these standards, combined with the high vacuum that must be maintained for normal operation of the CMS, provides a high degree of confidence that the CMS vacuum boundary maintains its integrity up to and during rupture disk actuation.

Each hydrogen transfer line has been evaluated to demonstrate the PC-3 seismic capability of the vacuum barrier [8, 9, 10], demonstrating that the CMS vacuum boundary exceeds its PC-2 minimum seismic requirement. In addition, analysis of the ability of the moderator vacuum barrier to withstand a rupture of the moderator vessel that releases hydrogen into the vacuum region concludes that the vent path can remove more than the hydrogen vapor generation rate expected from boiling in the vacuum vessel with a system pressure of 2 bar (29 psia) [12].

5.2.2.5 Assurance of Continued Operability

The vacuum barrier is considered a design feature and does not require ASE coverage. The configuration control program ensures that design features important to safety are maintained and can perform their safety functions. These features and their requirements have been included in Appendix A of the ASE.

Operations envelope coverage ensures operability of the rupture discs by requiring periodic inspections for deformation or other visual damage and replacement whenever the CMS pressure at the inlet to a rupture disk rises to the rupture disk deformation pressure, whenever the rupture disk safety head is disassembled, or at least once every 5 years. Furthermore, the relief path requires periodic surveillance to ensure the rupture disk discharge path remains open downstream of the rupture disk. The integrity and configuration of the vent paths from the rupture disks to atmosphere shall be visually verified at least annually (not to exceed 15 months). This check should include the piping and exhaust cover.

5.2.3 Service Bay and Core Vessel 2-Hour Equivalent Fire Barrier—Isolation Function

5.2.3.1 Safety Function

The isolation safety function of the service bay and core vessel fire barrier provides a physical barrier between the service bay and core vessel and combustibles located outside the service bay and core vessel. The barrier shall be designed to prevent migration of either combustibles or mercury across that barrier.

5.2.3.2 System Description

The following concrete and steel structures comprise the fire barrier surrounding the service bay and the core vessel:

- The concrete and steel structure and steel shielding that surround the core vessel and the bulk shielding liner drain cavity
- The concrete walls of the service bay and transfer bay
- The service bay floor and mercury collection basin
- The high bay floor over the service bay

The first of the four features listed above protects the core vessel, and the others protect the service bay.

5.2.3.3 Functional Requirements

The barrier shall prevent additional combustibles that may be located outside of the service bay from entering the service bay. Additionally, the barrier shall prevent significant quantities of mercury from being transported out of the service bay or core vessel. The barrier, including the foundation, floor, walls, and ceiling (high bay floor) of the service bay and the bulk shielding liner drain cavity, shall be qualified to perform its separation function following a PC-3 seismic event.

Although the structures are identified as a fire barrier, to provide this function these structures only need to act to provide separation and prevent combustibles or mercury from crossing the barrier. The fire barrier function of this structure is discussed in Section 5.2.4.

5.2.3.4 System Evaluation

Fire is a significant event with the potential for releasing hazardous material to the public. Events that include a fire are a focus for the target facility safety analysis because the target is liquid mercury, which would boil if its temperature exceeded 357°C (630 K) at atmospheric pressure. The Combustible Material Control program is followed to control configurations or accumulations of combustible material inside and outside the service bay. The target building contains combustible materials in components such as electrical wiring and instrumentation cables to an extent typical for an industrial or other similar facility, distributed throughout the facility, inside and outside the service bay. However, the target building's major combustible material hazard is found in the instrument hall, which surrounds the target service bay and monolith. Significant quantities of solid hydrocarbons are incorporated into the neutron shielding of some of the instrument enclosures found at the end of each beamline. Additional combustibles may be located inside the high bay above the service bay.

As discussed in Section 4.4, the seismic event is the most severe because it potentially combines assumed mechanical and structural failures with a potential service bay hydrogen explosion and the worst-case combustible loading in the service bay and instrument hall. The CMS hydrogen boundary design prevents hydrogen explosions, and the structural design of the fire barrier maintains separation of combustibles inside and outside the service bay. The full-facility fire is less severe because it does not involve the mechanical damage initiator of the seismic event. In both the seismic and non-seismic fire scenarios, the use of noncombustible (e.g., concrete and steel) neutron beamline shielding provides a buffer between the hydrocarbon-based neutron shielding instrument enclosures and the service bay. The mercury circulation loop piping and vessels are not credited against leakage during or after a seismic event. Spilled mercury in the service bay is assumed.

The fire barrier between the combustible shielding in the instrument hall and the mercury inside the service bay is designed and qualified to PC-3 requirements in accordance with DOE-STD-1020 [2]. The entire structure, including seismic interaction considerations, has been evaluated for PC-3 requirements [13]. The portions of the fire barrier provided by the service bay ceiling (high bay floor) and the walls of the service bay and monolith must survive a PC-3 seismic event such that they preclude combustibles on the outside of the service bay from migrating into the service bay because of the event. The analysis of the post-seismic fire scenario demonstrating the adequacy of the limited requirement on the fire barrier (i.e., maintaining separation between the mercury and combustibles outside the service bay) has been completed [14]. The central portion of the monolith is covered by removable concrete shielding beams. These beams are not necessary for the fire barrier function because of the large mass of steel shielding (inside and outside the core vessel) around and above mercury inside the monolith.

The fire barrier's ability to retain mercury spilled inside the service bay is satisfied by the PC-3 design of service bay structures and by the PC-3 design of the collection basin. Mercury spillage is channeled by gravity to flow along the sloped surfaces of the process bay floor underneath mercury process vessels and piping to the collection basin. The collection basin is PC-3 qualified per DOE-STD-1020 [2]. Mercury retention with respect to drainage from the monolith is ensured by the PC-3 design of the concrete pedestal on which the monolith rests and by the bulk shielding liner drain cavity where mercury leaking from a failed core vessel into the bulk shielding would flow by gravity. The drain cavity is a stainless-steel-lined, PC-3–qualified cavity within the PC-3–qualified concrete pedestal. Its approximately 200 gal capacity exceeds the maximum amount of mercury that could be spilled or pumped into the core vessel or monolith (assuming failure of the core vessel) after an earthquake. These design features ensure that mercury is retained within the service bay and monolith following an NPH event.

5.2.3.5 Assurance of Continued Operability

The fire barrier enclosing the target service bay and core vessel is considered a passive design feature and therefore does not require ASE coverage. The configuration control program ensures that design features important to safety are maintained and able to perform their safety functions. These features and their requirements have been included in Appendix A of the ASE.

5.2.4 Service Bay and Core Vessel 2-Hour Equivalent Fire Barrier—Fire Barrier Function

5.2.4.1 Safety Function

The service bay and core vessel fire barrier enclosing the service bay and the core vessel is meant to prevent a fire outside the service bay and core vessel from propagating into the service bay and core vessel for a 2 h equivalent fire.

5.2.4.2 System Description

The fire barrier is meant to prevent transmission of fire from outside the service bay to inside the service bay. By contrast, the safety function of the fire barrier isolation function (Section 5.2.3) is to maintain structural integrity in an earthquake to prevent additional combustibles from entering the service bay and to prevent mercury from being transported from the service bay to the basement.

The following concrete and steel structures comprise the fire barrier surrounding the target service bay and the core vessel:

- The concrete and steel structure and steel shielding surrounding (around and above) the core vessel (functions as a fire barrier separating the core vessel from the instrument hall, high bay, RTBT tunnel, and manipulator gallery).
- The concrete structure surrounding the bulk shielding liner drain cavity (functions as a vertical fire barrier separating the drain cavity from the basement).
- The outer walls of the service bay (functions as a vertical fire barrier separating the service bay from the manipulator gallery, decontamination room, and service gallery).
- The service bay floor (functions as a horizontal fire barrier separating the service bay from the basement).
- The high bay floor and removable concrete floor beams over the service bay.
- The doors, hatches, and other through-penetrations embedded within the above structures (function to complete the fire barrier).

5.2.4.3 Functional Requirements

The fire barrier shall meet the following requirements:

- The service bay fire barrier shall meet NFPA and/or FM requirements for an equivalent two-hour fire.
- The monolith shall provide equivalent protection for the core vessel by virtue of its very large mass of steel shielding. The fire barrier shall be qualified to perform the safety function during and following a fire initiated by a PC-2 seismic event.

Compensatory Measures

The service bay and core vessel 2-Hour equivalent fire barrier—fire barrier function ensures that a fire outside of the service bay or core vessel cannot propagate into the protected area. This barrier eliminates a substantial source of heat from the postulated scenario by limiting the size of the fire inside the service bay and eliminating the effects of any fires that might be outside the service bay, especially fires caused by burning polymer shielding in the instrument hall. However, this barrier is unnecessary for the preventing the release of airborne mercury if the mercury inventory of the mercury circulation loop has been drained to the storage tank. The storage tank is the lowest point in the mercury circulation loop, resting within a concrete and steel collection basin. Thus, if the mercury has been drained to the storage tank, then further protection from a fire is not necessary. Another consideration for the removal of service bay T-beams is their function to confine mercury in the case of a fire that originates in the service bay. Because the mercury circulation loop will be drained before the service bay T-beams are removed, the potential consequences of this event would be significantly less than other service bay fires, but there still exists the possibility that residual mercury could be vaporized and transported into the High Bay. Thus, the open top of the service bay necessitates that personnel in the high bay are promptly evacuated before the fire has time to develop such that substantial transport of mercury out of the service bay is probable.

- If mercury is not loaded into the mercury circulation loop, then the monolith and service bay T-beams may be removed.
  - Prior to removal of service bay t-beams, approved SNS procedures shall be in place to ensure safety of personnel in the high bay during the period when the T-beams are removed, including provision for evacuation of personnel in the case of a fire inside the service bay (Section 5.3.5.3).

The core vessel presents a reduced risk of fire propagation compared with the service bay. The core vessel does not normally contain combustibles. The core vessel is normally maintained with an inert atmosphere of >98% helium. The heavy shielding surrounding the core vessel provides multiple layers of protection from a fire. Because of the reduced risk, the monolith T-beams may be removed without draining the mercury under the following limited circumstances:

- Mercury may be loaded into the mercury circulation loop with the monolith T-beams removed provided the following compensatory measures are taken:
  - Bulk shielding remains in place (does not include shutters and shutter drive units).
  - A dedicated Operations Shift Technician will be stationed to operate the mercury circulation loop and will have written instructions to drain the loop in the event of a fire.
  - Lift restrictions supporting ASE Appendix Section 7 are followed.

With the bulk shielding in place, the core vessel is well protected from an external fire. With personnel in place to quickly drain the mercury loop, the risk is minimal that the fire affects the mercury. Lift restrictions are included to help ensure compliance with the high bay floor lifting requirements.

5.2.4.4 System Evaluation

The credited fire barriers and penetrations are designed based on existing approved 2 h UL-listed or FM-approved configurations or are shown by calculation to have equivalent performance. Applicable standards include the *Standard Building Code* (SBC) [46], NFPA-801*, Standard for Fire Protection for Facilities Handling Radioactive Materials* [15] and NFPA-251, *Standard Methods of Tests of Fire Endurance of Building and Construction and Materials* [16].

As noted in Section 5.2.1, the CMS hydrogen boundary prevents leakage of hydrogen and subsequent explosions that could damage the fire barrier walls. Construction and design requirements and maintenance of the fire barrier via the configuration control program ensures worker protection would be provided in the event of a fire. Structural analysis [13] has been performed to verify the barrier's ability to withstand the expected loading from a PC-3-level earthquake (i.e., the PC-3 seismic qualification for the safety function exceeds the minimum PC-2 requirement for the mission).

5.2.4.5 Assurance of Continued Operability

The 2 h equivalent fire barrier is considered a design feature and therefore does not require ASE coverage. The configuration control program ensures that the safety features of the design are maintained. These features and their requirements have been included in Appendix A of the ASE.

Approved operations procedures address administrative controls to control the position of access doors, the position of the removable concrete shielding structures (e.g., T-Beams), and verification of their reinstallation after having been removed. This requirement minimizes the potential for the propagation of fire from the outside to the inside of the target service bay, thereby ensuring that the 2 h equivalent fire barrier can perform its safety function, including when the mercury is drained to the storage tank but residual mercury remains in the loop.

To ensure the integrity of the fire barrier is maintained, the Combustible Material Control program ensures that combustible loading inside and outside the target service bay would not support a fire that could challenge the fire barrier's integrity.

5.2.5 Target Protection System

5.2.5.1 Safety Function

The TPS prevents boiling of mercury in the target mercury vessel (i.e., ensures mercury temperature does not exceed 357°C) by shutting off or preventing proton beam if inadequate mercury loop flow or cooling is detected.

An additional credited safety function prevents beam on target when the target carriage is not fully inserted. This provides an independent layer of control to support the PPS function preventing beam on target when target carriage position switches indicate the target carriage is not fully inserted.

5.2.5.2 System Description

The three process inputs to the TPS are (1) differential pressure across the mercury pump (related to mercury flow), (2) power use by the mercury pump (also related to flow), and (3) mercury temperature at the mercury heat exchanger outlet (related to heat exchanger cooling effectiveness). The mercury differential pressure signal cuts off the beam on low mercury loop flow, the heat exchanger exit temperature signal cuts off the beam on high mercury temperature, and the pump power trip cuts off the beam when power to the pump is excessively high or low, which indicates a severe abnormal condition likely to result in low mercury flow.

The TPS also includes a manual cutoff in the CCR, TCR, and target service gallery. The manual cutoffs are not credited in the safety analysis.

The TPS is an analog system with two-channel architecture. Each channel monitors redundant process signals as shown in Figure 5.1.

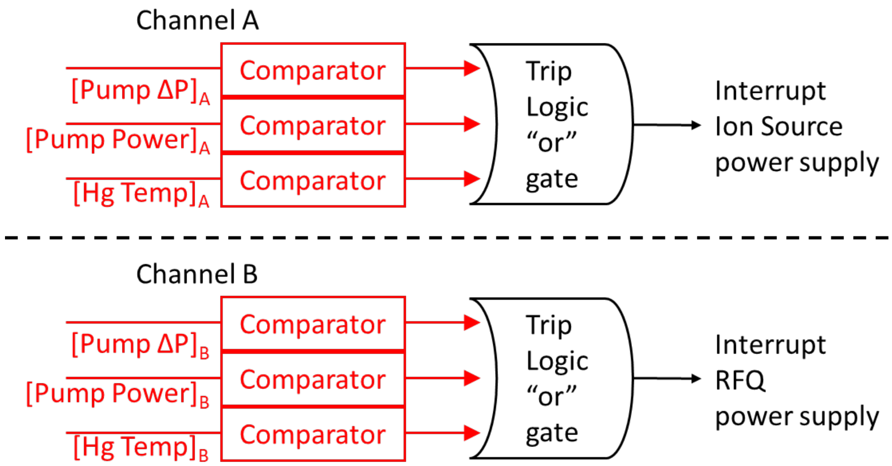


Figure 5.1. TPS two-channel 1-out-of-2 architecture.

A beam trip signal is generated when either of the two redundant channels receives an out-of-bounds input signal. The trip devices are permissive based, which means they must remain powered to permit continued operation. This feature and others provide the TPS fail-safe design concept.

The TPS actuates a proton beam cutoff in the front-end area of the accelerator by two redundant, independent, and diverse channels:

Channel A: Interrupts the −65 kV extraction power supply to the ion injector (located in the front end building)

Channel B: Interrupts the 2,100 V ac power input to the radio frequency quadrupole power supply (located in the klystron building adjacent to the front-end building)

Success by either channel shuts down the proton beam [18]. Using these two diverse cutoff mechanisms helps ensure reliability.

A mode-select feature for the TPS allows operations personnel in the CCR to select the bypass mode when it is desired to perform accelerator tuning with proton beam upstream of the target when the target is not ready to receive beam (e.g., no mercury flow, when the mercury has been drained, and when the target carriage is withdrawn). Although referred to as a bypass mode, the TPS is active and continues to provide automatic protection for the target. While in the bypass mode, the TPS does not trip the beam based on mercury process loop parameters. However, the TPS actively ensures that the proton beam is not directed to the target by monitoring the contactors that provide power to direct the proton beam to the target. Closing the ac power or dc power disconnects to the monitored bending magnet (RTBT.DH13) automatically transitions the TPS out of bypass mode (i.e., into beam-on-target mode). It will then automatically trip the beam based on the TPS mercury process input variables. This operating bypass is implemented by monitoring the power supplies to RTBT.DH13 (the 15° bending magnet between the ring and the ring extraction dump). RTBT.DH13 directs the proton beam either to the target or to the ring extraction dump. When this magnet is de-energized, the proton beam is extracted from the ring and directed to the extraction dump. When the disconnects are closed and the magnet is energized, the beam is directed to the target. Each TPS channel monitors the position of redundant power disconnects. Channel A monitors the position of the disconnect in the ac power to the 15° magnet power supply, and Channel B monitors the position of the disconnect in the dc output of 15° bending magnet power supply. This monitoring function accomplishes the additional safety function of preventing beam on target when the target carriage is withdrawn because the mercury process parameters cannot be satisfied if the target cart is withdrawn, resulting in an immediate proton beam trip if RTBT.DH13 is energized while the target cart is withdrawn.

The bypass mode is actuated manually from the CCR after both disconnects are opened. The opened disconnects actuate permissive contacts that allow an operator to close the momentary bypass-enable key switches in each channel. The independent TPS channels go into bypass mode separately. For a TPS channel to go into bypass mode, its channel-disconnect permissive must indicate that the bending magnet power is off, and the bypass-enable key switch for that channel must be manually actuated. Closing either the ac or dc power disconnects to the bending magnet or opening either channel's bypass-disable key switch automatically removes the trip bypass for the selected channel. That is, if any one of four conditions—a permissive for either disconnect or a bypass-disable switch in either channel—is not satisfied, then one TPS channel would change from bypass mode to normal/target mode and result in a proton beam trip if any of the trip parameters were in violation. The disconnect-permissive contacts are fail-safes because, on loss of power, they change the TPS from bypass mode to normal/target mode.

The TPS electronic circuits incorporate fail-safe features designed to ensure that a beam cutoff would occur in the event of damage to a circuit or other anomaly in the circuit. For example, if a lead were disconnected or severed, or if a short circuit occurred in one channel, then a proton beam cutoff would be initiated by that channel. Because the architecture is 1-out-of-2, a trip condition in either channel cuts off the proton beam.

The TPS mercury high-temperature cutoff circuit employs redundant resistance temperature detectors mounted in wells that protrude into the mercury pipe between the heat exchanger outlet and pump tank inlet. The mercury differential pressure cutoff circuit employs differential pressure transmitters with connections to the pump suction (i.e., mercury pump tank) and discharge piping.

The TPS includes status indicators in the TCR and CCR that indicate the status of each TPS channel. These indicators inform the operators whenever the TPS has actuated. The manual cutoff provides a means for shutdown but is not a required action for any accident. In addition, electronic, electro-optical, and mechanical relay isolation devices are used to connect the TPS to EPICS. The isolation devices prevent a malfunction in the non-safety system from propagating into the TPS. The outputs of the isolation devices connected to EPICS are not part of any credited engineered control. They are used for MPS beam trips and to provide alarm and data archive information using EPICS. The EPICS alarms do not provide a required safety function.

The TPS actuators that trip the proton beam are in the front-end building and the klystron gallery. The trip bypass equipment is in the RTBT service building. The bypass-enable and bypass-disable key switches are in the CCR. The operator indicators and manual shutdown switches are on panels located in the CCR and TCR, and the TPS process modules for Channel A are in the TCR and for Channel B in the service gallery. The inherent characteristics of the accelerator are such that the proton beam cannot continue to operate following a seismic event of greater than PC-1 severity or in the event of a serious fire. The permissive-based trip logic is designed to trip the proton beam on an out-of-range signal, which would include loss of signal, open circuit, short, or off-normal signal, ensuring beam trip in the event of damage to the TPS owing to natural phenomena or internal event such as fire.

Surge protection is provided at strategic points to help guard against lightning surges.

5.2.5.3 Functional Requirements

The TPS shall monitor differential pressure across the mercury pump and initiate a proton beam trip if differential pressure is below the minimum setpoint or above the maximum setpoint. Setpoints are chosen to indicate low mercury flow.

The TPS shall monitor the mercury outlet temperature of the mercury heat exchanger and initiate a proton beam trip if the temperature is above the maximum setpoint. The setpoint is chosen to indicate a loss of mercury heat exchanger cooling.

The TPS shall monitor the electrical power supplied to the mercury pump and initiate a proton beam trip if the supplied electrical power is below the minimum setpoint or above the maximum setpoint. Setpoints are chosen to indicate low mercury flow caused by malfunctions of the mercury pump or mercury process loop conditions.

The TPS shall detect conditions of low loop mercury flow, low mercury circulation pump power, or high mercury temperature and cut off the proton beam before mercury overheating occurs.

Because the TPS is credited to prevent boiling of mercury in the target mercury vessel, limited beam operations are permissible with the TPS inoperable if the delivered beam power is limited. An evaluation was performed to determine a bounding lower limit for the amount of delivered beam that has the potential to boil mercury under conservative conditions, such as no flow, and neglecting heat loss to the surroundings [48]. The TPS is also credited to prevent beam on target when the target cart is retracted.

- The TPS shall be operable whenever beam in excess of 5.6 kWh in any 24 hour period is directed onto target or when the target cart is retracted.

The TPS is designed with the intent that all redundant input signals shown in Figure 5.1 are functional. However, the TPS may still be considered operational in instances when one or more of the redundant inputs is out of service, provided appropriate written and approved compensatory measures (e.g., limit on time out of service, increase in testing and monitoring intervals, etc.) are taken to ensure reliability of both the temperature- and flow-related trip functions are maintained at design levels.

Compensatory Measures

The TPS serves as a second layer of defense to prevent beam transport to the target facility if the target cart is not fully inserted and ready to receive beam. However, it may be necessary to take the TPS out of service during a beam outage to perform maintenance or upgrades, contemporaneous with target replacement operations. In this case, the radiation safety hold process provides a reliable means for controlling critical devices to ensure beam transport to the target facility is precluded.

- If the TPS is not operable while the target cart is not fully inserted, beam on target shall be prohibited and controlled in accordance with the appropriate lock out of critical devices.

5.2.5.4 System Evaluation

The TPS, both by its design configuration and its procurement and fabrication, provides a high-integrity, high-reliability beam cutoff function, consistent with its designation.

