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Spallation Neutron Source Final Safety Assessment Document For Neutron Facilities

September 2011

SPALLATION NEUTRON SOURCE

A U.S. Department of Energy Multilaboratory Project

Argonne National Laboratory • Brookhaven National Laboratory • Thomas Jefferson National Accelerator Facility • Lawrence Berkeley National Laboratory • Los Alamos National Laboratory • Oak Ridge National Laboratory

SNS

Spallation Neutron Source
Final Safety Assessment Document
For Neutron Facilities

September 2011

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This document describes the SNS Neutron Facilities, identifies and analyzes associated hazards, and identifies appropriate controls to mitigate hazards in accordance with DOE Order 420.2C. This document is an update to the previous version (SNS 102030103-ES0018-R02, April 2007) and is issued to ensure the document remains "current and consistent" per the requirements of DOE Order 420.2C. The SNS Final Safety Assessment Document for Proton Facilities (102030103-ES0018-R02) serves as a companion document.

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TABLE OF CONTENTS

Page

LIST OF FIGURES

Figure **Page**

LIST OF TABLES

Table **Page**

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
ALD	Associate Lab Director
ANL	Argonne National Laboratory
ANSI	American National Standards Institute
ASE	accelerator safety envelope
ASME	American Society of Mechanical Engineers
ASO	accelerator safety order
atm	atmosphere
B&PV	Boiler and Pressure Vessel Code
BD	Identifier for Beam Dumps events
Be	beryllium
BG	Identifier for Target Building General hazard events
BNL	Brookhaven National Laboratory
BSS	beam shutdown stations
C	Celsius
CA	Identifier for Compressed Air System hazard events
CAA	Clean Air Act
CAC	credited administrative control
CCR	Central Control Room
CCTV	closed-circuit television
CEBAF	Continuous Electron Beam Accelerator Facility— (at Thomas Jefferson National Accelerator Laboratory—[TJNAF] [JLAB])
CEC	credited engineered control
CEDE	committed effective dose equivalent
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFCC	Conventional Facilities Central Control
CFD	computational fluid dynamics
CFR	Code of Federal Regulations
CHL	central helium liquefier
Ci	Curie
CLO	Central Laboratory and Office
CM	Identifier for Cryogenic moderator system hazard events
cm	centimeter
CMAA	Crane Manufacturers Association of America
CMS	cryogenic moderator system
CO_2	carbon monoxide
CRL	Central Research Laboratories
CUB	central utility building
CW	Identifier for cooling water loops 2, 3, and 4 hazard events
CWA	Clean Water Act
DBA	design basis accident

dc	direct current
DCF	dose conversion factor
DEM	digital elevation model
DI	deionized
DOE	Department of Energy
DTL	drift tube LINAC
EG	evaluation guideline
EPA	Environmental Protection Agency
EPICS	Experimental Physics and Industrial Control System
ERPG	Emergency Response Planning Guideline
ES&H	environment, safety, and health
ETTP	East Tennessee Technology Park (also known as the K-25 site)
F	Fahrenheit
FELK	Front End, LINAC, and Klystron
FHA	fire hazards analysis
FM	factory mutual
FNAL	Fermi National Accelerator Laboratory
fpm	feet per minute
FS	Identifier for Fire Detection and Suppression System hazard events
FSAD	final safety assessment document
FSS	fire suppression system
ft	foot/feet
FY	fiscal year
g	gram
G	Gauss
GeV	giga electron volts (10^9 eV)
GW	Identifier for Mercury offgas treatment, vacuum, and helium systems hazard events
GWS	gaseous waste system
h	hour
H^-	hydrogen ions
HA	hazard analysis
HAZCOM	hazard communication
HB	Identifier for high bay area hazard events
HC	hazard category
He	helium
HE	hazard evaluation
HEBT	high energy beam transport
HEPA	high efficiency particulate air
Hg	mercury
HOG	hot offgas
HUR	hydrogen utility room
HV	Identifier for Confinement Ventilation Systems hazard events
HVAC	heating, ventilation, and air conditioning
Hz	Hertz (cycles per second)
I&C	instrumentation and control
I/O	input/output
IC	initial condition
ICRP	International Commission on Radiological Protection
ICS	integrated control system
IEEE	Institute of Electrical and Electronics Engineers, Inc.
in.	inch(es)

INEEL	Idaho National Engineering and Environmental Laboratory
IOC	input/output controller
ISA	Instrument Society of America
ISCST	industrial source complex short term
ISM	Integrated Safety Management
ISO	International Organization for Standardization
J	Joule
JHA	job hazard analysis
JLAB	Thomas Jefferson National Accelerator Facility (TJNAF)
K	Kelvin
kg	kilogram
kV	kilovolt
kW	kilowatt
L	liter
LANL	Los Alamos National Laboratory
lb	pound
LBNL	Lawrence Berkeley National Laboratory
LEBT	low energy beam transport
LFL	lower flammability limit
LHe	liquid helium
LINAC	linear accelerator
LLLW	liquid low-level waste
LO/TO	lockout/tagout
LOC	level of control
m	meter
MCI	maximum credible incident
min	minute
MJ	megajoules
mm	millimeter
MOI	maximum offsite individual
MOTS	mercury offgas treatment system
MPa	megapascals
MPFL	maximum possible fire loss
mph	miles per hour
MPS	machine protection system
mrem	millirem
ms	millisecond
MSDS	material safety data sheet
MW	megawatt (million watts)
NEC	National Electric Code
NEPA	National Environmental Policy Act
NESHAP	National Emission Standards for Hazardous Air Pollution
NF	Neutron Facilities
NFDD	Neutron Facilities Development Division
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
nm	neutron mirror
NPH	Natural Phenomena Hazard
NSSD	Neutron Scattering Science Division
ODH	oxygen deficiency hazard
OPM	Operations Procedures Manual

ORNL	Oak Ridge National Laboratory, X-10
ORR	Oak Ridge Reservation
OSHA	Occupational Safety and Health Administration
OST	Operations Shift Technician
P2	pollution prevention
Pa	Pascal
PC	performance category
PCE	primary confinement exhaust
PCES	primary confinement exhaust system
PF	Proton Facilities
PLC	programmable logic controller
PPE	personal protective equipment
PPS	personnel protection system
PSAR	Preliminary Safety Analysis Report
psi	pounds per square inch
psia	pounds per square inch absolute
psig	pounds per square inch gauge
PW	process waste
PW	Identifier for process waste and sanitary waste systems hazard events
QA	quality assurance
QC	quality control
QF	quality factor
QS	qualification standard
rad	radiation absorbed dose
RAD	Research Accelerator Division
RCRA	Resource Conservation and Recovery Act
RCT	Radiological Control Technician
rem	unit of radiation dose (roentgen equivalent man)
RF	radio frequency
RH	remotely handled
RHIC	Relativistic Heavy Ion Collider
RRF	respirable release fraction
RSO	Radiation Safety Officer
RTBT	ring-to-target beam transport
RTD	resistance temperature detector
RWP	Radiological Work Permit
SAD	safety assessment document
SAR	Safety Analysis Report
SBC	Standard Building Code
SBMS	Standards-Based Management System
SCADA	supervisory control and data acquisition
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
SIS	safety-instrumented system
SNS	Spallation Neutron Source
SOP	standard operating procedure
SPCC	Spill Prevention Control and Countermeasures
sq	square

SSC	structures, systems, or components
T	Tesla
TBAC	Transfer Bay Access Control
TC	Identifier for Target Bay Service General Area hazard events
TDEC	Tennessee Department of Environment and Conservation
TJNAF	Thomas Jefferson National Accelerator Facility (JLAB)
TLDs	thermoluminescent dosimeters
torr	133.322 Pa
TPS	target protection system
TS	Identifier for Target Systems hazard events
TVA	Tennessee Valley Authority
UL	Underwriters Laboratories Inc.
UPS	uninterruptible power supply
μrem	microrem
μs	microseconds
USI	unreviewed safety issue
UT	University of Tennessee
UV	Identifier for Truck Bay and Utility Vault General Area hazard events
V	Volt
WH	Identifier for Contact Waste Handling and Decontamination area hazard events
WSS	work smart standards
WWS	window work station
y	year

1.0 INTRODUCTION

SNS is designed and operated as a user facility offering a wide variety of neutron-based research capabilities. The Spallation Neutron Source (SNS) Neutron Facilities (NF) are an integral part of the SNS accelerator complex. The Neutron Facilities are housed in the SNS target building and include the target systems, instrument systems, and related support facilities. The target systems include facilities necessary for the production of neutron beams, including the mercury target loop, associated cooling loops, the neutron moderators, and other necessary support systems required for the safe operation of the target. The instrument systems include components and systems associated with the neutron scattering instruments (beamline shielding, optical beamline components, choppers, instrument detectors, etc.).

The scope of this document is focused specifically on the safety evaluation of activities associated with the Neutron Facilities and serves as a companion document to the *Spallation Neutron Source Final Safety Assessment Document for Proton Facilities (FSAD-PF)*[1] which addresses hazards associated with the production of the proton beam. The FSAD-PF additionally addresses site-wide issues as well as the overall Oak Ridge National Laboratory (ORNL) institutional approach to safety. Together, the FSAD-NF and FSAD-PF provide a comprehensive safety assessment for hazards associated with the SNS as required by Order 420.2C[2].

Accelerator specific safety related controls identified in the FSAD documents combined with other applicable safety related ORNL institutional controls and management systems serve to ensure safety for all SNS activities.

The SNS is committed to providing a high degree of assurance of safety in all activities conducted at the site. Since the SNS is part of ORNL, the activities of the SNS are supported by laboratory resources, management systems, policies, and infrastructure. The SNS implements the ORNL Standards-Based Management System (SBMS) to ensure a uniform and proactive approach to safety. These elements, combined with specific safety features and practices outlined herein, ensure a high degree of safety.

A summary of the overall results and conclusions of the safety analysis is presented in Chapter 2. A detailed facility description and a description of the SNS approach to operations is provided in Chapter 3.

Chapter 4 presents the safety assessment, including the identification of hazards, risks, and controls. A large number of accident events were systematically postulated and evaluated. After evaluation, it was found that only a small fraction of the postulated events had the potential to lead to significant consequences. Each postulated event with the potential for significant consequences was evaluated, and mitigative controls (design features, engineered controls, and/or administrative controls) were selected. A systematic screening process was used to determine the events with the greatest hazard potential. Those events were analyzed in more detail.

Essential controls identified as necessary to mitigate significant postulated accident consequences in Chapter 4 are termed *Credited Controls*. Credited controls are described in detail in Chapter 5. The bases for the appropriate level of protection for credited controls in the Accelerator Safety Envelope (ASE) are also presented. The ASE is issued as a separate DOE-approved document, and the requirements therein are strictly adhered to.

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

Chapter 9 provides a summary of preparations and planning for the eventual Post Operational phase of SNS.

Chapters 6 and 8 provide references to the chapters in the FSAD-PF[1] that describe, respectively, interfaces between Proton Facilities and Neutron Facilities, and Quality Assurance.

1.1 REFERENCES

1. *SNS Final Safety Assessment* Document *for Proton Facilities,* SNS 102030103-ES0018-R02, Oak Ridge National Laboratory, Oak Ridge, TN, December 2010.
2. *Safety of Accelerator Facilities, DOE Order 420.2C,* U.S. Department of Energy, Washington, DC.

2.0 SUMMARY AND CONCLUSIONS

This document represents the culmination of a multi-year process involving close cooperation between designers, safety analysts, and operations personnel to produce a design that provides the facilities needed to meet ambitious operational and research goals while meeting applicable safety requirements. A structured process has been used to ensure effective integration of safety and design based on the requirements of DOE Order 420.2C[1] and the guidance of DOE Guide 420.2-1[2]. DOE Standard 3009[3] was used as a reference standard to help ensure that all appropriate accident scenarios were considered. The first formal safety analysis for the target facility was extensively reviewed by independent experts and approved by Department of Energy (DOE) in 2000 prior to beginning construction of the target facility. As the Spallation Neutron Source (SNS) design evolved, updates and revisions to the original analysis were issued following independent evaluation by external reviewers. The process of evaluating hazards and safety will continue for the life of the facility. The Safety Assessment Document (SAD) is a living document, to be periodically updated as needed.

The detailed safety analysis presented here verifies that the design of the SNS neutron facilities effectively mitigates hazards, primarily through the use of passive design features. A rigorous and comprehensive process has been employed to identify hazards and to assess the potential impacts 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 their operations have been assessed and, where needed, controls to effectively eliminate risks were developed and implemented. The analyses show that there is no credible mechanism, with the energy sources available (including the proton beam, a massive earthquake, potential fires, and combustion of hydrogen in the neutron moderator system), for enough mercury or any other radioactive material to be driven from the facility to cause other than negligible offsite impact.

Target Building Activities

The target building houses the SNS Neutron Facilities, which include the target systems and the neutron scattering instruments. Activities conducted within the facility consist primarily of (1) the operation and maintenance of target and support systems and (2) installation, operation, and maintenance of neutron scattering instruments.

Operation of the facility includes directing the proton beam onto the target, circulation of the mercury in the target loop, circulation of water through the associated cooling systems, circulation of hydrogen and helium for the cryogenic moderator system (CMS), and operation of other various support systems. Control of these systems is primarily accomplished from the central control room (CCR), with some hands-on controls located in various locations throughout the target building. Several radioactive components require periodic and remote replacement and disposal including the target module, proton beam window, and inner reflector/moderator plug. The facility has been engineered to accommodate efficient remote handling activities to minimize personnel exposures and facility downtime. Mercury was selected as the target material because of its superior heat removal and neutron production characteristics and because of safety advantages such as no need for decay heat removal after shutdown.

Use of SNS instruments by ORNL or external scientific investigators is governed by SNS policies and procedures. Experiments are normally conducted round-the-clock when the facility is operating.

Installation and upgrade of neutron scattering instruments are expected to be ongoing activities. Once the initial suite of instruments has been installed, it is anticipated that instruments will be replaced or upgraded at a rate of about two instruments per year.

Identification and Analysis of Hazards

A rigorous approach, based on the methodology of DOE-STD-3009[3], 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 screen out standard industrial and laboratory hazards and hazards with insignificant risk potential. Standard industrial and laboratory hazards are controlled and mitigated through implementation of appropriate procedures and subject areas in the ORNL Standards-Based Management System (SBMS). Over 180 events representing a comprehensive spectrum of accidents have been evaluated. A qualitative and semi-quantitative hazard evaluation was first performed and then a subset of representative bounding events in six basic categories was selected for detailed quantitative accident analysis.

Direct exposure to prompt radiation associated with the proton beam and exposure to the radioactive target mercury are the two primary accelerator specific hazards at the SNS site. Hazards and controls associated with the proton beam are primarily addressed in the FSAD-PF[7]. Hazards associated with the mercury are addressed here. Mercury becomes radioactive with proton beam irradiation and is chemically toxic. Approximately 1.6 m^3 of mercury is used in the target system. Radionuclides associated with the target mercury include hundreds of short- and long-lived spallation and activation products; however, six radionuclides (^{203}Hg, ^{197}Hg, ^{194}Hg, ^{189}Hg, ^{148}Gd, and ^{178}Ta) dominate the radiological hazard and account for more than 80% of potential radiation doses.

Radiological impacts presented in the safety analyses (Chapter 4) have been very conservatively assessed. All accident analyses assume the target mercury contains the maximum radionuclide inventory associated with 40 years of full power operations. 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.

Prompt radiation released from the interaction of the proton beam on the mercury produces lethal levels of radiation and is mitigated with massive shielding. Relatively high levels of neutron and gamma radiation are associated with the neutron beamlines of the scattering instruments. These hazards are mitigated through the use of shielding and personnel access control.

Toxicological impacts 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. Airborne mercury dispersion was calculated using conservative meteorological dispersion. Controls chosen to mitigate radiological impacts also mitigate toxicological impacts.

Proper evaluation of energy sources that could 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.

A generic safety analysis for hazards associated with neutron scattering instruments has been performed for the instrument systems. The hazards are largely controlled thru the use of the massive, seismically qualified shielding and other robust passive features. Necessary active controls, such as personnel protection system (PPS) protected access control, have been identified to ensure experimenter and staff safety. Instrument-specific reviews to assess hazards and controls associated with each instrument are conducted before each instrument goes into operation.

Development of Controls

Credited controls have been selected in accordance with the *SNS Policy for Selection of Safety Related Credited Control*[4] which favors reliance on passive over active design features and favors engineered over administrative controls. Mitigation of risks associated with the target facility is largely achieved with passive design features, consistent with the SNS policy.

The configuration of the target facility meets the SNS mission of producing an intense source of short pulsed 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 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 target service bay with only the target module extending into the core vessel. The entire target service bay is stainless steel lined and is enclosed by massive shielding designed to withstand natural phenomena including severe seismic events and high winds. The process bay floor is sloped one degree from horizontal 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 lbs) steel shielding structure of the monolith that provides additional assurance of mercury confinement. The facility has been designed to rigorous standards[5, 6] to withstand any credible natural phenomena, including a severe PC-3 (2500 year) earthquake, without excessive release of mercury or other radioactive materials to the workplace or environment. This is accomplished utilizing 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 personnel protection system (PPS) provides beam trips 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 when the target mercury cooling is lost. Proper function of active controls is ensured by complying with surveillance/maintenance requirements specified in the accelerator safety envelope (ASE).

Certain credited administrative controls (CAC) have also been identified. To a large extent, required administrative controls are addressed by integrated safety management (ISM) programs already well established and maintained through the SBMS at the Oak Ridge National Laboratory (e.g., radiological protection, fire protection, electrical safety, etc.). Credited Administrative Controls specific to SNS are addressed in the approved Operations Procedure Manual to ensure their safety function is maintained.

Key Results

The detailed safety analysis presented here verifies that the design of the SNS target facility effectively mitigates hazards to workers, experimenters, the public, and the environment; primarily through the use of passive design features.

Table 2-1 presents a summary of off-site impacts associated with postulated worst-of-class accidents taken from the basic accident categories. Toxicological impacts are presented in terms of the ratio of the calculated airborne mercury concentration at the site boundary divided by ERPG-2[8]. The off-site consequences are based on very conservative calculations that assume all active and administrative controls fail. 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 due to condensation of mercury vapor. As shown in Table 2-1, the off-site radiological consequences are all below 1 rem and toxicological impacts are all below ERPG-2.

Table 2-1 Maximum Potential Off-Site Accident Impacts

Postulated Event	**Radiological Dose**	**$[Hg]_{SB}$/ERPG-2**
Loss of Off-site Power - all power lost; emergency diesel and battery backed power sources fail (power not needed to remove decay heat).	0.0 rem	0.0
Full Facility Fire – Fire spreads throughout facility and into service bay, fire suppression system fails, no response from fire department.	0.081 rem	0.14
Hydrogen boundary failure - Cryogenic Moderator System hydrogen boundary fails, passive secondary boundary safely vents hydrogen and prevents combustion.	0.0 rem	0.0
Loss of Confinement - mercury spills onto target service bay floor and/or into core vessel, vapor transported out of building, no credit for deposition, plating or mercury adsorbers in the primary confinement exhaust system that remove mercury from exhaust.	0.034 rem	0.07
Loss of Hg Flow/Cooling – proton beam continues to heat target after Hg loop cooling is lost. Target Protection System (CEC), Machine Protection System and operator intervention fail. Proton beam heats and vaporizes mercury as it leaks from the failed target module. Mercury vapor and aerosol escape from the core vessel to the environment.	0.52 rem	0.53
High Bay Crane Load Drop - maximum load dropped from highest hook height, smashes through high bay floor onto the mercury loop. Violent impact causes widespread spill as well as mercury aerosol generation.	0.93 rem	0.08
Seismic Event - severe earthquake causes fire and mercury spill. Fire increases vaporization of spilled mercury.	0.11 rem	0.18

Conclusion

The SNS Neutron Facilities are well engineered and built to be mechanically and structurally robust; motivated not only by stringent safety goals but also by 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 mitigate risks to negligible levels. Operation of the SNS Neutron Facilities has been clearly shown to pose no significant radiological risk or toxicological 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.

2.1 REFERENCES

1. *Safety of Accelerator Facilities, DOE Order 420.2C,* U.S. Department of Energy, Washington, DC, July 2011.
2. *Accelerator Facility Safety Implementation Guide for DOE O 420.2B,* Safety of Accelerator Facilities, DOE Guide 420.2-1, U.S. Department of Energy, Washington, DC, July 2005.
3. *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Documented Safety Analyses,* DOE-STD-3009-94, July 1994, U.S. Department of Energy, Change Notice 1, January 2000, Change Notice 2, April 2002.
4. *SNS Policy for the Selection of Safety Related Credited Controls,* SNS 102030100-ES0005-R00, Oak Ridge National Laboratory, Oak Ridge, TN, March 2005.
5. *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities*, DOE-STD-1020-2002, Washington, DC, January 2002.
6. *Natural Phenomena Hazards Performance Categorization Guidelines for Structures, Systems and Components*, DOE-STD-1021-93, Change Notice 1, Washington, DC, Reaffirmed April 2002.
7. *SNS Final Safety Assessment* Document *for Proton Facilities,* SNS 102030103-ES0018-R02, Oak Ridge National Laboratory, Oak Ridge, TN, December 2010.
8. American Industrial Hygiene Association, Emergency Response Planning Guidelines for Mercury Vapor, 2003.

3.0 SITE, FACILITY, AND OPERATIONS

The activities of the Spallation Neutron Source (SNS) Neutron Facilities (NF) are centered in the target building. The purpose of the descriptive information provided in this chapter is to help the reader understand the safety evaluations and requirements derived and presented in Chapters 4 and 5. The following information is covered in this chapter:

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.

An overview of the SNS complex is provided in Section 3 of the *SNS FSAD-PF*.[1] The configuration of the target building, illustrated in Figure 3.0-1, supports the SNS neutron science mission by producing neutrons while satisfying safety needs, foremost of which includes confinement of the toxic radioactive target mercury and the attenuation of penetrating radiation generated by the spallation reaction. Confinement of mercury is satisfied by meeting design standards as well as providing credited controls found to be essential by the safety analyses summarized in Chapter 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 both 10 CFR 835[2] and the *SNS Shielding Policy*[3] to ensure radiation levels are as low as reasonably achievable (ALARA).

SNS follows a standards-based approach, embracing the ORNL Work Smart Standards (WSS)[4,5] and the standards and policies of the Oak Ridge National Laboratory (ORNL) Standards-Based Management System (SBMS). Standards that guided design of the SNS target facility 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 Department of Energy (DOE) research facility. For example, facility spaces are designed to meet National Fire Protection Agency (NFPA) requirements, such as NFPA 101,[7] with regard 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,[8,9,10,11] and the associated building codes. The target service bay and surrounding concrete structures have Performance Category (PC)-3 seismic qualification level. They perform passive radiation shielding functions and safety functions to protect the hazardous material within the target service bay (i.e., the shielded confinement structure that contains the mercury loop and associated irradiated components handling and packaging equipment) and the monolith.

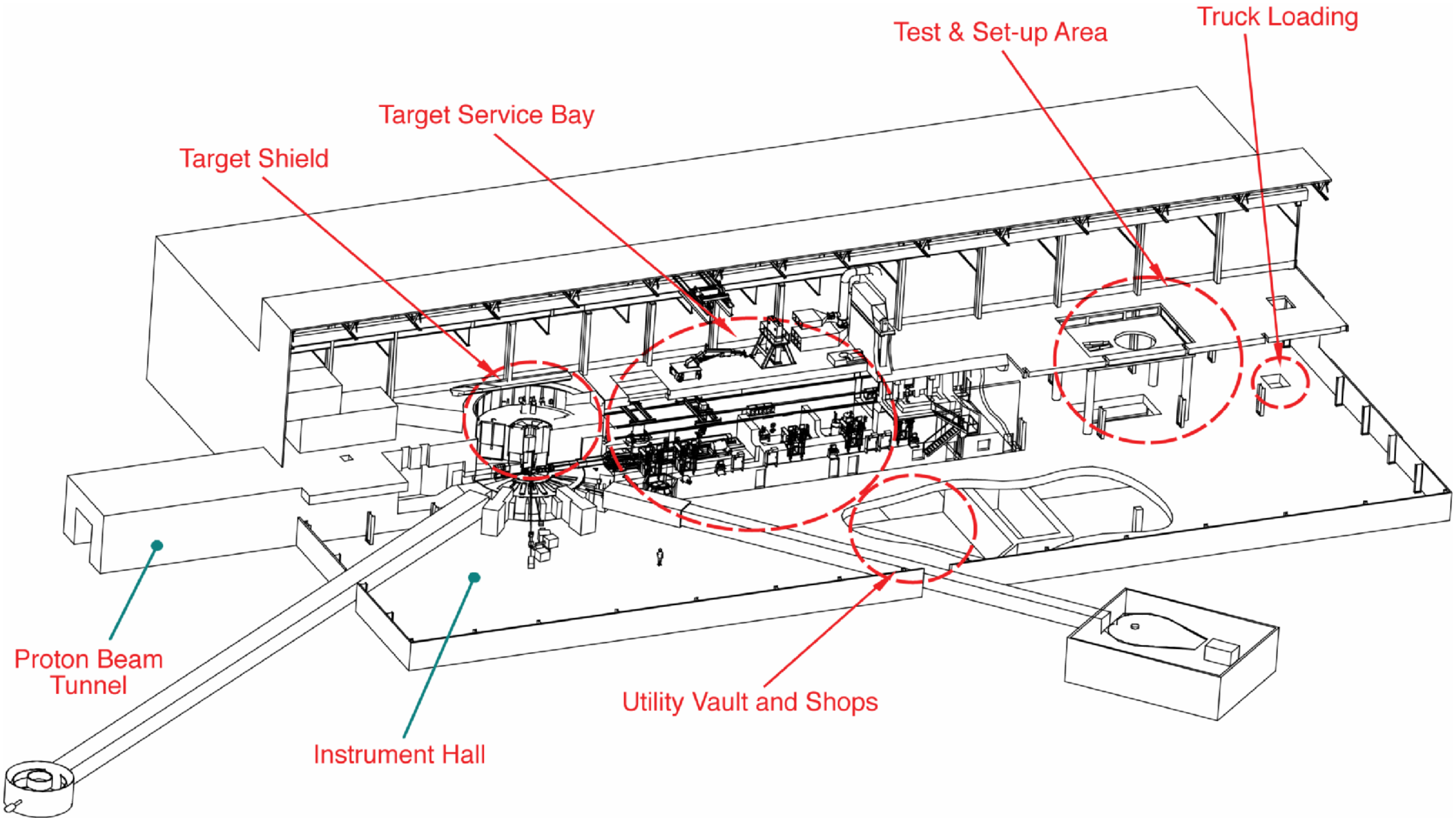


Figure 3.0-1 SNS Target Building

3.1 SITE

The SNS site including key structures and facilities are described in the *SNS FSAD-PF*[1]. The focus of this document is on the neutron facilities and related support facilities which are primary housed in the Target Building.