The TPS was designed to applicable requirements for safety systems as specified in DOE Order 420.1 [19]. The TPS design also follows the *Implementation Guide for Non-Nuclear Safety Design Criteria and Explosives Safety Criteria* [20]. The primary standards used as guidance as applicable to design and to operate the TPS are provided by the applicable portions of the Instrument Society of America (ISA) ANSI/ISA-84.00.01, *Functional Safety: Safety Instrumented Systems for the Process Industry Sectors* [21]. The TPS dual-channel design with independent and diverse methods of proton beam cutoff was originally designed to meet the single-failure criterion as provided in Institute of Electrical and Electronics Engineers, Inc. (IEEE) 379, *Application of the Single Failure Criterion to Nuclear Power Generating Station Class 1E Systems* [22]. These design features and the permissive-based design (both channels must remain energized for the TPS not to trip) allow the TPS to provide protection even if any credible single failure is assumed.

Because the TPS does not directly evaluate the condition of concern (i.e., mercury boiling inside the target module), engineering analysis is necessary to provide a robust correlation to the parameters being measured. This analysis accounts for the characteristics of the system and establishes a conservative envelope of the operational parameters to provide a high degree of certainty that the condition of concern will be prevented. This analysis includes evaluation of the specific instruments in use to account for instrument error and drift as well as transient effects. The setpoint analysis for mercury temperature, circulation pump power, and circulation pump pressure difference ensures the setpoints selected provide an adequate amount of overlap to cover the full spectrum of credible partial or complete loss-of-mercury flow or loss-of-mercury-cooling events.

The channel separation and fail-safe features designed into the TPS ensure that, in the event of a fire or seismic event, a cutoff would still actuate despite significant damage to TPS circuits. Unless both channels remain energized, the TPS will initiate a trip of the proton beam. The fail-safe characteristics mean that the TPS trip would automatically result in a beam trip if the voltage of a TPS signal cable for either channel is outside the design range. This feature ensures a beam trip for a wide variety of failure modes, from simple loss of power to shorts and open circuits. The fail-safe feature is designed to function for all credible accidents.

The TPS does not need to be seismically qualified beyond the PC-1 level because the accelerator is sensitive to ground motion and cannot continue making beam after a noticeable earthquake. Three categories of seismic effects on beam continuity are relevant: (1) the effects of seismic acceleration on superconducting cavity resonance, (2) the effect of ground motion on beam control in the linac, and (3) the effects of serious earthquake on infrastructure essential for accelerator beam production. Superconducting cavity resonance is the most sensitive of the three phenomena. Based on actual experience with the Continuous Electron Beam Accelerator Facility superconducting cavities, extension of that experience to the comparably sensitive SNS, and measurements on the SNS cavities [24, 25], an observable ground tremor would cause immediate beam termination, and operating during a damaging earthquake would be beyond credible. The most likely mode of beam shutdown would be by one or more of the many automatic self-protective cutoffs built into the SNS beam acceleration and control devices. Failing all automatic cutoffs, the very concentrated SNS linac beam would burn through the beam tube in the high-energy beam transport section that connects the linac and the ring, causing beam cessation because of loss of vacuum inside the beam tube. Ground motions less severe than the TPS design basis PC-1 ground motion are shown to result in beam cutoff because beam-control elements would not be able to prevent the beam from striking the beam tube and would cut off the beam by the mechanisms mentioned above. A severe earthquake with accelerations and ground motion in the PC-2 or PC-3 range would likely interrupt infrastructure services upon which the many beam acceleration and control devices depend, including electric power (a total of about 30 MW is required to operate the accelerator at full power), vacuum, and cooling utilities. The net effect of the three categories of seismic effects is that the accelerator would not be able to make beam during or after a PC-2 or PC-3 earthquake.

Design measures have been taken to ensure that the location of parts of the TPS outside the boundary of the target facility does not reduce system reliability. For example, the design features locking cabinets for the TPS cabinets at the accelerator front area to ensure control of physical access to the TPS control elements. The fail-safe design philosophy employed in TPS design helps to ensure that credible failure modes would result in a safe state, with the proton beam tripped. Operations and/or maintenance procedures are structured to ensure that any changes that could affect the TPS are reviewed and approved through the configuration control program.

5.2.5.5 Assurance of Continued Operability

Annual certification in accordance with approved SNS procedures ensures continued operability of the TPS.

5.2.6 Fire Suppression System Inside the Service Bay

5.2.6.1 Safety Function

The FSS inside the service bay shall detect and suppress a fire in the service bay.

5.2.6.2 System Description

The FSS inside the service bay is a water-based suppression system that is also referred to as the mist system. It uses a mist-type water spray that absorbs heat, displaces oxygen, and blocks radiant heat to control, suppress, or extinguish fires and is compliant with NFPA Standard 750, *Standard on Water Mist Fire Protection Systems* [20]. VESDA smoke detectors signal for automatic initiation of mist production.

The water mist system is required to be designed, installed, and tested in accordance with Section 15300 of the *Fire Suppression Master Specification* and with NFPA 750 [25]. The system is divided into two zones of operation. Suppression zone 1 covers the process and maintenance bays. Suppression zone 2 covers the transfer bay. Although suppression zone 2 provides coverage for the transfer bay, it is not a credited safety function. Actuation of the mist system is a life safety concern because the fog-like mist affects visibility and because the nitrogen driver gas displaces oxygen. Therefore, suppression zone 2 mist injection is intentionally disabled when workers are present in the transfer bay.

A cross-zoned smoke detection system is provided for each suppression zone. The system consists of two VESDA air-sampling detectors that provide redundant early detection and warning of a fire situation. An FM-approved releasing panel monitors the VESDA detectors, actuates the water mist system when both detectors indicate a fire is present, and provides outputs to the building fire alarm control panel. Automatic selector valves electrically open on receipt of a signal from the releasing panel and direct water to the appropriate suppression zone. The VESDA detectors and releasing panel have battery backup power supplies that allow full functioning of the system for 8 h upon loss of primary power. The mist system is a single-fluid, high-pressure design. The system uses a gas-driven pump unit to develop system pressure. The duration of water mist discharge is in accordance with NFPA-750.

5.2.6.3 Functional Requirements

The mist system shall:

1. Be designed, installed, operated, and maintained to meet NFPA-750 [20], including having a water supply and atomizing media adequate to suppress the design-basis fire as identified in the target building FHA [17].

2. Continue to be operable after a loss of building or site power for a period of 8 h.

Operability

The FSS inside the service bay must be operable whenever the mercury loop configuration is vulnerable to a fire inside the service bay. Draining the mercury from the loop places the mercury in a configuration that is protected from any credible fire in the service bay, so the FSS inside the service bay is not required to be operable while the mercury is drained. Analysis has also shown that the steel shielding that normally surrounds the mercury loop during operations is thick enough to prevent any significant effect on the mercury loop.

- The FSS in the process and maintenance bay portions of the service bay shall be operable unless:
  - The process mercury is drained to the storage tank, or
  - The steel shielding designed to cover the mercury loop is fully installed.

Compensatory Measures

ORNL institutional processes provide a robust program for management of the FSS for inspection, testing, and maintenance based upon industry standards and best practices. Additionally, provision is made to account for the hazard inherent in actuating the FSS system. For personnel, the FSS is designed to reduce oxygen concentration in the protected space for the purpose of suppressing the fire. The water discharged also has the potential to damage equipment and spread contamination. Thus, provision is made to allow ORNL processes to manage system outages for either routine inspection, testing, and maintenance or to reduce the possibility of personnel injury or operational impacts due to system discharge.

- Planned impairments associated with scheduled inspection, testing, and maintenance activities are performed in accordance with ORNL Fire Department instructions.
- Temporary impairment and bypasses of the system are allowed by approved SNS procedures for instances including but not limited to:
  - When personnel enter the service bay,
  - When activities are being conducted that have a high probability of actuating a false alarm (e.g., welding, cutting).

5.2.6.4 System Evaluation

An NFPA-750-compliant [25] system design and construction ensure the system can fulfill its safety function. Inspection, testing, and monitoring of the system, per NFPA-750, ensures the availability and reliability of the mist system, thereby reducing the frequency of an unchecked fire in the service bay.

If the mist system were to actuate in the process bay during or after a mercury spill, then water could contact spilled mercury on the floor while draining or in the collection basin (where all floor drainage in the process bay is routed). This situation would not affect the mist system's fire-suppression function.

Furthermore, the cooling effect and mercury coverage (water is lighter than mercury) of the mist system water would decrease the temperature and vapor pressure of the mercury to ensure the net effect would be within the bounds of the source terms analyzed in Section 4.

The mist system may be ineffective against fires inside the collection basin. However, the basin is protected against intrusion of solid combustibles by its design and is protected against excessive combustible fluid intrusion by the Combustible Material Control program. A fraction of water discharged from the mist system would drain to the collection basin, potentially having a mitigative effect.

5.2.6.5 Assurance of Continued Operability

Operability and testing considerations are handled through existing NFPA standards and SBMS requirements to ensure operability of the mist and smoke detection systems. The controls ensure the system is inspected, tested, and maintained to meet the requirements of NFPA-750. ASE coverage provides consistency with other SNS active CECs.

This system must be operable at any time that the mercury is not drained to the storage tank or when the mercury loop steel shielding is not fully installed (steel shielding is normally in place) unless appropriate compensatory actions are implemented.

To ensure operability, the service bay water mist fire protection system must be inspected, tested, and maintained per NFPA Standard 750 [25].

The Combustible Material Control program controls amounts, types, and configurations of combustible materials in the service bay.

5.2.7 Fire Suppression System Outside the Service Bay

5.2.7.1 Safety Function

The FSS outside the service bay shall automatically initiate sprinkler flow to control a fire that develops in areas directly adjacent to the service bay and in the high bay, instrument hall, or target building basement area and to prevent challenges to the structural integrity of the target building.

5.2.7.2 System Description

The FSS outside the service bay is provided to control a fire that initiates outside of the service bay. The FSS outside the service bay is a wet-pipe sprinkler system designed and installed in accordance with NFPA Standard 13 [26], *Standard for the Installation of Sprinkler Systems*.

Sprinklers are provided at the ceiling level in the target building basement area, instrument hall, high bay area, service gallery, decontamination room, and manipulator gallery. The detection needed for automatic initiation is a local function provided by the design of the NFPA-compliant sprinkler heads, which react to the thermal effects of the fire to initiate local sprinkler flow.

The wet-pipe sprinkler system outside the service bay is fed from a combined water service distribution loop supplied by a 300,000 gal elevated gravity tank. Approximately 170,000 gal in the elevated gravity tank are reserved for fire suppression. 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 of NFPA 24 [27]. The elevated gravity tank is designed to meet the general requirements of NFPA 22 [28].

5.2.7.3 Functional Requirements

The FSS outside the service bay shall be designed, sized, actuated, and supplied with a sufficient quantity and flow rate of water capable of controlling a fire that may develop outside the service bay based on the anticipated combustible loading and occupancy classifications of the areas as defined in the FHA [17]. Successful fire control shall protect the credited fire barrier (Section 5.2.4) and prevent challenges to the structural integrity of the building.

Operability

The FSS outside the service bay is installed and operated in accordance with ORNL fire protection requirements as promulgated by SBMS. These requirements are supported by decades of experience and represent best practices that have been demonstrated to ensure fire suppression system readiness. Given the degree of rigor already incorporated into these processes to support life safety, they have been directly adopted to govern the processes used to determine when the FSS should be taken out of service.

- The FSS outside the service bay shall be operable as required by the ORNL SBMS Fire Protection, Prevention, and Control subject area and approved SNS procedures.

Compensatory Measures

Maintenance and testing requirements for fire suppression systems are established by NFPA consensus codes and implemented at ORNL via the SBMS. These requirements are supported by decades of experience and represent best practices that have been demonstrated to ensure fire suppression system readiness. Given the degree of rigor already incorporated into these processes to support life safety, they have been directly adopted to provide assurance of FSS operability for accelerator safety purposes, including policy and processes for temporary impairments and requisite compensatory measures during impairments.

- Planned impairments associated with scheduled inspection, testing, and maintenance activities are performed in accordance with ORNL Fire Department instructions.
- Temporary impairment of the FSS outside the service bay is allowed when interim compensatory measures are conducted in accordance with approved SNS procedures.

5.2.7.4 System Evaluation

A system designed and constructed in accordance with NFPA 13 [26] ensures that the system has the rated capacity, sufficient water supply, and appropriate sprinkler spatial layout to fulfill its safety function. Inspection, testing, and maintenance of the system in accordance with the ORNL Work Smart Standards ensure the availability and reliability of the sprinkler system, thereby reducing the frequency of an unchecked fire outside the service bay. Design and construction of the elevated gravity-flow water tank and the main water distribution loop in accordance with NFPA-24 [27] and NFPA-22 [28] ensure the mechanical attributes and reliability of the water supply system are sufficient to supply the necessary water capacity to the wet-pipe sprinkler systems. Locking and monitoring of the status of control valves ensure the water path to the sprinkler system is open. These features, combined with valve and component labeling per NFPA-13, reduce the frequency of improper isolation valve positioning owing to human error.

5.2.7.5 Assurance of Continued Operability

The operability and surveillance of building sprinkler systems are covered under the established ORNL SBMS Fire Protection, Prevention, and Control program.

The following surveillance requirement ensures operability:

- Inspection, testing, and maintenance in accordance with the ORNL SBMS Fire Protection, Prevention and Control subject area.

The Combustible Material Control program (Section 5.3.3) ensures that the amounts and configurations of combustible materials in the target building outside the target service bay are within the capability of the wet-pipe sprinkler system outside the target service bay.

5.2.8 Confinement Function of Core Vessel and Neutron Beam Windows

5.2.8.1 Safety Function

The core vessel and neutron beam windows shall (1) retain liquid mercury in a confined location and (2) mitigate mercury vapor release inside the building in the event of a mercury spill inside the core vessel. The rupture disk ensures that the core vessel will relieve excess pressure.

5.2.8.2 System Description

The core vessel mitigates the potential release from a mercury spill into its interior by confining the spilled mercury to a relatively small space at the bottom of the vessel, thereby limiting the surface area for evaporation of the mercury, mitigating the mercury spill events analyzed in Section 4. A drain line allows any liquid accumulation in the core vessel to drain to a standpipe in the service bay, which is normally closed with a blind flange to ensure closure and contamination control as described in Section 3.

The core vessel contains the target, neutron reflectors, neutron moderators, and passively and actively cooled shielding elements. The stainless steel 316 vessel is designed and fabricated to meet the intent of ASME, B&PV Code, Section VIII [7] requirements with all welded connections.

The lower core vessel has 20 ports: 18 neutron beam ports, a proton beam port, and a target port. The neutron and proton beam ports do not include a leakage path for escape of liquid mercury because the volume of liquid mercury that could be pumped or drained into the core vessel would not raise the level of mercury to the level of the window. However, spilled activated cooling water that would be on top of the liquid mercury could reach the level of the windows.

The neutron beam windows that are part of the vessel inserts provide the pressure boundary at the neutron beam ports. The vessel inserts are sealed to the vessel port using a vacuum gasket made using two metal O-rings. Studs in the core vessel flanges and remotely installed nuts secure the core vessel inserts to the vessel flanges and provide the necessary sealing force.

The proton beam window and the target plug assembly are sealed to the vessel using inert-gas-inflatable seals. The inflatable seal relies on a pressurized stainless-steel bellows to maintain contact with the vessel-sealing surface. Leakage of the target module seals could allow gases or vapors in the core vessel to leak to the unoccupied service bay. Leakage around the proton beam window seals could release core vessel gases or vapors into the unoccupied target shielding monolith area.

A pressure relief rupture disk is provided for the core vessel to establish a relief-protected maximum internal pressure that protects the pressure boundary and does not cause failure of the inflatable seals.

5.2.8.3 Functional Requirements

The core vessel shall perform the following functions:

- Provide a free volume at the bottom of the core vessel of at least 183 gal,
- Provide overpressure relief by a rupture disk (nominal actuation pressure 7 psig),
- All parts of the pressure boundary shall be able to withstand an atmosphere contaminated with mercury vapor for at least 8 h.

Operability

The core vessel and neutron beam windows must be capable and available to retain and confine spilled mercury whenever a target module could leak. Although most of the boundary can be managed using configuration control processes, the core vessel rupture disk and vent path merit additional measures to ensure operability.

- The core vessel rupture disk and vent path are required to be operable when mercury is in the mercury circulation loop. If the core vessel rupture disk is not intact, then the mercury shall be drained from the mercury circulation loop.

5.2.8.4 System Evaluation

The designed-in ruggedness provided to meet the intent of ASME B&PV Section VIII [7] design and fabrication ensures that the core vessel can perform its safety function. The core vessel inserts and inner windows are designed and fabricated to applicable ASME B&PV Section VIII [7] requirements. The attached drain line meets ASME B31.3 [5].

The core vessel and attached drain line are made of stainless steel that is not sensitive to mercury. The neutron beam windows are aluminum, which can be corroded by mercury. However, tests at ORNL [30] have shown that the corrosion caused by mercury vapor exposure is slow enough to support the minimum 8 h safety function for the neutron beam windows in a mercury spill event. Because liquid mercury drains by gravity to the bottom of the vessel, the windows are not in a liquid mercury environment during a mercury spill event.

The core vessel rupture disk is sized to prevent failure of the neutron beam windows or core vessel boundary in the event of hypothetical hydrogen release caused by multiple CMS boundary failures inside the core vessel. This rupture disk provides a greater relief capacity than required for the mercury spillage/leakage events for which vapor/gas retention is required because these events do not involve coincident failure of the CMS. The 7 psig relief pressure is set to ensure optimum performance of the gas-pressurized seals and is more than adequate to protect the core vessel and neutron beam windows.

A failure of the proton beam window would not constitute a failure of the safety function because vapor would only be released into the interior of the proton beam tube within the unoccupied beam tunnel. Therefore, the proton beam window is not included in the definition of the core vessel safety functions.

The core vessel drain line is functionally an extension of the core vessel with respect to mercury retention. Its termination in the service bay is a standpipe configuration with a normally closed top that is above the level that mercury could fill the core vessel to in the event of a leak. This configuration prevents the uncontrolled overflow of the drain line and allows a portable pump to be used to pump out any spilled material in a controlled manner.

5.2.8.5 Assurance of Continued Operability

The core vessel and the neutron beam windows are considered passive design features and, therefore, do not require ASE controls. The configuration control program ensures that design features are maintained and able to perform their safety functions. These features and their requirements have been included in Appendix A of the ASE.

Operations envelope coverage ensures operability of the rupture discs by requiring periodic inspections for deformation or other visual damage and replacement whenever the CMS pressure at the inlet to a rupture disk rises to the rupture disk deformation pressure, whenever the rupture disk safety head is disassembled, or at least once every 5 years. Furthermore, the relief path requires periodic surveillance to ensure the rupture disk discharge path remains open downstream of the rupture disk. The integrity and configuration of the vent paths from the rupture disks to atmosphere shall be visually verified at least annually (not to exceed 15 months). This check should include the piping and exhaust cover.

5.2.9 Service Bay and Monolith Confinement of Mercury

5.2.9.1 Safety Function

To provide confinement of liquid mercury and mitigate the airborne mercury release by retaining the liquid mercury in a confined location in the target service bay or monolith.

5.2.9.2 System Description

Mercury containing components of the mercury process system are located in areas of robust construction inside the service bay and monolith. Robust construction includes the concrete floors and walls surrounding mercury-containing components in the service bay and the concrete and steel structures that surround the monolith.

The service bay is continuously lined on the mercury side with stainless steel supported from the structure to collect and channel mercury. The stainless steel has smooth welded seams and is designed to minimize pockets and avoid trapping excessive mercury. The liner in the service bay process bay is sloped to direct the flow of mercury to the collection basin located below the service bay floor level. A single cylindrical silo (sunk into the concrete) contains an enclosed storage tank mounted directly above the collection basin used for spill collection, as described in Section 3.

The interface between the service bay and monolith occurs at the core vessel (Figure 5.2). The service bay stainless-steel liner extends into the tunnel in the monolith through which the target plug travels periodically and is welded to the core vessel. The target plug seals to a flange face inside the liner/vessel weld line. Therefore, if the target loop leaks mercury outside the core vessel, including the target tunnel region, then the leakage is routed to the service bay collection basin by the system of sloping floors because the target tunnel floor is sloped underneath the carriage tracks toward the process bay (i.e., eastward). The carriage tracks and cart act as a heat shield, protecting mercury spilled in the tunnel from direct radiant energy of a fire. Leakage inside the core vessel is retained inside the core vessel in the void volume provided at the bottom of the vessel. If subsequent leakage were to occur from the void volume, then it would drain through the bulk shielding (steel blocks) into the bulk shielding drain line and would be collected in the closed, stainless-steel-lined chamber in the monolith support pedestal.

The mercury loop is surrounded by steel radiation shielding (minimum thickness of approximately 2 in.) that is in place normally and removed very infrequently. The steel shielding not only controls radiation levels inside the service bay but also minimizes the range of a spraying leak from the mercury loop. It also helps minimize mercury vaporization in the event of a fire near the mercury loop. This function is credited with mitigating off-site release of mercury vapor in the event of a PC-2 earthquake followed by service bay fire.

5.2.9.3 Functional Requirements

Service Bay

All areas of the service bay that could contact and collect leaked liquid mercury shall be lined with stainless steel.

The stainless-steel liner shall have smooth welded seams and shall be adequately configured and sloped to promote spilled mercury travel to the collection basin.

The collection basin shall be a double-walled stainless-steel vessel open at the top and placed directly under the mercury storage tank in a subfloor silo configuration described as the collection basin and storage tank silo.

The service bay liner and collection basin shall be qualified to perform the safety function after a PC-2 seismic event.

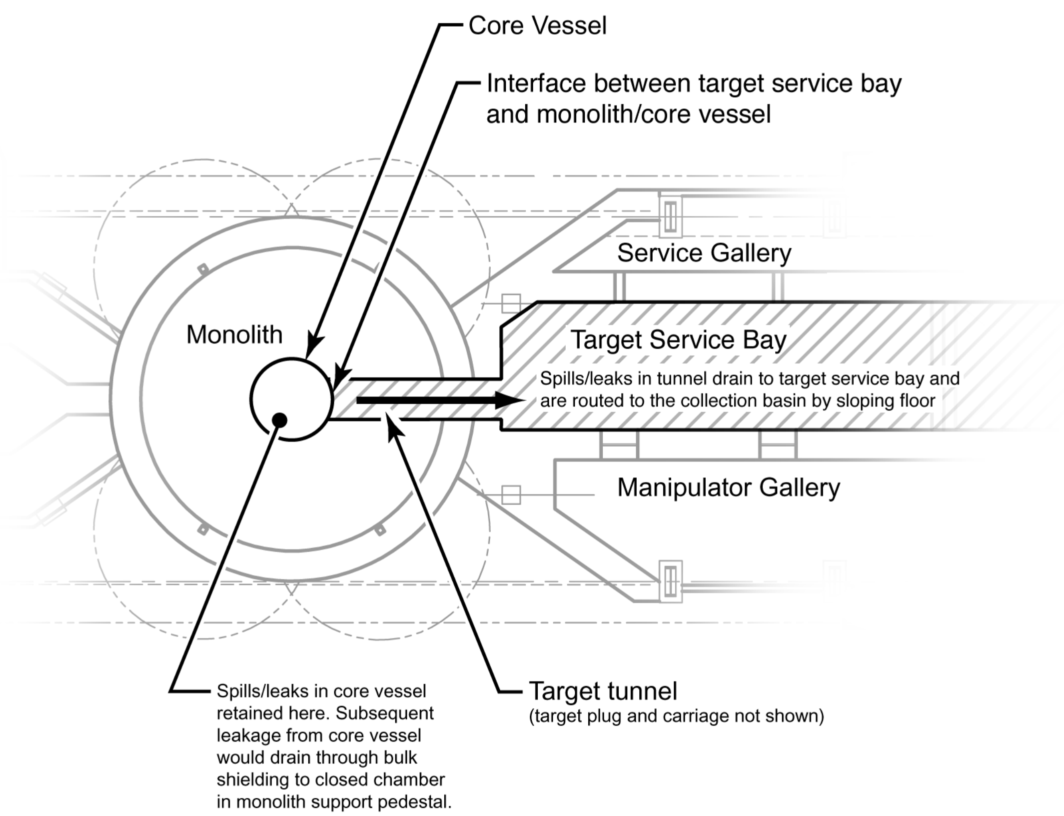


Figure 5.2. Interface between monolith, core vessel, and service bay.