As discussed in the Section 3.0 of the FSAD-PF[1], it is expected that activities at the SNS site will continue to evolve and expand and that additional on-site structures and facilities will be planned and erected in support of the science mission of the facility. Construction of one such facility, the Joint Institute for Neutron Sciences (JINS), has recently been completed. The JINS facility was constructed by the State of Tennessee, and is located adjacent to the Central Laboratory and Office Building (CLO). The JINS building includes laboratory facilities and offices and is operated by ORNL in conjunction with the University Of Tennessee. Activities conducted within the facility will involve standard industrial and laboratory hazards which will be safely managed in accordance with ORNL SBMS. Some work will involve routine radiological hazards encountered in laboratory environments such as the handling of calibration sources and low activity materials associated with neutron scattering, the use of radiation generating devices, x-ray microscopes, etc. Radiological hazards will be managed under the ORNL SBMS Radiological Protection Program.

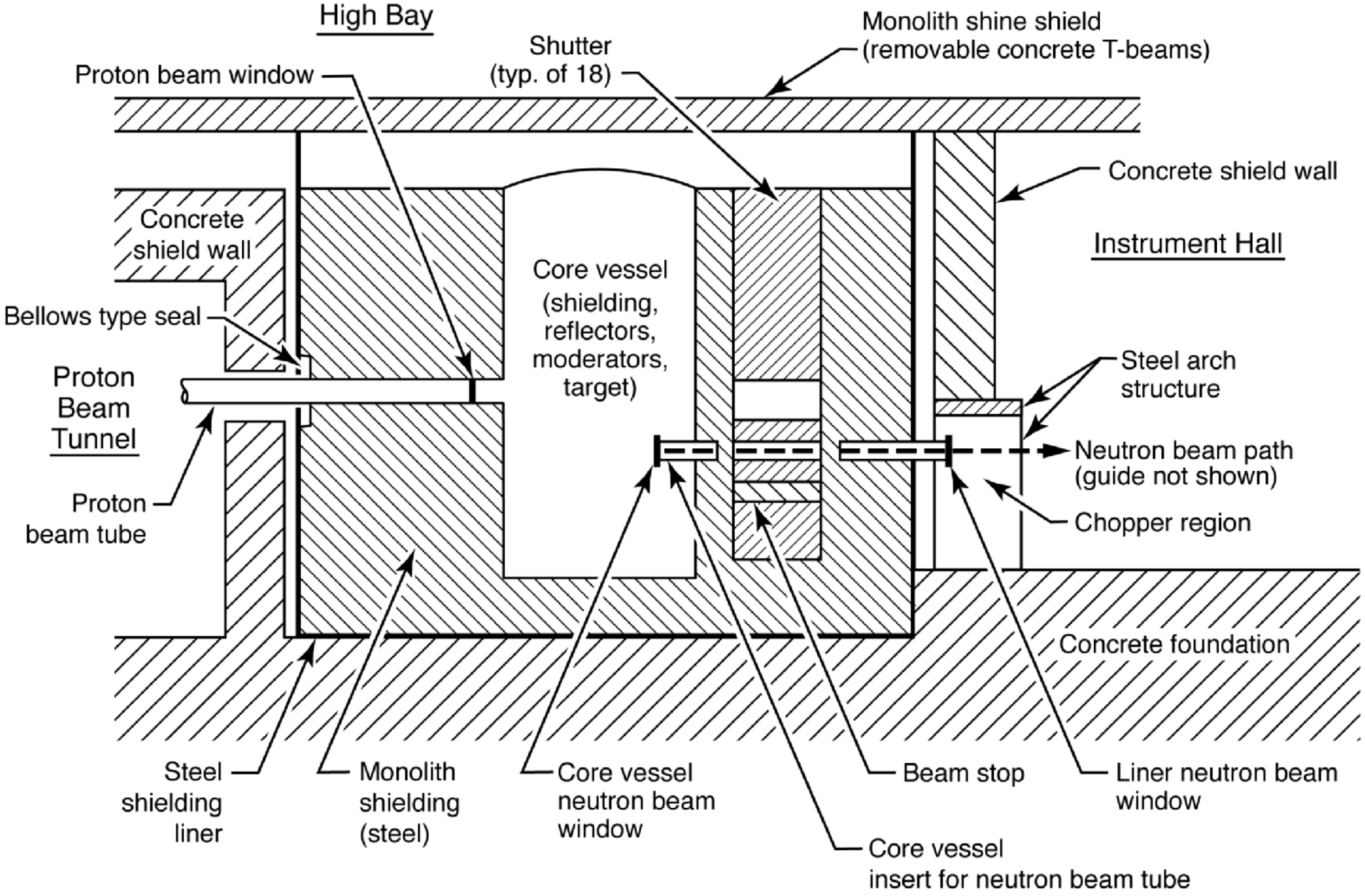
3.2 FACILITY LAYOUT AND STRUCTURES

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 Chapter 6 of the FSAD-PF[1]. The proton beam window is depicted in the schematic depiction of the monolith in Figure 3.2-1.

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, target service bay, and ring-to-target beam transport (RTBT) beam tunnel that terminates in the monolith. The basement beneath the instrument hall and target 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 entranceways 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 is allowed greater access into the occupied parts of the target service bay complex, the basement, and the high bay.

Division of the building into three ventilation confinement zones roughly parallels the zoning of personnel. This arrangement is intended to limit the potential spread of contamination and minimizes the exposure of workers. The innermost primary confinement zone, serviced by the primary confinement exhaust system (PCES), is normally kept under a negative pressure with respect to the secondary confinement zone, which is, in turn, maintained by the secondary confinement exhaust system (SCES) 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 heating, ventilation, and air conditioning (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. The angle between the proton beam tube and the neutron beam path shown above is about 120˚.

Figure 3.2-1 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 level, and high bay level are depicted in Figures 3.2-2 through 3.2-4. The target 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 connects to the proton beam window.

3.2.1 INSTRUMENT FLOOR

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

The target service bay complex is centrally located between the north and south instrument halls. Three rooms surround the target 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 target service bay and provisions for the remote handling operations necessary for operation of highly activated equipment in the target service bay are described in Section 3.3.5.

The target service bay concrete structure and adjacent concrete structures support the upper building floors and also provide for utility pathways while providing radiation shielding and confinement of the target mercury. The service bay wall design is credited with ensuring that credible fires in fire zones outside the service bay cannot cause significant releases of mercury. The outer wall of the target service bay complex is a two-hour rated firewall that separates the target 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 (see 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, and filtration equipment for the primary and secondary confinement systems (HEPA and charcoal adsorbers), waste handling systems, and the basement target control room. The basement area is used for a wide variety of activities including, but not limited to, those described below.

The basement provides facilities necessary to support target systems, including:

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

The utility vault contains activated cooling water system components (see 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 are used to protect personnel when accessing the vaults. During beam operations, routine personnel access to the utility vaults is prohibited due to 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 located in the target control room and CLO main control room. Utility control cabinets are located in the basement as are the helium and nitrogen gas distribution systems.

Commercial lifting devices for hands-on handling of items such as pumps and motors are provided, and the filters and ion-exchange columns have built-in shielding. Separation and/or shielding 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.

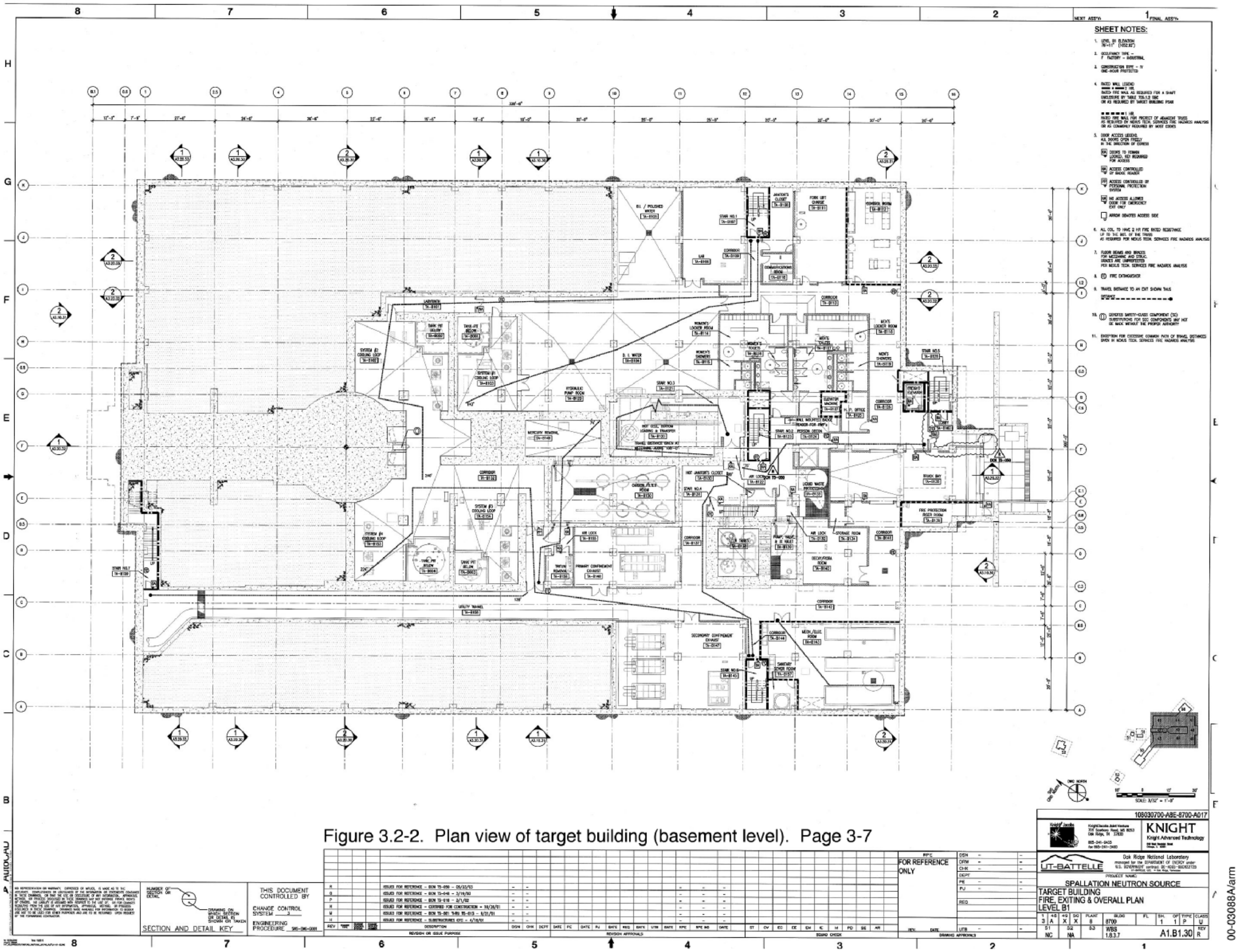


Figure 3.2-2 Plan View of Target Building — Basement Level

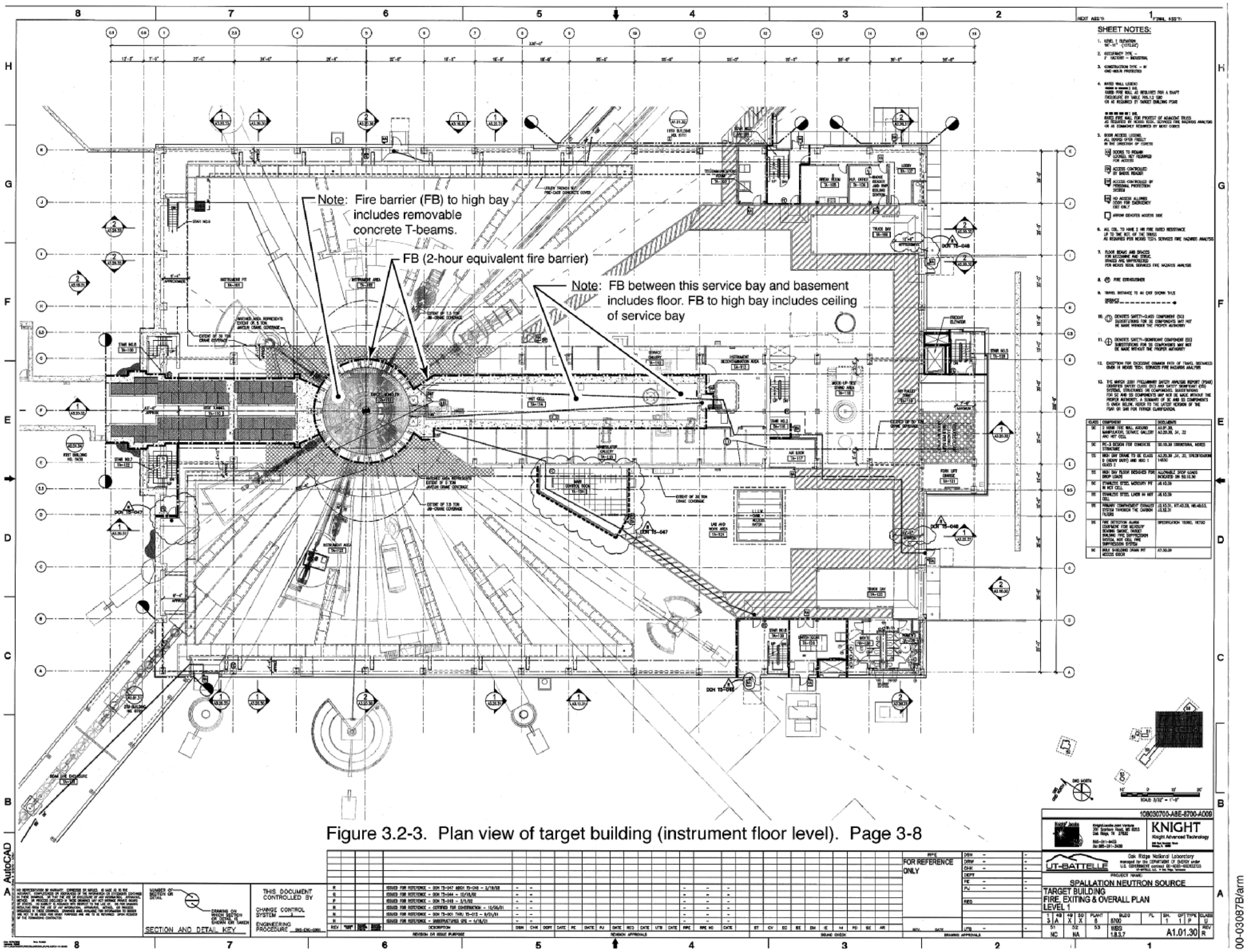


Figure 3.2-3 Plan View of Target Building — Instrument Level

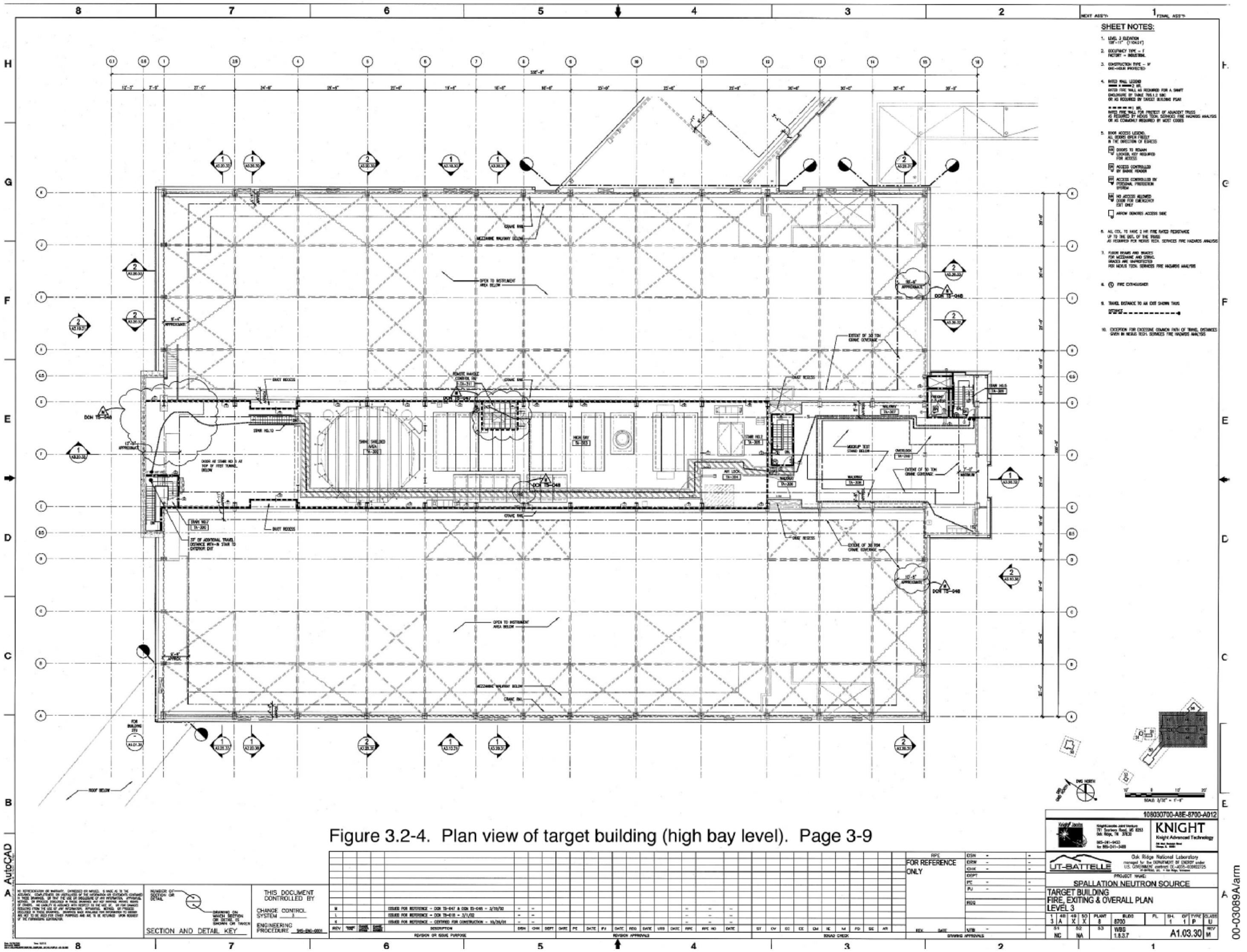


Figure 3.2-4 Plan View of Target Building — High Bay Level

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) are able to withstand the anticipated background radiation doses in the utility vault area. Features to facilitate the handling and transport of both 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 are provided.

There are capabilities, such as pits in the basement floor slab, to drain utility cooling water piping to dump or storage tanks. The vault has 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 materials of construction are compatible with the materials to be contained and have suitable radiation resistance.

The Mercury Target Development Laboratory provides a workspace for mercury process experiments, inspection of test target material, etc. Non-radioactive (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 ft × 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 functions to allow for storage of reusable components while they decay to levels that would 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, as needed, to maintain radiation levels ALARA for workers in the basement.

The sample handling laboratory provides workspace to handle samples associated with neutron beam experiments. Samples exposed to beam line 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, electrical equipment, etc. 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 target 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 between the five alternative locations where it can be installed.

Parts of the floor between the high bay and the target service bay consist of concrete T-beams. Removal of the target service bay T-beams is expected to be rare. Planned access to the target service bay is provided by removal of the top-loading port shield plug.

3.2.4 TRUSS LEVEL

The Hydrogen Utility Room (HUR) (see 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 Credited Engineered Controls (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 performance categories (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 the document entitled, *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 DOE seismic interaction requirements of DOE-STD-1021-93.[9]

The safety analyses of Chapter 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 the 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 to cause failure of the hydrogen boundary. The qualification of the surrounding structures is against the qualified mission of preventing hydrogen leakage. As a consequence of the hydrogen boundary PC-3 requirement, basic concrete structures of the building are PC-3 qualified and the steel superstructure of the building 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. At 2 MW, the 1 GeV proton beam provides ~ 2×10^{14} protons per pulse at a repetition rate of 60 pulses per second (2 mA proton beam current). Pulses extracted from the ring pass directly to the ring extraction dump unless diverted to the target through the active use of magnet DH-13. Magnet DH-13 diverts protons down the RTBT tunnel to the target. The target has a high-integrity interlock system, the target protection system (TPS), to ensure that beam cannot be sent to the target unless the mercury is flowing and its temperature is not excessive.

The need for heat removal from the target mandates 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 rejects heat to the tower water cooling system. The other 40% of the proton beam energy is dissipated in the moderators, reflectors, and shield blocks. Flowing light water coolant loops and one heavy water coolant loop cool the 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. Both safety instrumentation and non-safety instrumentation 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/or cavitation damage to the target module materials (stainless steel) necessitates periodic replacement of the target module. This is an operation in which the target process system must be drained and the mobile part disconnected from stationary parts. The operations necessary for this are accomplished remotely, primarily using manipulators. The target service bay is designed such that all required activities can be accomplished remotely, without human entry. Although the design goal and intent is for no human entry, the option is preserved for workers to enter the service bay under appropriate safeguards and controls.

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

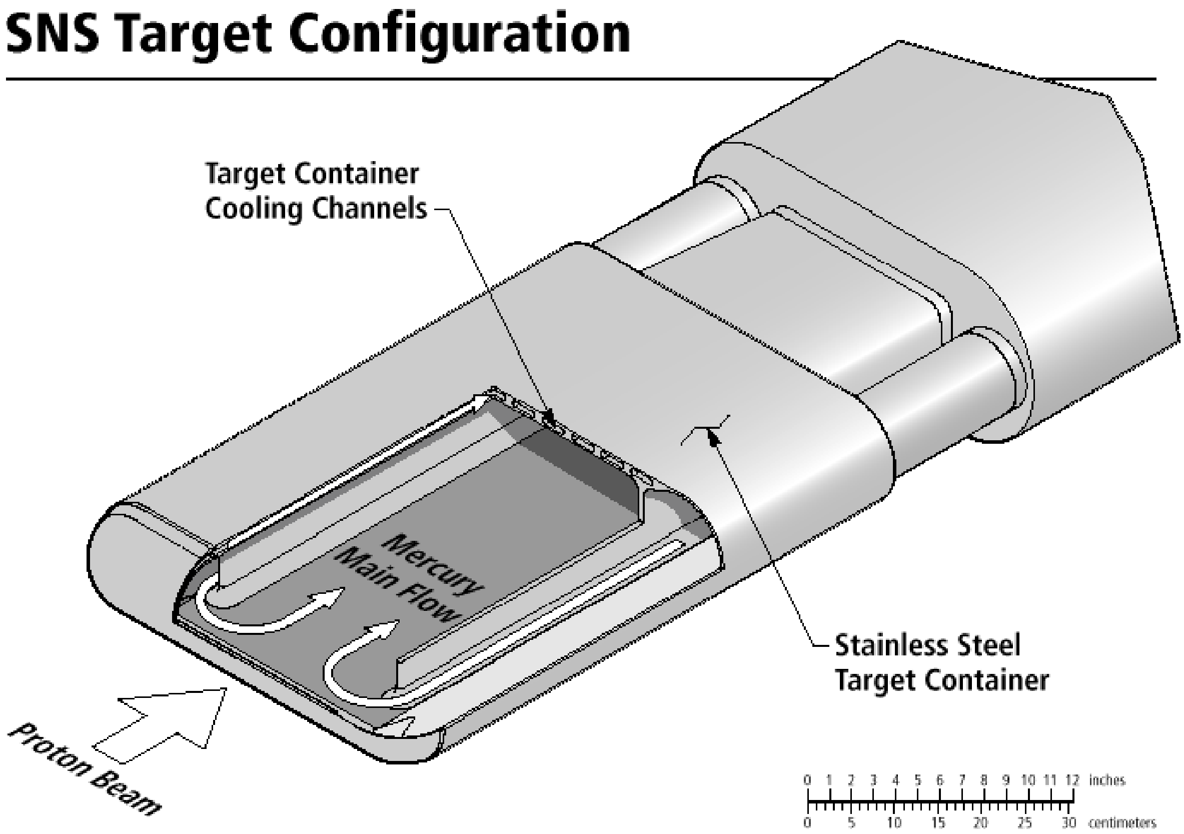
1. Provide shielding barriers against prompt accelerator radiation to minimize radiation levels in occupied spaces
2. Provide confinement of the radioactive mercury

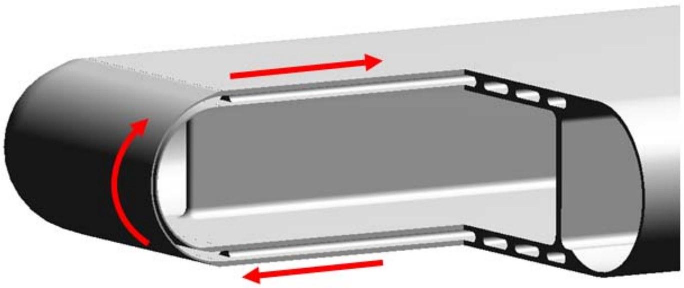
The confinement features are in addition to the boundaries of the mercury process system. These features include the PCES as well as features built into the target service bay floor structure to ensure a mercury spill would be channeled to the collection basin. This basin is located in a concrete silo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

The target system shielding was designed (i.e., thickness and composition set for target service bay walls and the monolith) in accord with the SNS Shielding Policy[3] to ensure radiation levels are ALARA. The SNS 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 Beam Lines, and Biological Shielding Monolith* (SNS Document No. 106100200-DA0001-R01). Since 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. Mercury collected from the in cell condenser is returned to the mercury loop. An offgas 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 by Figures 3.3.1-1 and 3.3.1-2, 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. It is held in place with eight bolts. Part of the module is a flange of approximately 25-in. diameter that incorporates an inflatable metal "bellows" seal comprised of two concentric stainless steel contact surfaces separated by an actively pumped cavity that separates the core vessel and target service bay volumes. The location of the target module is shown at the end of the target plug in Figure 3.3.1-3. The term target "plug" refers to the assembly that combines the target module, lengths of mercury loop piping, the carriage, and the shielding.





Mercury Window Flow

Figure 3.3.1-1 Target Module Illustration Showing Internal Mercury Flow Paths

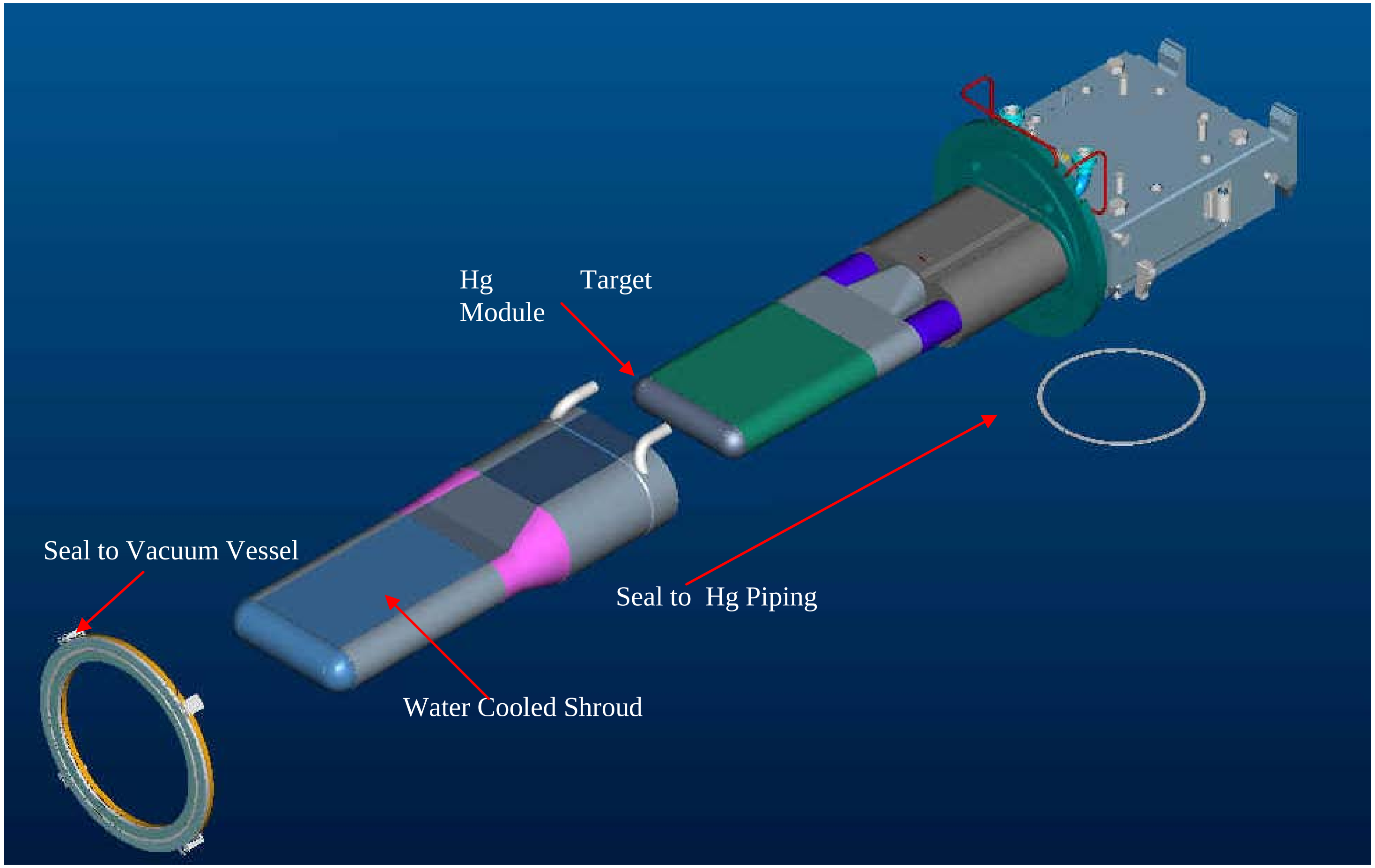


Figure 3.3.1-2 Exploded View of Target Module

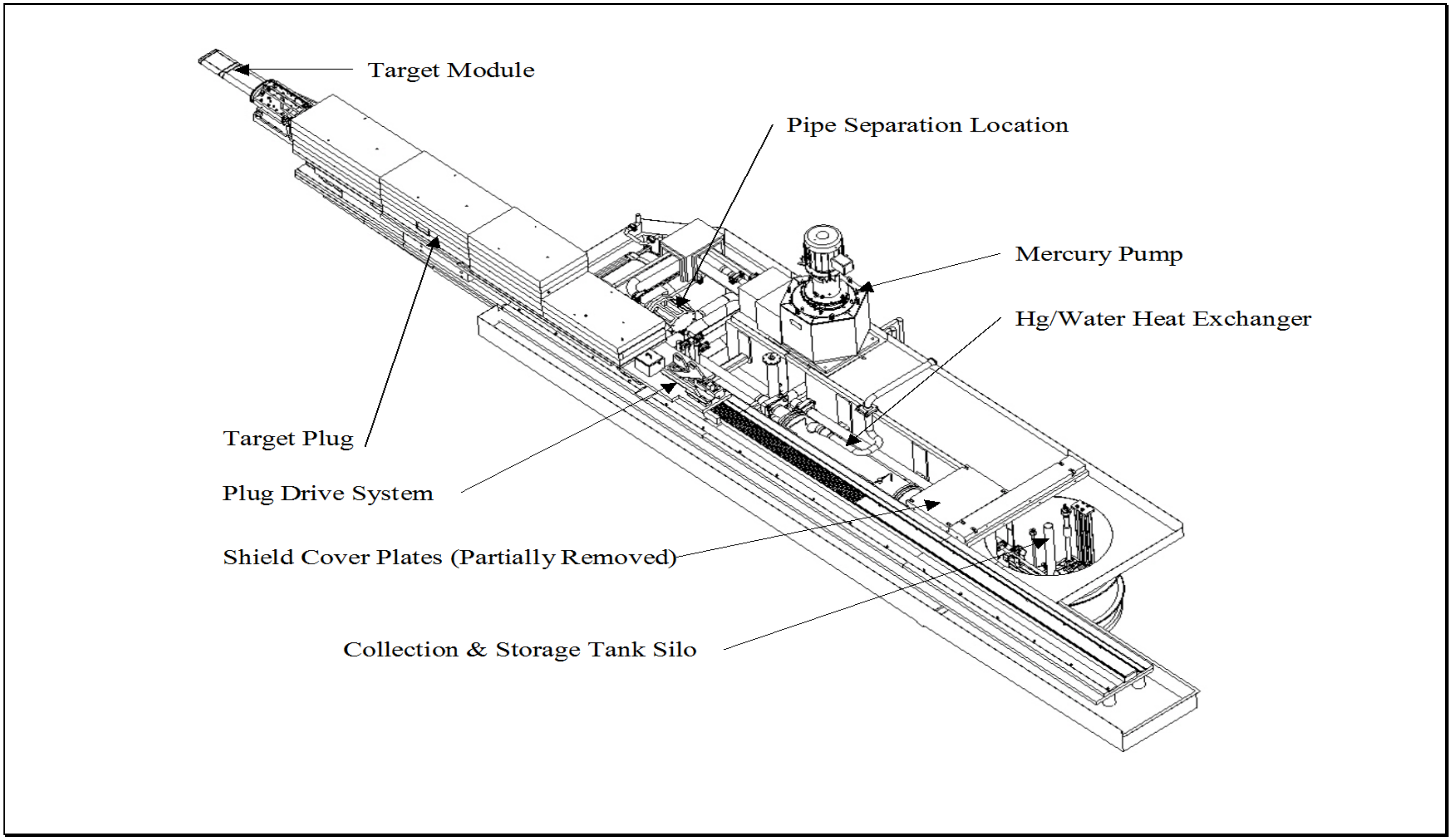


Figure 3.3.1-3 Components of the Mercury Target System

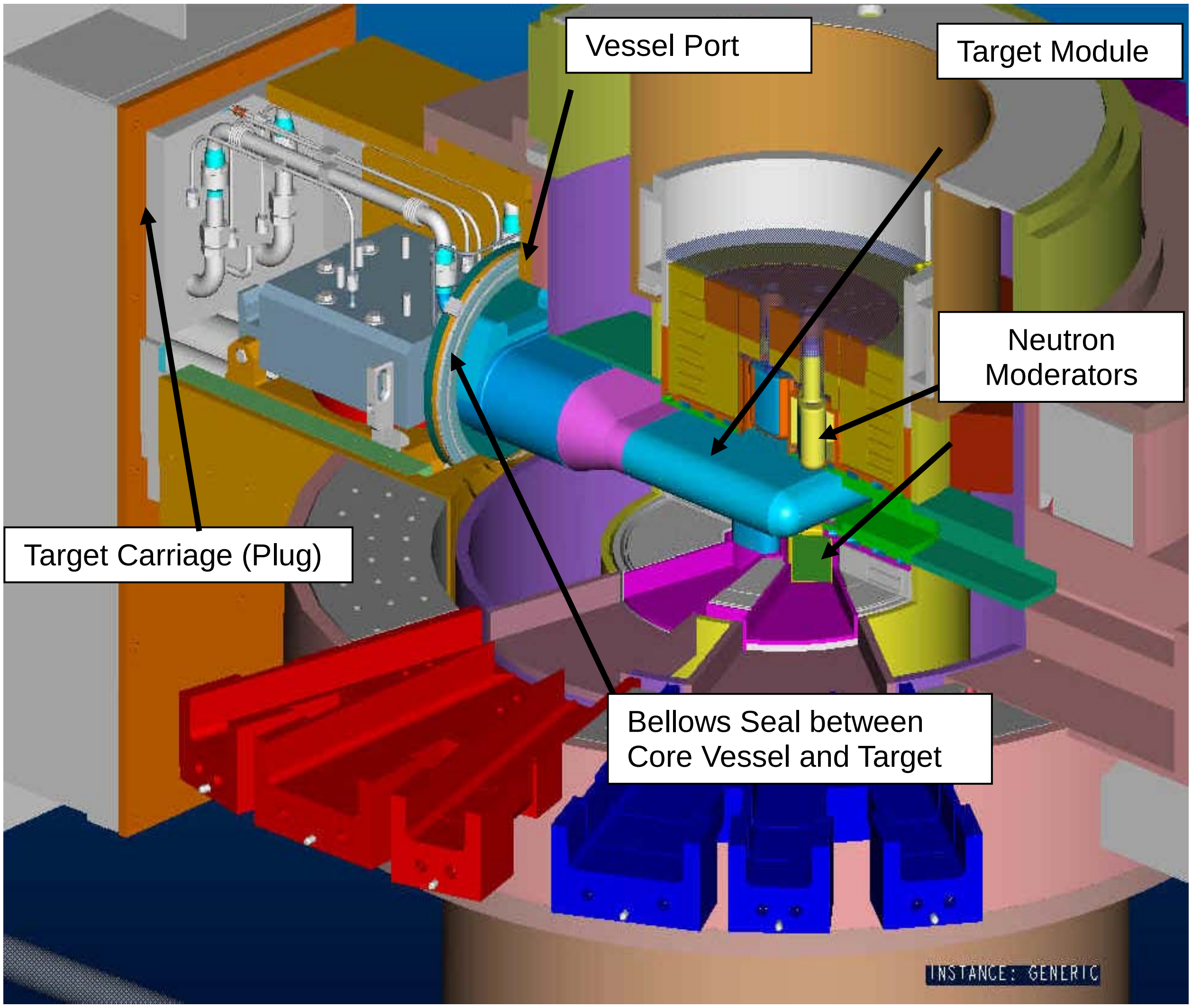


Figure 3.3.1-4 Target Module Interface with Core Vessel

In front of the inflatable seal flange, the module consists of two concentric vessels: an inner vessel for containing the target mercury and an outer vessel for containing mercury that may leak from the inner vessel. These vessels are of welded fabrication. The forward-most 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 with well-defined coolant flow conditions in the gaps between the walls. The walls of the inner vessel, referred to as the “mercury vessel,” are cooled by flowing mercury while the outer 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 a fixed orifice selected to yield window flow in the desired range.

The mercury vessel and water-cooled shroud provide redundant barriers against the leakage of mercury 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 (RTD) concept to detect the presence of liquid and is able to 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 with 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 provides both a leak-tight joint between the mercury flow channels on the module and those on a mating manifold at the end of the piping on the carriage and the ability to replace the sealing surface on the permanent carriage piping.

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 the carriage to points on the target module used for venting the mercury lines during filling and for interfacing to instrumentation installed on the target module.

The target module is designed for periodic remote replacement. Prior to replacement of the target module, the mercury is drained to the storage tank, piping connections are removed in the target service bay, and the target carriage locking mechanism is released. The target plug (i.e., the whole target carriage, including the target module) can then be driven from the operational position back into the target 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 firmly locked to prevent movement. The carriage assembly includes passive shielding surrounding the piping connecting the target module to the process systems. Figure 3.3.1-3 shows the target plug, target carriage, and the mercury process system.

A system of mechanical levers driven by pressurized water actuators is used to drive the carriage between its withdrawn position in the target 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 target service bay if a line failure occurred.

The mercury process loop contains a total of approximately 1.4 m^3 (~ 19,000 kg) of mercury circulating at a rate of between about 114 kg/s to 325 kg/s. The pump speed is varied between 150 rpm 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 a nominal ~ 60°C at the inlet to ~ 90°C at the outlet during normal operation. This corresponds to a 2 MW beam power within a pump speed of 400 rpm

The western half of the target 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 3.3.1-3. 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. Since the mercury is radioactive, the system is located in the target service bay and designed to be operated and maintained remotely. Components expected to require change-out are connected by remotely operated flanged connections. As detailed below, the stainless steel liner of the process bay is designed to allow spilled mercury to gravity drain to the collection basin. A double-wall heat exchanger configuration is used to present an extra barrier between the flowing mercury and its coolant water in the heat exchanger.

3.3.1.1 Mercury Storage Tank and Collection Basin

As shown in Figures 3.3.1-3 and 3.3.1.1-1, both the storage tank and the collection basin are located 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 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, etc). 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 ~ 1.4 m^3 of the mercury inventory is in the loop and ~ 0.2 m^3 in the storage tank. After loop drainage, the entire inventory (~ 1.6 m^3) is held in the storage tank. In order 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).

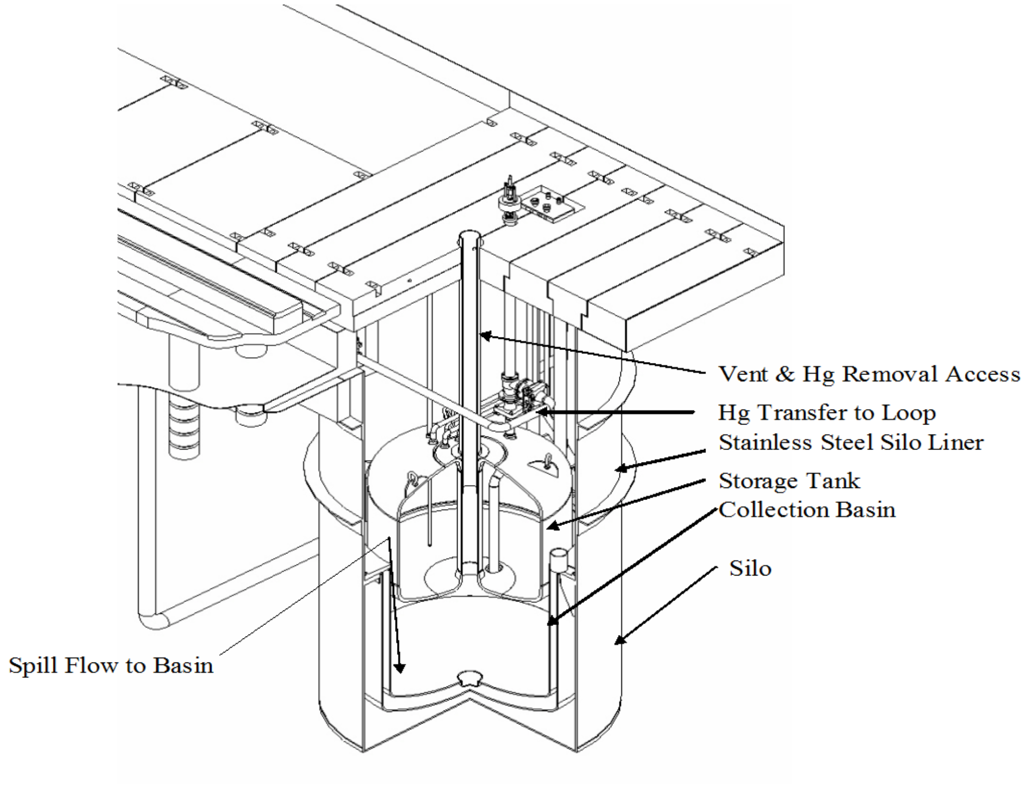


Figure 3.3.1.1-1 Storage and Collection Silo General Arrangement

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 is thus formed for the flow of all spilled mercury towards the collection basin. 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-wall stainless steel vessel open at the top and installed to be structurally independent from the surrounding concrete pit. The depth of the basin was determined so the entire mercury inventory could be contained in the volume between it and 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 is provided in the collection basin directly below the passage to facilitate the ability to remove liquid contents from the basin.

3.3.1.2 Mercury Spill Drainage Design Features and Function

The process bay part of the target service bay (i.e., the west approximately half of the target 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 one degree nominal slope specified for the stainless steel floor liner underneath mercury loop components. This feature provides mitigation for a loss of mercury confinement event by minimizing the surface area of mercury exposed to air and the duration of time it is exposed as it is draining to the collection basin. The drainage feature is a passive credited design feature as explained in more detail in Section 5.2.9.

Figure 3.3.1.2-1 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 floor of the carriage tunnel is sloped east to direct leaks in the tunnel back towards 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 target service bay that would help minimize the extent of contamination following a mercury spill event. This includes the ~ 12-in.-thick steel beams that cover the trench in which the heat exchanger and

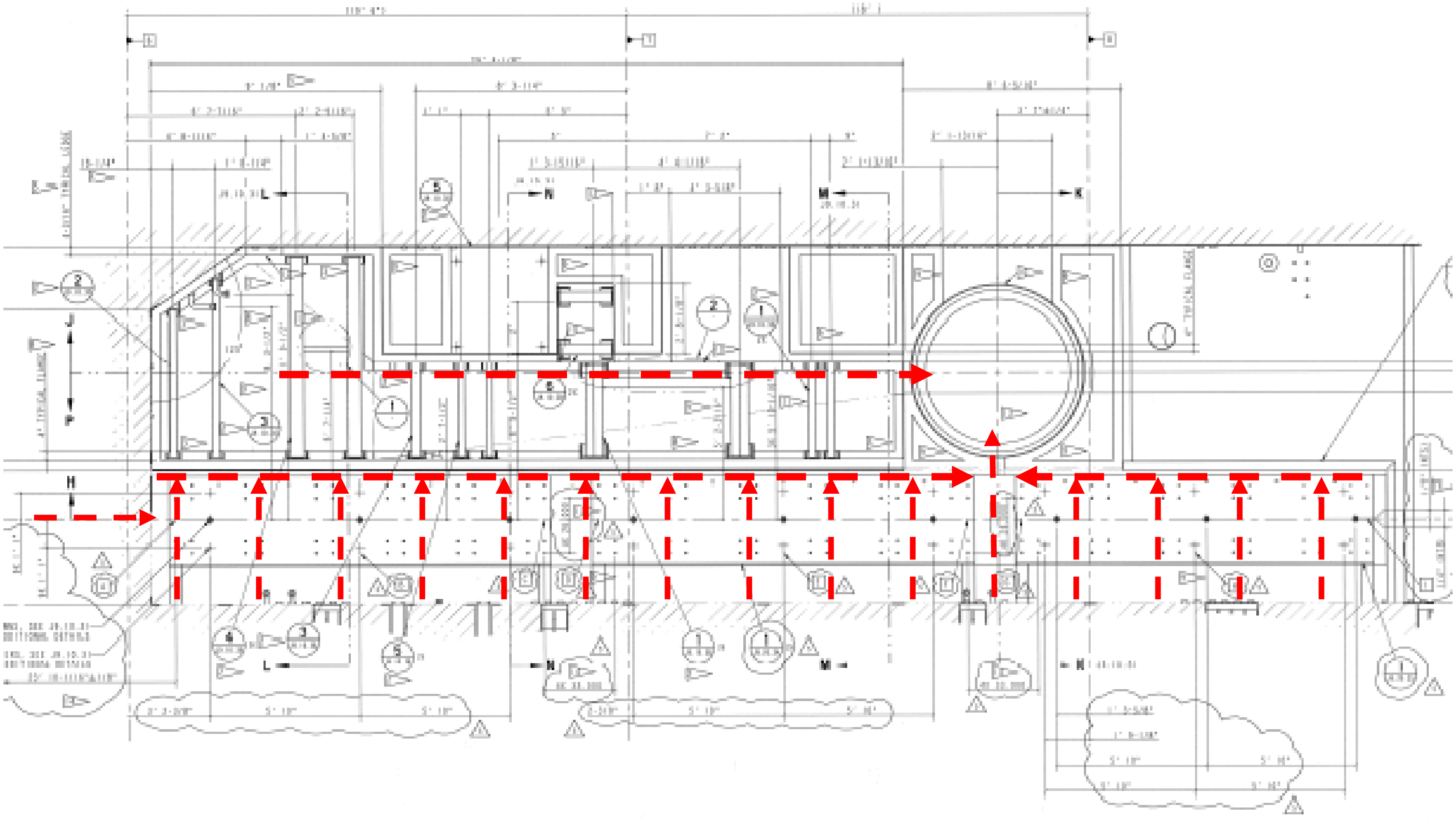


Figure 3.3.1.2-1 Target Service Bay Process Bay Spill Drainage Directions and Areas

collection basin are located as well as the “doghouse” shielding cabinets made of ~ 4-in.-thick steel that encloses 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). The purpose of this shielding is to minimize background radiation in the target service bay during operation so that electrical cables, etc., can have an adequate service life. The safety benefit is that leaks/breaks in the mercury loop would occur inside a largely closed space inside the target service bay. Figure 3.3.1.2-2 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 target service bay, whereby the radiation shielding would provide thermal shielding for the mercury loop piping inside.

3.3.1.3 Double-Wall Heat Exchanger Design

The mercury-to-water heat exchanger uses a robust double wall 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 3.3.1.3-1 indicates schematically the double-wall arrangement and associated instrumentation; Figure 3.3.1.3-2 gives pictorial views. The target mercury flows inside the tubes, 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,” it is recognized that 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 only on the order of a few mrem/h on contact. To achieve the heat transfer benefit of interstitial mercury, the gap has sufficient width to allow the filling to assure 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 since cooling water is kept at a higher normal pressure than the circulating, irradiated mercury. The heat exchanger integrity is verified by periodic measurements of the ability of the interstitial space to retain pressure and/or vacuum.