Monolith

The drainage volume inside the monolith support pedestal shall (1) be stainless-steel lined, (2) have volume sufficient to hold all the volume of mercury that could leak from the core vessel, and (3) be qualified to PC-3 seismic level or higher.

5.2.9.4 System Evaluation

Service Bay

This feature reduces the potential release of mercury vapor by minimizing the surface area of the spilled mercury. Passive, robust features (e.g., the sloping floor) ensure this function is highly reliable. Experiments performed in 1999 [31] show that mercury flows freely on stainless steel at angles as small as 0.5°. The service bay liner slope in the process bay is greater than 0.5°. The nominal design requirement is for a 1.0° slope.

The locations of penetrations are such that even if passage to the collection basin were blocked, spilled mercury would not escape from the service bay.

The service bay liner and mercury loop shielding are designed to withstand PC-2 seismic accelerations. The collection basin is qualified to PC-3 because it provides part of the fire barrier function.

Monolith

The configuration of the bulk shielding is such that leakage of mercury into the bulk shielding would flow by gravity to the steel liner of the support pedestal and from there through the liner drainpipe into the closed chamber in the support pedestal. The support pedestal, chamber liner, and access hatch are designed to withstand PC-3 accelerations because they perform part of the fire barrier isolation function.

5.2.9.5 Assurance of Continued Operability

The safety features of the target service bay and monolith are considered a design feature and therefore do not require ASE coverage. The configuration control program ensures that the design features important to safety are maintained and able to perform their safety functions. These features and their requirements have been included in Appendix A of the ASE.

5.2.10 Primary Confinement Exhaust System

5.2.10.1 Safety Function

The PCE system ductwork protects workers inside the target building from exposure to mercury vapor by preventing leakage of confinement exhaust from the service bay into occupied areas. Design features of the PCE system also support the service bay and core vessel 2 h equivalent fire barrier by preventing transmission of hot gases into or out of the service bay via the PCE system intake ducting.

5.2.10.2 System Description

The PCE system routes service bay exhaust via stainless-steel ductwork to exhaust filtration stages that reduce airborne mercury vapor released to the exhaust stack. Operation of the PCE system blowers draws a sufficiently negative pressure on the service bay to ensure in-leakage to the service bay with all exhaust passing through the filtration stage. The mercury removal medium is commercially available sulfur-impregnated activated charcoal manufactured for removal of mercury from gaseous mixtures. The removal of mercury function of the charcoal adsorbers is considered a non-credited function of the PCE system. The core vessel vacuum pumps also exhaust through the sulfur-impregnated charcoal adsorbers, ensuring filtration of any mercury vapor leaked into the core vessel.

The atmosphere in target service bay is normally maintained at a negative pressure relative to adjacent areas and is monitored and alarmed by the target service bay differential pressure monitoring system (Section 5.2.14). A HEPA filtration stage is located directly downstream from the charcoal adsorbers; however, the HEPA filters are not credited in the accident or hazard analysis. Although the exhaust stack that serves the PCE system would elevate any release, the likely reduction in consequence because of the stack elevation feature is also not credited.

The PCE system includes several sections of ducting that provide both inlet and exhaust flow to areas of the target building. However, only a subset of this ducting is included in the credited scope of the system. The credited ducting is the exhaust portion of the PCE system that extends from the PCE system exhaust duct connection to the target service bay up to the exhaust side of the charcoal adsorbers. Specification TS0883R06, Section 15895, *Stainless Steel High Pressure Ductwork and Accessories (Certified Materials)* [33], describes the PCE system ductwork as stainless steel-piping with welded seams and joints for systems operating up to 5,000 fpm and 0 to −60 in. of water gauge static pressure. A minimal amount of sheet metal transition is necessary to connect the exhaust piping to the backdraft dampers installed in the system. The backdraft dampers are installed in the PCE system inlet. The PCE system inlet portion extends between the inlet to the upstream backdraft damper to the inlet line connection to the service bay. The backdraft dampers are parallel-blade counterbalanced dampers that are leak tested by the manufacturer per ASME N 510, *Testing of Nuclear Air Treatment Systems* [34].

Although not credited, HEPA filtration is also provided on the intake side of the PCE system. HEPA filters are provided to remove particulate matter that could enter the service bay and become contaminated in the service bay. Non-credited HEPA filtration is also provided on the target service bay exhaust inlets as a good practice to minimize transport of radioactive particulates into the PCE system ductwork.

Fire in the charcoal adsorber units is very unlikely because of the design of the units as well as the lack of heat sources or chemical vapors in the service bay off-gas stream. Nevertheless, a non-credited heat detector is provided at the outlet of each of the eight units. Each detector interfaces with the fire alarm system and will provide early warning of a charcoal adsorber fire, allowing the fire department to isolate an affected unit and add water as needed.

5.2.10.3 Functional Requirements

The PCE system is required to operate during and after mercury spill events and to provide confinement protection during certain fire events. The credited function of the system is the passive design of the associated ductwork, not the active motive force of the ventilation system or the filtration functions. The following functional requirements are established:

- PCE system ductwork provides confinement and direction of service bay atmosphere exhaust to sulfur-impregnated charcoal mercury vapor removal filters.
- Supply-side air intake location (close to floor) minimizes intake of hot air in the event of fire outside service bay.
- Supply-side backdraft dampers minimize the potential for reversal of airflow from the service bay in the event of a service bay fire or loss of normal negative pressure.

- The use of fire retardant filter medium in the filter housings discourages transmission of fire from the service bay to the charcoal adsorbers.

The PCE system is not required to operate during or after a seismic event. Because the PCE system acts in conjunction with other features to provide defense-in-depth and because a power outage does not lead to significant mercury release, it is not required to have a safety-related backup power supply.

Operability

Backdraft dampers in the inlet ducting of the PCE system may be periodically disabled or removed for maintenance or repair. Because this component of the PCE system is credited to prevent exposure of personnel inside the target building to vaporized mercury resulting from a fire in the service bay, they may be taken out of service when the mercury is drained from the loop, eliminating the risk of vaporizing the major source of mercury inside the service bay.

- The backdraft dampers shall be operable when mercury is loaded in the mercury circulation loop.

Compensatory Measures

The PCE system ducting that connects the service bay atmosphere to the PCE system charcoal adsorbers ensures that mercury vapor from the service bay is captured by the adsorbers and cannot leak into other target building areas during mercury spills in the service bay. If the credited portion of the PCE system ducting will be opened, then appropriate provision shall be made to remove the risk of a large mercury release inside the service bay, ensure personnel exposure to residual mercury vapor is monitored and controlled, and account for the potential effects on the negative pressure inside the service bay.

- If the leak-tight integrity of the PCES ductwork is compromised:
  - The mercury shall be drained from the mercury circulation loop.
  - Personnel occupancy in the area of the compromised ducting shall be monitored and controlled in accordance with approved SNS procedures.
  - Appropriate measures shall be implemented to account for potential effects on SBDPMS.

This provision is not intended for an unexpected discovery of a breach in the PCES ducting. If a breach in the PCES ducting is discovered, then draining of the mercury loop should be avoided because this evolution has been observed to result in a release of mercury vapor and other radioactive gases into the service bay atmosphere as the storage tank vents, potentially leading to a release of hazardous gases from the PCES ducting near the breach.

5.2.10.4 System Evaluation

The PCES stainless steel ductwork is welded in compliance with ASME-N509 [32], including the supply-side service bay air intake ductwork as well as the exhaust side ductwork to the downstream side of the charcoal filtration stage. The passive confinement function of the ductwork from the service bay to the sulfur-impregnated charcoal adsorber is maintained regardless of whether the PCES fans continue to operate during an event. If the fans continue to operate, then flow would be forced into the service bay and out to the filters. If the fans stop, then the motive force would be insufficient, except during the early stages of a fire event, to move significant quantities of hazardous material out of the service bay. In such a scenario, backdraft dampers would prevent mercury-laden smoke from flowing to inhabited areas (via reversing flow in the inlet line). Two backdraft dampers in series are provided in the service bay inlet duct, but correct functioning of either of the two dampers would adequately perform the backdraft prevention safety function.

Maintaining negative pressure inside the service bay ensures the in-leakage is routed through the filtration stage. Indication of a loss-of-negative pressure would require a local evacuation followed by appropriate compensatory measures. Section 5.2.14, "Service Bay Differential Pressure Monitoring System," addresses the negative pressure detection and alarm system, and Section 5.3.5 addresses proper response to a loss-of-negative-pressure alarm.

Locating the service bay air intake close to the floor minimizes the volume of hot gas that would be drawn into the service bay in the event of a fire in the fire zone that includes the decontamination room, the service gallery, and the manipulator gallery.

5.2.10.5 Assurance of Continued Operability

The PCES ductwork between the service bay and the charcoal adsorbers is considered a design feature and therefore does not require ASE coverage. The configuration control program ensures that the design features important to safety are maintained and able to perform their safety functions. These features and their requirements have been included in Appendix A of the ASE.

Testing/inspection of the backdraft dampers are addressed in the operations envelope to ensure operability.

5.2.11 High Bay Crane Design

5.2.11.1 Safety Function

The high bay crane design prevents failures in the high bay crane that could result in a dropped load.

5.2.11.2 System Description

The high bay crane is a remote-pendant-operated 50-ton bridge crane that services the full length of the high bay and into the instrument hall over the truck loading bay. The crane is used to lift loads such as the core vessel IRP, a primary shutter within a shielding cask, and the concrete shielding beams located above the core vessel. It also lifts smaller maintenance or housekeeping parts and containers. Accordingly, it can deliver loads from the high bay area to the basement level through floor hatches in each level.

The crane is designed and analyzed in compliance with ASME NOG-1-2002, *Rules for Construction of Overhead and Gantry Cranes* [35], in accordance with the seismic requirement for a Type I crane to the extent referenced in Specification TS0025R02, Section 14631, *50-Ton NOG-1 Crane* [36]. In accordance with this specification, the crane was constructed and tested in accordance with the requirements of NUREG 0554, *Single-Failure-Proof Cranes for Nuclear Power Plants* [37].

The crane shall be operated and maintained in accordance with the ORNL SBMS Hoisting and Rigging Program.

5.2.11.3 Functional Requirements

The crane shall have design features that reduce to acceptable levels the probability of an in-service crane failure that could result in dropping a suspended load in the high bay, potentially breaching the monolith or service bay T-beams and impacting target mercury or the cryogenic moderator system.

- If the high bay crane does not meet the requirements of ASME NOG-1, then it shall not be used to lift loads over the service bay or monolith.

5.2.11.4 System Evaluation

This crane was designed to the standards of ASME NOG-1, which define~~s~~ a Type I crane as a crane that is used to handle a critical load. It has been designed and constructed so that it would remain in place and support the critical load during and after a seismic event without having to be operational after this event. Single-failure-proof features were included so that credible failure of a single component on the crane would not result in the loss of capability to stop and hold the critical load. The design criteria of Specification TS0025R02, Section 14631 [36], includes operational and impact loads specified in Crane Manufacturers Association of America Specification 70-1994 [38], as well as seismic loads specified in ASME NOG-1, Section NOG-4136. In addition, component parts subject to wear and exposure were required to be designed for 115% of the design rated load in accordance with NUREG 0554 [37].

5.2.11.5 Assurance of Continued Operability

The high bay crane design is considered a design feature and, therefore, does not require ASE coverage. Adherence to the ORNL SBMS Hoisting and Rigging Program ensures proper maintenance of the crane and ensures the crane continues to meet its functional requirements. These features and their requirements have been included in Appendix A of the ASE.

5.2.12 High Bay Floor Design

5.2.12.1 Safety Function

To prevent a dropped load from contacting the interior of the process bay or core vessel by ensuring that the high bay floor can withstand a load drop for all allowable crane lifts (i.e., the maximum load and height above floor allowed by administrative controls). The service bay and core vessel 2 h equivalent fire barrier functions, which include the high bay floor, are described in Sections 5.2.3 and 5.2.4.

5.2.12.2 System Description

The high bay floor is constructed of concrete with reinforcing steel. The parts of the high bay floor designated as a credited engineered controls are: (1) the floor directly above the process bay and (2) the removable shine shield beams above the core vessel.

Figure 3.28 shows the service bay in cross section and shows the removable roof t-beams that make up the high bay floor. Part of the floor is designed to be removable, but no use of this capability is presently planned other than the infrequent change out of large components. The concrete floor above the service bay (including the removable beams) is designed for a static loading of approximately 4,000 lb/ft^2.

Figure 3.24 shows the removable shine shield floor beams above the core vessel. The beams over the core vessel are designed for a static loading of approximately 200 lb/ft^2 and are removed whenever a major component inside the monolith is replaced.

5.2.12.3 Functional Requirements

The floor shall resist failure modes that would allow a dropped load or structural debris to fall on the mercury process system in the service bay or core vessel and cause its failure. The requirement shall be satisfied for any load drop that could occur during any lift allowable under the ORNL Hoisting and Rigging Program.

Operability

Designing the high bay floor to withstand the maximum possible load drop from the high bay crane is not practical, so the mercury circulation loop is protected by a combination of floor design, crane design and administrative control. The crane design, described in Section 5.2.11, prevents catastrophic malfunctions of the high bay crane, ensuring that crane drops are only credible from the intended lift height of a load. Administrative controls are implemented to constrain the possible range of lifts, providing a useful range of possible load drops to support design and evaluation of the high bay floor. Because the target mercury is protected from a load drop if it is drained to the storage tank, these administrative controls are not required if mercury is not loaded into the mercury circulation loop.

- Administrative limits on crane lifts in the high bay (Section 5.2.12.4) shall be in force whenever mercury is loaded into the mercury circulation loop.

Compensatory Measures

The fire barrier function of the high bay floor provides the conditions for removal of T-beams, which account for all the functions of the high bay floor. This section does not describe the method of control but does identify the additional requirement for crane lifts that pass over the core vessel.

- T-beams may be removed from the high bay floor as described in Section 5.2.4.3.

- If the monolith T-beams are removed with mercury loaded in the mercury circulation loop, then lifts that pass over the core vessel must be approved by the SNS operations manager.

5.2.12.4 System Evaluation

Shielding and cask weights dictate a robust floor design. A load-drop analysis [39] was performed to determine drop-load criteria for high bay crane lifts that travel over the service bay. Table 5.1 provides the drop load criteria for lifts over the service bay.

Table 5.1. Limits for Load Drops Over the Service Bay Ceiling

Drop height (in.)	Drop load (t)
2	30
3	25
6	20
11	15
25	10
54	7
107	5

The T-beams that cover the core vessel are thinner than the T-beams that cover the service bay and have a greater span. They only accommodate smaller 20 inch-ton load drops for load paths that approach the center of the monolith, as defined in the load-drop analysis [39]. Table 5.2 provides the drop-load criteria for lifts over the monolith shine shields.

Table 5.2. Limits for Load Drops Over the Monolith Shine Shield

Drop height (in.)	Drop load (t)
1	7.5
2	5
6	3.5
20	2
36	1

If planned load movements over the service bay or monolith exceed the applicable envelope defined in Table 5.1 and Table 5.2, then the mercury circulation loop must be drained to the storage tank before the movement occurs.

5.2.12.5 Assurance of Continued Operability

The high bay floor design is credited with providing a means of preventing a dropped load from contacting the service bay. This feature is considered a design feature and therefore does not require ASE coverage. The Configuration Control Program ensures the design feature is maintained and able to perform its safety function. These features and their requirements have been included in Appendix A of the ASE.

In general, maximum loads, lift heights, and safe lift paths above the floor are limited by administrative controls described in the ORNL Hoisting and Rigging Program. Conditions that prohibit lifts exceeding the limits shown above are specified in the operations envelope.

5.2.13 Mercury Heat Exchanger Double-Wall Design

5.2.13.1 Safety Function

The mercury heat exchanger's double-walled design prevents a release of target mercury into cooling water, possibly leading to escape from the service bay via the loop 1 cooling water system.

5.2.13.2 System Description

The mercury-to-loop 1 cooling water heat exchanger is a double-walled heat exchanger. The inner tube has a spiral braiding for centering inside of the outer tube. A simplified schematic of the heat exchanger is shown in Figure 3.15. The design includes a double tube sheet with stagnant mercury in the interstitial space pressurized to a pressure higher than either the mercury loop or the loop 1 cooling water. The inner and outer tubes are connected at both ends to independent separated tube sheets so that the process mercury and cooling water are separated by two walls at all points in the heat exchanger.

The interstitial volume between the tube sheets is filled with mercury. Approximately 20 gal of interstitial mercury is required. The interstitial mercury is essentially unirradiated, although the unirradiated mercury picks up stray neutrons and slowly becomes slightly radioactive.

The interstitial pressure and interstitial mercury level are monitored to facilitate detection of a leak in the heat exchanger tubes.

5.2.13.3 Functional Requirements

The mercury loop heat exchanger shall perform the following functions:

- Provide two barriers against escape of irradiated process mercury into the loop 1 cooling water system,
- Provide a means to detect failure of a single boundary.

The double wall design of the mercury heat exchanger is required to perform its function whenever the target mercury is in the mercury process loop. This is assured by verifying the integrity of the double wall design prior to each fill of the mercury loop.

Operability

- The double-walled barrier shall be intact when mercury is loaded in the mercury circulation loop.

5.2.13.4 System Evaluation

The heat exchanger tube and tube sheet design ensure a robust and leak-resistant design. The heat exchanger vessel was designed and fabricated in accordance with ASME Section VIII [7], and all materials used in the construction of the heat exchanger vessel are grade 304L or 316L stainless steel. All materials used in the fabrication that encompasses the internal surface of the heat exchanger vessel (mercury or water pressure boundary including nozzle piping) is corrosion-evaluated material subjected to testing per ASTM A262, *Standard Practices for Detecting Susceptibility to Intergranular Attack in Austenitic Stainless Steels.*

All welded joints in pipes and nozzles connecting to the heat exchanger were examined by radiography. The manufacturer provided a design report, including pressure vessel calculations and assembly structural design calculations. The structural analysis verifies the complete heat exchanger assembly support structure—including anchorage bolts—is designed to the allowable stresses in accordance with ANSI/AISC N690, *Specification for the Design, Fabrication, and Erection of Steel Safety-Related Structures for Nuclear Facilities* [40].

The pressure of the interstitial mercury is maintained by a trapped volume of helium. This pressure is higher than the pressures of the flowing mercury and cooling water systems and is monitored for operational purposes. Any unexpected leaks would be detected as a decrease in indicated pressure. Because of the heat exchanger's double-walled design, a loss of helium overpressure does not indicate that the heat exchanger has failed but that one wall of the heat exchanger tube may have failed. Therefore, the loss of pressure can be assumed to be a loss of interstitial mercury, and the location of the leak can be determined (i.e., into the intermediate cooling water system or into the mercury loop). Defense-in-depth against mercury leaking into the intermediate cooling water system or into the tower water system is provided by the normal operating mode in which the tower water is maintained at a higher pressure than the intermediate cooling water, which is maintained at a higher normal pressure than the normal operating mercury pressure.

5.2.13.5 Assurance of Continued Operability

The heat exchanger is considered a design feature. The Configuration Control Program ensures the design features important to safety are maintained and able to perform their safety functions.

The operations envelope includes a requirement to periodically verify the integrity of both the mercury and water boundaries within the heat exchanger.

- The integrity of both barriers shall be verified to be intact prior to each fill of the mercury circulation loop.

5.2.14 Service Bay Differential Pressure Monitoring System

5.2.14.1 Safety Function

The SBDPMS is credited to ensure prompt evacuation of personnel from areas adjacent to the service bay if confinement exhaust is not maintaining sufficient negative pressure or system flow to ensure confinement of the service bay atmosphere.

5.2.14.2 System Description

The SBDPMS provides (1) a means of monitoring differential pressure between the service bay and adjacent areas, (2) an alarm for evacuation of adjacent areas upon loss of service bay negative pressure, and (3) an alternate alarm mode based on PCES exhaust air flow. The alternate alarm mode is for when the configuration of service bay openings causes differential pressure to be too low to indicate adequate service bay confinement, such as when the transfer bay personnel door is open.

The SBDPMS alarms are initiated by a PLC-based logic that uses four differential pressure inputs in groups of two. Any one of the four differential pressure inputs can provide the required alarm. Therefore, only one instrument needs to be operable at any given time. The instruments are grouped such that one instrument in each group can be bypassed for maintenance or testing using logic built into the PLC. The audible and visual alarms are delayed by approximately 10 s to avoid alarms caused by momentary low differential pressure when switching from an operating ventilation fan to the standby fan.

Differential pressure is monitored for two high-occupancy areas adjacent to the service bay: (1) the area between the service bay and the manipulator gallery, and (2) the area between the service bay and decontamination room. If either of these areas has inadequate differential pressure, then the SBDPMS initiates the evacuation alarm in the six areas that could potentially be occupied by workers and affected by loss of service bay negative pressure: the manipulator gallery, the service gallery, the decontamination room, the bottom loading hatch room, the high bay area above the service bay, and the high bay area above accelerator tunnel.

The SBDPMS interfaces with non-safety instruments, but the design includes provisions to protect the system from faults in the systems to which it is interfaced.

The alternate alarm mode is implemented using one flow instrument (measuring PCES air flow in the duct between charcoal adsorbers and the HEPA filter bank). When in the alternate alarm mode, the system provides the evacuation alarm based on low PCES flow rather than differential pressure. The alternate alarm mode is operator selected but limited by a 24 h timer in the PLC that reverts automatically to differential pressure mode if the operators do not reset the timer before it times out.