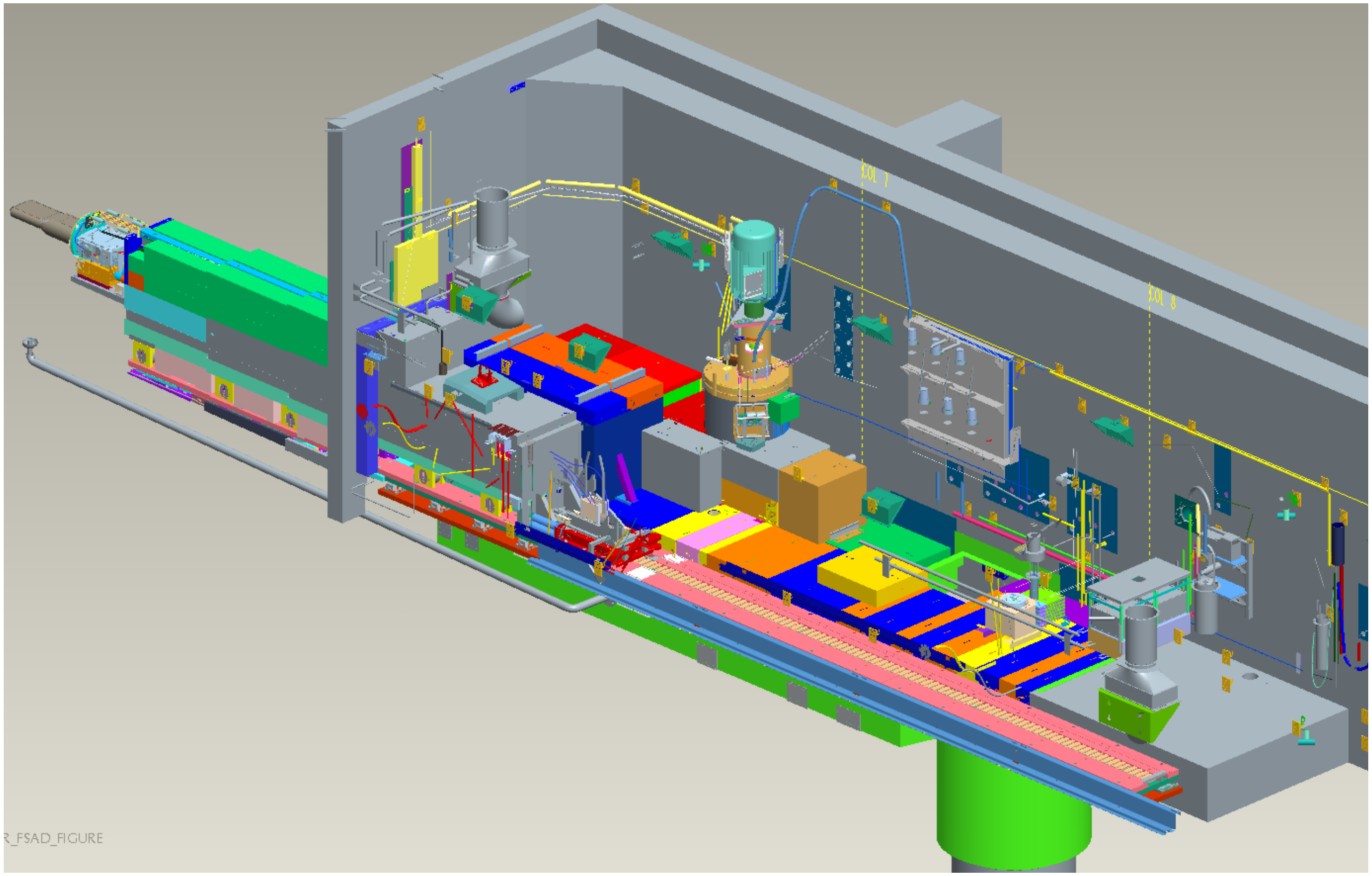
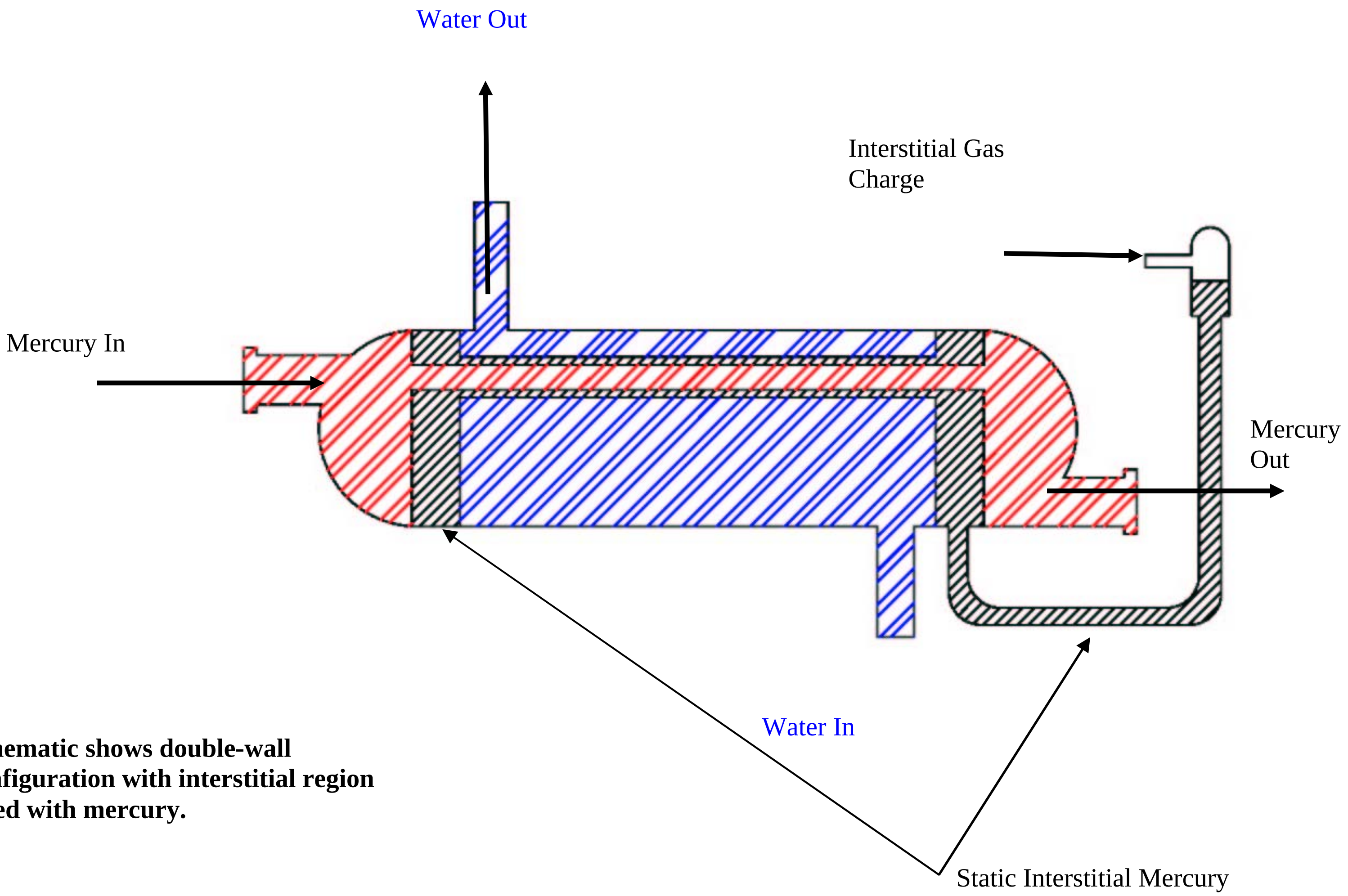


Figure 3.3.1.2-2 Isometric of Process Bay Showing Mercury Loop Shielding with Target Plug Carriage Inserted into the Monolith in Operational Position [the part of target service bay to south (left) of carriage tracks omitted for clarity]



Schematic shows double-wall configuration with interstitial region filled with mercury.

Figure 3.3.1.3-1 Double-Wall Mercury-Water Heat Exchanger Schematic Depiction

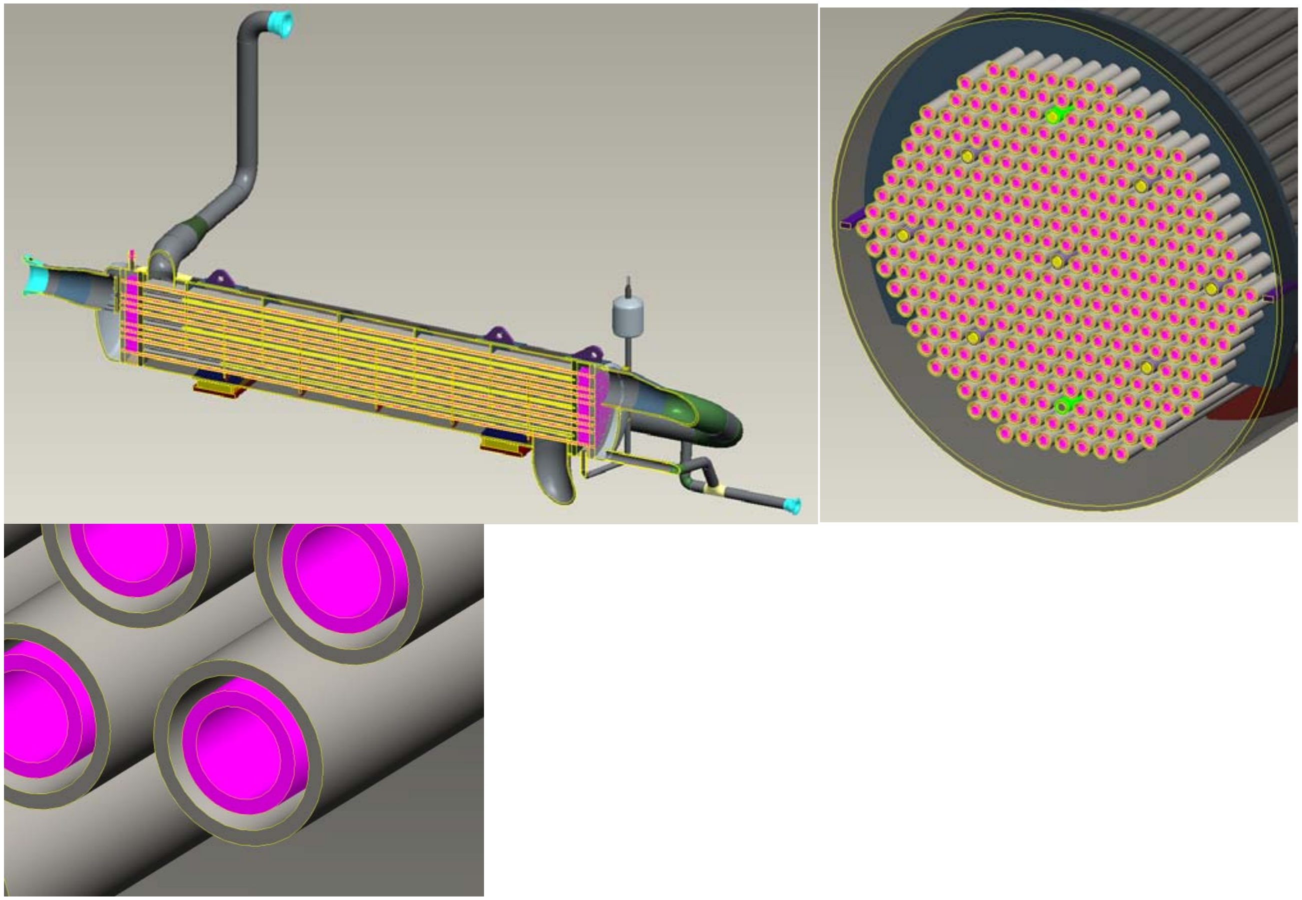


Figure 3.3.1.3-2 Double-Wall Mercury-Water Heat Exchanger Pictoral Schematic Depiction

3.3.2 CORE VESSEL AND INTERNALS

The core vessel (Figure 3.3.2-1) 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 (see 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 disc having relief characteristics certified by the manufacturer. In the event of an overpressure within the core vessel the rupture disc 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/or air from the core vessel. The core vessel is designed to withstand either vacuum or an overpressure of 1 atmosphere [i.e., internal pressure between ~ 0 and 2 atm (29.4 psia)]. In operation, however, the core vessel rupture disc is set to actuate at 7 psi over atmospheric.

The core vessel provides credited confinement functions as further described in Chapter 5. These 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. An approximately 0.7 m^3 (183 gallons) void volume at the bottom of the vessel provides the liquid retention function. The mercury vapor leakage minimization function is provided 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 3.3.2-2, the drain line terminates in a standpipe that can be remotely accessed in the Service Bay. The stand pipe is closed with a blind flange to facilitate closure and contamination control in the target service bay. The standpipe is designed such that it can accommodate the maximum feasible spillage of mercury into the core vessel without overflowing mercury into the target service bay when the blind flange is removed.

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 a double-walled Inconel 718 (or equivalent) shell with active water cooling. The proton beam window is periodically replaced due to 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 one year at maximum beam power.

3.3.2.2 Inner Reflector Plug

The inner reflector plug is composed of three elements: (1) the upper inner plug; (2) the intermediate inner plug; and (3) the lower inner plug (see Figure 3.3.2-1). The moderator vessels are integrated with the lower inner reflector plug. The inner reflector plug is replaced periodically as a unit, including the moderator vessels, coolant lines, and cryogenic transfer lines.

The lower inner reflector plug 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 inner reflector plugs are stainless or carbon steel. The neutron beam channels for the top and bottom upstream moderators are cadmium lined for neutron physics reasons.

The inner reflector plug 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

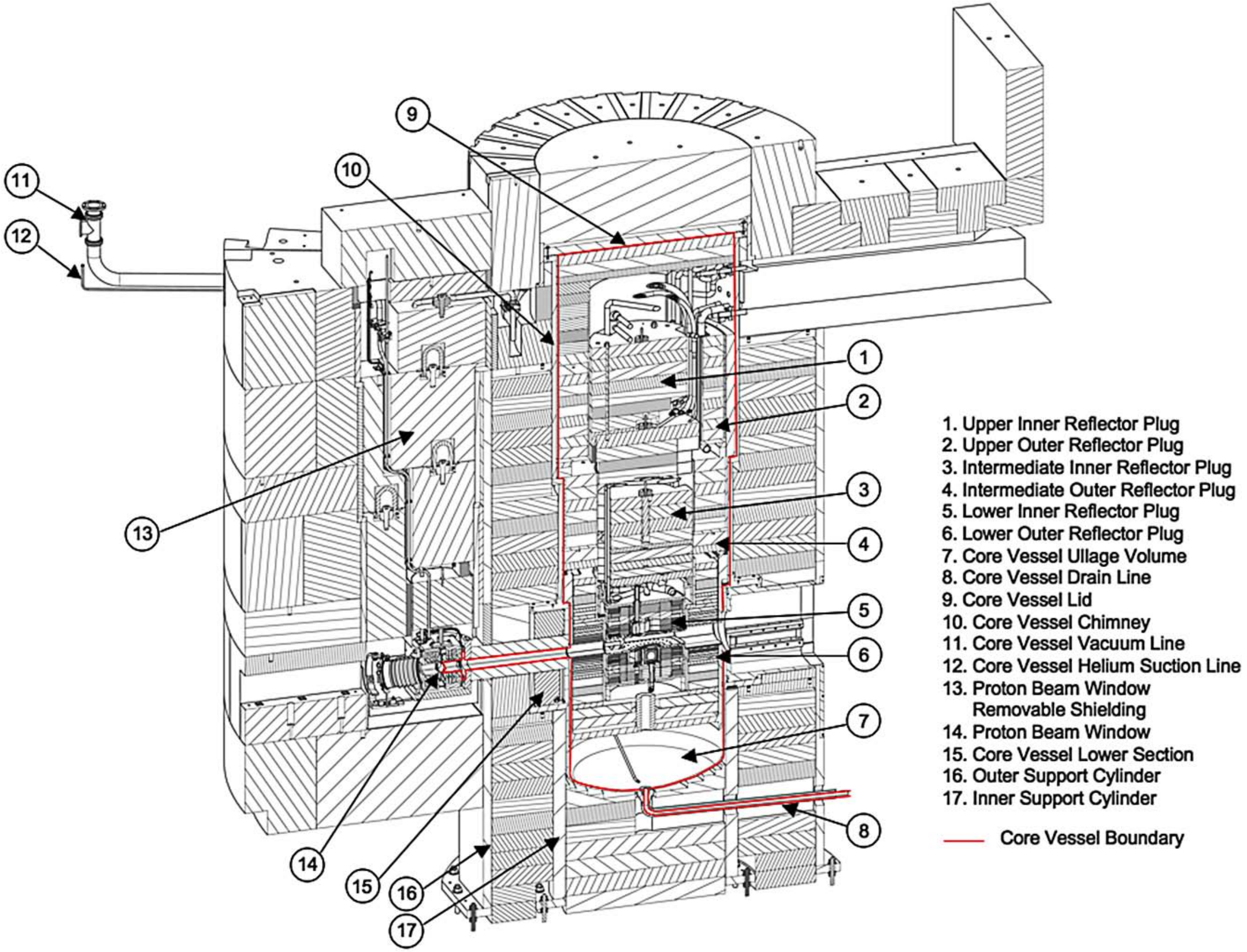


Figure 3.3.2-1 Core Vessel and Internals

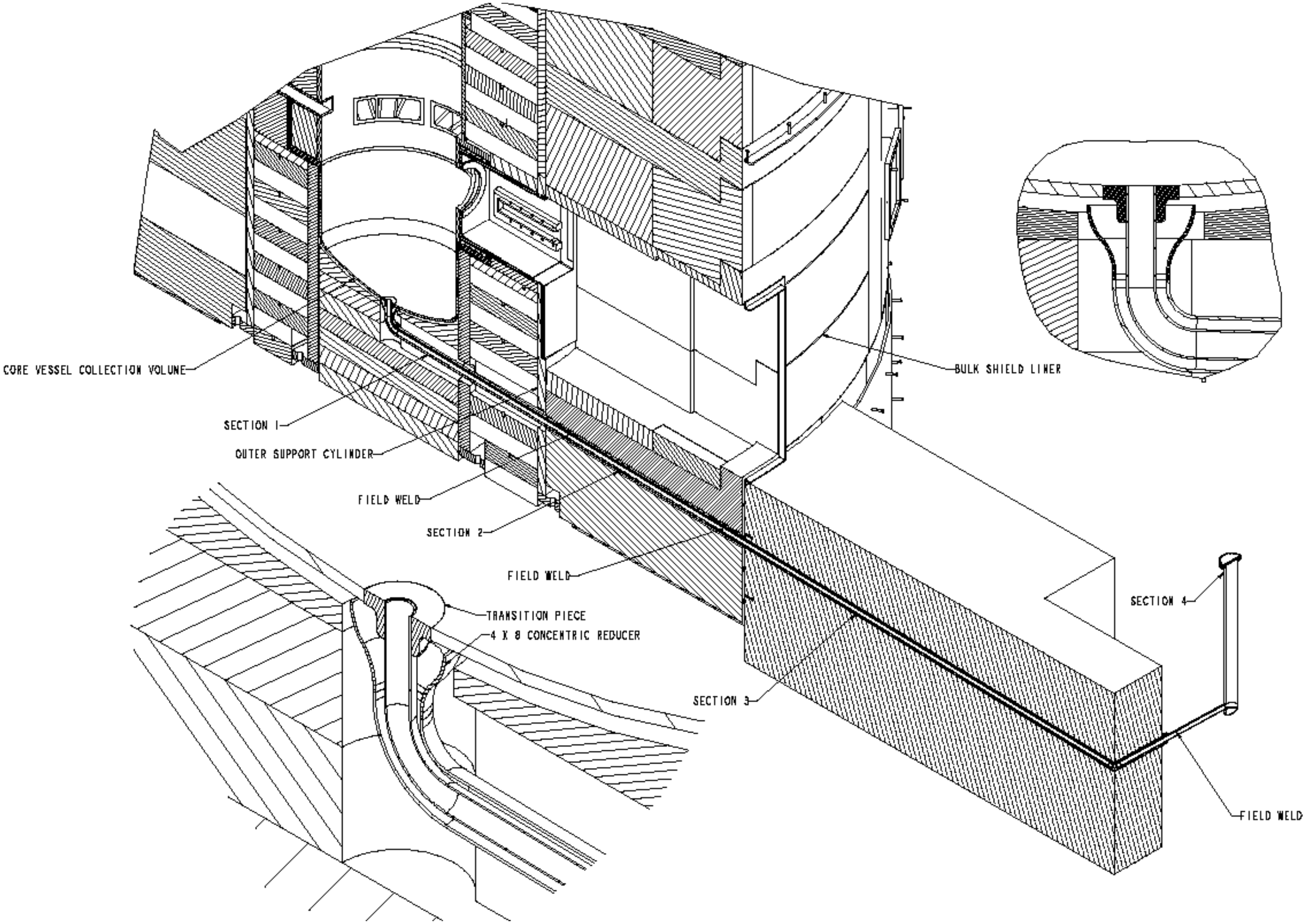


Figure 3.3.2-2 Core Vessel Drain Line

The lower inner and intermediate inner reflector plugs are cooled by coolant loop 4 (see Section 3.3.6). The upper inner reflector plug is passively cooled by conducting heat to the actively cooled plugs. Maximum operating water pressure in coolant loop 4 is approximately 90 psig.

The inner reflector plugs are connected so they can be installed as one unit. They are designed with removable connecting bolts between the sections so that it can be removed in pieces sized for shielding containers. The inner reflector plug may be changed out as research priorities change but probably no more frequently than about once every three years at maximum beam power on account of neutronic considerations associated with the burn-up of gadolinium, cadmium and boron features associated with the moderators.

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 relies on 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 at slightly sub-atmospheric pressure. The helium atmosphere serves to promote 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. Due to the core vessel radiation environment, elastomer seals are generally avoided except for the ethylene propylene radiation-resistant o-ring that seals the vessel lid (Part 9 in Figure 3.3.2-1) 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 is Chapter 5.

Although an inert atmosphere is required only for operational purposes, atmosphere control provides an un-credited layer of safety by normally excluding significant oxygen from the core vessel. In the highly unlikely event that both the cryogenic moderator hydrogen and the vacuum boundaries (both CECs) should 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 prior to backfilling with He (capacity ~ 150 ft^3/min) exhaust to the PCES upstream from the sulfur-impregnated charcoal adsorbers filters. The charcoal filters prevent excessive mercury release in the unlikely event of leakage of mercury to the core vessel under vacuum conditions when the vacuum pump exhaust could be transporting mercury vapor.

3.3.3 MODERATOR SYSTEMS

The primary hydrogen boundary of the cryogenic moderator system (CMS), including its pressure relief function, performs a credited safety function (see Section 5.2.1). The vacuum boundary and its pressure relief also perform a credited safety function that provides an additional layer of safety (see Section 5.2.2). For both the primary and secondary hydrogen boundaries, the safety function is to prevent the release of hydrogen into the core vessel. Inherent design characteristics of the CMS function to prevent significant oxygen from accumulating inside the system; hydrogen is vented without operator action in the event that heat transfer conditions become degraded. The 19-bar (275.5 psia) maximum design pressure of the CMS hydrogen boundary ensures robust hydrogen containment inside the core vessel.

Three of the four moderator systems employ cryogenic supercritical hydrogen controlled during normal operations to temperatures close to 20 K. 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. 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 (see Section 3.3.6).

3.3.3.1 Cryogenic Moderator System

Figure 3.3.3.1-1 shows the four moderator vessels arranged above and below the target inside the core vessel. Figure 3.3.3.1-2 shows the location of the CMS components and transfer line 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 (See

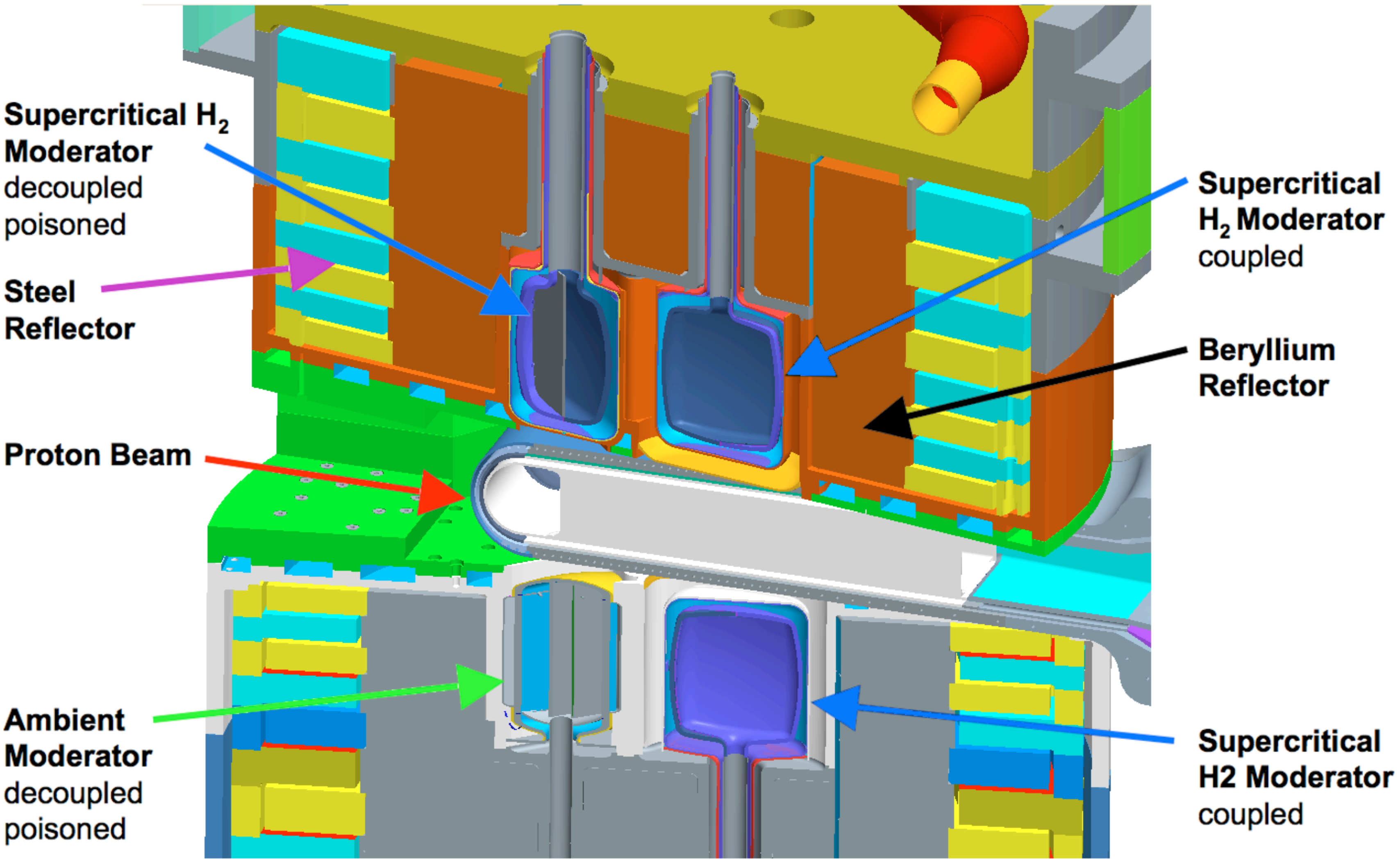


Figure 3.3.3.1-1 Configuration inside the Core Vessel of the Moderator Vessels Above and Below the Mercury Target

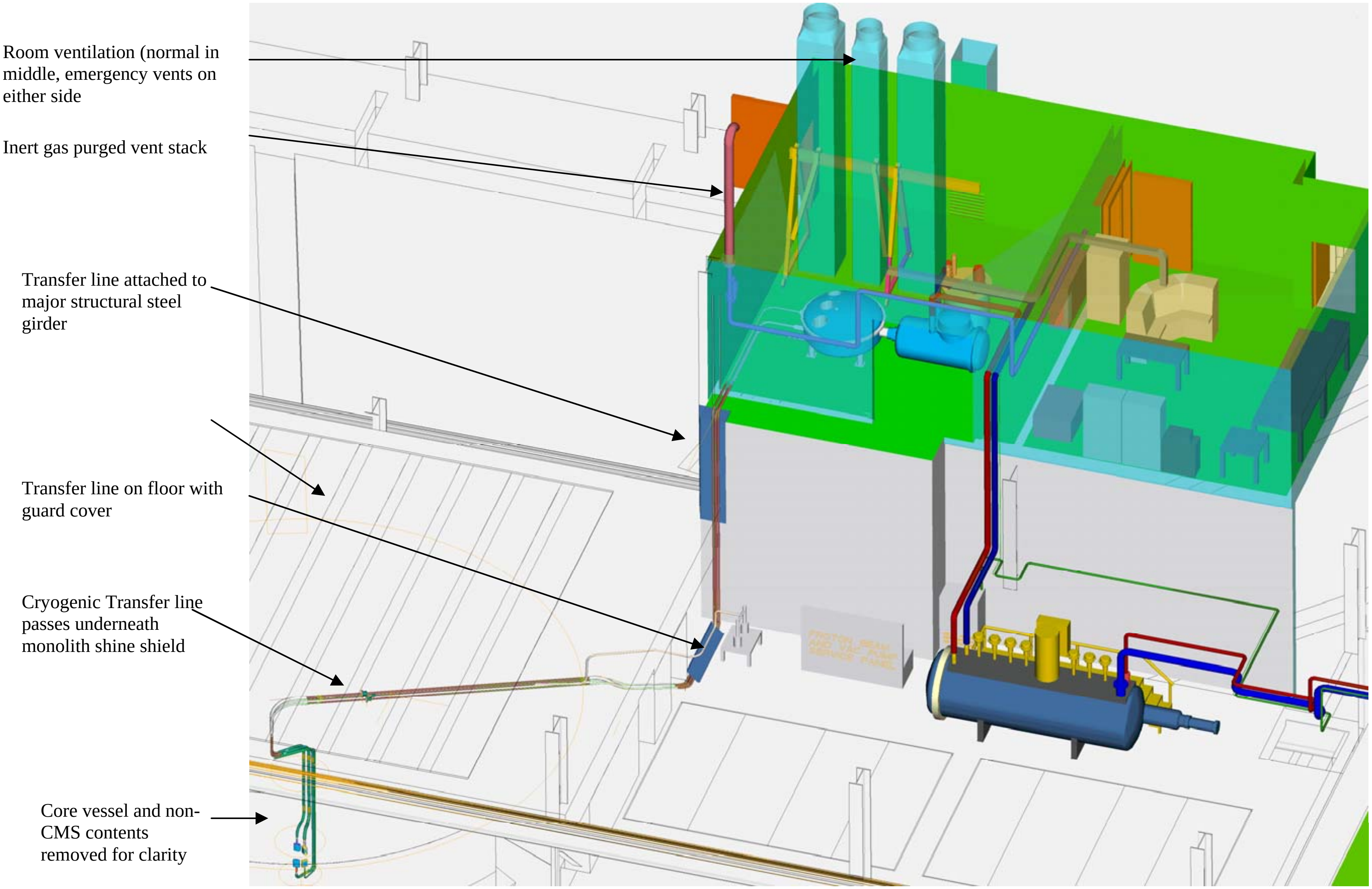


Figure 3.3.3.1-2 Route of Cryogenic Moderator System (CMS) Cryogenic Transfer Lines between Monolith and Hydrogen Utility Room

Figure 3.3.3.1-3). As described below, the CMS cannot physically be operated with a degraded vacuum layer because the resulting heat up of the system 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 (see Figure 3.3.3.1-1) to control the shape of neutron pulses produced by the moderators. Decoupled moderators have cadmium coating on the unviewed surfaces of the moderator vessel. Poisoned moderators have a gadolinium plate in the approximate center of the moderator.