PCES air flow is an indirect measurement of service bay confinement, whereas differential pressure is a direct indication. Thus, the alternate alarm mode should only be used when necessary for operational configurations that can provide reasonable assurance that confinement is maintained but where differential pressure cannot be expected to remain above the setpoint (i.e., creating false alarms). Three frequently opened penetrations to the service bay have been evaluated for alternate alarm mode operation:

the transfer bay personnel door, the top loading port, and the bottom loading port [53, 54]. As discussed elsewhere [53], alternate mode operation of the SBDPMS may also be useful for other major maintenance activities, such as those that require removal of the service bay T-beams. However, owing to the breadth of potential configurations, such activities will be evaluated via the USI process on a case-by-case basis to ensure that alternate alarm mode operation of the SBDPMS is appropriate and adequate to ensure protection of personnel in areas adjacent to the service bay.

5.2.14.3 Functional Requirements

The SBDPMS shall (1) measure differential pressure between the service bay and the manipulator gallery and between the service bay and the decontamination room and (2) automatically sound audible evacuation (subject to an approximate 10 s time delay) in the potentially affected areas of the target building when the negative pressure of the service bay is inadequate to ensure inflow from the manipulator gallery and the decontamination room to the service bay. An alternate alarm mode is also provided to allow temporary operation of the system using PCES flow rate rather than differential pressure to initiate the evacuation alarm.

Operability

The SBDPMS protects workers during various postulated scenarios that could lead to hazardous levels of airborne mercury in the service bay atmosphere. The SBPDMS must provide protection whenever one of these scenarios is possible. One category of scenario is a significant release of mercury from the mercury circulation loop, leading to a rapid increase in airborne mercury vapor concentration. These scenarios are addressed by requiring the SBDPMS to be operable whenever mercury is loaded into the mercury process loop. A second category is a loss of PCE ventilation in when the mercury vapor concentration in the service bay already exceeds hazardous levels because of historic mercury circulation loop operations and events. This category is addressed by requiring SBDPMS operation anytime the measured airborne mercury concentration exceeds the Occupational Safety and Health Administration (OSHA) ceiling of 0.1 mg/m^3. The OSHA ceiling is used because it represents a low hazard threshold (a factor of 40 less than ERPG-3) that is still above normal operational levels outside of excursions resulting from operations such as target nose cutting and storage tank venting. Finally, a third requirement is connected to event TS1-4, which postulates a fire occurs in the service bay when the service bay T-beams are removed. Although the frequency of this configuration has been much less than originally expected, the large opening between the service bay and high bay when T-beams are removed merits a heightened sensitivity to maintaining confinement ventilation and rapid response to its loss.

To protect personnel in areas adjacent to the service bay, the SBDPMS shall be operable if any of the following conditions exist:

- Mercury is loaded in the mercury circulation loop,
- Airborne mercury concentrations inside the service bay exceed the OSHA ceiling of 0.1 mg/m^3,
- One or more service bay T-beams are removed.

Compensatory Measures

The SBDPMS provides a robust and reliable means to ensure that confinement ventilation is in operation during routine operations. However, short periods with SBDPMS inoperable can be safely managed by SNS procedures that ensure personnel are sensitized to the inoperable system and that establish processes to ensure timely evacuation of personnel from affected areas. Even in the most severe scenarios, the service bay atmosphere is not expected to rapidly escape in sufficient quantity to make adjacent spaces hazardous for personnel, so a timely personnel response is deemed sufficient to provide protection.

- Personnel access to areas adjacent to the service bay may be allowed by approved SNS procedures that ensure personnel evacuation upon loss of PCES ventilation. The SNS procedures shall also ensure personnel safety upon subsequent reentry.

By comparison, entry into the transfer bay with the SBDPMS inoperable is a higher risk activity. The less robust separation between the transfer bay and the more contaminated portions of the service bay demands a more rigorous approach to manage the risk to workers in the transfer bay, although the hazard is still expected to be well controlled so long as PCES ventilation is maintained. These measures are in addition to the requirements provided above.

- The transfer bay personnel door may be opened, and personnel allowed to enter only when the following conditions are met:
  - The RSO and SNS operations manager (or designees) visually verify that both the upper and lower intrabay doors are in the closed position.
  - Prior to fully opening the transfer bay personnel door, airborne mercury concentration in the transfer bay and surrounding area shall be measured.
  - The SNS operations manager (or designee) shall review the airborne mercury concentration measurements and shall ensure that appropriate controls are in place to protect the worker prior to authorizing entry.
  - Mercury airborne concentrations in the transfer bay and surrounding areas shall be monitored when personnel are in the transfer bay.

Procedures are also needed to ensure a timely response to a change in the operating status of the SBDPMS should issues arise during a transfer bay entry.

- In the event that the SBDPMS becomes inoperable while the transfer bay personnel door is open, response shall be performed in accordance with approved SNS procedures.

5.2.14.4 System Evaluation

The SBDPMS monitors service bay pressure with respect to the manipulator gallery and the decontamination room, and it alarms in the following areas that are adjacent to the service bay: the manipulator gallery, the service gallery, the high bay, the decontamination room, and several rooms in the basement, with the most affected being the bottom loading room. Failure of the PCE system, along with continued operation of the SCE system, would reverse the differential pressure and could cause airflow from the service bay to the adjacent areas. The target service bay air could, upon differential pressure reversal, flow into these areas depending on the air leak rate. The PCE system backdraft dampers (Section 5.2.10) would prevent reversed flow of service bay air through the PCE system ductwork to the decontamination room. Reverse flow through miscellaneous cracks would provide a way for potentially contaminated air to flow into the potentially occupied spaces; however, this event would not pose a significant hazard unless it occurred during an event involving unusual airborne mercury inside the service bay. This event would be of greater concern if it occurred when the personnel access door was open for transfer bay access because the intrabay doors are not airtight and workers in the area could be exposed to potentially contaminated air. An automatic cutoff of the operating SCE system blower in response to loss of the PCE system provides a defense-in-depth function to minimize the potential spread of contamination.

Design estimates [43] and operational measurements indicate that the concentration of mercury in the service bay air is likely to be below ERPG-3 for mercury toxicity (the concentration that could cause injury if breathed by a worker for 1 h), but this level cannot be guaranteed for the life of the facility.

Therefore, adjacent areas are evacuated if service bay negative pressure is lost. The SBDPMS provides automatic alarms to evacuate the affected areas in the target building on loss of negative pressure.

Target service bay differential pressure monitoring system instrumentation meets the requirements of ISA-S84.01 [42], which provides a structured guidance for maintaining instrumented system reliability for a safety life cycle extending from design through operations. Under the standard, this system is a Safety Integrity Level one (SIL-1) system.

As noted in *Setpoint Analysis for the Target Service Bay Differential Pressure Monitoring System* [43], the PCE system was analyzed to determine the areas to monitor that would detect loss of negative pressure in the service bay with respect to any surrounding occupied area. The analysis determined that if the service bay pressure were negative with respect to the manipulator gallery and the decontamination room, then it would be negative with respect to other surrounding occupied areas. Therefore, the logic of the SBDPMS is to sound the evacuation alarms if the service bay pressure is not negative with respect to either of these two areas. A setpoint analysis is required to define an appropriate set point so that the minimum differential pressure requirement is maintained while avoiding spurious evacuation alarms that could affect operations. The basis of design for the SBDPMS [41] specifies that the loss of differential pressure alarm is required to be audible in the transfer bay as well as other areas adjacent to the service bay, parts of the high bay above the service bay, and parts of the basement that are occupied and below the service bay (e.g., the bottom loading room).

The alternate alarm mode is adequate because the measurement of service bay exhaust flow is evidence that the service bay is maintained under negative pressure and maintaining inward air flow adequate to protect workers. The 24 h period allowed for the alternate flow alarm mode of operation is acceptable because the combined probability of an accident requiring PCES mitigation and loss of PCES flow measurement both occurring during this period is negligible.

5.2.14.5 Assurance of Continued Operability

The ASE requires annual certification to ensure continued operability.

5.2.15 Mercury Pump Tank Exhaust Line Loop Seal

5.2.15.1 Safety Function

The mercury pump tank exhaust line loop seal prevents liquid mercury from escaping the service bay via the MOTS in the event of a mercury pump tank overfill during routine mercury circulation loop filling operations.

5.2.15.2 System Description

The line that connects the MOTS to the pump tank is routed through an elevated loop above the normal level of the mercury in the pump tank before looping down to connect into the MOTS components in the service bay. A simplified schematic is provided in Figure 3.32. Mercury is routinely drained to the storage tank located below the floor level. Mercury is returned to the mercury loop by supplying helium pressure to the mercury storage tank to force the mercury up and into mercury circulation loop. The pump tank is the highest intended elevation for the mercury. When the fill operation is complete, the operator closes the valve between the pump and storage tanks. Several non-safety features provide defense-in-depth against the overfill condition that would allow mercury to escape from the service bay during the pump tank filling operation. During the fill operation, the operator monitors the pump tank level. When the fill is complete, the operator closes the valve between the loop and mercury storage tank. If the overfill were to continue past full without operator action, automatic controls would isolate the helium supply, thereby ending the fill before overflow. The elevated loop was selected as the credited level of defense against mercury escaping from the service bay through the MOTS because it prevents the accident scenario by using a robust, passive, engineering design feature.

5.2.15.3 Functional Requirements

Liquid mercury is prevented from escaping from the service bay in the event that the following multiple failures occur: (1) the helium pressure regulator fails, supplying helium pressure to the storage tank at the maximum actuation pressure of the helium supply line safety relief valves (115.5 psig, which is the nominal actuation pressure of 105 psig plus the 10% blowdown factor required for the relief valve to reach its full rated flow); (2) the helium supply interlock on high pump tank level fails; and (3) operators fail to notice the overfill condition.

Operability

The mercury pump tank loop seal is considered operable when its elevation is above the maximum credible level that could be reached during a mercury loop filling evolution as described above.

- The top of the loop seal, as installed in the service bay, must be sufficiently high to prevent the inert gas pressure in the mercury storage tank from forcing liquid mercury over the top of the loop seal.

Compensatory Measures

The mercury pump tank loop seal is only needed to provide its credited function during a mercury loop filling evolution, so by preventing a mercury loop fill, the potential for an overfill is eliminated. Since the mercury loop is filled by pressurizing the mercury storage tank with helium, venting the storage tank to atmospheric pressure prevents filling the mercury loop.

- If the mercury pump tank loop seal does not satisfy the operability requirement, the mercury storage tank shall be vented to atmospheric pressure.

5.2.15.4 System Evaluation

The top of the loop seal is sufficiently high compared with the bounding inert gas pressure used in the mercury storage tank to force liquid mercury up to the top of the loop [56]. The maximum credible inert gas pressure is determined by safety relief valves on the inert gas supply line. Therefore, liquid mercury cannot escape from the pump tank into the MOTS during the loop overfill event even if multiple operator and equipment failures occur.

5.2.15.5 Assurance of Continued Operability

The elevation of the pump tank exhaust line is considered a design feature and therefore does not require ASE coverage. The Configuration Control Program ensures that the design features important to safety are maintained and can perform their safety functions. These features and their requirements have been included in Appendix A of the ASE.

5.2.16 Transfer Bay Access Control System

5.2.16.1 Safety Function

The safety function of the TBAC system is to (1) prevent opening of the transfer bay personnel door unless both intra-bay doors are closed and (2) sound an alarm if the intrabay doors are opened while the personnel door is open.

5.2.16.2 System Description

The system is as described in Section 3.3.8.4, "Transfer Bay Access Control System."

5.2.16.3 Functional Requirements

The transfer bay access control interlock prevents opening of the transfer bay personnel access door when the intrabay shielding door (both upper and lower segments) is not closed. If workers are accessing the transfer bay (transfer bay access door is open), then the system sounds an alarm if the intrabay shielding door begins to open. A bypass may be used to allow worker access past the intrabay door in accordance with strict administrative control, as described in Compensatory Measures below.

Operability

The radiation and mercury toxicity hazards of the service bay are not reduced to safe levels by preventing beam to target, so personnel access to the service bay must be controlled to ensure personnel safety. If the TBAC is bypassed or not operable, then the transfer bay personnel door should be locked in the closed position and tagged with a radiation safety hold to prevent inadvertent personnel access unless appropriate compensatory measures have been implemented to allow transfer bay access without TBAC.

- The TBAC system shall be operable unless the transfer bay personnel door is locked in the closed position and tagged with a radiation safety hold.

Compensatory Measures

Normally, TBAC should control access to the transfer bay to ensure that the intrabay doors are closed to provide shielding to personnel. However, circumstances sometimes arise that require access to the transfer bay either with the TBAC inoperable or with the intrabay doors open. Two compensatory measures have been developed to support these infrequent operations. The first focuses on an inoperable or bypassed TBAC with the intrabay doors closed. The second focuses on a transfer bay entry with the intrabay doors open.

In the case of a transfer bay entry with the intrabay doors shut, the TBAC provides an engineered means to ensure the workers are protected by the intrabay doors. If the TBAC is inoperable, then the compensatory measures primarily need to provide an administrative means to accomplish the same goal. This goal is accomplished by visual verification of the intrabay door position and lock out of the drive mechanism for the doors to ensure they are not inadvertently opened. These administrative processes functionally accomplish the two safety functions of the TBAC. Additionally, entry in accordance with an RWP is enforced to ensure an intentional and systematic approach to evaluating and documenting the radiological conditions inside the transfer bay. This process ensures that the goal of protecting the worker from radiation has been truly accomplished.

- Entry into the transfer bay with the intrabay doors closed and the TBAC system inoperable must adhere to the following restrictions:
  - The intrabay doors shall be visually verified to be in the closed position and the electrical breakers that supply power for opening the intrabay doors are locked out and tagged as a radiation safety hold to prevent opening.
  - Entry is conducted in accordance with an approved Radiological Work Permit.

Entry into the transfer bay when the intrabay doors are open requires bypassing the TBAC. The risk associated with this operation is increased with the intrabay doors out of the closed position, so increased measures are implemented to ensure organizational engagement with the evolution and appropriate hazard mitigation measures are implemented. Because the conditions necessitating this evolution could take several forms. Associated procedures and RWPs will likely be tailored to match the specifics of each entry. In general, procedures would address the hazards for which the intrabay doors normally provide protection (i.e., access control to the maintenance bay, radiation shielding, and mercury vapor management).

- Entry into the transfer bay and other areas of the service bay with the TBAC system inoperable or key bypassed and the intrabay doors open must adhere to the following restrictions:
  - Beam on target shall be prohibited and controlled in accordance with the appropriate lock out of critical devices.
  - Entry is conducted in accordance with an SNS procedures approved by the RSO and SNS operations manager (or designees) that require radiation surveys to be conducted in accordance with an RWP. Entry shall be approved by the RSO and SNS Operations Manager (or designees).

Provision is also made to ensure an appropriate response by personnel in the unlikely case that the TBAC becomes inoperable while the transfer bay personnel door is open.

- If the TBAC becomes inoperable while the transfer bay personnel door is open, response shall be performed in accordance with SNS procedures.

5.2.16.4 System Evaluation

This system is a single-channel system built to safety integrity level SIL-1 per ISA standard S84.01 [42]. This reliability level is adequate because this system supplements the stringent administrative controls that are in place, and a noncredited trapped key system also helps prevent operation of the intra-bay shielding door when the personnel access door is open (and vice versa). This control works in conjunction with procedures and training controlling access to the service bay.

5.2.16.5 Assurance of Continued Operability

Annual certification is required to ensure continued operability.

5.2.17 Target Personnel Protection System

5.2.17.1 Safety Function

The safety function of the PPS is to protect workers against prompt accelerator radiation, as described in Section 5.2.1 of the FSAD-PF [45]. The target PPS is a segment of the PPS that provides the PPS safety functions within the target facility. The following PPS safety functions are performed by the target PPS:

- 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.

5.2.17.2 System Description

The system, as described in Section 3.3.8.3, is a part of the PPS described in the FSAD-PF [45], following the same architecture and design guidance. Because the target PPS is a downstream segment of the PPS, it uses the PPS critical devices in the front end, controlled by the linac segment, when needed to interrupt the proton beam to protect workers. The target PPS trips the proton beam or prevents proton beam generation as required to perform the necessary safety functions. Alternatively, if upstream critical devices are aligned to prevent beam transport to the target facility, such as the HEBT dipoles or RTBT.DH13, then beam operations in further upstream segments are permitted to continue even in circumstances when the target segment would trip the beam.

The target PPS supports the instrument PPS. The target PPS monitors the instrument PPS status outputs (fault/no fault) for each of the instruments. When an instrument fault occurs, the target PPS trips the beam as needed to protect workers. For some instrument lines, the target PPS trips the proton beam immediately. For others, it first attempts to close the primary shutter for that instrument, tripping the proton beam if the primary shutter fails to close after a predetermined time interval.

The target PPS controls access to the shutter drive equipment room and basement utility vault; however, measurements show that dose hazards in those areas do not rise to the level of requiring a credited control (Section 4.3.3). Access control to these areas will not be considered a credited function of the PPS system until dose rates in these areas are measured and determined to warrant PPS protection as a credited control consistent with the SNS policy for the selection of credited controls.

5.2.17.3 Functional Requirements

The target PPS is a part of the PPS, so its functional requirements are described in the FSAD-PF, except for one functional requirement of the PPS that is unique to the target PPS, which supports the safety function to prohibit beam to target when the target cart is out of the “cart inserted” position. Event TS4-1, discussed in Section 4.3.1, credits the PPS to prevent beam to target if the target cart is not fully inserted. The PPS performs this function by monitoring redundant position switches that actuate when the target cart is fully inserted. PPS logic controls two critical devices to ensure that beam cannot be transported to the target unless the target cart position switches indicate that the cart is fully inserted.

Operability

The target PPS conforms to the operability requirements for the PPS as described in the FSAD-PF.

Compensatory Measures

The target PPS conforms to the compensatory measures described for the PPS in the FSAD-PF.

In addition to the provisions described in the FSAD-PF, the target cart position monitoring function of the PPS is addressed here. The target cart position switches for the PPS are located within the service bay.

Compared with most other PPS components, this environment increases the risk of component failure caused by radiation effects and chemical effects from mercury vapor. The need for remote operation also means that replacement of the position switches will require more extensive planning to accommodate the hazardous environment and complexities of remote operations. Thus, it is prudent to make provision for continued operation of the facility with the target cart position sensing function in a degraded state.

In essence, the target cart position monitoring function provides a reliable means to ensure that a key piece of target monolith shielding is in place, namely the target cart. Although automated interlocks accomplish this function with a high degree of reliability, administrative control of the target cart position can be accomplished with a high degree of assurance. Three key factors contribute to this approach. First, a second credited engineered system, the TPS, accomplishes the same function (Section 5.2.5). Second, the position of the target cart is readily observed through service bay windows with no ambiguity about its general position. Third, the position of the target cart, once properly aligned for target operations, is not easily changed, and its movement can be rigorously prevented by locking out key devices.

The TPS is independent from the PPS, but it has many parallel features. It prevents beam production unless the mercury circulation loop is operating within defined setpoints for flow and temperature or RTBT.DH13 is deenergized, ensuring beam cannot go to the target (Section 5.2.5). Because the target cart contains a major portion of the mercury circulation loop, which must be disconnected to retract the target cart, it is not possible for the TPS to have mercury loop flow within the setpoints unless the target cart is inserted, completing the mercury circulation loop. As such, so long as the TPS is operable, beam to target will be prevented unless the target cart is inserted.

Visual verification of the target cart position is an effective means to ensure it is properly inserted. The target cart is operated on tracks, and its course of movement is limited to an area directly in front of the service bay windows. This safety function is only concerned with the position of the target cart as monolith shielding rather than the status of the mercury circulation loop, so visual position verification is sufficient and consistent with processes for configuration control of other major portions of shielding.

Once the target cart is configured for beam-to-target operations, a complex evolution is required to retract it. The mercury process piping connections must be unmade, which requires unstacking of doghouse shielding over the connections and using the in-cell servomanipulator to open two reflange connections using specialized tools. Then the target cart drive unit must be engaged to retract the cart. Although inadvertent cart retraction is unlikely, to prevent inadvertent retraction of the target cart with the PPS position switches bypassed, the cart hydraulic drive unit is locked out and tagged to prevent energization.

These measures provide a high degree of assurance that the target cart is inserted and remains inserted throughout beam operations if the target cart position switches are bypassed.

- Beam to target may be allowed with the PPS target cart position interlock bypassed so long as the following restrictions are in place:
    - 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.

5.2.17.4 System Evaluation

The target PPS is designed to the same high standards as the PPS and can be expected to have commensurate reliability, as described in the FSAD-PF [45].

5.2.17.5 Assurance of Continued Operability

Annual certification in accordance with approved SNS procedures ensures continued operability of the PPS.

5.2.18 Instrument Personnel Protection System

5.2.18.1 Safety Function

The safety function of the instrument PPS is to provide beam containment and access violation protection for identified exclusion areas in instrument beamlines. This system protects personnel from potentially injurious radiation exposure to prompt radiation in instrument enclosures.

5.2.18.2 System Description

The instrument PPS is described in Section 3.3.8.3 and consists of numerous system modules that are interfaced to the target PPS. Each instrument PPS module generally operates independently of the other modules but relies upon the target PPS to perform key functions such as operating the associated primary shutter or tripping the proton beam. Each instrument PPS module typically serves a single neutron instrument, although instruments with a common primary shutter communicate with each other as needed to manage primary shutter operation and position monitoring.

Instrument PPS modules often include radiation monitors and oxygen deficiency monitors, although they are not typically credited. They also sometimes interface with machine safety functions of the beamline such as motion control interlocks on doors or other equipment. Instrument PPS modules also include noncredited features common in the PPS such as beam stop stations, stack lights, sweep stations, and configuration control aids such as trapped keys. These features are discussed in detail in the FSAD-PF.

It is also common for an instrument PPS module to interface with the beamline secondary shutter, including motion control and position monitoring. In some instrument PPS modules, especially those on beamlines that share a primary shutter, the secondary shutter position is monitored using credited devices and provides beam containment in a role consistent with a primary shutter. This configuration improves instrument productivity by reducing cycle time and allowing access to enclosures on a beamline without stopping beam to the associated instrument that shares a primary shutter.

5.2.18.3 Functional Requirements

The instrument PPS is a part of the PPS and is operated in accordance with the functional requirements defined for that system in the FSAD-PF [45].

5.2.18.4 System Evaluation

The instrument PPS is designed to the same high standards as the PPS and can be expected to have commensurate reliability.

5.2.18.5 Assurance of Continued Operability

Annual certification in accordance with approved SNS procedures ensures continued operability of the instrument PPS.