Each loop comprises a moderator vessel inside the core vessel, a coaxial stainless steel transfer line to carry the cryogenic hydrogen to and from major components, and, in the hydrogen utility room (HUR), a circulator, a heat exchanger, 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 below. Since hydrogen in the CMS is maintained at ~ 20 K and above the critical pressure, it is technically correct to refer to it as “supercritical” rather than “liquid” hydrogen although the density is close to that of liquid hydrogen. 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. Cryogenic helium circulated through the heat exchanger removes heat that the cryogenic hydrogen absorbs from surroundings and from incident gamma rays and neutrons (significant in regions near the target module).

The accumulator has stainless steel bellows to accommodate expansion associated with normal and anticipated off-normal operational swings in temperature without the need to add or subtract hydrogen to or from the system. The purpose of the accumulator is to minimize pressure swings 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] with the system at temperature with the proton beam off, but increases only to 16 bar (232 psia) when the beam reaches full power due to the action of the accumulator.

The moderator vessel and several meters of the transfer line inside the core vessel receive significant neutron and gamma irradiation. CMS boundaries in this zone that are not in direct contact with the cryogenic hydrogen are cooled to maintain temperatures within normal design range. This is accomplished by a water jacket that surrounds the outer layer. The water jacket also performs a neutron

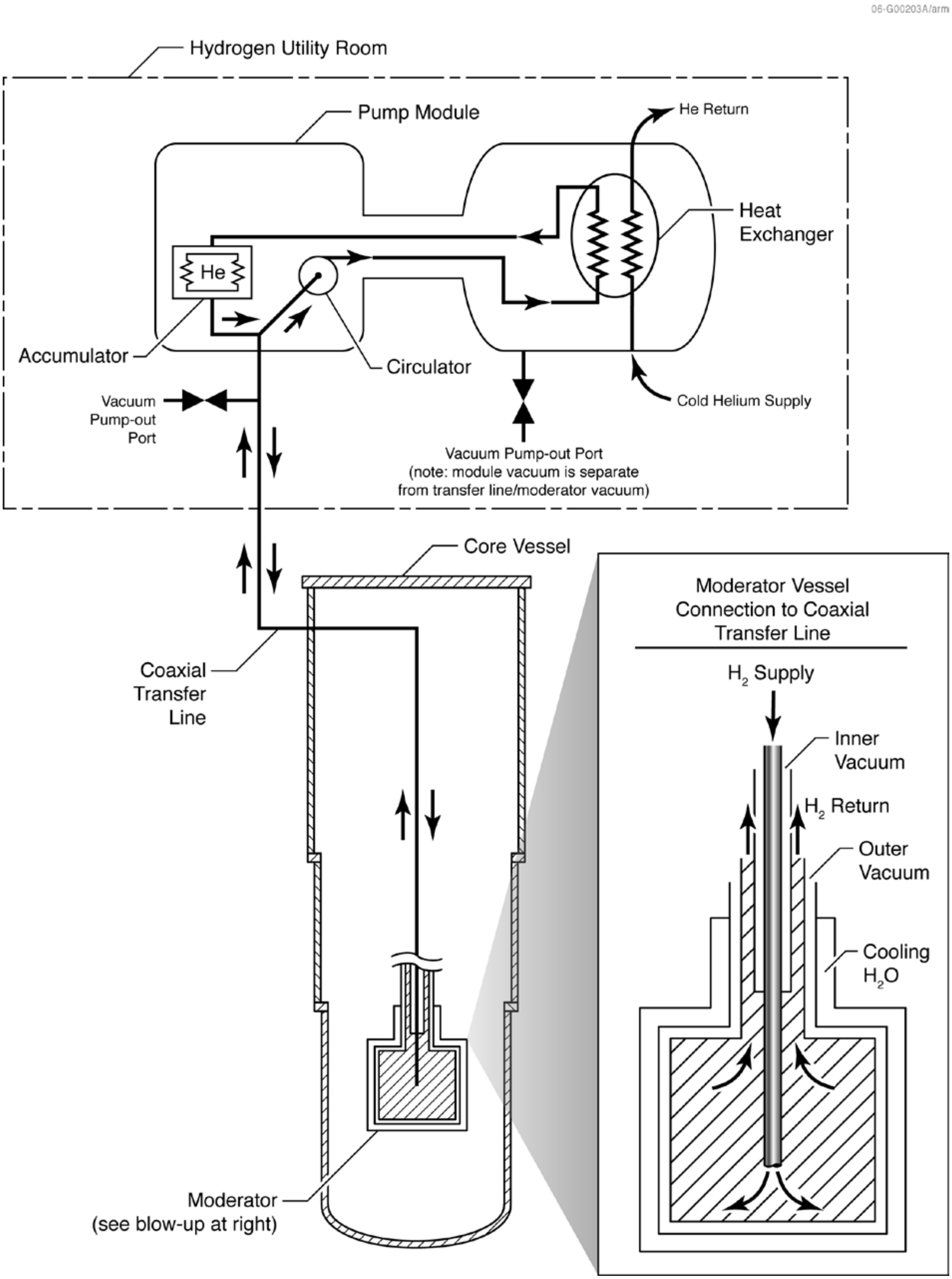


Figure 3.3.3.1-3 CMS Schematic Layout (typical of 3 CMS units)

pre-moderation function by helping slow down 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 operation of the CMS:

- 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. It should be noted that 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 located in the HUR except for control valves in the hydrogen supply cabinets, which are located inside 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 pump module and heat exchanger module are interconnected by the vacuum system (See Figure 3.3.3.1-3). 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 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 made available to the EPICS digital information bus.

The system must be charged with hydrogen before cryogenic operation is achieved. Multiple precautions are taken to minimize the opportunity for introduction of oxygen into the system. This includes the use of VLSI hydrogen and an interlocked, computer-controlled hydrogen fill system. The charging operation is initiated starting 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. After this is completed, 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 14-bar (203 psia) system operating pressure. 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 would have a potential to release a significant quantity of hydrogen into the HUR in a short period of time. Thus, 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 (see HUR discussion below).

When cooldown to the desired operating temperature is complete, the three isolation valves are closed, cutting off the connection with 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 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 needs to be accomplished, the regulating valve can be bypassed. Multiple vacuum pumpdown and inert gas purging cycles remove residual hydrogen from the system before it is opened for maintenance. Note that any maintenance of the CMS that involves opening of the hydrogen boundary will involve the dumping of the entire hydrogen inventory as part of the preparation for the maintenance. There is no attempt to avoid dumping the entire hydrogen inventory before the maintenance. This simplifies ensuring 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 operation of the CMS is the ability to maintain a high-vacuum envelope as thermal insulation around all parts of the system that contain cryogenic hydrogen. The ability to hold ~ 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 are designed to provide pump-down to the required (~ 10^{-6} torr) vacuum range. The vacuum utilities (pumps) are connected during initial pumpdown. After initial pumpdown the vacuum volume is isolated from the vacuum pump by closing of valve(s). The vacuum insulation will routinely not 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 with all welded connections minimize the chance of leakage. Any significant leakage of hydrogen into the vacuum barrier allows greater than normal heat transfer and causes hydrogen temperature to increase. If sufficient leakage brought the vacuum into the range of 10^{-2} torr or greater, rapid temperature and pressure increase would occur, 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/or the 19-bar (275.5-psia) rupture discs, discharging into the inert-gas-purged vent line.

A major key to the safety of the CMS is the provision of redundant barriers against hydrogen release within the core vessel and the protection of the barriers against internal over-pressurization 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 code stamped and designed and built according to applicable requirements of Section VIII of the ASME B&PV Code. The all-welded assembly of the cryogenic loop piping helps minimize the probability of leakage. The design and fabrication of all piping meets the requirements of ASME B31.35. 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 disc and 18 bar (261-psia) spring-loaded relief valve
- Vacuum boundary: 2-bar (29-psia) rupture disc

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

1. Sudden and total loss of vacuum to one atmosphere (helium or air)—expanding hydrogen is relieved through 18-bar (261-psia) spring loaded relief valve and/or 19-bar (275.5-psia) hydrogen rupture disc within acceptable pressure for hydrogen boundary (no hydrogen leakage to vacuum layer).
2. Leakage of cryogenic hydrogen into vacuum space—relief through hydrogen and vacuum rupture discs accommodated within the design pressure of hydrogen and vacuum boundaries and within allowable combined thermal and pressure stress limits of vacuum boundary that sees rapid temperature decrease due to contact with cold hydrogen.

Water leakage into the vacuum insulation space could occur in the moderator vessel or the several meters of transfer line that is cooled by the water jacket (which is the outermost layer). If that occurred the water would freeze rapidly but it is not expected that the hydrogen boundary would fail either through thermal stress or through physical pressure exerted by the newly formed ice. 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 both external as well internal pressure to help ensure that boundary failure does not occur and allow water in leakage. 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, 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, however, the less volatile components of the in-leaking air (e.g., O_2 and N_2) would solidify on the inner boundary of the (outer) vacuum space. In order to make sure that a significant quantity of air could not solidify on cold surfaces of the vacuum space, the following actions are built into routine operation:

- During cryogenic operations, the vacuum space is maintained statically, i.e., without active vacuum pumping. It is, however, periodically pumped as needed to maintain the desired high vacuum.
- If static vacuum cannot be maintained, the affected CMS unit is warmed up to ~ room temperature every 3 months (not to exceed 4 months). This periodic return to non-cryogenic temperatures would eliminate any solidified gaseous elements.
- If significant vacuum degradation is identified, the cause is investigated. If air in-leakage is suspected, continued cryogenic operation would not be supported. Residual gas analysis or other suitable technique is used for this determination of the cause of unusual need for vacuum pumping.

In the unusual event that one or more of the CMS loops were to loose cryogenic cooling, beam on target power is limited to ensure the affected moderator vessel does not overheat. The maximum design temperature for the moderator vessels is 393K, above which the T6 temper state may be lost and allowable stresses reduced.

Protection of the hydrogen boundary is important to safety throughout the system. The prevention of uncontrolled escape of hydrogen is an industrial safety concern, as addressed below in Section 3.3.3.2. Release of hydrogen into the core vessel would be, in addition, a hazardous material safety-related concern, as described in Chapter 4.

The hydrogen boundary is credited as a hydrogen confinement barrier. Although the hazardous material safety concern is with escape of hydrogen into the core vessel, the hydrogen boundary is designated to high quality standards throughout the cryogenic system (inside and outside the core vessel). The reason for crediting more than just the boundary inside the core vessel is the possibility that hydrogen leaking into the vacuum volume could escape into the core vessel if the vacuum boundary were also leaking. In order 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.

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, etc.) are not of radiological safety concern outside the core vessel.

Figure 3.3.3.1-2 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 (forklifts, cranes, etc.). This is facilitated 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 slots 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)[15] and in the equivalency document (SNS Document Number 108030700-ES0001-R01, April 2006). The summary information is given below. 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 up for maintenance. As stated previously, the hydrogen is vented and purge/vent cycles completed before the equipment is opened up.

The HUR houses active components of the CMS, including circulators, valves, and heat exchangers. The HUR has its own ventilation system, including 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 on detection of excessive hydrogen in the HUR. The emergency blowers are powered by the uninterruptable power system (UPS) and activate automatically upon detection of hydrogen in the room atmosphere. If the level exceeds 25% of the lower flammability limits (LFL) (i.e., > 1% hydrogen by volume) a local alarm sounds and the emergency blowers actuate. If the level is 50% of the LFL or more, 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 communicating directly with the truss level and the other with the adjacent preparation and control instrumentation 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, 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 lower flammability limit (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 control room are of a hydrogen-safe design per NFPA-70. Valve operators are pneumatic and employ non-incendive controls. The room ventilation system is designed to prevent hydrogen explosions per NFPA-69 and therefore the building is not equipped with blowout panel(s).

As provided by the ORNL WSS for engineering design,[4] the SNS project has prepared an equivalency determination (SNS Document Number 108030700-ES0001-R01, April 2006) to support the following desired design feature:

- The doors of the room may be located such that they allow access to and from the interior of the target building.

The HUR is seismically qualified to withstand a PC-3 earthquake without causing a failure of the CMS venting capability. This is a hazardous material safety requirement, the reason for which is explained above. Since 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 post-seismic-event leakage 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 (see 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 at ~ 408-in. diameter. The design accommodates major interfaces such as the cooling water systems, the ring-to-target proton beamline, and the instrument halls. Figure 3.3.4-1 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 one cubic meter of liquid before reaching the level of the door that separates the cavity from the basement. This door is also a fire barrier. Instruments are provided at or near the drain line termination so operators can tell if liquid is present inside the drain line. These instruments are designed to distinguish between water and mercury. It should be noted that 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 (see Section 3.3.2). It has been postulated that a severe seismic event could cause such failures. The cavity and fire door are PC-3 seismically qualified structures.

Figure 3.3.4-2 shows the bulk shielding drain line configuration in schematic form. 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 shutters are a system that provides a safe, non-obtrusive method to close a beamline so that downstream parts of the neutron beamline(s) can be accessed. The shutters have a position indication feature that is part of the instrument PPS so that

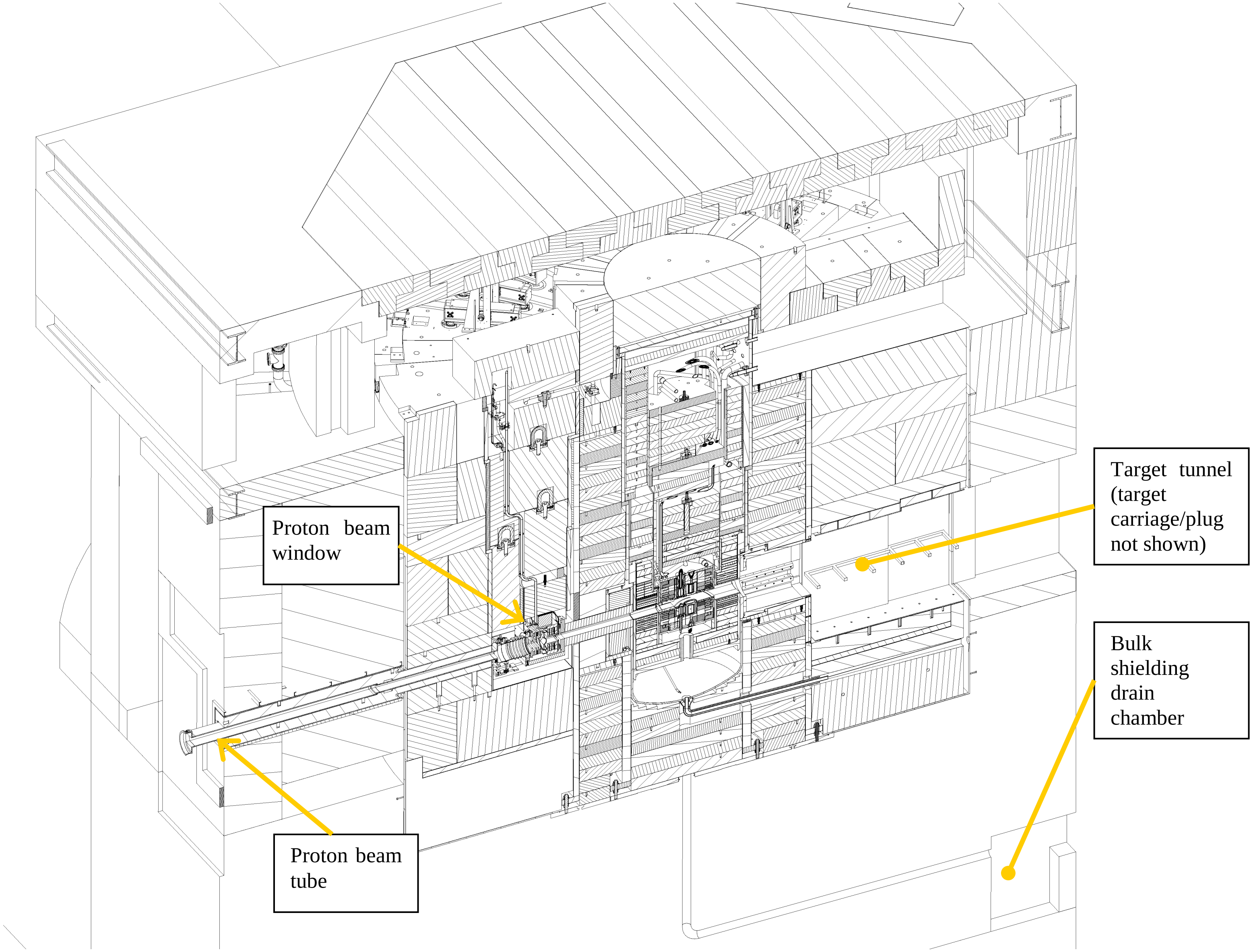


Figure 3.3.4-1 Target Monolith Cross-Section View, Sheet 2: 0° and 180° to Proton Beam Direction

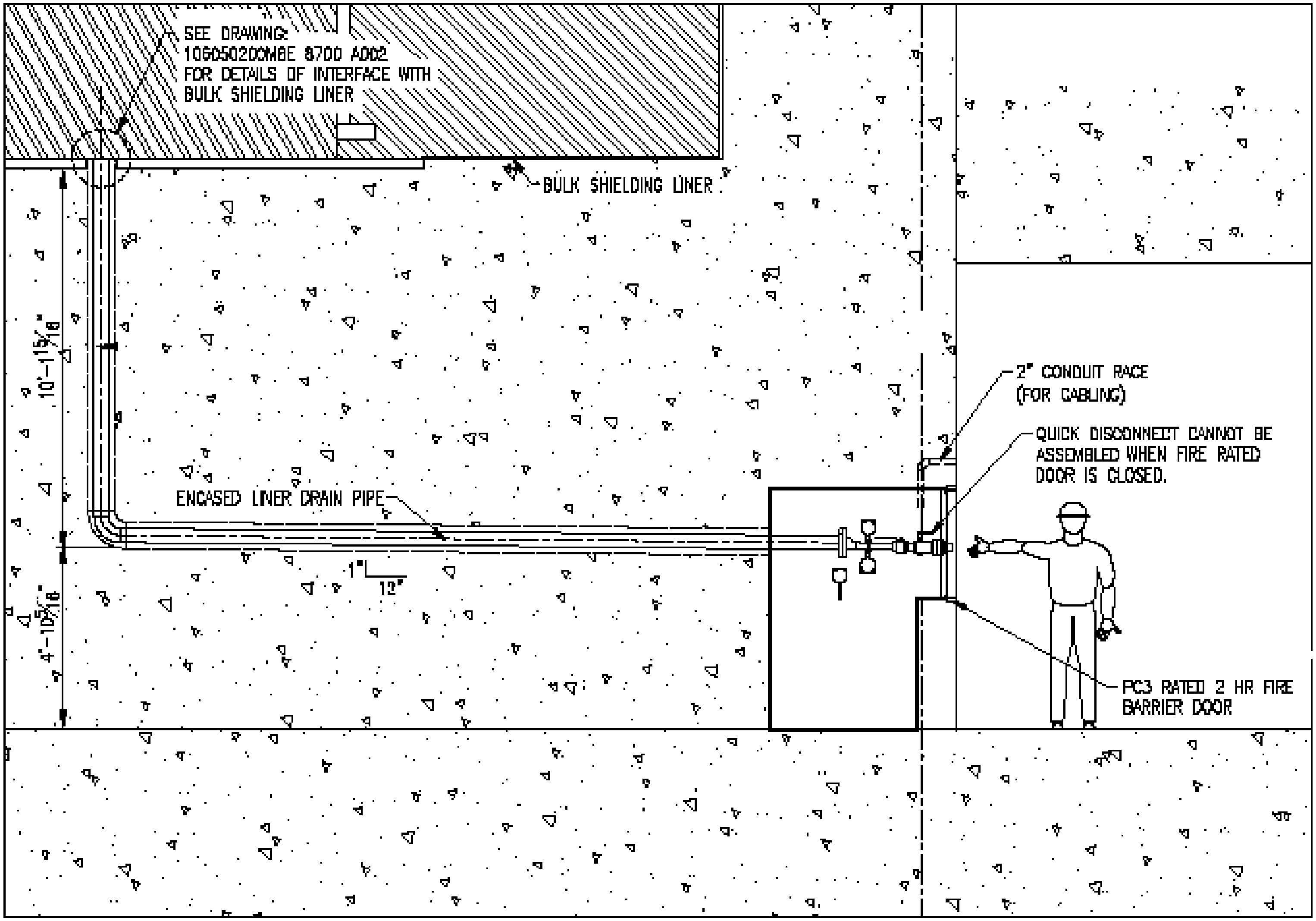


Figure 3.3.4-2 Schematic Diagram of Bulk Shielding Liner Spill Drainage Provision

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 an instrument PPS activity.

There are two broad types of shutters. The single channel shutters each include a single large steel assembly that weighs about 30 tons and serves a single instrument. The multi-channel shutters are wider and are composed of three major steel segments weighing a total of about 50 tons. Multi-channel shutters can serve two or more instruments. Both types of shutters operate in exactly the same manner. Figure 3.3.4.1-1 locates typical shutters in the monolith. A typical single-channel shutter is shown on Figure 3.3.4.1-2 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 which very accurately align the insert with the core vessel insert. This preserves the neutron guide alignment configuration and greatly increases the neutron beam flux.

The hydraulic system that powers the hydraulic cylinders uses water. The use of water as hydraulic fluid is possible because the system is designed for a relatively low pressure at 15.5 MPa (2250 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. This means that a shutter can be placed in the closed position (up) and the hydraulic system can be depressurized and the shutter will still remain in the closed position. In addition there is a manual safety pin that can be used to lock the drive system in the closed position and can be used for "lock out tag out" procedures.

The independent indicator switches and indicator rod are shown in Figure 3.3.4.1-3. This equipment is part of the PPS (see Section 3.3.8). It has no function for control of 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.

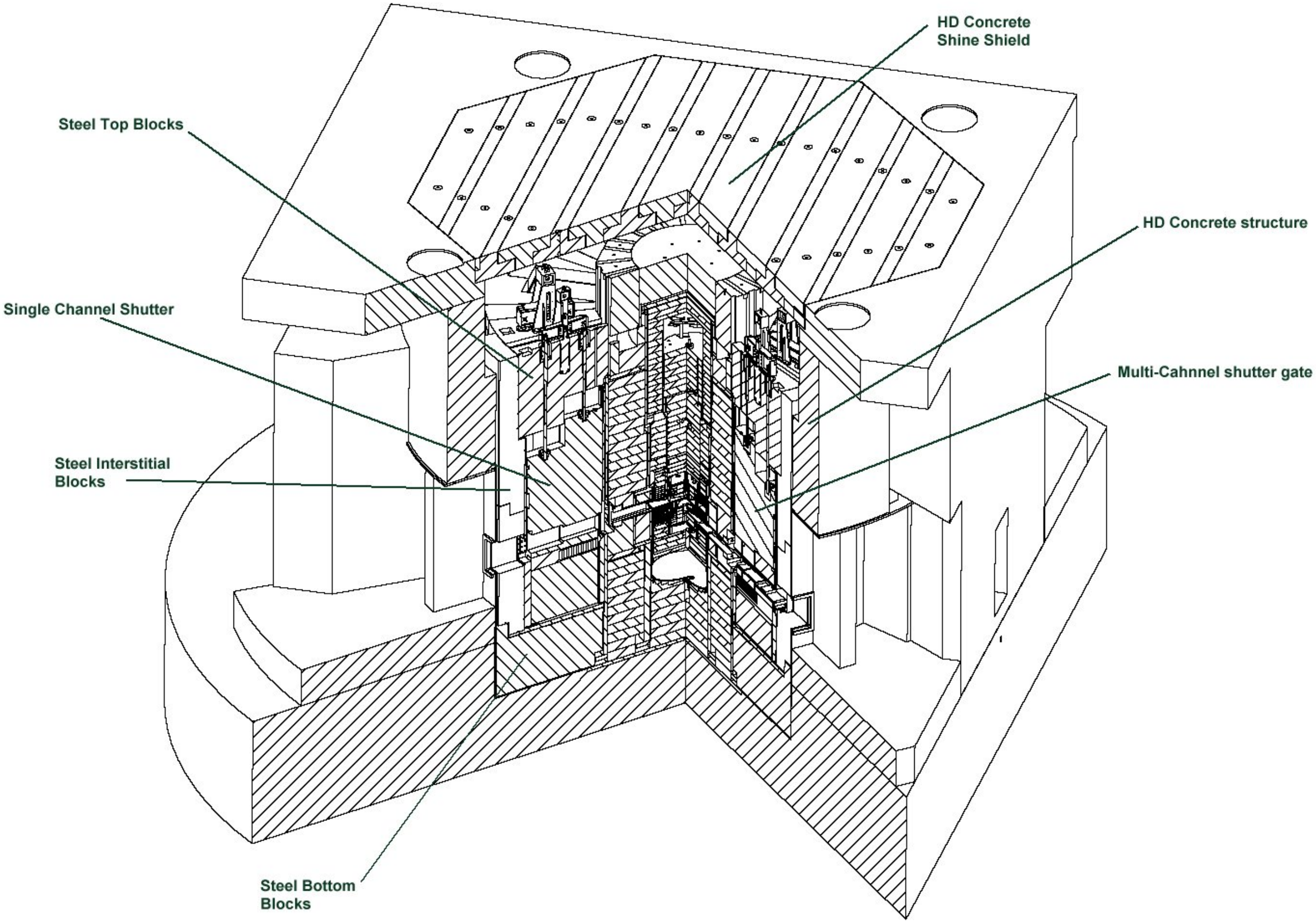


Figure 3.3.4.1-1 Location of Shutters in Context of Monolith Structure

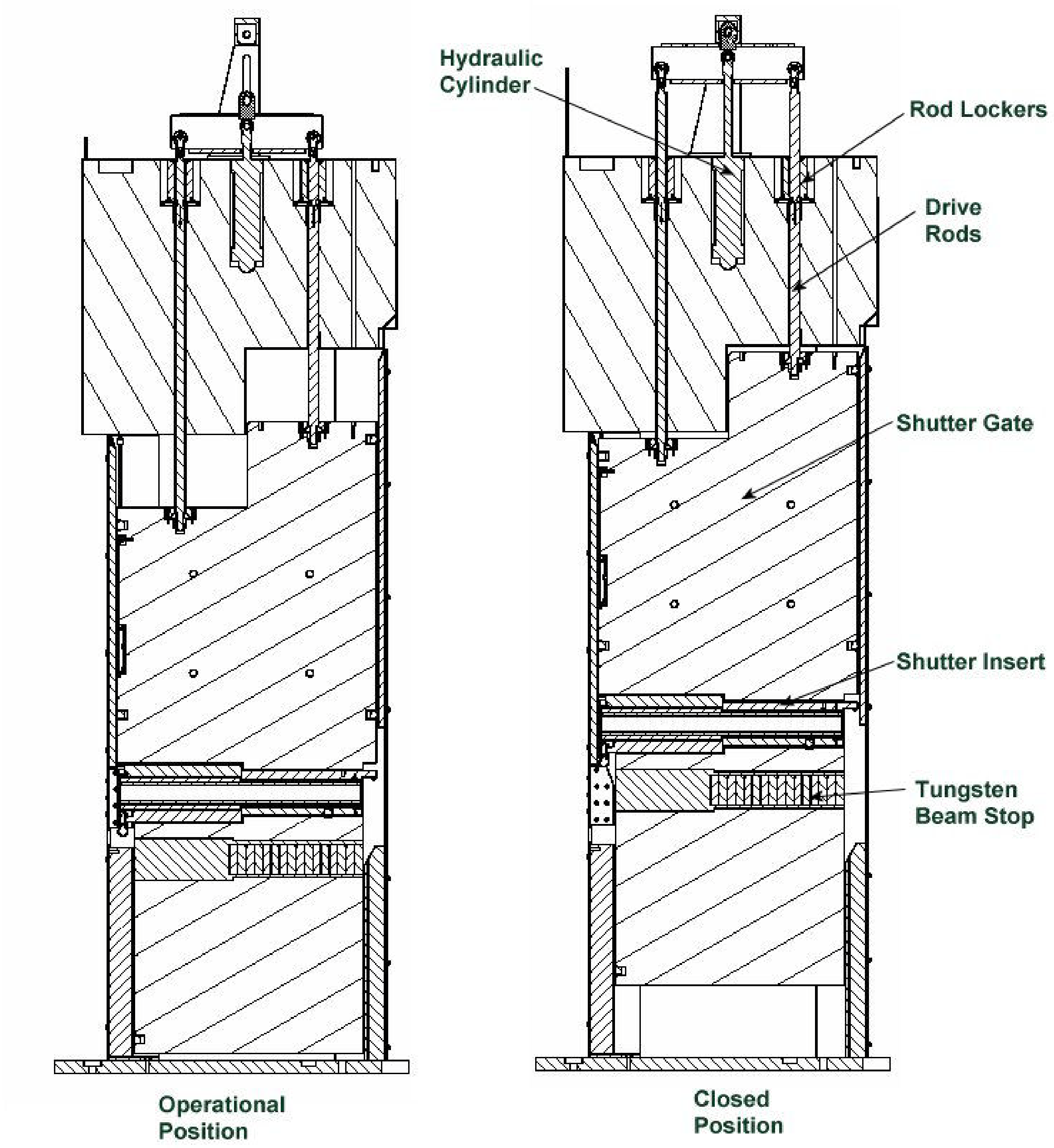


Figure 3.3.4.1-2 Typical Shutter

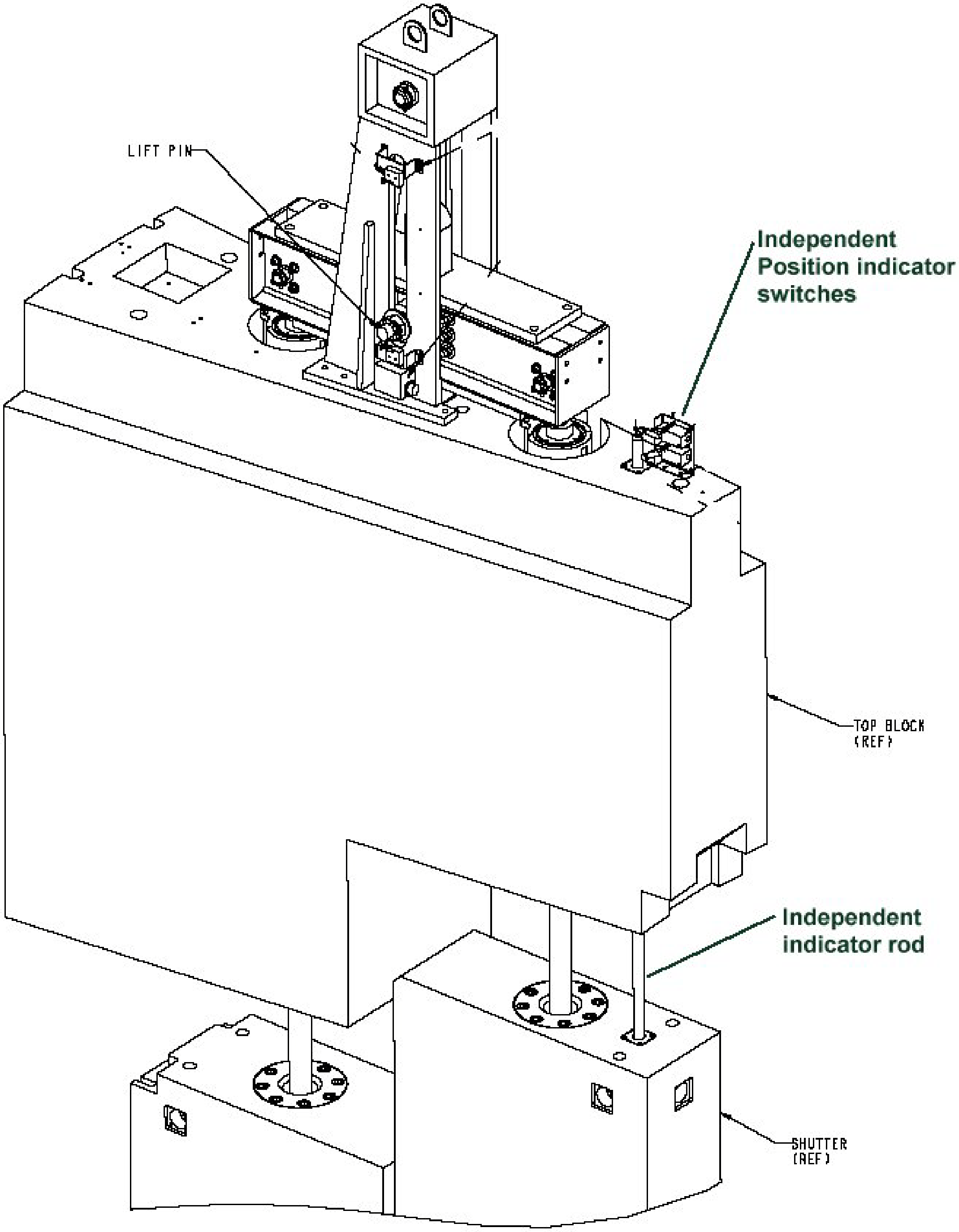


Figure 3.3.4.1-3 Shutter Position Indicators

3.3.5 TARGET SERVICE BAY AND REMOTE HANDLING SYSTEMS

Figure 3.3.5-1 shows the location of different parts of the target 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, Transfer Bay Access Control System.

3.3.5.1 Target Service Bay

The target 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 Sections 3.3.5.2.

The target service bay structure includes the heavy concrete shielding provided by the ~ 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 two-hour fire barrier and is a CEC for fire events. In addition, the concrete wall between the instrument hall and the target service and manipulator galleries is a two-hour firewall. The fire barrier (shown in Figure 3.2-3 above) is seismically qualified to PC-3 (see Section 3.2.5).

The target service bay (see Figure 3.3.5-1) consists of:

- the interconnected mercury process bay and maintenance bay; and
- the adjoining transfer bay separated from the maintenance bay by the steel intrabay shield door.

The process bay contains the target mercury process loop components including the power cables and the entire system for circulating and cooling the mercury (consisting of the pumps, piping and pipe support structures, vessels, heat exchanger, and local shielding), is located in the process bay. Water cooling is piped to the secondary side of the mercury heat exchanger. There are piping and pipe support structures 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 that is able to 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.

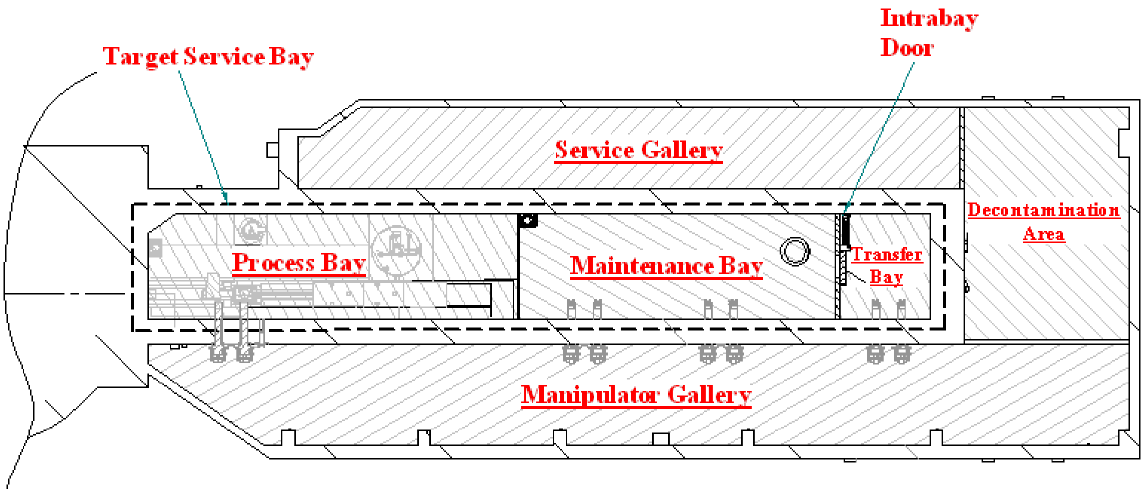


Figure 3.3.5-1 Location of Functional Areas of the Target Service Bay Complex

The maintenance bay contains remote handling equipment used to handle activated components. The area also provides space for holding activated components for decay prior to 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 robot to move to the transfer bay for maintenance and for general entry or exit of materials to or from the service bay.

The service bay roof structure also serves as the high bay floor (see Chapter 5 for description of the high bay floor and interior service bay structure safety functions). Parts of the target service bay roof are constructed of concrete T-beams that can be removed should major mercury loop component replacement become necessary.

Target service bay penetrations for utilities (piping, electrical, helium, vacuum, nitrogen, etc.) 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 target 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 target service bay. Normally capped lines in the target service bay provide a connection to the LLLW system (see Section 3.3.12). To remove liquid from the target service bay, one of these drain lines must be remotely uncapped and connected to a sump pump. It is possible that liquid mercury and/or 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 such that liquid mercury could not be inadvertently discharged into the LLLW system by this means. 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 and are of sufficient thickness 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 target service bay provides three specific areas as illustrated in Figure 3.3.5-1: the process bay, the maintenance bay, and the transfer bay. Figure 3.3.5.1-1 shows a cut-away isometric view, while Figures 3.3.5.1-2 and 3.3.5.1-3 depict cross-sectional views of the target service bay from side and 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 target 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 and job hazard analysis.

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

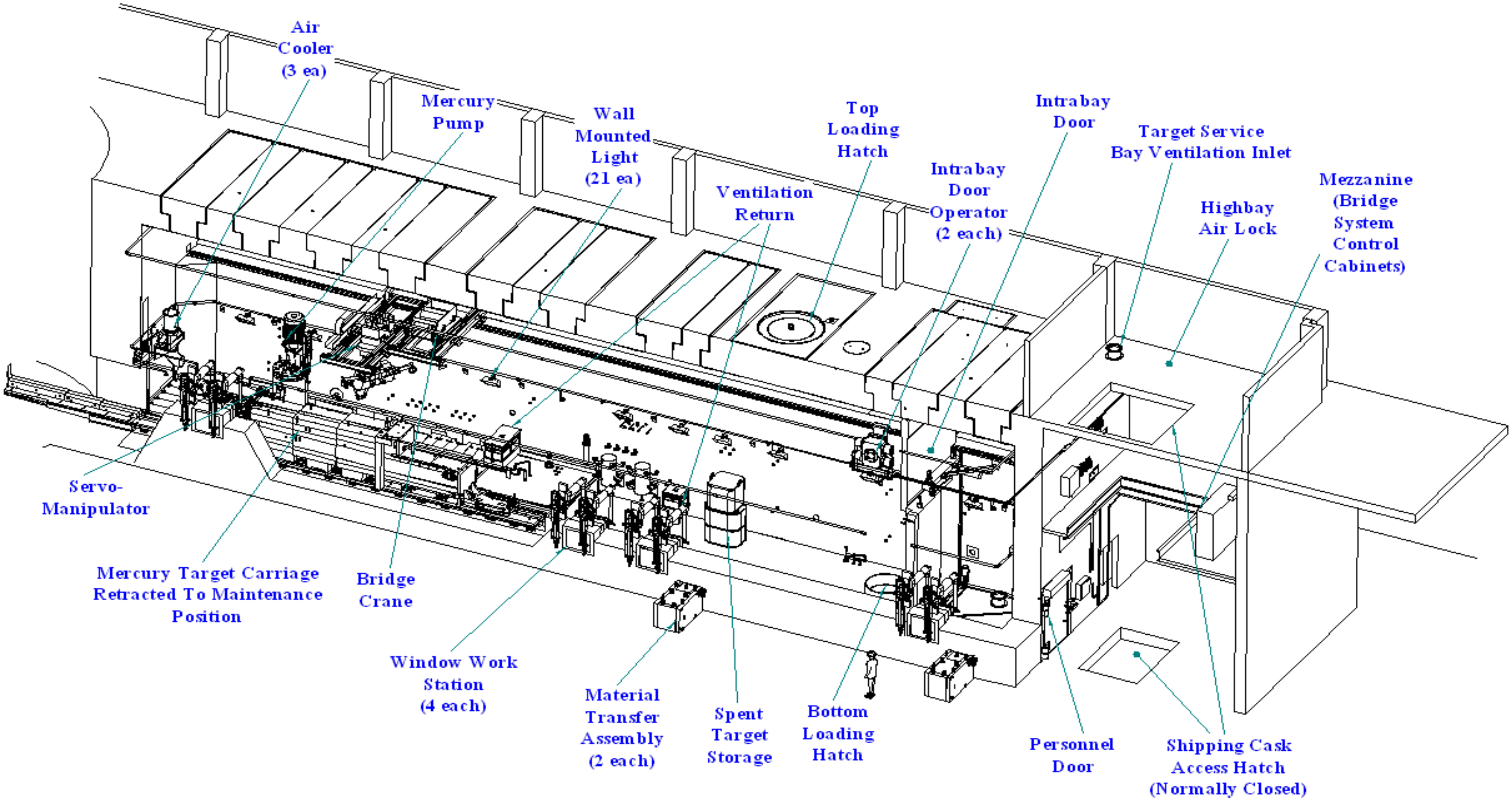


Figure 3.3.5.1-1 Cut-Away View of Target Service Bay from the Southeast (target carriage in withdrawn position)

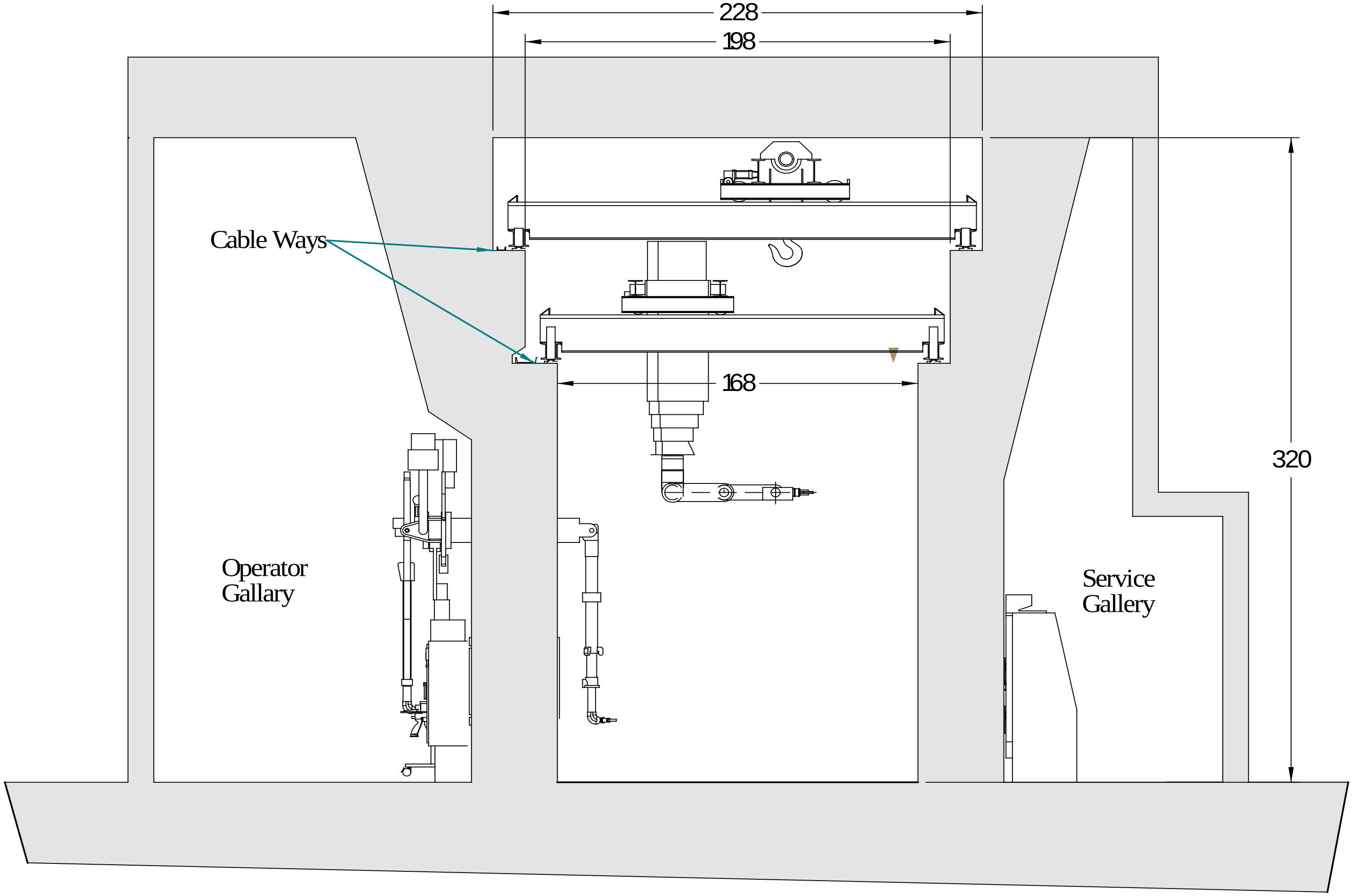


Figure 3.3.5.1-2 Cross-Section View of Target Process Bay and Galleries

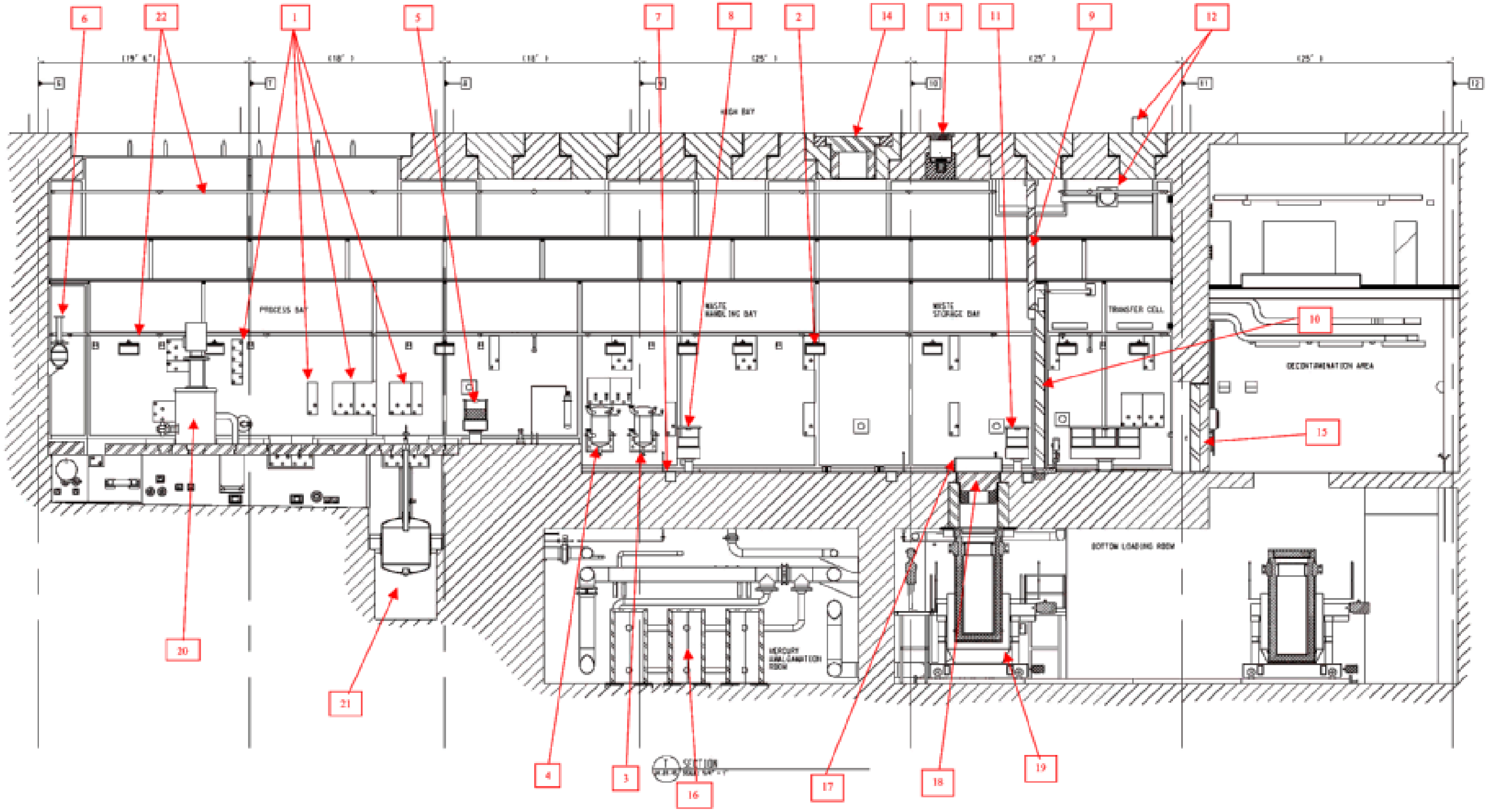


Figure 3.3.5.1-3 Target Service Bay Cross-Section View, Sheet 1 of 2 (shielding beams above process bay shown removed, a very rare nonoperational configuration)

Sheet 2 of 2 of Figure 3.3.5.1-3

Key to numbered items on Sheet 1:

Note: the target service bay (i.e., the “maintenance” bay) is divided into the process bay and maintenance bay. The transfer bay is part of the target service bay but it is labeled separately because of the intent to maintain it in a relatively contamination free state to facilitate infrequent 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 list below).

1. Penetration banks, typical of 50 within the target service bay. Both electrical and piping penetrations are shown.
2. Light fixture, typical of multiple light fixtures within the target service bay.
3. Deferred low temperature condenser (for use only during regeneration of the gold amalgamation bay exhaust treatment medium, is not installed for initial operation).
4. Deferred water-cooled condenser (to be used only during regeneration of the gold amalgamation bay exhaust treatment, is not installed for initial operation).
5. Process bay PCE system exhaust port (each exhaust port fixture holds a HEPA filter).
6. In-bay air cooler, typical of 3 within the target service bay (service bay air recirculates through each water-cooled heat exchanger).
7. Floor sump, typical of 3 within the maintenance bay.
8. PCES exhaust port, typical of 2 in maintenance bay.
9. Upper rotating intrabay shielding door (~ 8-in.-thick steel).
10. Lower rolling intrabay shielding door (~ 11-in.-thick steel).
11. PCES 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. Deferred PCE system gold amalgamation air treatment stages (shown in place in the basement but is not initially installed. Items 3 and 4 support this item and also are not installed for initial startup).
17. Curb structure for bottom-loading port (prevents maximum credible water accumulation from leaking out of the target 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.