5.2.19 Mercury Pump Tank Rupture Disk and Discharge Path

5.2.19.1 Safety Function

The mercury pump tank rupture disk and discharge path works in conjunction with the mercury pump tank exhaust line loop seal and orifice (Section 5.2.20) to prevent liquid mercury from leaking outside of the service bay via the MOTS during any credible mercury level transient.

5.2.19.2 System Description

The mercury pump tank was designed with a rupture disk overpressure protection device mounted on a standpipe in the pump tank lid. This rupture disk is intended to prevent over pressurization of the tank for the case in which the exhaust paths become blocked. For purposes of this credited control, it is used to limit the height of the free surface of mercury during transient conditions. Because of mercury's high density, only about 2 in. of mercury are needed to produce 1 psi of hydrostatic head. Thus, the rupture disk opening pressure can be directly correlated to a height of mercury above the rupture disk elevation. By ensuring the rupture disk is sized to open at a mercury height below the top of the mercury pump tank loop seal, a rising mercury level in the tank will be arrested when the rupture disk opens and begins discharging mercury from the tank. So long as the discharge rate of the rupture disk exceeds the volumetric expansion in the mercury system, no further level rise would occur.

Because the mercury pump tank rupture disk has now been repurposed to prevent mercury from overflowing the loop seal, a modification was made to attach a discharge path on the outlet of the rupture disk. This discharge path directs the discharged mercury down to a plug in the shielding with an opening that will allow the mercury to fall onto the credited sloped floor of the service bay and flow into the retention basin surrounding the storage tank. This path is expected to help control mercury contamination in the service bay, ensure that the free liquid mercury is protected by the steel shielding, and promote drainage of mercury to the retention basin where it can be recovered and returned to the loop. However, the discharge path also introduces flow resistance, potentially affecting the capability of the rupture disk to arrest the mercury level rise in the mercury process system. As such, the discharge path must be evaluated and specified in coordination with the rupture disk to ensure that the total flow resistance of the system does not compromise the safety function. This approach is discussed in detail in the literature [49]. The previously evaluated configuration [49] has been modified by the PPU project, particularly by the addition of the OFT, such that target gas injection no longer introduces a hazard that requires controls. The storage tank gas transient was evaluated [50], and the existing loop configuration was demonstrated to be sufficient to prevent significant mercury escape from the loop.

5.2.19.3 Functional Requirements

The mercury pump tank rupture disk and discharge path is designed in coordination with the design of the mercury pump tank exhaust line loop seal and orifice (Section 5.2.20). These two systems work together to prevent liquid mercury from escaping the service bay via the MOTS. As such, the functionality of each system relies upon a matching, coordinated design and specification in the other.

Operability

The following functional requirements support the safety function of the mercury pump tank rupture disk and discharge path and shall be satisfied whenever the storage tank is pressurized above atmospheric pressure:

- The mercury pump tank rupture disk shall be sized to rupture at a pressure less than that developed by a column of liquid mercury that reaches the top elevation of the mercury pump tank exhaust line loop seal.
- The mercury pump tank rupture disk and discharge path must be able to discharge mercury from the pump tank at a rate that ensures the mercury pump tank exhaust line loop seal and orifice are capable of preventing liquid mercury from leaking outside the service bay via the MOTS during any credible mercury level transient.

Compensatory Measures

Pressurized gas in the storage tank is the source of the hazard that this control is protecting against, so any time that the mercury pump tank rupture disk and discharge path is not considered operable, the storage tank is vented to ensure that the hazard is removed. Additionally, the mercury circulation loop should not be operated if it is open to the service bay atmosphere, so the mercury is drained from the loop if the rupture disk is not intact.

- If the mercury pump tank rupture disk and discharge path do not satisfy the operability requirements specified above, then the mercury storage tank shall be vented to atmospheric pressure.
- If the rupture disk is not intact, then the mercury shall be drained from the loop.

5.2.19.4 System Evaluation

The mercury pump tank rupture disk and discharge path are required to provide safety protections for the mercury fill transient event as determined in Section 4.3.1 for Event TS3-36. Analysis [49, 50] indicates that a nominal 15 psig burst disk, in conjunction with the other existing pump tank controls (i.e., discharge path, loop seal, and orifice), satisfactorily performs the required safety function. Use of 15 ± 2 psig burst disk (or less) satisfies the safety function and functional requirements.

As discussed elsewhere [49], the rupture disk is positioned at a height of 42.3 in. The height of the loop seal is 121 in., 78.7 in. above the rupture disk height. The hydrostatic pressure associated with a 78.7 in. column of mercury is equivalent to approximately 38 psig; therefore, the rupture disk will actuate well before a static column of mercury could reach the height of the loop seal. Thus, the current configuration meets the functional requirement for the rupture disk.

Previous analysis [50] shows that the discharge rate associated with the design configuration of the mercury pump tank rupture disk and discharge path is adequate to meet the functional requirement.

The effectiveness of the integrated performance of the rupture disk, discharge path, mots loop seal, and orifice has been evaluated [50], showing that mercury is contained within the system and is not transported over the MOTS loop seal described in Section 5.2.20.

5.2.19.5 Assurance of Continued Operability

The mercury pump tank rupture disk and discharge path are considered design features. The configuration control program ensures design features important to safety are maintained and able to perform their safety function. These features and their requirements have been included in Appendix A of the ASE.

The operations envelope coverage is required for operability of the mercury pump tank rupture disk, which requires periodic inspections for deformation or other visual damage and replacement whenever the system pressure at the inlet to a rupture disk rises to the rupture disk deformation pressure, whenever the rupture disk safety head is disassembled, or at least once every 5 years.

The mercury pump tank discharge path requires periodic visual surveillance to ensure the configuration has been maintained consistent with the design requirements (e.g., no significant crimping of the discharge tube that could impede flow during venting).

5.2.20 Mercury Pump Tank Exhaust Line Loop Seal and Orifice

5.2.20.1 Safety Function

The mercury pump tank exhaust line loop seal and orifice works in conjunction with the mercury pump tank rupture disk and discharge path (Section 5.2.19) to prevent liquid mercury from leaking outside of the service bay via the MOTS during any credible mercury level transient.

5.2.20.2 System Description

Gases enter the mercury process system from various sources, so a pathway to vent these gases and cleanup entrained radionuclides via the MOTS is provided. This vent path was also identified during the construction phase to introduce a potential pathway for mercury to escape the mercury process system, so a loop seal was installed that rises several feet above the top of the pump tank before coming back down to connect to the valve panel and ultimately MOTS. The initial design of the loop seal was focused on a postulated scenario during mercury loop filling operations in which the maximum available helium pressure is allowed to pressurize the storage tank [52], providing the basis for the mercury pump tank exhaust line loop seal as described in Section 5.2.15.

As the facility has matured, other identified scenarios have taken advantage of the loop seal design feature to prevent mercury from escaping the mercury pump tank into the MOTS. Because these scenarios have been transient, the loop seal has been coupled with an orifice installed at the bottom of the loop seal, sized to restrict the flow of liquid mercury without significantly limiting the passage of off-gas during operations. Much like the pump tank rupture disk, the sizing of this orifice was based upon a composite evaluation of a transient gas release event that includes the rupture disk pressure, flow resistance in the discharge path, and flow restriction provided by the orifice [55]. However, PPU modifications have been made that passively mitigate that scenario [55], particularly the OFT installation, so only the storage tank gas transient remains that requires this credited control [50].

The loop seal is described in Section 5.2.15. It consists primarily of a flex hose with a mounting point high on the wall of the service bay [56]. The orifice is made of stainless steel and was sized consistent with previous evaluations [50, 55].

5.2.20.3 Functional Requirements

The mercury pump tank exhaust line loop seal and orifice is designed in coordination with the design of the mercury pump tank rupture disk and discharge path (Section 5.2.19). These two systems work together to prevent liquid mercury from escaping the service bay via the MOTS. As such, the functionality of each system relies upon a matching, coordinated design and specification in the other.

Operability

The following functional requirements support the safety function of the mercury pump tank exhaust line loop seal and orifice and shall be satisfied whenever the storage tank is pressurized above atmospheric pressure.

- The top of the mercury pump tank exhaust line loop seal, as installed in the service bay to meet the requirements described in Section 5.2.15, also ensures that the rupture disk actuates before a column of mercury could reach the top elevation of the mercury pump tank exhaust line loop seal.
- The installed mercury pump tank exhaust line loop seal and orifice must be designed and built to provide sufficient flow resistance to ensure that the mercury discharge rate of the mercury pump tank rupture disk and discharge path is sufficient to prevent liquid mercury from leaking outside of the service bay via the MOTS during any credible mercury level transient.

Compensatory Measures

If the mercury pump tank exhaust line loop seal and orifice does not satisfy the operability requirement, then the mercury storage tank shall be vented to atmospheric pressure.

5.2.20.4 System Evaluation

The mercury pump tank exhaust line loop seal and orifice are required to provide safety protections for the mercury fill transient (event TS3-36 in Section 4.3.1). The mercury pump tank exhaust line loop seal is also used as a credited control designed to ensure confinement of liquid mercury during a loop overfill accident (Section 5.2.15), and this evaluation credits the height of the loop seal consistent with the existing evaluation.

The rupture disk is positioned at a height of 42.3 in. [49]. It is rated to actuate at pressure of 15 ± 2 psig. The height of the loop seal is 121 in., 78.7 in. above the rupture disk height. The hydrostatic pressure associated with a 78.7 in. column of mercury is equivalent to about 38 psig; therefore, the rupture disk will actuate well before a static column of mercury could reach the height of the loop seal. Thus, the current configuration meets the functional requirement for the elevation of the mercury pump tank exhaust line loop seal.

The mercury pump tank exhaust line orifice is a 0.125 in. stainless-steel orifice incorporated between the loop seal and mercury pump tank. It is designed to restrict mercury flow into the loop seal while allowing normal operation of the MOTS. This orifice has been demonstrated effective at preventing mercury from escaping the service bay via MOTS when operating in conjunction with the other associated credited controls [50].

The 121 in. loop seal and 0.125 in. orifice provide sufficient flow resistance to ensure that the mercury discharge rate of the mercury pump tank rupture disk and discharge path is sufficient to prevent liquid mercury from leaking outside of the service bay via the MOTS during any credible mercury level transient [50].

5.2.20.5 Assurance of Continued Operability

The mercury pump tank exhaust line loop seal and orifice are considered design features. The Configuration Control Program ensures that design features important to safety are maintained and able to perform their safety function. These features and their requirements have been included in Appendix A of the ASE.

The normal fluid passing through the orifice is helium with trace amounts of mercury vapor and spallation gases. Experience indicates that stainless steel is a robust material in a mercury environment because the immediate effects of the proton beam are not present. As such, no mechanism is anticipated to change the dimensions of the orifice and no surveillance or maintenance is required.

5.2.21 Cryogenic Moderator System Catalytic Converter Retention Elements

The cryogenic moderator system ortho-para catalytic converter retention elements are credited to prevent direct exposure to on-site workers resulting from activation of catalyst media following escape of the media from its confinement into the cryogenic moderator loop [51].

5.2.21.1 Safety Function

The CMS catalyst retention elements confine the iron oxide catalyst media to its designed canister and prevent the transport of iron oxide catalyst media into the CMS loop.

5.2.21.2 System Description

An iron oxide catalyst bed is incorporated into each of the three cryogenic moderator loops to reduce the time for each loop to reach a high fraction of parahydrogen following CMS cooldown. The catalyst beds are installed in line with the normal circulation flow between the circulators and accumulators in the HUR. Each of the three loops has a catalyst bed sized for the hydrogen volume of the loop. Figure 5.3 shows an exploded view of the component parts of the catalyst bed.

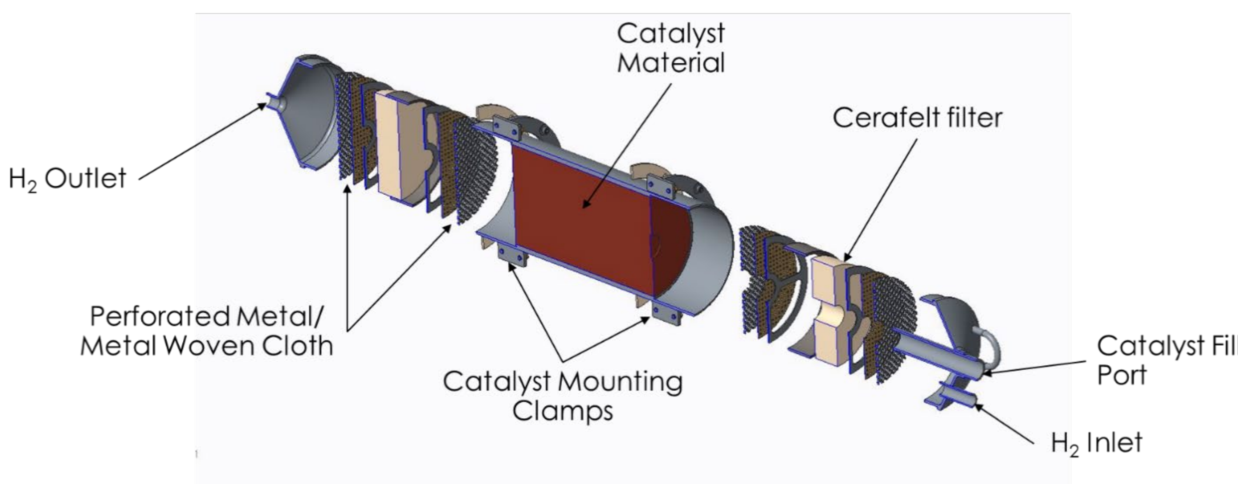


Figure 5.3. Exploded view of the catalyst bed components.

The catalyst media is confined by a catalyst module. The pressure boundary is constructed of 316 stainless steel and includes a hydrogen inlet, hydrogen outlet, and catalyst fill tube. Between the inlet and outlet are the inlet retention element, catalyst media, and outlet retention element. The catalyst fill tube penetrates from the outside of the pressure boundary through the inlet retention element to allow access to fill the area between the retention elements with catalyst. During operation, this penetration will be closed with a welded cap. The retention elements are designed to allow cryogenic hydrogen to flow through while confining the iron oxide catalyst media.

The retention elements have a layered design to provide a robust barrier for the catalyst media. The central element is Cerafelt filter media. This is held in place on either side by layers consisting of perforated metal sheets and woven metal cloth. The metal layers are welded to a retaining ring that encircles the entire assembly. These rings are then welded into the assembly on either side of the tube that will contain the catalyst media.

The construction of the catalyst module is all-welded, primarily of Type 304L and 316 stainless steel and is built to satisfy the requirements of ASME B31.3. The material of construction of the catalyst module is also certified consistent with the ASME B&PV Code Section II. The modules are sized to reduce the pressure drop across the module and to reduce the stress on the retention elements.

The catalyst media is specified for particle size to a US Sieve standard mesh size of 30 × 50 in accordance with ASTM D2862 and has a maximum of 5% of the particles undersize. The woven wire mesh incorporated into the retention elements is specified to a US Sieve standard mesh size of 60. Sieve size in this range is the number of wires per inch, so a higher number corresponds to a smaller opening size.

5.2.21.3 Functional Requirements

The CMS catalytic converter retention elements shall be designed and fabricated to ensure that at least 95% of iron oxide catalyst is retained by the retention elements under all anticipated operational conditions of the CMS.

The catalyst media characteristics (e.g., particle size) shall be specified consistent with the design of the CMS retention elements.

Operability

The CMS catalytic converter retention elements must be operable whenever catalyst media is loaded into the associated catalyst module.

5.2.21.4 System Evaluation

The design and construction of the CMS catalyst modules meets the requirements of ASME B31.3 design standard for piping systems. This standard provides a high degree of confidence in the reliability of the welds and pressure boundary of the system. Selection of robust materials such as Series 300 stainless steel, combined with quality verifications, ensures the long-term performance of the system. The all-welded design approach for the retention elements reduces failure modes that could allow escape of catalyst media. Redundant layers of woven steel mesh coupled with Cerafelt media ensure near-perfect retention of media. The woven steel mesh is specified as a size 60 sieve, which is finer than the fine screen, size 50, used to establish the specified particle size for the catalyst. As such, at least 95% of catalyst media (i.e., assuming the maximum 5% undersize particles could escape) would be retained by the woven steel mesh. The Cerafelt, which has a high unspecified filtration efficiency, is likely to capture any undersize particles that might work their way through the bed to the outlet retention element. This capability is confirmed by experience at the Japan Proton Accelerator Research Complex, where nearly identical catalyst modules have been operating for approximately 10 years. However, to prevent significant consequences from catalyst activation, only 95% retention is required. Because the outlet retention element incorporates two wire mesh screens that are each specified to a finer mesh size than 95% of the catalyst media, the wire mesh screens are considered sufficient to meet the functional requirements of the credited control. The Cerafelt filter elements protect system components from circulating media fines, acting as a backup to the wire mesh screens and an additional layer of safety.

The degree of activation required to cause significant safety consequences requires long-term circulation of the catalyst through the loop. Because the catalyst modules are designed to be an in-line component in the flow, the inlet retention element for each catalyst also prevents catalyst activation. If a failure in the outlet retention element allowed the escape of a portion of the catalyst media, then it would likely be recaptured once it made a single pass through the loop and reached the inlet retention element, which is identical in design to the outlet. Thus, in addition to redundant woven wire mesh layers in each retention element, the entire retention element is effectively redundant after a single circulation pass.

Based upon these design characteristics, the CMS catalytic converter retention elements are deemed to be a robust, passive design feature that will effectively prevent significant safety consequences.

5.2.21.5 Assurance of Continued Operability

The CMS catalytic converter retention elements are considered a robust design feature and thus do not require periodic surveillance or certification. The Configuration Control Program ensures design features important to safety are maintained and able to perform their safety functions. These features and their requirements have been included in Appendix A of the ASE.

5.3 CREDITED ADMINISTRATIVE CONTROLS

CACs identified in Section 4 are described in the following subsections. The CACs are described either as administrative programs or as procedures. The programs typically comprise a suite of administrative actions applied on a continuous or generic basis, whereas the procedures are specified for particular operations. SNS-specific administrative controls are covered by the Operations Envelope and Operations Procedure Manual as needed to assure the safety functions are maintained. When the identified CACs are already well covered by existing ORNL SBMS programs, no further stipulations are necessary to assure the functionality is maintained.

5.3.1 Radiological Protection Program

The Radiological Protection program is specifically credited with providing a means of controlling the radiological exposure received by facility workers. The Radiological Protection program ensures that worker exposure to radiation is limited by means such as access controls to areas where radiological hazards exist, control of work involving radiological hazards, and monitoring of worker exposure.

SNS uses the ORNL Radiological Protection program as promulgated and maintained in the ORNL SBMS Radiological Protection management system, which ensures radiological safety across the entire ORNL complex. The ORNL Radiological Protection program provides robust protection of workers against radiological hazards and is designed to ensure exposures are maintained ALARA and in compliance with 10 CFR 835, *Occupational Radiological Protection*. The program provides a credited level of protection for several of the accidents evaluated in Section 4. For each of these accidents, the elements of a properly functioning radiological protection program work together to avoid inadvertent radiological exposure. Examples of specific salient features of the Radiological Protection program are listed below to illustrate the types of protection the program affords for the Section 4 events that credit the program.

- Event HV3-5 is an inhalation overexposure caused by a mishap during HEPA filter replacement. Work in radiological areas involves planning through work packages that include RPWs requiring approvals commensurate with the predicted hazards. Need for personal protective equipment (PPE), protective clothing, and radiological controls technician coverage is considered for each RWP.

- Event SH4-2 involves overexposure caused by voids or cracks in shielding concrete. The Radiological Protection program enforces periodic surveys in selected, occupied areas conducted in accordance with an approved schedule.
- Event SH4-4 involves excessive radiation exposure caused by a mishap during removal or handling of a highly irradiated component such as a neutron beam shutter. Work in radiological areas involves planning through work packages that include RWPs requiring approvals commensurate with the predicted hazards. Need for PPE, protective clothing, and radiological controls technician coverage is considered for each RWP.
- Event TC4-2 postulates excessive radiation exposure after violent breakage of a service bay viewing window caused by a service bay crane load handling accident. Workers who routinely perform tasks in the manipulator gallery must have radiation worker training, which would enable them to understand the shielding value of the thick viewing windows and, thus, to evacuate when they break.
- Event CW4-1 postulates a worker gains access into the delay tank pit (requires removal of massive concrete shield blocks and ladder to access) during high power operations. The Radiological Protection program controls access into radiological areas and controls placement of shielding that would prevent worker access.
- Event GW3-2a postulates a release of MOTS flow into the GAR caused by a system leak upstream of the ambient charcoal adsorbers. The Radiological Protection program provides a means of controlling the exposure received by facility workers by controlling access to radiological areas and the placement of shielding. In this case, the Radiological Protection program ensures that the shielded GAR door is locked shut with a radiation safety hold during beam operations and that GAR access is controlled as appropriate for the radiological conditions in the room.
- Event SH4-3 postulates worker exposure caused by the inadvertent opening of a shutter when beamline shielding is not in place. The Radiological Protection program ensures proper controls are in place for operations when beamline shielding is not in place (ensures applicable primary shutter is locked in place with approved radiation safety hold).
- Event SH4-1 postulates worker exposure in the high bay caused by a misaligned target module, proton beam window, or core vessel. The Radiological Protection program ensures radiation surveys occur as appropriate after replacement of shielding associated with these components.
- HB4-3 postulates worker exposure caused by inadvertent removal of shielding in the high bay area. The Radiological Protection program controls access into radiological areas and controls placement of shielding that would prevent worker access.

Controlling worker exposure to the radiological hazards of mercury includes preventing exposure to airborne mercury products, which also effectively protects against the toxicological hazards of mercury. During the early phases of the project, before significant activation of the target mercury, the Chemical Safety Program (discussed below) was credited to ensure workers were protected from the toxicological hazards of mercury vapor. Radioactivity levels associated with target mercury are such that controls provided by the ORNL Radiological Protection program protect the worker from both radiological and toxicological hazards of the target mercury.

The ORNL Radiological Protection program is implemented through the SBMS program, which ensures that entries into areas with significant radiation hazards are controlled and that personnel exposure to radiation is controlled. Because the ORNL institutional SBMS program provides and maintains this protection, no further coverage is required.

5.3.1.1 Chemical Safety Program

The Chemical Safety program was credited in the early phases of the project with providing a means of controlling worker exposure to mercury and is implemented within the ORNL SBMS subject area, “Chemical Safety,” within the Worker Safety and Health management system.

The ORNL Chemical Safety program, as implemented through the SBMS program, ensures that entries into areas with significant mercury levels are controlled and that personnel exposure to mercury is controlled. Because the ORNL SBMS program provides and maintains this protection, no further coverage is required.