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 insures worker protection (See 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 (contact handled wastes, samples for analysis, tooling for repair, etc.) 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.

3.3.5.2.1 Remote Handling Systems

The target 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 target 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 3.3.5.1-1. The through-the-wall manipulators are operated by workers occupying the manipulator gallery. Two types of manipulators are installed: seven Central Research Laboratories (CRL) Model F (or equivalent) mechanically linked master-slave manipulator pairs and one CRL Model E. The manipulators are used for in-bay tasks requiring high dexterity such as handling wrenches, small fixtures, positioning bridge and servomanipulator-held components, and performing inspections with swipes or closed-circuit cameras. The maximum capacity of the manipulators is ~ 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 ~ 100 lb. The system is used throughout the bay to handle tools, lift fixtures, and other loads. The manipulator can be fitted with conventional parallel pinch grips, hook and tool holding hands. The servomanipulator has a vertical travel allowing activities between floor level and approximately 13 ft above the bay floor over 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 target service bay. Generally this includes only components with 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 35 ft. This allows it to lower loads into a shielded cask docked at the bottom loading hatch or to reach a load in the collection basin/storage tank pit (i.e., the crane is designed to reach below target service bay floor level for these required activities). The hook can approach to within ~ 12 in. of all the bay walls.

The remote handling control room houses the main control stations for the crane, servomanipulator and video systems. Other systems operated from the control room include the intrabay door, air coolers and lights. Due to the size of the target service bay, video cameras are required to provide viewing for the operators. Video cameras (initial installation of 11) are mounted on the walls and bridge systems throughout the target service bay. The cameras provide viewing 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.

3.3.5.2.2 Material Transfer Systems

Four paths have been provided for loading materials into and out of the target service bay, each 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 prior to 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 shipping cask tentatively selected for certain irradiated SNS materials (e.g., the TN-RAM 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 of the target service bay is used for the insertion of irradiated, potentially contaminated components such as the spent proton beam window or core vessel inserts from the high bay. These components are disassembled and packaged for loading into the TN-RAM shipping cask.

Pass-Thru Ports: Two are provided, one at WWS 3 and one at WWS 4 (these are shown on Figure 3.3.5.1-1 labeled as “Material Transfer Assembly”). Each Pass-Thru Port is a shielded pass-through device mounted at floor level that allows small items to be transported in and out of the target service bay. A curb is built into the structure of the pass-through to make it impossible for the greatest water spill event to allow contaminated water to flow out of the target service bay through this device.

Transfer Bay Personnel Door: New equipment enters the target 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 target service bay such that the flow of air is into the target service bay with the personnel door open. New equipment to be loaded into the bay may be positioned inside the bay with 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 man-lift platform loaded into the transfer bay on an as-needed basis. 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 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 desired due to preferred neutronics properties. Although neutronic calculations indicate a significant benefit for heavy water in Loop 4 in terms of ability of the target assembly to provide moderated neutrons for research, budgetary constraints have required that initial operation of the reflector cooling loop utilize light water. Table 3.3.6.1-1 shows components and design heat loads for each loop.

The cooled components are located in the target 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 below to avoid repetition.

Table 3.3.6.1-1 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 3.3.6.1-1. 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. In addition, 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 holdup time needed to allow short-lived isotopes such as N-16 (7.1 second half-life) to decay. Cooling loop 1 is unique in that the water is not expected to be activated. It circulates water through the mercury heat exchanger located in the target 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. At least two boundary failures would be required in loops 2, 3, and 4 to contaminate tower water with activated water (note: loop 1 cooling water is not expected to be activated and three boundary failures would be required to contaminate tower water with activated mercury). In addition, 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. Consequently, any leakage through the barriers that separate the fluids would be from the tower water side to the higher temperature process side of the heat exchanger.

Delay tanks are employed in the return line of each activated water loop 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.

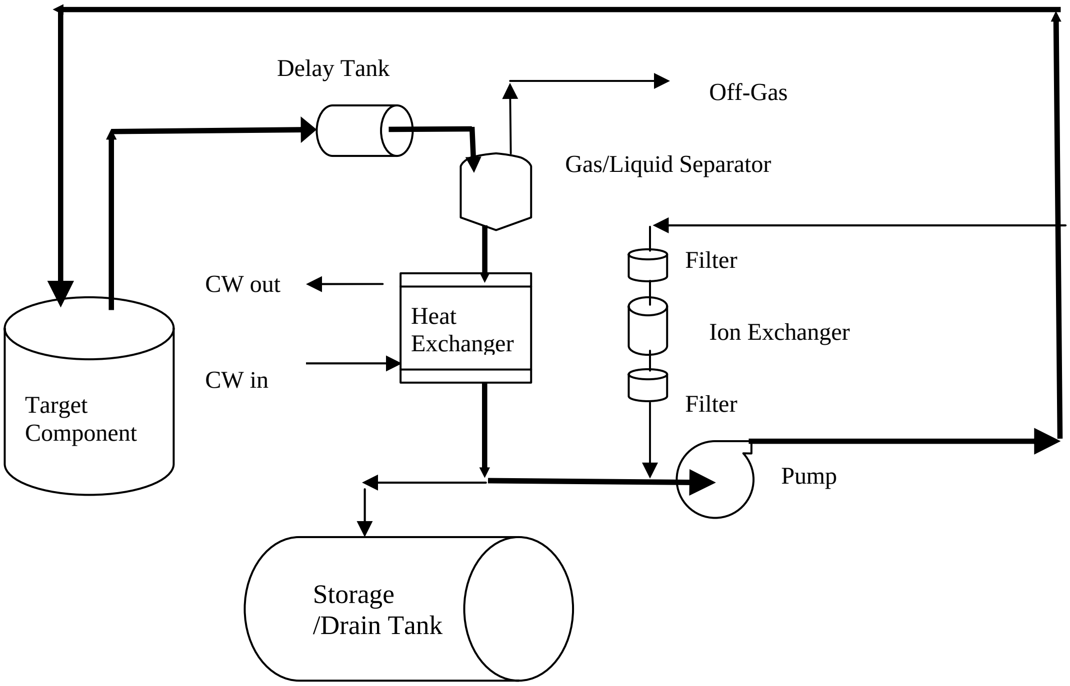


Figure 3.3.6.1-1 Generic Schematic Illustration of Cooling Loop Components

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

Separation of gases generated in the water loops due to spallation and/or the radiolytic decomposition of water is achieved in a gas/liquid separation tank to be 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 to below the lower flammable limit. The separator tank head space vents to the HOG system.

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 sub-assemblies are replaced as needed based on either 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. The heavy water may be replaced periodically, as needed, to replace losses or to control tritium concentration. Alternatively, light water may be used in cooling loop 4 with no impact on safety.

Pipe leak and break accidents are considered in the HA for these systems (see Section 4.3). Results indicate that cooling loops 2, 3, and 4 cannot threaten workers or exceed public evaluation guidelines. Two primary reasons account for this conclusion: (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 indicated 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 prior to backfilling with an inert gas and to activate seals employed between the target 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 PCES (see 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. 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 lower flammability limits, to perform seal leak checks and to purge the core vessel vent line. A gas distribution system is provided to supply the nitrogen for various uses.

3.3.7 MERCURY OFF-GAS TREATMENT SYSTEM (MOTS)

Helium purge or other inert cover gas that is in contact with process mercury is routed through the mercury offgas treatment system (MOTS), which is located in the target service bay and in the tritium removal room areas. It removes mercury, noble gases, iodine, and tritium from the target offgas. Other target service bay process exhausts that are not significantly mercury-contaminated (i.e., other than the target service bay exhaust, see Section 3.3.9) are routed directly to the hot offgas (HOG) system (described in Section 3.3.9.3).

The MOTS consists of the following elements (see Figure 3.3.7-1 for schematic diagram):

1. Two gold amalgamation adsorbers in series
2. A CuO/desiccant oxidation/adsorption system
3. A cryogenically cooled charcoal adsorber

The gold adsorber (Al_2O_3 pellets containing a gold impregnant) is sized to hold the quantity of mercury that would exit into the offgas during the anticipated operational period (the preliminary estimate is 50 g of Hg/year).

The CuO bed is the next component in the system. It functions to oxidize tritium and other hydrogen isotopes in the gas stream. It operates at a temperature on the order of 195°C. The CuO supplies oxygen

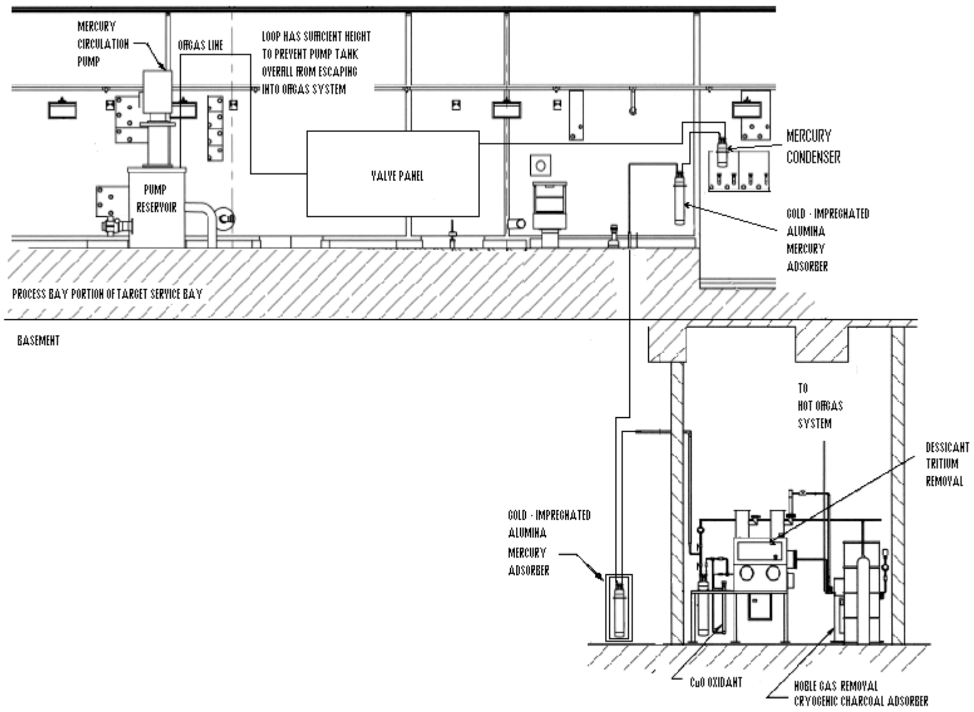


Figure 3.3.7-1 Mercury Offgas Treatment System Schematic

to react with tritium, and becomes reduced to copper metal in the process, and therefore requires periodic regeneration. The regeneration is expected to be performed during shutdowns for target module maintenance, when the offgas system is not operating. Because mercury is known to decrease the effectiveness of CuO catalyst, monitoring of the bed condition and periodic replacement of the bed is 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. Since the quantity of hydrogen isotopes is expected to be small, capacity loss should not be an issue until the bed is completely deactivated.

Downstream of the CuO bed is a set of desiccant beds filled with a molecular sieve (such as Linde 5A). The hydrogen oxides are removed in this bed and the bed is heated periodically to remove the moisture. Removed moisture is adsorbed in another desiccant bed that is discarded when full. Neutronics calculations indicate as much as 2000 Curie of tritium is expected to be produced by spallation of mercury during a three month period at the 2 MW full beam power. The bed may be changed-out to maintain the quantity of tritium on an individual bed below desired levels to facilitate ease of disposal.

The last component in the treatment system is a cryogenically cooled charcoal bed. This component is present to remove noble gas spallation products (principally krypton and xenon) from the offgas stream. The bed requires shielding but should never require replacement. The charcoal bed also serves to remove residual mercury and tritium from the gas stream.

There are two gold adsorbers in the system, one located in the target service bay and the other in the gold amalgamation room (room TA-B149, see Figure 3.2-2). The desiccant beds are located inside a glove box in the tritium recovery room. The charcoal bed is located in a separate shielded area also in this room.

As shown on Figure 3.3.7-2, helium is admitted into the mercury storage tank to force mercury to flow up into the pump tank when filling the process loop with mercury. Typically about 40 to 50 gallons of mercury remain in the storage tank after the loop is filled. Excess helium pressure would force a greater than normal quantity of mercury into the pump tank. An automatic alarm and interlock are provided to isolate the helium in the event that the pump tank reaches an abnormally high mercury level. An elevated loop is provided in the line that connects the offgas system to the pump tank to provide positive assurance that a pump tank overfill event could not result in the transfer of mercury out of the target service bay. The top of the loop (see Figure 3.3.7-2) is at a high enough elevation that it would prevent mercury from escaping from the target service bay assuming the following multiple failures:

1. The helium pressure regulator fails, increasing the pressure of helium in the storage tank to the maximum actuation pressure of the helium supply line safely relief valves (nominal 105 psig actuation pressure plus 10% uncertainty allowance ≤ 115.5 psig).
2. The automatic helium isolation on pump tank high level fails to actuate when level exceeds the alarm setpoint.
3. The operator fails to respond properly during the events.

The loop seal arrangement is a CEC, as discussed in Chapter 5.

3.3.8 PROTECTION SYSTEMS AND INTEGRATED CONTROL SYSTEM

Monitoring and control of the mercury process system and related support systems are accomplished through three systems: the TPS, the target service bay differential pressure monitoring system, and the target control system that is part of the integrated control system (ICS). The branch of the PPS that provides target system personnel protection functions is known as the target PPS, and the branch that serves the neutron instruments is called the instrument PPS.

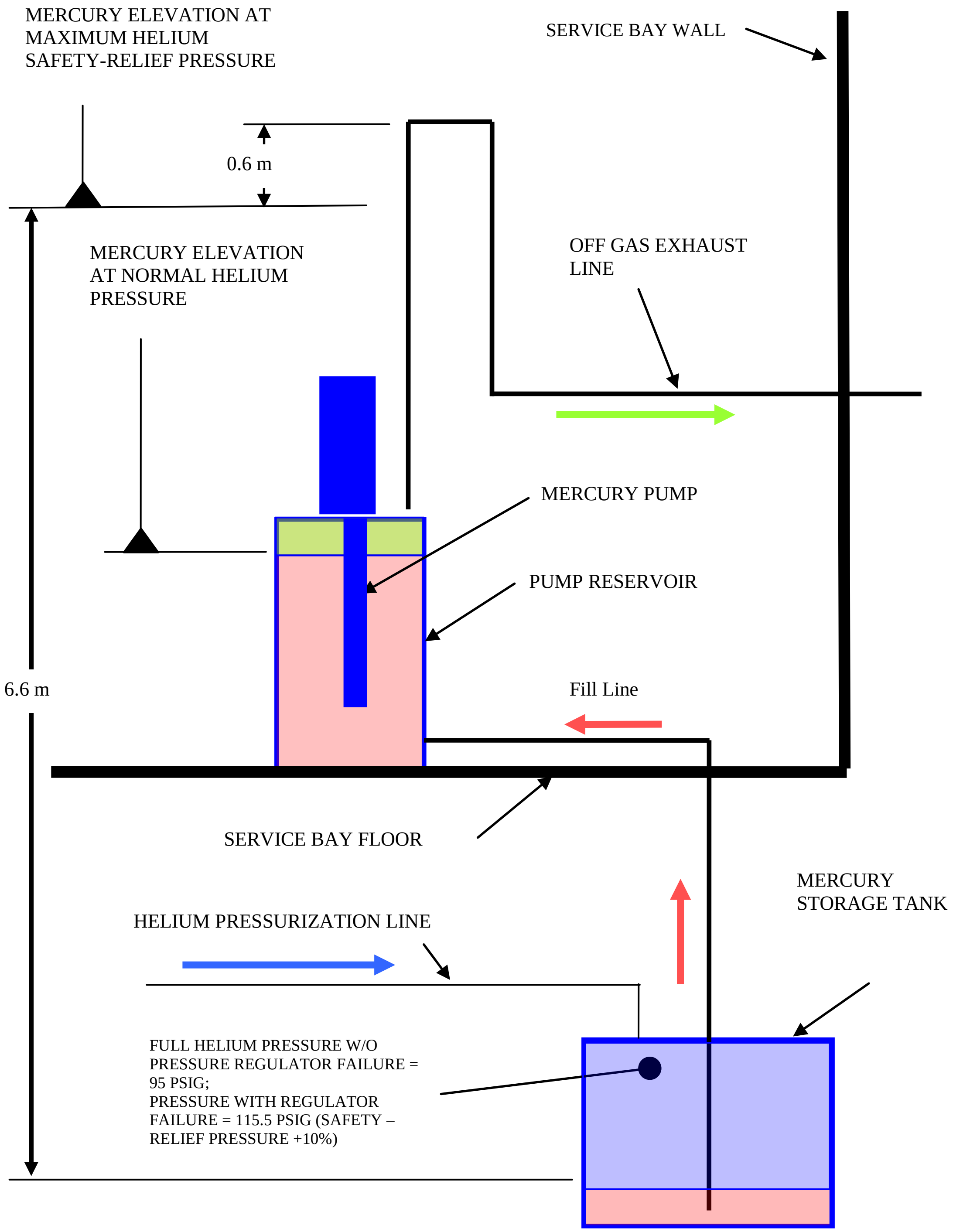


Figure 3.3.7-2 Schematic Diagram of Elevations Pertinent to Pump Tank Overfill

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 experimental physics and industrial control system (EPICS) standard architecture. This system has a standards-based architecture (using 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.

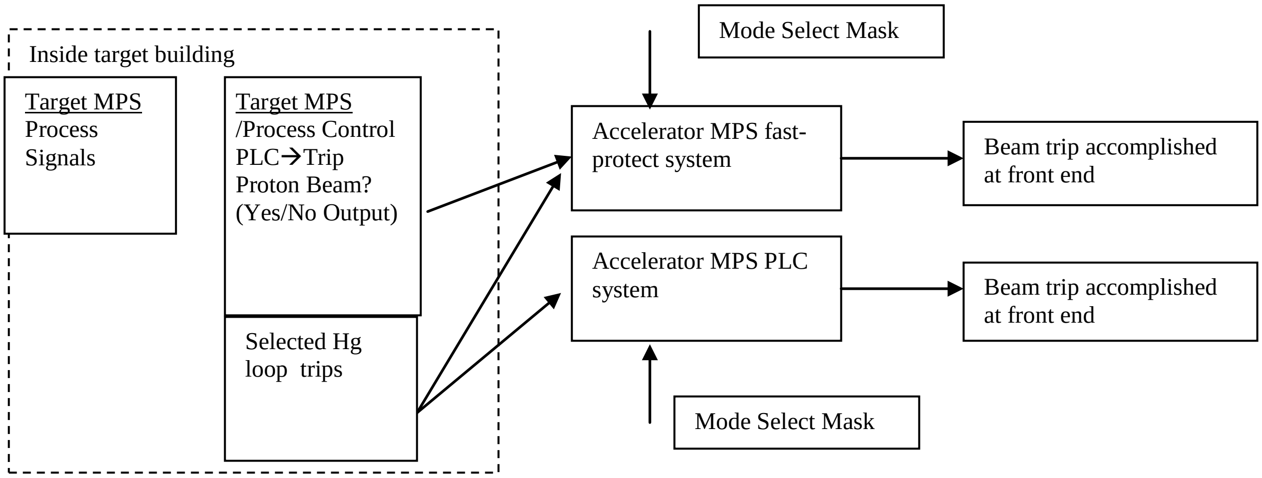
The TPS and target service bay differential pressure monitoring systems, discussed in Section 3.3.8.2 are credited controls. The TPS is the CEC that trips the proton beam when necessary to prevent overheating of the mercury by the proton beam. The service bay differential pressure monitoring system provides the credited alarm on inadequate target service bay negative pressure. The target PPS and the instrument PPS are credited 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), input/output (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 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 has a proven capability to integrate large numbers of control systems and parameters based on its performance at 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 serve primarily to interface between the PLCs, which perform the control and interlocks for 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 main control room, the target control room, 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 main control room or the target control room by receiving PLC data and sending setpoints to the target PLCs. Each contains a processor, network interfaces, and some I/O modules.

The MPS provides equipment protection that is a non-safety function. The MPS does, however, contribute 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 with 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 is illustrated schematically in the sketch below. All of the 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 provides redundancy and diversity for selected mercury loop parameters because both MPS systems can trip the proton beam.



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 failsafe signal in that 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 to 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. Both 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 below in Section 3.3.8.3.

The CLO building central control room (CCR) contains multiple workstations and consoles that can be used for controlling the target during normal operation, and it has hardwired TPS indicators and manual shutdown switches. The target building control room is located in the basement of the target building. The operators normally use the target building control room during startup of the target systems and during support activities such as target replacement, system maintenance, and scheduled activities for the target equipment. Otherwise, the target building control room is not normally staffed.

Process indicators and TPS manual shutdown switches are located in the CCR in the CLO and in the target building control room. The operators in the CCR and the target building control room 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 of 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 are provided to make the TPS single failure proof. Since the TPS is a CEC, a more detailed description and evaluation can be found in Chapter 5. The service bay differential pressure monitoring system performs a credited alarm function as explained in Chapter 5.

3.3.8.3 Target and Instrument Personnel Protection Systems

The target personnel protection system (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 QA Level 1 and are configuration controlled in accordance with SNS procedures. As shown in Figure 3.3.8.3.1-1, the scope of the PPS encompasses both the Proton and Neutron Facilities. The reader is referred to the *FSAD for Proton Facilities*[1] for more detailed description of the entire PPS.

3.3.8.3.1 Target Personnel Protection System

3.3.8.3.1.1 *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 redundant 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
- Chipmunk radiation detectors 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

Figure 3.3.8.3.1-1 Overall Scope of the Personnel Protection System

secondary shutters are downstream, between the monolith and the instrument enclosure. When closed they prevent the neutron beam from reaching the instrument enclosure.

Chipmunks are used in the target building to measure radiation from prompt sources. If abnormal radiation levels are detected, the Chipmunk signal will result in a trip of the beam at the front end. Chipmunks may also be applied to selected instruments, based on the hazard evaluation process for that instrument. The reader is referred to the *FSAD for Proton Facilities*[1] for description of a chipmunk.

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. In the event of an unsafe condition, the instrument PPS can directly control the secondary shutter when provided. If the instrument PPS cannot place the instrument in a safe state, 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.

If beam were transported to the target building when the target cart is rolled back, 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.

3.3.8.3.1.2 *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.

3.3.8.3.1.3 *Operating Modes*

The target PPS is designed to allow the target segment to be in one of three modes as listed in Table 3.3.8.3.1.3-1 below:

Table 3.3.8.3.1.3-1 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 due 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.

3.3.8.3.1.4 *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 8.3.1.4-1 below:

Table 3.3.8.3.1.4-1 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

3.3.8.3.1.5 *System Architecture*

The PPS System architecture is described in the FSAD-PF.[1] Signals are communicated between the target PPS equipment and the accelerator facility segments via hardwired input and output 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. This includes keys required to enter Target and Instrument PPS controlled areas and keys for entry into the Transfer Bay. Key accountability, custody and custody transfer will be tracked via log book 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 or in a lock box controlled by the Instrument Hall Coordinator. The keys 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 our tracking database and will not be reused (the type of trapped key used by SNS has 625 unique codes).

3.3.8.3.1.6 *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. There are three ways to prevent beam transport to the target building:

Beam Production

Beam production is inhibited by disabling the RF to the RFQ and the 65-kV power supply or the Plasma RF supply (see *Final SAD for Proton Facilities*,[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 DH.13

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.

3.3.8.3.1.7 *Chipmunks*

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

Chipmunks are located in the target building as specified by the Radiation Safety Officer (RSO). Chipmunks may be applied to detect prompt radiation due to a proton beam control fault upstream of the target or to detect radiation from an improperly shielded beamline. The radiation monitors produce two digital outputs used by the PPS. 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, a digital output is produced that stops beam production.

The PPS makes use of the chipmunk pulsed output to supplement the immediate cut-off function available via the 100-mrem/h fixed alarm output. Dose rates are indicated by a pulsed output (e.g., Chipmunks produce a pulse for each 2.5 μrem). The PPS totalizes the number of pulses over a unit time to determine dose rate. Adjustable dose rate limits are used to activate area alarms and stop beam production. These adjustable dose rate limits are specified by the RSO during the installation of a Chipmunk. These limits are based on a rolling average to prevent spurious trips. A rolling average value of the dose rate is calculated over a 15-min period. This average value is compared to the dose-rate limit or alarm or beam shutoff functions and if the limit is exceeded the alarm or beam shutoff function is executed. For example, with a 20 mrem/h trip limit, the system allows up to 5 mrem over a 15-min period. If the system detects more than 5 mrem over a 15-min period, the system shuts off the beam. Similarly, if the Chipmunk were exposed to a field of 40 mrem/h, the beam would shut off after 7 ½ minutes. Chipmunks have a keep-alive gamma source that will cause an output pulse to be generated every 6 to 60 seconds (depending on the quality factor) regardless of radiation levels. The PPS monitors the pulse output and stops beam production if no pulses are detected after a time delay. The time delay is automatically adjusted by the PPS depending on the quality factor setting of the Chipmunk (e.g., from 120 seconds for a QF=1 to 20 seconds for QF=10).

The radiation levels measured by the Chipmunks 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 backup Chipmunk data in the event the main archiver malfunctions.

3.3.8.3.1.8 *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 (see Section 4.3). Nevertheless, the basement utility vault and the shutter drive equipment room are equipped with PPS-controlled access systems as described below. Any decision to change the PPS-access control features of these areas requires approval by the SNS Radiation Safety Committee.

Personnel Protection System Access Control for the Basement Utility Vaults

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 is obtained to the vault 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 prox 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 is provided to indicate status and facilitate 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, see below). Beam Shutdown Stations (BSS) are located inside the vault area. These devices provide a local visual indication of the vault status and an audible warning prior to the vault being placed in 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 using redundant position switches. A tricolor stack light outside the door indicates the status of the vault.

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 is provided to allow access during low power operations when radiation levels from water activation are low. The use of 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 is obtained to the room via a single shielded door controlled by the PPS. Due to the design of the shielding door, 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 BSS is located inside the room opposite the door. This device provides a local visual indication of the room status and an audible warning prior to the area being placed in beam permit mode.