This protection was only required during the early phase of SNS operations while the radioactivity of the mercury was relatively low. Now that the mercury activity has become significant, the Radiological Protection program effectively serves as a control against toxicological hazards of target mercury. Although no longer credited, the ORNL Chemical Safety program as promulgated through SBMS remains in effect for activities at SNS.

5.3.2 Combustible Material Control Program

The Combustible Material Control program is credited with providing a means of ensuring that combustible loading limits are maintained to prevent the results of fires outside the service bay from challenging the fire barrier surrounding the service bay and core vessel or causing gross building structural failure and limiting the combustible loading inside the service bay to reduce the frequency and intensity of a fire in that location, thereby protecting the on-site workers as well as the public.

Combustible Material Control Program Outside the Service Bay

The Combustible Material Control program is credited with providing a means of ensuring that any fire outside the service bay or core vessel would not challenge the service bay and core vessel 2 h equivalent fire barrier. The potential effect of all combustible materials outside the service bay is considered. The Combustible Material Control program outside the service bay is controlled through the ORNL SBMS subject area, “Fire Protection, Prevention and Control,” and is implemented in the SNS Combustible Controls program. As indicated in the following paragraph, special guidelines have been developed for controlling the configuration of hydrocarbon shielding used in conjunction with neutron instruments.

The Combustible Material Control program outside the service bay has provisions to ensure that the following design requirements for the hydrocarbon configuration and encasement on the instrument floor (Section 3.3.13.7) are maintained to help achieve the fire protection goals formulated to guide the safe use of large quantities of hydrogenous shielding material in the instrument halls:

- Quantities of hydrocarbon exceeding 2,000 lb inside the instrument hall shall be encased in steel or other approved material.
- Individual encasements shall not exceed 4,000 lb of hydrocarbon.
- The steel-encased hydrocarbon shall withstand heat flux from an adjacent fire without escaping from the steel, considering potential thermal expansion and phase change.
- The steel assembly shall have sufficient integrity to withstand anticipated mechanical challenges of installation and lifetime maintenance activities.

- The encasement is complete except for filling holes that may be either left open or provided with rupture disks, depending on the hydrocarbon used and the overall configuration, orientation, and structural integrity of the encasement.
- For instrument stations with 4,000 lb or more of hydrocarbon, additional design measures may be needed as documented in an HE to ensure instrument hall fire protection goals are achieved.
- Instrument stations with more than 4,000 lbs of hydrocarbon require a documented HE to ensure that instrument hall fire protection goals are met.

Combustible Material Control Program Inside the Service Bay

The Combustible Material Control program is credited with providing a means of ensuring that a fire in the service bay is limited in effective duration and intensity. The quantity of combustible material in the service bay during normal operations is limited to an equivalent 3,600 MJ localized fire. This includes the requirement for use of only noncombustible (or limited quantities of sufficiently high flash point/fire point) hydraulic fluid or other lubricating fluids in equipment used in the process bay.

General requirements for control of combustible materials in the target building are controlled through the ORNL SBMS subject area, “Fire Protection, Prevention, and Control.” Therefore, no further coverage is required. Requirements specific to the target building are promulgated through the operations envelope and the Operation Procedure Manual.

5.3.3 Ignition Control Program

The Ignition Control program is credited to help provide a second level of control against a fire occurring in the instrument hall after a seismic event (Event BG7-1). Several SBMS subject areas help in a general sense to prevent ignition of fires: (1) “Electrical Work;” (2) “Fire Protection, Prevention, and Control;” and (3) “Welding, Burning, and Hot Work.” The SNS instrument halls are intended to host numerous diverse experiments during the facility life and some of them may employ one-of-a-kind equipment that is not UL listed. The Ignition Control program as credited in the SNS hazard analysis ensures the following with regard to the configuration of instruments and experiments:

- No routine operations with pyrophoric material are performed in the instrument hall except as approved by the SNS experiment safety review process. This assumption does not include activities such as welding that are governed by SBMS subject areas.
- Equipment shall be UL listed or approved by the authority having jurisdiction.
- Electrical installation meets requirements of NFPA-70, National Electric Code.

ORNL SBMS programs provide and maintain fire protection and minimize ignition likelihood; therefore, no further coverage is required. Reviews of experiment configuration are administered via the SNS experiment review process.

5.3.4 Hoisting and Rigging Program

Crane lifts at ORNL are conducted in accordance with the ORNL Hoisting and Rigging Program as specified and maintained in SBMS. The ORNL Hoisting and Rigging Program provides a structured approach for hoisting and rigging activities, establishes operator qualification and training requirements, and ensures equipment is maintained in proper operating condition. Because the ORNL institutional SBMS Program provides and maintains this protection, no further coverage is required.

5.3.4.1 Restrictions on Crane Lifts in the High Bay

Crane lifts in the high bay are conducted in accordance with the ORNL Hoisting and Rigging Program. Administrative load height and weight restrictions (Section 5.2.12) are credited with ensuring the crane lifts over specific areas of the high bay floor do not exceed the design capacity that these sections of floor were designed to resist. These are imposed through the Operations Envelope.

The high bay floor sections comprise both the service bay T-beams (in the area directly above the mercury loop) and the monolith shine shields (i.e., T-beams)

The proton beam-to-target is required to be terminated and the mercury drained to the storage tank before load movements in excess of the load height and weight limits over the core vessel region or the mercury process system portion of the service bay.

5.3.4.2 External Crane Lifts over the Target Facility

All external crane lifts over the target building fall under the purview of the ORNL SBMS Hoisting and Rigging Program. This requirement for the external crane is credited with providing a means of reducing the frequency of an external crane load drop onto safety-related equipment or primary mercury containment to protect the on-site workers. Conducting lifts in accordance with the ORNL SBMS Hoisting and Rigging Program ensures that lifts are performed in a safe and responsible manner using certified equipment and trained operators. Because the ORNL institutional SBMS Program provides and maintains this protection, no additional coverage is required.

5.3.4.3 Certification and Preventive Maintenance for the Target Service Bay Crane and Gantry Servomanipulator

The appropriate levels of certification and preventative maintenance for the service bay crane and servomanipulator are maintained under a routine preventative maintenance program by trained service personnel.

5.3.5 Procedures and Training

The analysis presented in Section 4 identified several instances in which procedures and training for specific items are required as CACs. These items are discussed in the following subsections. The overall procedures and training programs for the SNS neutron facilities are described in Section 3.4. Operational safety requires that procedures can be modified readily as process knowledge matures or modified operations are undertaken. Approved procedures that fulfill the following credited safety functions are maintained in the OPM. Workers are trained as needed to ensure effective execution of the procedures.

5.3.5.1 Procedures and Training for Evacuation of Adjacent Areas from SBDPMS Alarm

Procedures and training are provided to workers to ensure proper response to the SBDPMS alarm to include: (1) worker evacuation of the service bay and transfer bay; (2) closing the transfer bay personnel access door upon evacuation in the event of a service bay fire (if is safe to remain in area to do so); (3) worker evacuation of areas adjacent to service bay; (4) subsequent evacuations, if required; (5) reentry requirements after alarm evacuation; and (6) requirements that must be satisfied to bypass the alarm. These procedures are addressed in the OPM to ensure the procedures exist and that they meet their credited safety function.

5.3.5.2 Procedures and Training to Control Mercury Inventory on PCES Charcoal Adsorbers

The operations envelope requires procedures to be maintained and followed to ensure that the mercury loading on the charcoal adsorbers is maintained within the limits specified in Section 4. Specifically, mercury loading on each charcoal adsorber is limited to 19.4 kg, and the total mercury loading on all the charcoal adsorbers is limited to 155.2 kg.

5.3.5.3 Emergency Response Procedures and Training

The following three emergency response procedures and training are identified as CACs in the safety analyses in Section 4, and they require OPM coverage to ensure they exist and meet the credited functions:

- Emergency response procedures and training to close the personnel door upon evacuation from service bay fire.
- Emergency response procedures and training for evacuation from service bay fire with common air flow.
- Emergency response procedures and training for evacuation from external crane drop on target building.

5.4 REFERENCES

1. Spallation Neutron Source Policy for Selection of Safety Related Credited Controls, SNS 102030100-ES0005-R00, Spallation Neutron Source, Oak Ridge, Tennessee, March 2005.
2. Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities, DOE STD-1020-2002, US Department of Energy, January 2002.
3. Natural Phenomena Hazards Performance Categorization Guidelines for Structures, Systems, and Components, DOE STD-1021-93, Change Notice 1, Reaffirmed April 2002.
4. Spallation Neutron Source Standards for Design and Construction of the Target Facility, SNS 102030102-ES0012-R1, Spallation Neutron Source, Oak Ridge, Tennessee, October 2002.
5. Process Piping, American Society of Mechanical Engineers, ASME B31.3, 1996.
6. Cryogenic Moderator Pressure Vessel Equivalent Protection, SNS 106020200-PN0002-R00, April 2020.
7. Boiler and Pressure Vessel Code, ASME, Section VIII, American Society of Mechanical Engineers.
8. Bottom Downstream Hydrogen Transfer Line Design Analysis and Calculations, 106020000-DA0002-R00, March 2018.
9. Top Upstream Hydrogen Transfer Link Design Analysis and Calculations, 106020000-DA0003-R00, March 2018.
10. Top Downstream Hydrogen Transfer Line Design Analysis and Calculations, 106020000-DA0004-R00, March 2018.
11. USID for Beam on Target during Venting of the Cryogenic Moderator System, 102030102-ES0025-R01, February 2023.
12. Vacuum Vessel Venting Analysis following Hydrogen Moderator Failure, 106020200-DA0002-R03, December 2017.

13. N. E. Stone, SNS Target Building Seismic Ruggedness Study, Design Analysis Calculation, Rev. 0, BWXT Y-12, LLC, June 2002.
14. R. M. Harrington, Fire Accident Source Terms and Consequences, SNS 102030102-CA0001-R01, Oak Ridge National Laboratory, Oak Ridge, Tennessee, September 26, 2003.
15. Facilities Handling Radioactive Materials, NFPA 801, National Fire Protection Association 1998.
16. Standard Methods of Tests of Fire Endurance of Building Construction and Materials, NFPA-251, National Fire Protection Association, 1999 Edition.
17. P. A. Thornton, Fire Hazards Analysis, Target Buildings 8700, 8702, 8705, 8707, 8711, and 8760 at SNS, Rev. 0 December 2008, SNS 108030700-ES0008-R00.
18. J. Staples, Security of Front End Cutoff Devices, 106080000-DA0001-R00, September 2000.
19. Facility Safety, DOE Order 420.1, US Department of Energy, Washington, D.C., Change 2, October 1996.
20. Implementation Guide for Non-Nuclear Safety Design Criteria and Explosives Safety Criteria, DOE G 420.1-X, US Department of Energy, Washington, D.C.
21. ANSI/ISA-84.00.01-2004 Part I, Functional Safety: Safety Instrumented Systems for the Process Industry Sector—Part I: Framework, Definitions, System Hardware and Software Requirements, approved 2 September 2004.
22. Application of the Single Failure Criterion to Nuclear Power Generating Station Class 1E Systems, IEEE 379, Institute of Electrical and Electronics Engineers, Inc.
23. T. L. Grimm and J. Popielarski, Microphonic Measurements of Beta=0.81 Elliptical Cryomodules in the Spallation Neutron Source Tunnel, SNS 102030102-TR0008-R00, Spallation Neutron Source, Oak Ridge, Tennessee, July 2005.
24. K. Davis and J. Delayen, SNS SRF LINAC Earthquake Response Testing at 4K, SNS 102030102-TR0009-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, July 2005.
25. Standard on Water Mist Fire Protection Systems, NFPA-750, National Fire Protection Association, 1996.
26. Standard for the Installation of Sprinkler Systems, NFPA-13, National Fire Protection Association, 1996.
27. Standard for the Installation of Private Fire Service Mains and Their Appurtenances, NFPA-24, National Fire Protection Association.
28. Standard for Water Tanks for Private Fire Protection, NFPA-22, National Fire Protection Association, 1996.
29. Standard for Inspection, Testing, and Maintenance of Wet-Pipe Sprinkler Systems, NFPA-25, National Fire Protection Association.
30. S. J. Pawel and E. T. Manneschmidt, Corrosion of Type 6061-T6 Aluminum in Mercury and Mercury Vapor, Fifth International Workshop on Spallation Materials Technology, Charleston, South Carolina, May 19–24, 2002.
31. S. J. Pawel, "Draining Hg from Tubes," E-Mail Transmitted to D. Lousteau, April 1999.
32. ASME N 509, "Adsorbers," Specification TS072R01, Section 15475, Rev. 1, American Society of Mechanical Engineers, June 2002.

33. Stainless Steel High Pressure Ductwork and Accessories (Certified Materials), Specification TS0883R06, Section 15895, October 2001.
34. Testing of Nuclear Air Treatment Systems, ASME N 510, American Society of Mechanical Engineers, 1989.
35. Rules for Construction of Overhead and Gantry Cranes, ASME NOG-1-2002, American Society of Mechanical Engineers.
36. 50-Ton NOG-1 Crane, Specification TS0025R02, Section 14631, May 2002.
37. Single-Failure-Proof Cranes for Nuclear Power Plants, NUREG 0554.
38. Crane Manufacturers Association of America Specification CMA 70-1994.
39. Target Building – Evaluation of High Bay Load Drop Limits, SNS 108030700-CA0028, March 2018.
40. Specification for the Design, Fabrication, and Erection of Steel Safety-Related Structures for Nuclear Facilities, ANSI/AISC N690.
41. R. M. Harrington, Normal and Off-Normal Concentrations of Mercury in Target Service Bay Air and Related Need for Safety-Related Equipment, SNS 102030102-CA0002-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, October 2001.
42. Application of Safety Instrumented Systems for the Process Industries, ANSI/ISA S84.01-1996.
43. J. R. Devore, Setpoint Analysis for the Target Service Bay Differential Pressure Monitoring System, 108030700-DA0006-R00, March 2006.
44. SNS Operations Procedure Manuel, Procedure No. 2.J-3, Target Building Combustible Controls.
45. Spallation Neutron Source Final Safety Assessment Document for Proton Facilities, SNS 102030103-ES0018-R02, Oak Ridge National Laboratory, Oak Ridge, Tennessee, December 2010.
46. Standard Building Code (SBC), Southern Building Code Congress 1997.
47. Target Building Facility Use Agreement, FUA-CRC_8700.
48. Accelerator Safety Envelope Adiabatic Target Beam Limit, SNS 106000000-DA0001-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, April 2006.
49. *Description of Changes Made in Response to Mercury Fill Incidents*, SNS 106010200-TR0013-R00, June 2019.
50. *Evaluation of Mercury Containment during a Large Gas Release from the Storage Tank*, SNS 106010200-DA0015-R01, May 2019.
51. Hazard Analysis for Loss of Confinement of o-p Catalyst in Cryogenic Hydrogen Loop, PPUP-103-TR0002-R00, June 2020.
52. *Mercury Process System Mercury Operational Parameters Final Design*, SNS Design Analysis Calculation, SNS 106010202-DA0018-R01, Oak Ridge National Laboratory, Oak Ridge, Tennessee, March 2006.
53. *USID for Modifications to Service Bay Differential Pressure Monitoring System (SBDPMS)*, 102030102-ES0018-R00, February 2006.
54. *USID for Modifications to Service Bay Differential Pressure Monitoring System (SBDPMS)*, 102030102-ES0018-R01, January 2009.
55. *Mercury Process System Safety Scenario Evaluations*, 106010200-DA0011-R00, September 2017.
56. *Height of Hg System Loop Seal*, 106010200-TD0001-R00, April 2006.

6. INTERFACE BETWEEN PROTON AND NEUTRON FACILITIES

Interfaces between the neutron facilities and the proton facilities are described in Section 6 of the FSAD-PF.

7. INSTRUMENT SYSTEMS HAZARDS

Instruments at SNS involve a diverse array of research activities. The presence of scientific users is discussed in Section 3.4.7. Hazards range from radiation hazards to standard industrial and laboratory hazards. SNS has implemented the ORNL SBMS to guide the mitigation or prevention of hazards and hazardous materials, and this guidance applies to instrument system hazards. Hazard mitigation requirements for standard industrial and laboratory hazards and other hazards are promulgated through SBMS and SNS policies and procedures. The instrument review process is described in Section 3.4.6. The instrument review ensures that hazards not addressed by SBMS controls are reviewed and that adequate hazard mitigation is provided.

Experiments performed on SNS instruments undergo an experiment safety review process to identify any hazards associated with a particular experiment and to ensure the hazards are appropriately mitigated. All experiments must be approved via the SNS experiment review process.

7.1 CHEMICAL HAZARDS

Waste accumulation areas are established, as needed, per ORNL and SNS standards and/or procedures, and responsible operations personnel are required to receive appropriate training. This limits the types and volume of chemicals stored and used in work areas. Personnel handling these materials are required to receive adequate training in specific chemical handling procedures and proper use. Any nonstandard chemical usage included in an instrument experiment is reviewed during the SNS experiment safety review process. Chemicals used in experiment samples, or as part of an instrument experiment apparatus, are subject to the ORNL and SNS policies and procedures and are subject to the experiment review process. This process ensures that hazardous materials concerns associated with experiments are identified as early as possible and are handled appropriately. Because the design of all beam experiments cannot be identified and described beforehand, the experiment review process is active throughout the life of the facility.

The risk associated with hazardous chemical use is kept very low through the OSHA-compliant (e.g., 29 CFR 1910.1200 and 29 CFR 1910.1450 [1]) SBMS chemical and hazard communication standards and/or directives, training, and instrument and experiment review.

7.2 CRYOGENIC HAZARDS

Cryogenic systems may be utilized as part of individual instrument operations. SBMS procedures are followed for work with cryogens. Typical applications include the transfer of liquid nitrogen and/or liquid helium from various sized dewars for use in instrument components. Personnel involved in these operations receive adequate safety training. Appropriate safety equipment is required when handling cryogenic fluids. Any nonstandard cryogenic systems included in an instrument experiment are reviewed during the SNS experiment safety review process. Instrument components designed for cryogenic use are reviewed during the instrument review process. Section 7.7 discusses oxygen deficiency hazards.

7.3 ELECTRICAL HAZARDS

Experimental devices are required to meet the intent of the NEC; therefore, NEC rules are followed for instruments (e.g., fusing, connector types, and cable types) where reasonably achievable. Section 5.3.4, “Ignition Control Program,” explains the approach followed to minimize the possibility for instrument and experiment systems becoming ignition sources for fire.

Instrument equipment is typically operated using the electrical power distributed to the instruments from a 115/208 V system. The installation of equipment and electrical utility routing conforms to applicable codes and requirements. Additionally, instrument equipment is UL listed and/or FM approved or requires approval by the division electrical safety officer (DESO). All personnel performing service on equipment are required to receive training in and to adhere to ORNL SBMS procedures related to lock/tag/verify [2]. Compliance with the electrical safety requirements is strictly enforced. Work on energized equipment may be required on some instrument equipment. Only specifically qualified personnel work on equipment or electrical circuitry that has not been deenergized. Such individuals can work safely on energized circuits and are familiar with the proper use of special precautionary techniques, PPE, insulating and shielding materials, and insulated tools. Any work on energized circuits must follow applicable SBMS procedures. This hazard is a common industrial hazard and is well controlled by SNS policies, procedures, and training. Per the ORNL SBMS, NFPA 70 E is followed. Users are restricted from most activities in which 70 E might apply and will follow 70 E for allowed activities in which 70 E is applicable.

7.4 FIRE HAZARDS

Fire protection for the target building, including the instrument halls, is discussed in Section 3.3.10.3. Fire is a standard industrial hazard that is mitigated by applying the NFPA codes in building design and operation. A special concern is the use of combustible hydrocarbon shielding materials in some of the instrument enclosures. The quantities of hydrocarbon are sufficient to justify concern from the point of view of conventional fire protection and from the point of view of preventing the potential release of hazardous material caused by postulated severe fire events. This topic is explored in Section 3.3.13.7 where design features required to mitigate the hazard, such as encapsulation, are explained.

The automatic sprinkler system in the target building is designed to provide an Extra Hazard, (Group I) density, and the water supply can provide protection for a 2 h fire. These safeguards combine to make the fire risk of the encapsulated combustible shielding for instrument enclosures extremely low.

7.5 MAGNETIC FIELD HAZARDS

Magnets may be used in instrument optical components and ancillary equipment. Any significant magnetic fields produced by these magnets are contained within instrument enclosures or limited-access sample areas administratively controlled and/or interlocked while energized. Any regions with fields greater than 5 G are plainly marked, and “No Pacemakers or Other Medical Electronic Devices” signs are posted. Personnel involved in operating, maintaining, and testing magnets are trained in the hazards and precautions associated with magnetic energy, including those relating to ferrous metals, health effects, and medical implants. Any nonstandard magnet systems included in an instrument or experiment are reviewed during the SNS experiment safety review process.

With mitigation provided by SNS magnetic field hazard posting requirements and related training, the risk from magnetic field hazards is well controlled.

7.6 MECHANICAL HAZARDS

Instrument beamlines typically contain rotating machinery, including pumps, blowers, and fans (neutron choppers are discussed below). Proper guarding is designed, and procedures require the equipment to be locked out before the safety guards are removed to service the equipment. Potential pinch points are required to be identified by appropriate warning signs.

Neutron choppers incorporate a rotating mass (i.e., a rotor) capable of storing mechanical energy. Most neutron chopper designs can contain rotor components in the event of a failure. Otherwise, the potential failure modes are analyzed and the design is made sufficiently conservative to ensure that the probability of such failure is extremely low. Comprehensive stress analysis is performed to ensure adequate mechanical design, to identify and minimize potential failure modes, and to provide basis information for routine/planned maintenance. The SNS commitment that choppers shall be designed to either contain rotor fragments in the event of rotor failure or to ensure that the probability of such failure is extremely low renders the mitigated risk from chopper rotating masses extremely low.

Positioning the beamline and instrument components requires forklifts, overhead cranes, and specialized lifting equipment. The use of lifting equipment is governed by SNS and ORNL SBMS safety standards and procedures. Hoisting and rigging operations for large equipment are performed by properly trained and qualified operators, as required, using certified lifting equipment. Some small experimental equipment is manipulated by instrument users with local jib cranes, hoists, and dollies. These personnel are required to receive adequate training in the use of this equipment, and usage requirements are reviewed during the SNS experiment safety review process when appropriate.

Other mechanical hazards are standard industrial hazards adequately controlled by ORNL and SNS policies and procedures.

7.7 OXYGEN DEFICIENCY HAZARDS

An SNS safety goal is that instrument areas are ventilated and do not contain materials in sufficient quantity to contribute to an oxygen-deficient atmosphere during access periods. Therefore, confined spaces, especially permit-required confined spaces, are generally eliminated by design. For cases in which confined spaces are not eliminated by design, atmospheric testing and confined-space work permits may be required per OSHA Standard 29 CFR 1910.146 [1]. Workers who enter confined spaces are trained and qualified in accordance with ORNL SBMS and SNS policies and procedures.

Instruments and sample environments use cryogenic liquids and inert gases that can create an oxygen deficiency hazard under particular circumstances. This hazard is consistent with standard industrial usage and is appropriately managed by SBMS requirements. Processes are in place to evaluate the oxygen deficiency hazard risk and identify controls to protect personnel. Appropriate protection, training, and procedures are required to ensure the hazard is appropriately mitigated in all phases of design and operation.

7.8 RADIATION HAZARDS

Radiation limits for the instrument hall have been set in compliance with 10 CFR 835 [5] and the *SNS Shielding Policy* [6] to ensure shielding is adequate to reduce radiation to ALARA levels. The radiological design goal for shielding in unrestricted work areas is no more than 0.25 mrem/h (shield face). A design goal adopted for instrument design for the maximum radiation level within restricted access spaces such as instrument enclosures is 2.0 mrem/h during personnel occupation. The shielding necessary to meet these guidelines is monitored by configuration control.

Restricted-access spaces are typically accessed only when the instrument shutter blocks the neutron beam upstream of the occupied space. Many of these restricted-access spaces require the shutter to block the neutron beamline to meet the acceptable radiation dose limits. As summarized by Table 7.1, potential radiation hazards exist if personnel attempt to enter these enclosures during beam operation while the shutter is not blocking the neutron beamline. In-beam and area dose rates vary greatly by beamline. The

Table 7.1 analysis is generic and assumes the worst case in beam/area dose rates. Some of the instruments may incorporate features that greatly reduce beam-on dose rates in the enclosure.

The localized neutron dose rate in the beam may be roughly on the order of 100–1000 rem/h. This dose rate assumes a 2 MW proton beam on target, the shutter fails open, all choppers fail open, and the collimating slits of the reflectometer are at their maximum opening. The fall-off in dose rates is substantial, assuming a person stays out of the beam (incident beam collimation, get lost tubes, etc.). Generally, it is not physically feasible for a person to insert their whole body into the beam. At a 1 ft radius from the sample (excluding the incident and transmitted beam), the dose rate typically falls off to levels on the order of about 1–10 rem/h. These risks must be mitigated by a series of personnel protection interlocks. Any limited-access spaces are clearly identified with logical signage indicating beam and shutter status. These spaces comprise comprehensive interlock and safety features included in the instrument PPS as described in Section 3.3.8.3, “Target and Instrument PPS.” The instrument PPS is a CEC.

Some neutron choppers may become significantly activated. The choppers are well shielded when installed in beamline shielding but may present a radiation hazard to personnel during maintenance. These components require periodic maintenance. To reduce worker radiation exposure from these activated components during maintenance, special design features and procedures—including remote handling features to limit the worker exposure during installation or removal processes, special transfer casks to reduce worker exposure during transfer to maintenance areas, and remote utility connections—may be required. These features and procedures are all intended to reduce the personnel exposure.

With application of SNS procedures and controls for radiation shielding and restricted areas, the resultant mitigated risk is extremely low.

Table 7.1. Qualitative risk assessment for the instrument hall—prompt radiation inside instrument enclosures

Facility Name	SNS instrument hall	Number: EX-2		
System:	Neutron instruments			
Subsystem:	Enclosures			
Hazard:	External prompt radiation			
Event	Worker inside instrument enclosure when shutter not closed			
Possible Consequences, Hazards	Excessive radiation exposure			
Potential Initiators	Failure to follow procedures			
Risk assessment before mitigation				
Note: Refer to Figure 4.1 of the FSAD-PF 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
Frequency	**(X) Anticipated high**	( ) Anticipated medium	( ) Unlikely	( ) Extremely unlikely
Risk category	( ) High risk	**(X) Medium**	( ) Low risk	( ) Extremely low
Hazard mitigation	1. Instrument operations procedures 2. Worker/experimenter training 3. Shutter-open warning lights and/or alarms 4. Instrument PPS enclosure door lock 5. Instrument PPS interlock automatic beam cutoff if enclosure door opened when shutter open			
Risk assessment after 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**
Does the hazard require a credited control per Section 4.2.2.4? Y/N Yes (unless demonstrated otherwise on case-by-case basis based on approved instrument specific hazards analysis).				

7.9 VACUUM AND PRESSURE HAZARDS

Many beamlines are maintained and operated under vacuum. Beamline components in vacuum include guides, choppers, and large scattering chambers. All beamline vacuum components are designed to meet, withstand, or eliminate the full range of stresses encountered in vacuum service. Vacuum and pressure systems are reviewed during the instrument review process. Implosion of any vacuum component could pose a potential health risk from flying objects. Because the pressure differential is less than 15 psi, these chambers are not required to meet the ASME B&PV Code, Section VIII, Division 1 [7], or to be code stamped. However, as good practice they are designed to meet the stress level requirement of the ASME B&PV Code. These vacuum vessel designs must also meet any additional requirements identified by the Instrument Safety Committee.

Vacuum window lifetime is evaluated conservatively, so windows are changed before they fail accidentally in service. Neutron windows and feedthroughs are protected from casual impacts or object strikes. Instrument scattering chambers may require large neutron windows. These windows pose a potential health risk from the threat of implosion.

To protect personnel when these chambers are evacuated, access to neutron windows may need to be prevented by secondary enclosures or exclusionary zones interlocked with an appropriate automatic safety instrumented system. Personnel access to these areas is allowed only when the chamber is vented with air and minor pressure differentials exist. When vacuum components are vented for repair or maintenance, a dry nitrogen or air purge may be used for venting. Because most vacuum lines are small in diameter, it is impossible for an individual to insert his/her head into a pure nitrogen atmosphere. If dry nitrogen or gas other than normal dry air is used to re-vent an evacuated vessel with large access hatches, then this vessel requires proper oxygen monitoring and venting equipment interlocked with the PPS system or by stand-alone safety interlocks.

The design criteria for vacuum vessels, including use of shields for neutron windows, lock/tag/verify of vacuum source when close personnel access is required, and possible use of automatic interlocks, combined with the instrument and experiment review processes, provide abundant layers of safety to make the mitigated risk extremely low.

Almost all the scattering chambers and all the sample chambers are intended to be vacuum only. For cases in which these chambers could become pressurized, pressure relief valves or rupture disks are installed. A few of the scattering chambers contain argon gas at roughly atmospheric pressure. For those cases, pressure relief valves are installed, and the argon is appropriately vented.

7.10 NANOPARTICLE HAZARDS

Although specific health effects resulting from the biological uptake of nanoparticles are not fully understood, current practice identifies and controls engineered nanoparticles as potential hazards. At SNS, this hazard is controlled under the SBMS subject area, “Unbound Engineered Nanoparticles.” The experiment review process specifically examines the potential for nanoparticles, and commensurate controls are implemented if nanoparticles will be used. In general, controls focus on preventing airborne dispersion of the particles by characterizing them as bound or unbound, and performing work on unbound particles is allowed only inside HEPA-filtered local exhaust ventilation.

7.11 BIOLOGICAL HAZARDS

Biological materials are controlled under the SBMS subject area, “Biohazards,” and are required to comply with applicable CDC and NIH guidelines as well as other regulations. The experiment review process specifically examines the potential for biological material, and commensurate controls are implemented if biological materials will be used. In general, each biological material is characterized for its specific risk, and controls—including PPE, immunizations, monitoring, and special handling—are selected.

7.12 OTHER HAZARDS

Other hazards are evaluated as the need arises under the ORNL SBMS subject area, “Work Control,” which provides procedures and guidelines for implementing ISM and safely evaluating and controlling hazards associated with proposed neutron beamline activities.

7.13 REFERENCES

1. Code of Federal Regulations, Title 29, “Labor,” Part 1900, US Government Printing Office, Washington, D.C.
2. Standards Based Management System, “Lock/Tag/Verify” Subject Area, Oak Ridge National Laboratory, (https://sbms.ornl.gov/sbms/sbmsearch/SubjArea/LOTO/sa.cfm).
3. “Safety for Cryogenic Operations at SNS,” Appendix D, Spallation Neutron Source Final Safety Assessment Document for Proton Facilities, SNS 102030103-ES0018-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, June 2005.
4. SNS Policy for Selection of Safety Related Credited Engineered Controls, SNS 102030100-E0005-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, March 2005.
5. Code of Federal Regulations, Title 10, “Energy,” Part 835, “Occupational Radiation Protection,” US Government Printing Office, Washington, D.C.
6. Spallation Neutron Source Shielding Policy, SNS 102030000-ES0008, Oak Ridge National Laboratory, Oak Ridge, Tennessee, November 2005.
7. ASME Boiler and Pressure Vessel Code, AMSE, Section VIII, American Society of Mechanical Engineers.

8. QUALITY ASSURANCE

Quality assurance at SNS is addressed in the FSAD-PF.

9. POST-OPERATIONS PLANNING

9.1 INTRODUCTION

This section describes provisions that facilitate post-operations of the SNS facility after its expected operating life. It provides: (1) a description of regulatory requirements; (2) a description of the design and operational considerations; and (3) a summary description of the conceptual post-operations plan.

9.2 REQUIREMENTS

Several laws, regulations, and DOE orders can be expected to apply to future SNS post-operations activities. The primary requirements will be derived from the National Environmental Policy Act, the Resource Conservation and Recovery Act, and the Comprehensive Environmental Response, Compensation, and Liability Act. Requirements under the Clean Air Act and National Emission Standards for Hazardous Air Pollution, Clean Water Act, OSHA, and numerous DOE orders may also be applicable. Various state laws and regulations that implement the federal laws—such as the Federal Facilities Agreement between the Tennessee Department of Environment and Conservation, EPA, and DOE—may also apply to post-operations activities. An important requirement that applies to SNS is DOE Order 430.1, *Real Property Asset Management*. Its implementation guides provide project management, environment, safety, and health requirements and guidance related to future SNS transition and disposition activities, including facility dismantlement.

9.3 POST-OPERATIONS CONSIDERATIONS

Determining the activities and their associated hazards to successfully dismantle the SNS facility will require a systematic approach that will take into consideration several important factors and objectives. The approach includes consideration of the following steps:

1. Establish the expected baseline conditions of the facility at the end of its operating life.

   The first objective in planning is to determine and to manage the risks posed by the facility. Radiation is usually the primary risk, but risks from hazardous and toxic materials and physical condition of the facility are also considered. The expected baseline conditions of the facility at the end of its operating life can be established by estimating the radiation and contamination levels and physical conditions based on activation calculations, design requirements, facility operating parameters, and waste disposal operations requirements. Additionally, methods will be put in place to track spills, spill response actions, information from any beam-loss events, and records of materials replacement to aid in establishing the baseline.

   In accordance with DOE Order 430.1, a post-operations plan, including requirements for characterizing the facility before post-operations activities begin, will be prepared for the facility. This characterization will confirm or reestablish the baseline conditions, will enable a risk assessment to support the safety analysis and alternatives selection, and will help establish surveillance and maintenance required to maintain the facility in a safe standby mode until post-operations activities begin.

2. Understanding the kinds and volume of waste present at the time of shutdown, and the effort required to properly and safely dispose of it, is an important element of the baseline. The wastes are estimated based on the characteristics of specified materials, expected life of components and materials, planned replacement schedules, planned maintenance of the facilities, and waste management practices being developed for operation of the facilities. Consideration of long-term records management throughout

the life of the facility will provide the necessary records to help establish the baseline to facilitate post-operations activities.

3. At the beginning of post-operations activities, facility structures and process equipment will generally be solid wastes. Accordingly, the resulting inventory is expected to be composed largely of process components and structures that are either potentially recyclable (e.g., scrap metal) or are solid wastes. The *Spallation Neutron Source Decontamination and Decommissioning Study* [1] identified 14 general waste categories and approximate volumes expected to be present at the time of post-operations activities as an important component of the baseline.

4. Determine the desired endpoint of the facility and the criteria required for the endpoint conditions.

   The overall facility endpoint goals must be stated very early in the planning process because they form the basis for other specific goals and activities that must occur. The goals for the hazard category and safety basis of the deactivated facility will be established, and defense-in-depth protection measures will be determined.

   Essential to planning the dismantling alternatives for the facility post-operations are determining (1) the desired end product, (2) the final site configuration, and (3) the risks present.

   The post-operations plan will address the baseline conditions and consider all the alternatives that will be evaluated. The dismantlement alternatives are (1) reuse for a similar function, (2) safe storage, (3) Brownfield condition, or (4) Greenfield condition. Institutional control is assumed to remain in place under federal oversight for several years after dismantlement.

   The process for evaluating the most cost-effective alternative and for providing an approach resulting in the least amount of exposure of workers to radiation during the post-operations activities involves considering the pros and cons of each. For example, the front-end facility and the auxiliary/support facilities will be relatively clean and could be expected to be removed, whereas the target building and beam dumps will be highly activated, and the safest and most cost-effective alternative could be a combination of decontamination and safe storage. A combination of the alternatives is a likely scenario to achieve the desired end conditions.

5. Determine the applicable state and federal laws, consensus standards, DOE directives, and other requirements applicable to the post-operations activities, especially those required to meet the endpoint criteria.

   Regulations affecting post operations fall into three categories:

   (1) Those that directly affect post-operations (e.g., the as-needed removal of radioactive materials to reduce future risk)

   (2) Those that protect the worker and the public during dismantling operations

   (3) Those that apply if hazardous or toxic materials that require remediation are present in the facility

   Several orders actually cover two or more of the categories, so requirements often overlap across categories. Sound planning for interacting with the regulatory agencies and compliance with these regulatory requirements are critical to timely and successful completion of post-operations activities and must be an integral part of the initial planning activities.

6. Select the methods that will accomplish the decontamination and dismantlement of the equipment and facilities in a safe and efficient manner while meeting the endpoint criteria.

   Methodologies will be chosen based on the condition of the facility at the time of post-operations (the baseline) and the effectiveness of the methods to achieve the desired end use of the buildings. Additional criteria applied in choosing the methodologies are the ability of the methods to keep personnel exposure ALARA and to protect the environment. For example, some parts of the linac and the support buildings will be contact-handled at shutdown of operations, other parts will require a short decay period to achieve contact-handled levels of activation, and other parts of the facility will be remote-handled for many years. Additionally, although decontamination is not a large part of the SNS post-operations, surface decontamination techniques will be applied to certain areas and equipment that become contaminated during operation or during post-operations activities. Therefore, a variety of techniques and removal methods will be analyzed to select the approach that efficiently accomplishes the goals and optimizes safety to the workers and the environment.

7. Evaluate treatment requirements and disposal options for the wastes remaining from operations as well as those generated by the post-operations activities.

Multiple waste streams will be managed during post-operations. Some could be treated and/or disposed of locally, but much of the waste will be sent off-site for disposal. Studies are required to determine the treatment requirements for the waste streams, the acceptance criteria for potential disposal sites, and the methods of packaging and shipment to meet the criteria. Pollution prevention measures have also been identified in the design/construction of the facility and were implemented, where possible, to help reduce the quantities of waste generated. Present treatment technologies for certain wastes, such as the activated lead and mercury, are time-consuming and expensive. Disposal criteria for these wastes are an uncertainty, and studies will be conducted to determine the optimum.

9.4 DESCRIPTION OF CONCEPTUAL PLANS

Although a detailed post-operations plan has not been established for SNS, a study and a preliminary plan have been conducted for the dismantlement of the SNS facility after operations cease and the facility shuts down [1]. The study recommends actions that could be taken during the design phase to reduce post-operations costs and exposure of personnel during post-operations activities.

The baseline alternative established in the study is decontamination of the entire facility. This alternative would allow for the entire facility to be demolished and removed from the site. All SNS material will be contact-handled and can be removed by conventional methods, except for the target and its associated components, the maintenance bay, and the beam-dump copper targets. However, dismantling and removal of the beam-dump targets will have to be accomplished remotely, with shielding in place, to protect the personnel during removal and shipping off-site. Dismantling the SNS facility will require a combination of standard techniques and specialized use of equipment to accommodate unusual conditions.

The general approach applied in the study for dismantling the front-end facility and user-support facilities is to use conventional methods. These methods can be applied because the facilities are aboveground, are not activated or contaminated except for the two 10,000 ft^2 areas in the technical support and service buildings, and mostly comprise standard equipment and structures. Dismantling the accelerator systems, from the linac tunnel to the target building, will require innovative techniques. These facilities have confined spaces with low head room, areas of high radiation dose levels, and multiple configurations of heavy components, such as the magnets and collimators, and could present challenges in application of conventional techniques. Therefore, considerable effort must be made toward developing approaches to effectively dismantle the SNS accelerator systems and structures while maintaining ALARA principles.

Based on their use in other equally difficult conditions, the approaches and techniques presented in the baseline are judged to be capable of dismantling the facilities while meeting required criteria.

9.5 REFERENCES

1. *Spallation Neutron Source Decontamination and Decommissioning Study,* SNS 102030200-TR0002-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, November 1999.

APPENDIX A. THE CONTROLS MATRIX

Table A-1 presents the controls matrix for the Spallation Neutron Source (SNS) neutron facilities. The controls matrix lists each accident sequence (hazard event) determined by the hazard analysis to require one or more credited controls.

The credited controls (credited engineering controls [CECs] and credited administrative controls [CACs]) are grouped into columns that represent levels of control (LOCs). As described in Section 4.2.2.4, an LOC is defined as “one or more structures, systems, components, administrative controls, or inherent features which can be readily expected to act to prevent or mitigate the release of hazardous material to an unwanted location.”

Credited controls listed in a particular column for a particular event make up the LOC credited to protect the receptor group listed at the top of the column. Often, multiple credited controls are listed together to make up a single LOC. In other instances, a single control suffices as the entire LOC.

The controls matrix shows credited controls that protect three different worker groups defined as follows:

- Worker group (WG)1 includes workers nearest to the hazard.
- WG2 includes workers inside the building but not in the immediate vicinity of the hazard.
- WG3 includes workers outside the building.

Terminology has changed since the original analysis in which the term “Onsite-1” is used to refer to both WG 1 and WG 2 groups together. The term “Onsite-2” is now used to refer to the WG 3 group. The terms “Onsite-1” and “Onsite-2” are used in the Section 4 analysis; however, the three WG categories (i.e., WG1, WG2, and WG3) are retained in the controls matrix because they offer a more detailed definition of effects and facilitate a better understanding of the origin and purpose of credited controls listed to mitigate each event.

Table A-1. SNS controls matrix

Event	Description	Public Evaluation		Worker Evaluation						
		Radiological	Chemical	Radiological				Chemical		
				Worker Group 1	Worker Group 2	Worker Group 3		Worker Group 1	Worker Group 2	Worker Group 3
		CEC/CAC (1, 2)*	CEC/CAC (3)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (5)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*
TS1-2a	Medium sized fire: Fire starts outside of the service bay and propagates into the service bay. Release of mercury and activated water from the systems in the service bay.	Not required	Radiological controls for WG 3 are adequate for chemical protection of public	FSS Outside the Service Bay	FSS Outside the Service Bay	Service Bay and Core Vessel 2-Hour Equivalent Fire Barrier Combustible Material Control Program Outside the Service Bay PCES Air Intake Location	FSS Outside the Service Bay	Radiological controls for WG 1 are adequate for chemical protection	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection
TS1-2b	Medium sized fire: Fire starts in the PCES charcoal absorber room in the target building basement and engulfs a single charcoal absorber.	Not required	Radiological controls for WG 3 are adequate for chemical protection of public	FSS Outside the Service Bay	FSS Outside the Service Bay	Service Bay and Core Vessel 2-Hour Equivalent Fire Barrier Combustible Material Control Program Outside the Service Bay PCES Air Intake Location Procedures and Training to Control Mercury Inventory on PCES Charcoal Adsorbers	FSS Outside the Service Bay	Radiological controls for WG 1 are adequate for chemical protection	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection
TS1-3	Service bay fire: Release of mercury and coolant inventory due to a fire in service bay (during startup when shielding may not be in place) breaching the mercury process system and shroud cooling water system.	Not required	Radiological controls for WG 3 are adequate for chemical protection of public	TBAC	SBDPMS Procedures and Training for Evacuation of Adjacent Areas from SBDPMS Alarm	Service Bay and Core Vessel 2-Hour Equivalent Fire Barrier PCES Backdraft Dampers PCES Flame Retardant Exhaust Filters Combustible Material Control Program Inside the Service Bay	FSS Inside the Service Bay	Radiological controls for WG 1 are adequate for chemical protection	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection
TS1-4	Fire in service bay during maintenance activities when the service bay, transfer bay, and high bay are all open to common air flow and mercury is drained to the storage tank.	Not required	Not required	TBAC	SBDPMS Procedures and Training for Evacuation of Adjacent Areas from SBDPMS Alarm Emergency Response Procedures and Training for Evacuation from Service Bay Fire with Common Air Flow	Not required	Not required	Radiological controls for WG 1 are adequate for chemical protection	Radiological controls for WG 2 are adequate for chemical protection	Not required

Event	Description	Public Evaluation		Worker Evaluation						
		Radiological	Chemical	Radiological				Chemical		
				Worker Group 1	Worker Group 2	Worker Group 3		Worker Group 1	Worker Group 2	Worker Group 3
		CEC/CAC (1, 2)*	CEC/CAC (3)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (5)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*
TS1-6	Fire during maintenance activities with a worker in the transfer bay and the personnel door in the open position.	Not required	Not required	TBAC	SBDPMS Procedures and Training for Evacuation of Adjacent Areas from SBDPMS Alarm	Service Bay and Core Vessel 2-Hour Equivalent Fire Barrier PCES Backdraft Dampers PCES Flame Retardant Exhaust Filters Combustible Material Control Program Inside the Service Bay Emergency Response Procedures and Training to Close the Personnel Door Upon Evacuation from Service Bay Fire	FSS Inside the Service Bay	Radiological controls for WG 1 are adequate for chemical protection	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection
TS3-4	Release of mercury and shroud cooling water into core vessel due to catastrophic failure of target module caused by a loss of material integrity.	Not required	Not required	Physical access within core vessel not credible with systems operational	Confinement Function of Core Vessel and Neutron Beam Windows	Not required	Not required	Physical access within core vessel not credible with systems operational	Radiological controls for WG 2 are adequate for chemical protection	Not required
TS3-6	Release of shroud cooling water into the mercury process system due to a leak from the cooling water loop 2 system through the helium-filled interstitial region. Water boils and results in release of mercury and shroud cooling water into core vessel.	Not required	Not required	Physical access within core vessel not credible with systems operational	Confinement Function of Core Vessel and Neutron Beam Windows	Not required	Not required	Physical access within core vessel not credible with systems operational	Radiological controls for WG 2 are adequate for chemical protection	Not required
TS3-7	Loss of mercury (small break or leak): Release of mercury inside the service bay from various locations.	Not required	Not required	TBAC	Service Bay Confinement of Mercury PCES Ductwork SBDPMS Procedures and Training for Evacuation of Adjacent Areas from SBDPMS Alarm	Not required	Not required	Radiological controls for WG 1 are adequate for chemical protection	Radiological controls for WG 2 are adequate for chemical protection	Not required
TS3-8	Loss of mercury (small break or leak): Release of mercury inside the core vessel due to a leak or a break in the mercury process system from a loss of material integrity.	Not required	Not required	Physical access within core vessel not credible with systems operational	Confinement Function of Core Vessel and Neutron Beam Windows	Not required	Not required	Physical access within core vessel not credible with systems operational	Radiological controls for WG 2 are adequate for chemical protection	Not required

Event	Description	Public Evaluation		Worker Evaluation						
		Radiological	Chemical	Radiological				Chemical		
				Worker Group 1	Worker Group 2	Worker Group 3		Worker Group 1	Worker Group 2	Worker Group 3
		CEC/CAC (1, 2)*	CEC/CAC (3)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (5)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*
TS3-9	Release of intermediate cooling water into the mercury process system due to a break in the mercury heat exchanger that leads to a mercury release in core vessel.	Not required	Not required	Physical access within core vessel not credible with systems operational	Mercury Heat Exchanger Double-Wall Design	Not required	Not required	Physical access within core vessel not credible with systems operational	Radiological controls for WG 2 are adequate for chemical protection	Not required
TS3-10	Loss of mercury (large break): Release of mercury inside the service bay due to a large break in the mercury process system.	Not required	Not required	TBAC	Service Bay Confinement of Mercury PCES Ductwork SBDPMS Procedures and Training for Evacuation of Adjacent Areas from SBDPMS Alarm	Not required	Not required	Radiological controls for WG 1 are adequate for chemical protection	Radiological controls for WG 2 are adequate for chemical protection	Not required
TS3-11	Partial loss of mercury flow: Release of mercury and shroud cooling water inventory due to overheating of target module caused by partial loss of mercury flow from a dislodged object blocking the flow path to the window region or installing the wrong orifice.	Not required	Not required	Physical access within core vessel not credible with systems operational	Confinement Function of Core Vessel and Neutron Beam Windows	Not required	Not required	Physical access within core vessel not credible with systems operational	Radiological controls for WG 2 are adequate for chemical protection	Not required
TS3-12	Full loss of mercury flow: Release of mercury and shroud cooling water inventory into core vessel due to overheating of target module caused by loss of mercury flow.	Not required	Not required	Physical access within core vessel not credible with systems operational	TPS Beam Trip on Low Mercury Loop Flow	TPS Beam Trip on Low Mercury Loop Flow	Not required	Physical access within core vessel not credible with systems operational	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection
TS3-13	Loss of heat sink: Release of mercury and shroud cooling water inventory into the core vessel due to overheating of the target module caused by loss of cooling to mercury process system due to failure in the intermediate cooling water system.	Not required	Not required	Physical access within core vessel not credible with systems operational	TPS Beam Trip on High Mercury Loop Temperature	TPS Beam Trip on High Mercury Loop Temperature	Not required	Physical access within core vessel not credible with systems operational	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection
TS3-14	Loss of heat sink: Release of mercury and shroud cooling water inventory into the core vessel due to overheating of target module caused by loss of cooling to mercury process system due to flow blockage in the intermediate cooling water system.	Not required	Not required	Physical access within core vessel not credible with systems operational	TPS Beam Trip on High Mercury Loop Temperature	TPS Beam Trip on High Mercury Loop Temperature	Not required	Physical access within core vessel not credible with systems operational	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection

Event	Description	Public Evaluation		Worker Evaluation						
		Radiological	Chemical	Radiological				Chemical		
				Worker Group 1	Worker Group 2	Worker Group 3		Worker Group 1	Worker Group 2	Worker Group 3
		CEC/CAC (1, 2)*	CEC/CAC (3)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (5)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*
TS3-15	Loss of heat sink: Release of mercury and shroud cooling water inventory due to overheating of target module caused by loss of cooling to mercury process system due to failure in the intermediate cooling water system.	Not required	Not required	Physical access within core vessel not credible with systems operational	TPS Beam Trip on High Mercury Loop Temperature	TPS Beam Trip on High Mercury Loop Temperature	Not required	Physical access within core vessel not credible with systems operational	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection
TS3-16	Loss of heat sink: Release of mercury and shroud cooling water inventory into core vessel due to overheating of target module caused by loss of cooling to mercury process system due to failure in the intermediate cooling water system.	Not required	Not required	Physical access within core vessel not credible with systems operational	TPS Beam Trip on High Mercury Loop Temperature	TPS Beam Trip on High Mercury Loop Temperature	Not required	Physical access within core vessel not credible with systems operational	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection
TS3-18	Release of mercury inventory into the service bay due to a heavy load drop by the service bay crane.	Not required	Not required	TBAC	Service Bay Confinement of Mercury PCES Ductwork SBDPMS Procedures and Training for Evacuation of Adjacent Areas from SBDPMS Alarm	Not required	Not required	Radiological controls for WG 1 are adequate for chemical protection	Radiological controls for WG 2 are adequate for chemical protection	Not required
TS3-21	Release of mercury to the cooling tower due to breach in the mercury heat exchanger while operating with an existing breach in the cooling loop 1/tower water heat exchanger that causes mercury contamination of tower water.	Not required	Not required	Not required	Not required	Not required	Not required	Mercury Heat Exchanger Double-Wall Design	Mercury Heat Exchanger Double-Wall Design	Not required
TS3-22	Partial loss of mercury flow: Release of mercury and shroud cooling water inventory due to continuous reduction of mercury flow over time and subsequent overheating of the target module from a worn or failing component.	Not required	Not required	Physical access within core vessel not credible with systems operational	TPS Beam Trip on Low Mercury Loop Flow	TPS Beam Trip on Low Mercury Loop Flow	Not required	Physical access within core vessel not credible with systems operational	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection

Event	Description	Public Evaluation		Worker Evaluation						
		Radiological	Chemical	Radiological				Chemical		
				Worker Group 1	Worker Group 2	Worker Group 3		Worker Group 1	Worker Group 2	Worker Group 3
		CEC/CAC (1, 2)*	CEC/CAC (3)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (5)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*
TS3-23	Partial loss of mercury flow: Release of mercury and shroud cooling water inventory due to immediate partial loss of mercury flow and subsequent overheating of the target module.	Not required	Not required	Physical access within core vessel not credible with systems operational	TPS Beam Trip on Low Mercury Loop Flow	TPS Beam Trip on Low Mercury Loop Flow	Not required	Physical access within core vessel not credible with systems operational	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection
TS3-24	Partial loss of mercury flow: Release of mercury and shroud cooling water inventory due to immediate partial loss of mercury flow and subsequent overheating of the target module from pump failure.	Not required	Not required	Physical access within core vessel not credible with systems operational	TPS Beam Trip on Low Mercury Loop Flow	TPS Beam Trip on Low Mercury Loop Flow	Not required	Physical access within core vessel not credible with systems operational	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection
TS3-25	Partial loss of mercury flow: Release of mercury and shroud cooling water inventory due to partial loss of mercury flow and subsequent overheating of the target module from motor speed controller failure.	Not required	Not required	Physical access within core vessel not credible with systems operational	TPS Beam Trip on Low Mercury Loop Flow	TPS Beam Trip on Low Mercury Loop Flow	Not required	Physical access within core vessel not credible with systems operational	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection
TS3-26	Partial loss of mercury flow: Release of mercury and shroud cooling water inventory due to partial loss of mercury flow and subsequent overheating of the target module from an obstruction in line.	Not required	Not required	Physical access within core vessel not credible with systems operational	Confinement Function of Core Vessel and Neutron Beam Windows	Confinement Function of Core Vessel and Neutron Beam Windows	Not required	Physical access within core vessel not credible with systems operational	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection
TS3-27	Partial loss of mercury flow: Release of mercury and shroud cooling water inventory due to partial loss of mercury flow and subsequent overheating of the target module from foreign material left in the system during maintenance.	Not required	Not required	Physical access within core vessel not credible with systems operational	Confinement Function of Core Vessel and Neutron Beam Windows	Confinement Function of Core Vessel and Neutron Beam Windows	Not required	Physical access within core vessel not credible with systems operational	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection
TS3-28	Release of liquid mercury into the mercury off-gas treatment system during initial filling of the mercury pump tank.	Not required	Not required	Mercury Pump Tank Exhaust Line Loop Seal	Not required	Not required	Not required	Not required	Not required	Not required
TS3-36	A rapid injection of pressurized helium gas into the mercury process loop from the storage tank during filling operations causes liquid mercury to be pushed into the mercury off-gas treatment system.	Not required	Not required	Mercury Pump Tank Rupture Disk and Discharge Path Mercury Pump Tank Exhaust Line Loop Seal and Orifice	Not required	Not required	Not required	Not required	Not required	Not required

Event	Description	Public Evaluation		Worker Evaluation						
		Radiological	Chemical	Radiological				Chemical		
				Worker Group 1	Worker Group 2	Worker Group 3		Worker Group 1	Worker Group 2	Worker Group 3
		CEC/CAC (1, 2)*	CEC/CAC (3)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (5)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*
TS4-1	Inadvertent beam on target when the target module is in the withdrawn position (e.g., for maintenance or retargeting).	Not required	Not required	PPS Prevents Beam to Target if Target Cart is Not Inserted	PPS Prevents Beam to Target if Target Cart is Not Inserted	PPS Prevents Beam to Target if Target Cart is Not Inserted	TPS Prevents Beam to Target if Target Cart is Not Inserted	Not required	Not required	Not required
TS4-2	Direct radiological exposure from residual mercury during target changeout activities in the service bay.	Not required	Not required	TBAC	TBAC	Not required	Not required	Not required	Not required	Not required
CM2-1a	Breach of cryogenic moderator vessel allows hydrogen to escape from the moderator vessel (large leak) into the surrounding area within the core vessel. Hydrogen accumulates in concentrations greater than the LEL in air, is inadvertently ignited, and explodes releasing mercury and activated cooling water. A follow-on fire results.	Not required	Radiological controls for WG 3 are adequate for chemical protection of public	Physical access within core vessel not credible with systems operational	CMS Hydrogen Boundary	CMS Hydrogen Boundary	CMS Vacuum Boundary	Physical access within core vessel not credible with systems operational	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection
CM2-1b	Breach of cryogenic moderator vessel allows hydrogen to escape from the moderator vessel (large leak) into the surrounding area within the core vessel. Hydrogen accumulates in concentrations greater than the LEL in air, is inadvertently ignited, and explodes releasing mercury and activated cooling water. No follow-on fire results.	Not required	Radiological controls for WG 3 are adequate for chemical protection of public	Physical access within core vessel not credible with systems operational	CMS Hydrogen Boundary	CMS Hydrogen Boundary	CMS Vacuum Boundary	Physical access within core vessel not credible with systems operational	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection
CM4-1	Media is released from CMS o-p catalytic converters into the moderator loop, becomes activated, and exposes workers in the high bay.	Not required	Not required	Catalytic Converter Retention Elements	Not required	Not required	Not required	Not required	Not required	Not required

Event	Description	Public Evaluation		Worker Evaluation						
		Radiological	Chemical	Radiological				Chemical		
				Worker Group 1	Worker Group 2	Worker Group 3		Worker Group 1	Worker Group 2	Worker Group 3
		CEC/CAC (1, 2)*	CEC/CAC (3)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (5)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*
CW4-1	Direct radiological exposure of personnel to activated cooling water in loops 2, 3, or 4. Personnel in direct line-of-sight and in immediate vicinity of cooling water systems in basement utility vault, service bay, or high bay (with shielding blocks removed during beam operations or immediately after beam shutdown prior to short-lived nuclide decay).	Not required	Not required	Radiological Protection Program	Radiological Protection Program	Not required	Not required	Not required	Not required	Not required
GW3-2	Leak or breach of mercury off-gas treatment system within the service bay results in the release of mercury vapor and off-gases into the service bay atmosphere.	Not required	Not required	TBAC	Not required	Not required	Not required	Radiological controls for WG 1 are adequate for chemical protection	SBDPMS Procedures and Training for Evacuation of Adjacent Areas from SBDPMS Alarm	Not required
GW3-2a	Leak or breach of mercury off-gas treatment system within the GAR results in the release of radioactive gases, exposing personnel in the GAR.	Not required	Not required	Radiological Protection Program	Not required	Not required	Not required	Not required	Not required	Not required
HV3-5	Breach of HEPA filter confinement package from mishandling or defect results in release of radiological material (during replacement).	Not required	Not required	Radiological Protection Program	Radiological Protection Program	Not required	Not required	Not required	Not required	Not required
SH4-1	Misaligned target module results in radiation streaming into the service bay and the adjacent operating/service galleries. Or misaligned proton beam window plug assembly or core vessel inner plug assembly (with moderator vessels) results in radiation streaming into the high bay.	Not required	Not required	Radiological Protection Program	Radiological Protection Program	Not required	Not required	Not required	Not required	Not required
SH4-2	Voids or cracks in concrete shielding result in abnormally high radiation levels in occupied areas of the target building.	Not required	Not required	Radiological Protection Program	Radiological Protection Program	Not required	Not required	Not required	Not required	Not required
SH4-3	Inadvertent shutter opening during operations when beamline shielding is not in place.	Not required	Not required	Radiological Protection Program	Not required	Not required	Not required	Not required	Not required	Not required

Event	Description	Public Evaluation		Worker Evaluation						
		Radiological	Chemical	Radiological				Chemical		
				Worker Group 1	Worker Group 2	Worker Group 3		Worker Group 1	Worker Group 2	Worker Group 3
		CEC/CAC (1, 2)*	CEC/CAC (3)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (5)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*
SH4-4	Direct radiological exposure to worker during shutter removal.	Not required	Not required	Radiological Protection Program	Radiological Protection Program	Not required	Not required	Not required	Not required	Not required
TC3-1	Loss of confinement from service bay allows leakage of mercury vapor and other radiological material to occupied areas (assumes loss of PCES ventilation in service bay during transfer bay access).	Not required	Not required	SBDPMS Procedures and Training for Evacuation of Adjacent Areas from SBDPMS Alarm	SBDPMS Procedures and Training for Evacuation of Adjacent Areas from SBDPMS Alarm	Not required	Not required	Radiological controls for WG 1 are adequate for chemical protection	Radiological controls for WG 2 are adequate for chemical protection	Not required
TC3-2	Target module drive mechanism drives target module into core vessel colliding with the core vessel. Alternately, target drive mechanism drives target module into service bay during module removal for retargeting. The target module collides with service bay components. Residual mercury remaining in the module is spilled into the service bay.	Not required	Not required	TBAC	SBDPMS Procedures and Training for Evacuation of Adjacent Areas from SBDPMS Alarm	Not required	Not required	Radiological controls for WG 1 are adequate for chemical protection	Radiological controls for WG 2 are adequate for chemical protection	Not required
TC3-3	During beam operations, the target module drive mechanism activates, driving the target module and shielding plug out of the core vessel while the target module is filled with mercury. Mercury and shroud cooling water spill into the service bay. Beam stays on and mercury pump continues to pump until pump tank level is below impeller suction.	Not required	Not required	TBAC	Service Bay Confinement of Mercury PCES Ductwork SBDPMS Procedures and Training for Evacuation of Adjacent Areas from SBDPMS Alarm	Not required	Not required	Radiological controls for WG 1 are adequate for chemical protection	Radiological controls for WG 2 are adequate for chemical protection	Not required
TC4-1	Inadvertent opening of intra-bay shield doors between transfer bay and service bay while personnel are working in transfer bay due to worker error or drive motor short that results in excessive worker exposure.	Not required	Not required	TBAC	TBAC	Not required	Not required	Not required	Not required	Not required

Event	Description	Public Evaluation		Worker Evaluation						
		Radiological	Chemical	Radiological				Chemical		
				Worker Group 1	Worker Group 2	Worker Group 3		Worker Group 1	Worker Group 2	Worker Group 3
		CEC/CAC (1, 2)*	CEC/CAC (3)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (5)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*
TC4-2	Load suspended from the service bay crane swings during sudden lateral movement of the crane trolley. Load swings into shielded viewing window, partially or fully shattering the window. Personnel in the manipulator gallery are exposed to direct radiation from the service bay.	Not required	Not required	TBAC	Hoisting and Rigging Program Radiological Protection Program	Not required	Not required	Not required	Not required	Not required
TC4-3	Direct exposure to radioactive mercury due to a breach in the mercury and cooling water loop 1 heat exchanger.	Not required	Not required	Mercury Heat Exchanger Double-Wall Design	Mercury Heat Exchanger Double-Wall Design	Not required	Not required	Not required	Not required	Not required
TC4-4	Direct radiological exposure to worker performing maintenance activities in the transfer bay with personnel door in the open position due to mercury vapor from a loss of ventilation.	Not required	Not required	SBDPMS Procedures and Training for Evacuation of Adjacent Areas from SBDPMS Alarm	SBDPMS Procedures and Training for Evacuation of Adjacent Areas from SBDPMS Alarm	Not required	Not required	Not required	Not required	Not required
HB2-2	Release of radiological material (mercury) from the core vessel as a result of a high bay crane or pedestal manipulator load drop on the core vessel causing sufficient displacement of the inner reflector plug to breach the cryogenic moderator vessels and the mercury target, spilling hydrogen and mercury within the core vessel. Released hydrogen is ignited and explodes within the core vessel.	Not required	Radiological controls for WG 3 are adequate for chemical protection of public	Physical access within core vessel not credible with systems operational	High Bay Crane Design Hoisting and Rigging Program CMS Hydrogen Boundary	High Bay Crane Design Hoisting and Rigging Program CMS Hydrogen Boundary	High Bay Floor Design Hoisting and Rigging Program	Physical access within core vessel not credible with systems operational	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection
HB3-2	Dropped transfer cask from crane failure or operator error results in release of radiological material.	Not required	Not required	High Bay Crane Design Hoisting and Rigging Program	High Bay Crane Design Hoisting and Rigging Program	Not required	Not required	Not required	Not required	Not required
HB3-3	High bay crane load drop onto the service bay results in release of radiological material (mercury) from the service bay. There is no explosion.	Not required	Not required	TBAC	High Bay Crane Design Hoisting and Rigging Program	Not required	Not required	Radiological controls for WG 1 are adequate for chemical protection	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection

Event	Description	Public Evaluation		Worker Evaluation						
		Radiological	Chemical	Radiological				Chemical		
				Worker Group 1	Worker Group 2	Worker Group 3		Worker Group 1	Worker Group 2	Worker Group 3
		CEC/CAC (1, 2)*	CEC/CAC (3)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (5)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*
HB3-6	Dropped transfer bay shielding door from failure of suspension system or operator error results in release of radiological material.	Not required	Not required	TBAC	TBAC	Not required	Not required	Not required	Not required	Not required
HB3-7	Release of radiological material (mercury) from the core vessel as a result of a high bay crane load drop on the core vessel causing sufficient displacement of the inner reflector plug to breach the cryogenic moderator vessels and the mercury target, spilling hydrogen and mercury within the core vessel. No explosion occurs.	Not required	Not required	Physical access within core vessel not credible with systems operational	High Bay Crane Design Hoisting and Rigging Program	Not required	Not required	Physical access within core vessel not credible with systems operational	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection
HB4-3	Excessive radiation exposure due to inappropriate removal of movable shielding in the high bay (e.g., by use of the high bay crane).	Not required	Not required	Radiological Protection Program	Radiological Protection Program	Not required	Not required	Not required	Not required	Not required
BG1-1	Facility wide fire results in release of hazardous material (fire originates outside of the service bay).	Not required	Radiological controls for WG 3 are adequate for chemical protection of public	TBAC	Service Bay and Core Vessel 2-Hour Equivalent Fire Barrier Combustible Material Control Program Outside the Service Bay PCES Air Intake Location	Service Bay and Core Vessel 2-Hour Equivalent Fire Barrier Combustible Material Control Program Outside the Service Bay PCES Air Intake Location Procedures and Training to Control Mercury Inventory on PCES Charcoal Adsorbers	FSS Outside the Service Bay	Radiological controls for WG 1 are adequate for chemical protection	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection
BG6-11	External crane drops load on target building or impacts building resulting in release of radiological material (mercury).	Not required	Radiological controls for WG 3 are adequate for chemical protection of public	Hoisting and Rigging Program	Hoisting and Rigging Program	Hoisting and Rigging Program	Emergency Response Procedures and Training for Evacuation from External Crane Drop on Target Building	Radiological controls for WG 1 are adequate for chemical protection	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection

Event	Description	Public Evaluation		Worker Evaluation						
		Radiological	Chemical	Radiological				Chemical		
				Worker Group 1	Worker Group 2	Worker Group 3		Worker Group 1	Worker Group 2	Worker Group 3
		CEC/CAC (1, 2)*	CEC/CAC (3)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (5)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*
BG7-1	Damage to target building and subsequent release of hazardous material due to NPH event followed by an explosion and follow-on fire.	Not required	Radiological controls for WG 3 are adequate for chemical protection of public	N/A (instinctive worker evacuation of the target building in a severe seismic event)	N/A (instinctive worker evacuation of the target building in a severe seismic event)	Service Bay and Core Vessel 2-Hour Equivalent Fire Barrier Combustible Material Control Program Outside the Service Bay Combustible Material Control Program Inside the Service Bay CMS Hydrogen Boundary Procedures and Training to Control Mercury Inventory on PCES Charcoal Adsorbers	Service Bay Confinement of Mercury Ignition Control Program	Radiological controls for WG 1 are adequate for chemical protection	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection
BG7-2	Structural damage to target building from an earthquake results in release of radiological material. No explosions or follow-on fires.	Not required	Not required	N/A (instinctive worker evacuation of the target building in a severe seismic event)	N/A (instinctive worker evacuation of the target building in a severe seismic event)	Not required	Not required	Radiological controls for WG 1 are adequate for chemical protection	Radiological controls for WG 2 are adequate for chemical protection	Service Bay and Monolith Confinement of Mercury
BG7-3	Structural damage to system components and target building from an earthquake followed by hydrogen explosion results in release of radiological material.	Not required	Radiological controls for WG 3 are adequate for chemical protection of public	N/A (instinctive worker evacuation of the target building in a severe seismic event)	N/A (instinctive worker evacuation of the target building in a severe seismic event)	CMS Hydrogen Boundary CMS Vacuum Boundary	Service Bay and Monolith Confinement of Mercury	Radiological controls for WG 1 are adequate for chemical protection	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection

*Numbers in parentheses correspond to criteria for selection of credited controls outlined in Section 4.2.2.4