3.3.8.3.1.9 *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 are activated 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 located in troughs located in the shielding blocks (to allow the cabling to be moved when shutter maintenance removal or installation is required). Due to the increased probability of cable damage due to this type of installation, both the normally open and normally closed limit switch contacts are monitored. This 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 if beam is allowed to the target building. As explained in 3.3.8.3.4, 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, 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 towards the closed position, the shutter continues to the fully closed position and the command is ignored.
- Close-Momentary—the shutter should close. If this shutter is moving towards the open position, the shutter stops immediately and proceeds towards the closed position.
- Absolute Close-Maintained—the shutter should immediately close if open, and, if closed, 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 operation of the instrument is permitted. An additional trapped key for each corresponding shutter is required to be in place on PPS CAB11 (described below) to allow shutter motion.

When maintenance of a shutter 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 being performed.

An emergency shutter close pushbutton is provided in the target basement control room and the main control room. 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 target basement control room. The purpose of this panel is to allow 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. If a primary shutter fails, the instrument is still designed to be safe with the full beam on. Therefore, shutter failure is not a safety issue but it is an operational issue since 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, it would be necessary either to extend the shutdown, or else to leave that instrument out of operation until it was possible to fix the shutter during a subsequent facility shutdown.

3.3.8.3.1.10 *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 (see 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 are provided inside the process bay to monitor the cart position. When the target cart is not in position, both the ring extraction septum and the RTBT dipole DH13 critical devices prevent beam transport to the target building.

3.3.8.3.2 Instrument Personnel Protection System

Each instrument installed at the SNS has a dedicated instrument PPS package to protect workers from prompt radiation. Each package is designed to meet the requirements for each instrument. Due to varying requirements for each instrument, the design of each instrument PPS is reviewed by the Instrument Safety Committee. Although design concepts vary, the common elements described below are generally applicable.

Instrument PPS packages are provided for each instrument at SNS. To the greatest extent possible, each is designed to handle access control, area radiation monitoring and beam containment for the associated instrument. In the event that the instrument PPS (i.e., for a particular instrument) cannot correct an unsafe condition, 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 with potential 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, etc. 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, 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 are areas that have elevated but not immediately hazardous prompt radiation levels during beam operation. These radiation levels are in the neighborhood of 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 others the shutter has multiple open positions to provide different neutron beams. Secondary shutters that meet PPS requirements are tied to the instrument PPS and used for beam containment, along with the primary shutter for that beamline. Secondary shutters meet the following criteria:

- Redundant open and closed limit switches dedicated to the instrument PPS.
- An interface with the instrument PPS to allow it to control the shutter position. In some cases (such as pneumatically operated shutters) it directly controls the shutter. In other cases (multi-position 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 (restricted sample areas, 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) and 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 serve as a tool to 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 the Radiation Work Permit requirements. The Transfer Bay Access Control system enforces engineered controls required for access as discussed below.

The transfer bay access control (TBAC) system, which is not connected to the PPS, provides automatic interlocks designed to prevent worker overexposure to radiation associated with use of the transfer bay and/or transfer bay access door. As mentioned previously, the maintenance bay portion of the target service bay contains equipment related to the mercury target. The adjoining transfer bay is provided to allow shielded personnel access for insertion of equipment or performance of 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 in a direction perpendicular to the long axis of the target service bay to facilitate equipment and personnel access into the service bay. The TBAC system is provided to ensure that the intrabay doors are closed when personnel access is allowed to the transfer bay via the personnel access door.

The TBAC system is a CEC with the following two credited functions: (1) prevent the personnel access door from opening 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, 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, 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 with the remote detector 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 with either intrabay door is open. This feature is used to allow personnel access to the service bay during initial low power operations or during major maintenance activities. The use of this key is administratively controlled in accordance with procedures specified in the *Operations Procedures Manual*.

Operations will conduct administrative “sweeps” by procedure to assure the area is clear of personnel before it is closed up 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 prior to inducing significant activity in the Hg.

3.3.9 VENTILATION SYSTEMS

Ventilation systems complement physical barriers to minimize the spread of radioactive contamination and other hazardous materials during both normal operation and off-normal conditions. Three separate exhaust systems are provided: (1) the PCES; (2) the SCES; and (3) the HOG system. The overall target building design provides a coordinated approach to confinement of hazardous materials, involving both passive structures and active ventilation systems. The building is divided into three ventilation zones, which offers 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 target service bay) is serviced by the PCES. It is maintained under a negative pressure with respect to the secondary confinement zone, which is, in turn, maintained by the SCES 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 non-confinement zone before entering into 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 SCES provides the capability for connecting ventilation to each neutron instrument station where local ventilation exhaust is required.

The HOG, PCES, and SCES are separate systems though not mixed prior to the filtration stage, 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, is designed to limit onsite 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

Confinement of mercury and radioactivity is provided by the target service bay configuration and by the PCES. This system, shown in Figure 3.3.9.1-1, maintains negative pressure on the target service bay and on the monolith, and also receives exhaust from the core vessel vacuum pumps during routine vacuum operation. In addition, the system can be used to maintain a ventilation flow into the core vessel during maintenance activities when the core vessel upper head is removed. The PCES removes mercury and particulate from the exhaust and has the credited safety functions described in Chapter 5.

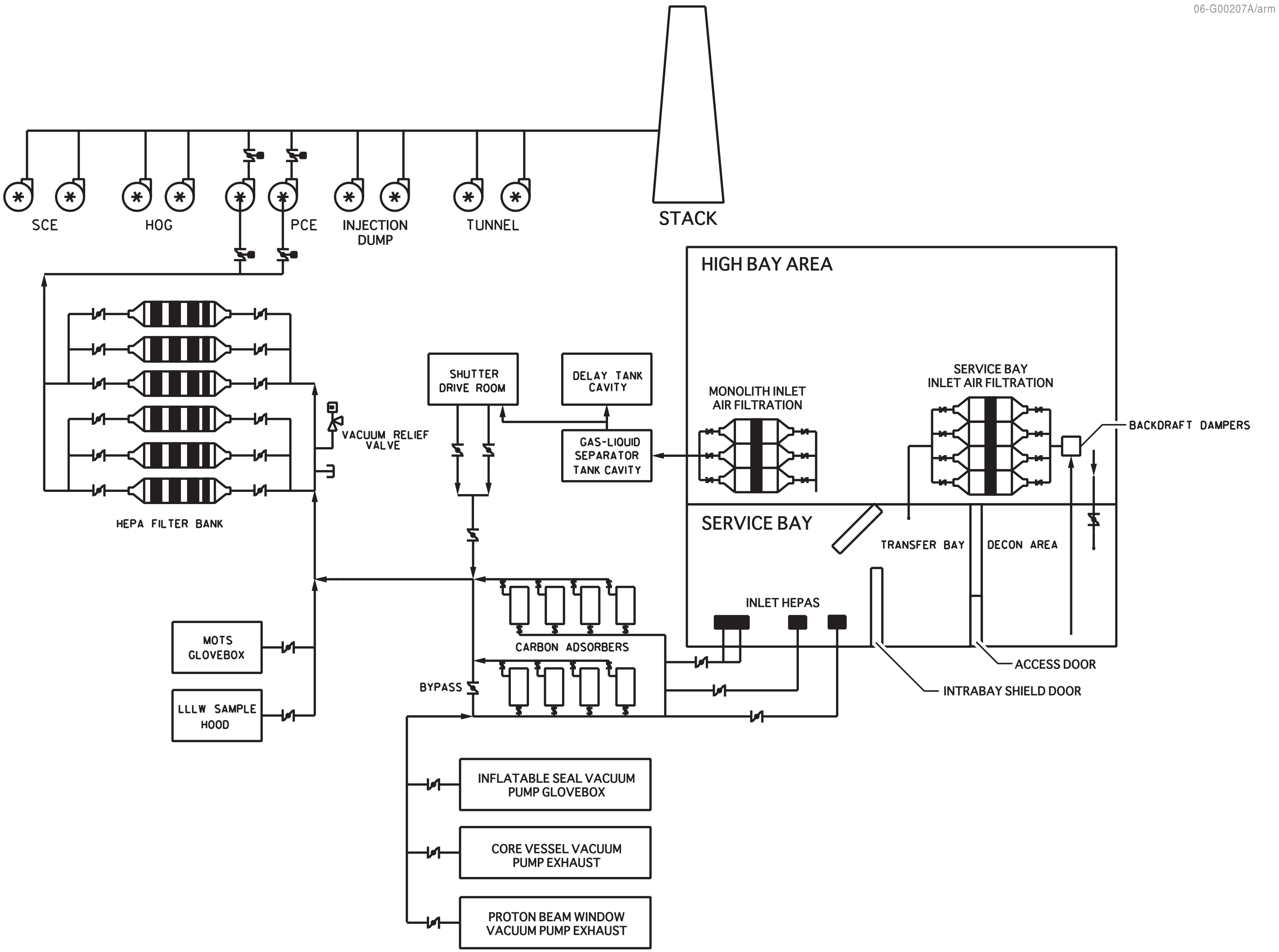


Figure 3.3.9.1-1 Schematic Diagram of Primary Confinement Exhaust (PCE) System

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 WSS for engineering design,[4] ASME N-509 was used in designing the confinement exhaust system with the exception of the charcoal adsorbers. Since ASME N-509 does not specifically address mercury adsorbers, the parts the designers determined to be applicable were used.

The PCES exhausts the target service bay and the transfer bay at flow rates adequate to:

- assure that required design negative pressure levels are maintained under normal operating conditions and defined accident conditions (see Chapters 4 and 5);
- provide reliable means to achieve a minimum flow velocity of 100 ft/min across temporary openings in the target service bay confinement barrier (plug openings, personnel access door, pass thru ports, etc.); and
- 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 target service bay is optimized to minimize the flow of air being processed by the mercury removal system. The PCES maintains the target 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 (most negative to least negative): target service bay, transfer bay, and manipulator/service galleries. 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, which helps 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 conveying 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 reversal of flow.

The PCES has the capability to remove mercury from the ventilation air exiting the target service bay and selected other areas that could experience mercury contamination. This system consists of a sulfur-impregnated charcoal adsorber system that consists of a set of eight cylindrical filtration beds manifolded together in a parallel flow arrangement. The purpose of using multiple beds is to facilitate safe handling and replacement of the charcoal, as well as to provide adequate bed residence time. The total quantity of charcoal is approximately 9000 lb, and its expected lifetime is on the order of five years, depending on the actual mercury release rate and the activity of the adsorbed mercury. Prior to operations, mercury inventory on the adsorbers was expected to rise at a rate of ~2.2 kg/year. Measured accumulation after ~ 5years of operating experience (including three target change outs) was less than 0.2 kg. Plans are to change the charcoal before the surface dose of the adsorbent exceeds 200 mrem/h, the limit for contact-handled waste. During routine high power operations, it is expected that the activity will build up to the ~200 mrem/hr level well before reaching the limitation on Hg inventory. High inventory levels would only be expected from an unanticipated major release in the Target Service Bay. The radiation level on the exterior of each individual adsorber is periodically measured to help track the inventory and to facilitate change-out. The adsorbers minimize the discharge of mercury vapor to the environment.

The adsorbent is activated charcoal impregnated with approximately 10 weight percent sulfur, and nominal mercury removal capability is specified as follows: exit concentration of 0.1 $\mu g/m^3$ when inlet mercury vapor concentration is 50 $\mu g/m^3$. Given that the removal process is chemical adsorption and the amount of sulfur impregnant involved (about 10 weight percent), it can be roughly estimated that it would take more than 3000 kg of mercury to saturate (i.e., all sulfur reacted to form HgS) all eight filter units. The charcoal adsorbers are to be maintained with less than 155 kg of mercury (all eight adsorbers) during normal operation.

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

Although combustion in the charcoal adsorber medium is considered highly unlikely, temperature monitors are provided on the exhaust side of each charcoal adsorber unit to detect elevated exhaust temperature. In the event that elevated temperature(s) indicate the possibility of combustion, operational options would include isolation of individual charcoal adsorber units or manual initiation of water flooding of the affected units.

3.3.9.2 Secondary Confinement Exhaust System

The SCES (Figure 3.3.9.2-1) serves the target service bay support areas by maintaining desired air circulation and keeping them at a negative pressure with respect to the non-confinement zones in the building such as the instrument halls and east end of the basement.

The SCES also provides capacity for equipment and glove-boxes located from each neutron instrument station 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 SCES blowers and central exhaust stack.

The SCES 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 central exhaust facility. At the basement wall, the ductwork transitions to high-density polyethylene (HDPE) for the underground portion between the building and stack.

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

3.3.9.3 Hot Offgas System

The HOG system serves to remove 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 mercury target offgas treatment system. Components that may contain activated or gaseous radioactive materials are, in general, ventilated through the HOG system. A schematic diagram of Hot Offgas System is shown in Figure 3.3.9.3-1.

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). Offgas 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 (see Section 3.3.7) before discharge to the HOG system. The other gaseous wastes go directly to the HOG system.

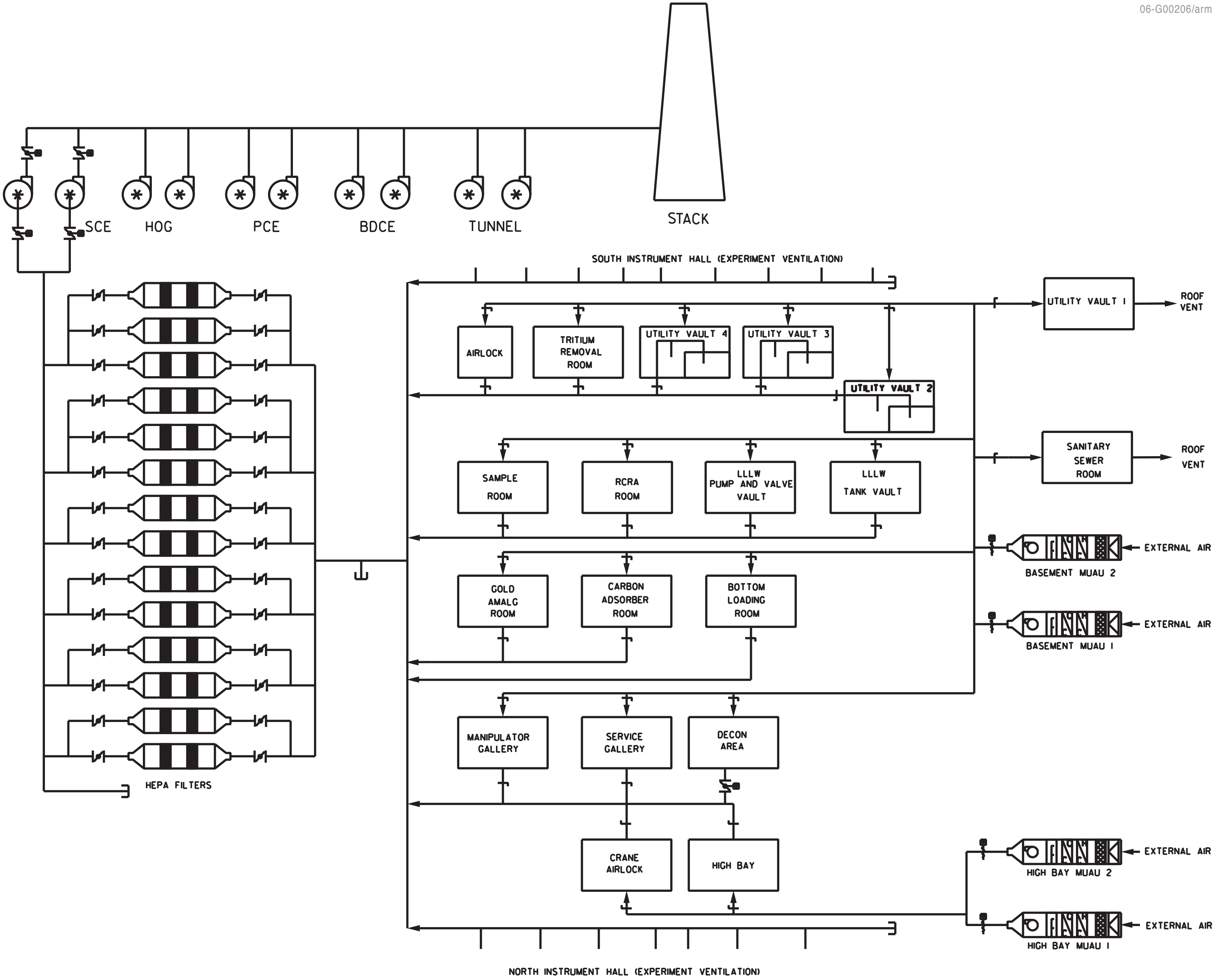


Figure 3.3.9.2-1 Schematic Diagram of Secondary Confinement Exhaust (SCE) System

Under normal conditions, offgases from the target mercury/water cooling loop, target shroud and proton beam window cooling loop, cryogenic and ambient moderator cooling loops, reflector heavy-water cooling loop, are routed to the offgas decay tank. This system delays the gases to provide for decay of short-lived isotopes 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 offgas lines. Trapped liquid droplets and backwash from the mist eliminators is transferred to the process and LLLW systems respectively.

The HOG 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 two banks 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 aboveground portions of the ductwork at the central exhaust facility. At the basement wall the ductwork transitions to HDPE 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.

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 in the building in accordance with direction from the RSO. The monitors are strategically located to provide coverage in areas that have frequent occupancy and/or are adjacent to locations that could have unexpected 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 the occupied areas of the target building, radiation detectors help operations to track and detect elevated radiation levels and thereby maintain these levels ALARA.

The facility radiation monitoring system does not perform a “credited” function but rather is used as a tool to maintain doses ALARA. The facility radiation monitoring system is not associated with the PPS system.

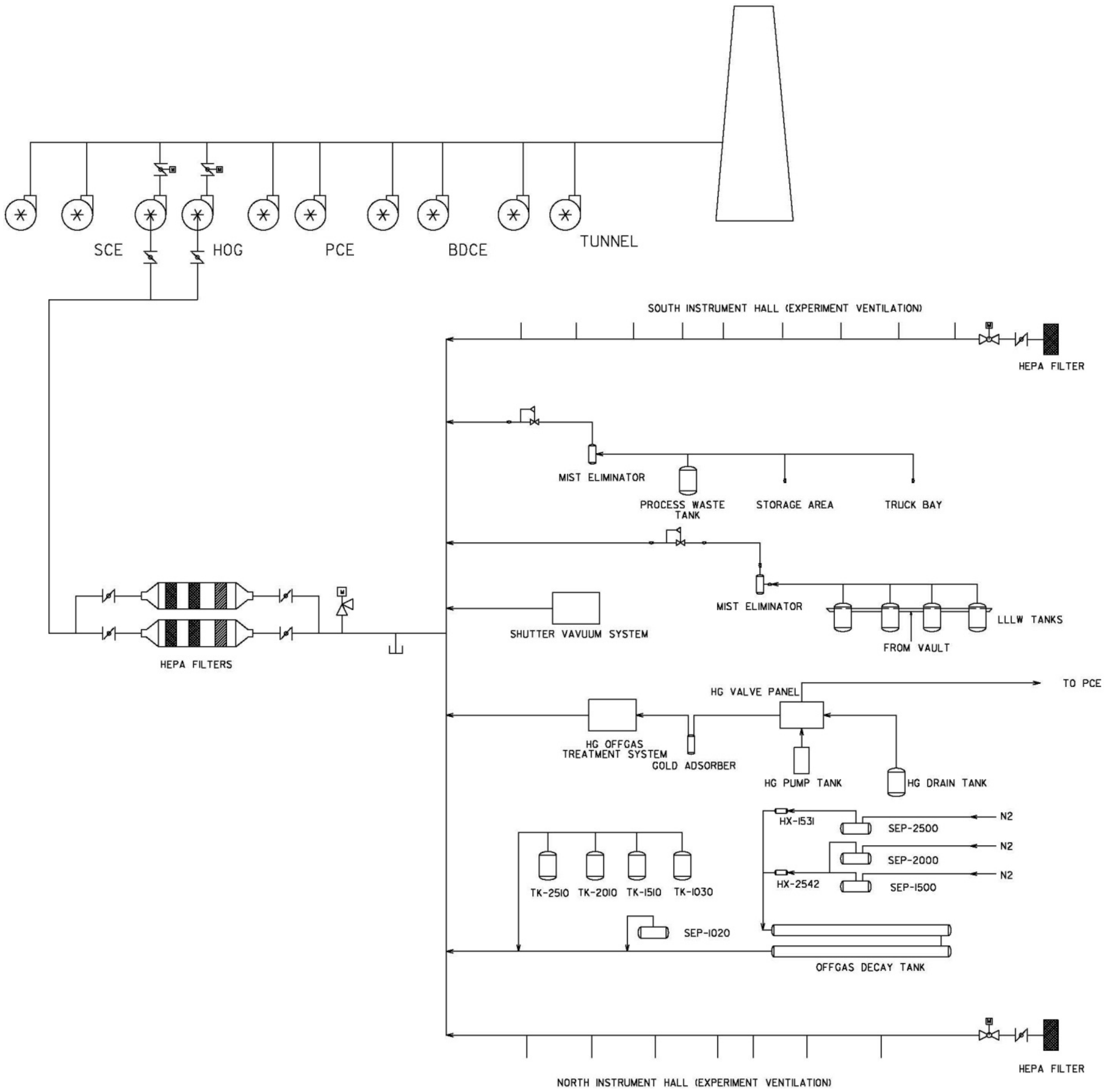


Figure 3.3.9.3-1 Schematic Diagram of Hot Offgas System

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 non-routine maintenance activities. Portable elemental mercury vapor monitors (e.g., Jerome meters) are also available and can in detecting the presence of mercury vapor. Fixed air monitors are not used because the significant potential for airborne radioactivity exists only within the target service bay which is not routinely occupied. Moreover, the primary confinement exhaust system (Section 3.3.9.1) maintains normal airflow direction into the target service bay and a credited alarm (see 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 Central Exhaust Facility (CEF) using an in-line radiation detector. The detector is a sodium iodide 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 U.S. EPA approved document entitled, DOE/ORO/2196, *Compliance Plan, National Emission Standard for Hazardous Air :Pollutants for Airborne Radionuclides on the Oak Ridge Reservation, Oak Ridge Tennessee*, March 30, 2005.

3.3.10.3 Fire Protection Systems

A fire hazards analysis[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 fire hazards analysis.

3.3.10.3.1 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 3.2-3.

3.3.10.3.2 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 also alarmed at the ORNL Fire Department, which responds to every fire alarm. This puts professional fire fighting resources into action within a short period of time.

An automatically initiated water mist FSS is used inside the target 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 target service bay fire. See Chapter 5 for additional discussion of 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.[20] The system is divided into two zones of operation. Suppression Zone 1 covers the process and maintenance bay portion of the Service Bay. Suppression Zone 2 covers the transfer bay. Two water mist systems are utilized to provide coverage of the two suppression zones.

Gas Powered Unit (GPU) #2 provides coverage for Suppression Zone 1, and GPU #1 provides coverage for both Suppression Zones 1 and 2. Both GPU's are automatically activated by signals provided by the VESDA™ detection systems. VESDA™ Unit #1 and #2 provide detection for Suppression Zone 2, and VESDA™ Unit #3 and #4 provide detection for Suppression Zone 1. Activation of VESDA™ unit #1 and #2 will activate GPU #1. Activation of VESDA™ unit #3 and #4 will activate GPU #1 and GPU #2.

3.3.10.3.3 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 ORNL Building 2500. Fire alarm/supervisory signals are also sent to a redundant supervising station in the CLO control room.

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

3.3.10.3.4 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 onsite ac power supply system, and uninterruptible power systems (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 ~ 0.5 mile from the SNS site and is routed to 13.8-kV transformers located in the SNS Switchyard. 13.8-kV feeders provide service from the primary plant service transformers and associated medium voltage switchgear. 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.

Onsite backup ac power supplies and uninterruptible power supply systems are provided to power loads that must remain operable in the event of the loss of offsite 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 onsite ac power supply consists of multiple diesel engine-generator units installed at various locations on the SNS site. Emergency power is supplied at 480 V-ac 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.

Also, emergency onsite ac power is supplied at 480 V-ac 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, main control room 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 onsite ac power is not a CEC. The reasons for this are that the proton beam cannot be maintained without offsite power and that active cooling is not needed for decay heat removal. In a loss of off-site power, the onsite 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 selected to be on the UPS system are loads necessary to provide safety to facility personnel and to prevent economic loss in the event of primary power supply failure. Loads that are connected to the UPS systems include the safety interlock system, the vacuum system I&C, the critical power supply controls and protection, the main control room servers and network hardware, selected telecommunications equipment, and selected alarm systems. The UPS systems are not safety credited.

The UPS systems provides 120 V-ac, nominal, single phase, 2-wire, 60 Hertz (Hz) and 120/208 V-ac, nominal, 3-phase, 4-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 for offsite disposal or treatment in approved packaging.

3.3.12.2 Solid Waste Systems

Typical examples of solid waste streams which may be generated in the neutron facilities include LLW, MLLW, and HAZ, and sanitary/industrial waste, and the programmatic management of these wastes is described in the *SNS Waste Management Plan* (SNS 1020300000-TR002).

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 is provided in the basement for handling wastes such as ion exchanger resins and other solid wastes.

Remotely handled low-level waste 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 offsite shipping casks. On-site storage of wastes may be periodically required depending upon the availability of offsite 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 offsite 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 waste water 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 prior to discharge to the sanitary sewer in accordance with approved procedures. If contaminated, the wastewater 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 offgas and HOG system. Components that may contain activated or radioactive liquid materials are connected to the LLLW systems through hot drains. The SNS LLLW system consists of four 1000 gallon storage tanks located in a storage vault. The system has a circulation pump, a set of filters, and a loading system for transfer of 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 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 above.

3.3.13 INSTRUMENT SYSTEMS

Neutron research is the reason for construction and operation of the SNS complex. Instrument systems include the facilities where the neutron research is done. As used 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 below. Instrument systems hazards are addressed in Chapter 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, “Radiation Barriers,” of the *SNS 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. Other means are exercised to 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:

- procedures and acceptance criteria;
- configuration control of beamline shielding, including approved mechanical fastening or padlocking where necessary;
- physical barriers as appropriate; and
- 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 exist for excessive radiological exposure (i.e. beamline shutter in the open position) and shuts down the accelerator if improper access is gained or 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 is provided with 18 beam ports capable of providing neutron beamlines to more than 24 instruments when completely outfitted. Figure 3.3.13.1-1 provides a schematic view 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 *Code for Safety to Life from Fire in Buildings and Structures* (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 of the order of <1 mm^3 to several cm^3, 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 is administered through a process involving screening and review of 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 one meter (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:

- 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 chambers;
- 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 and shielding as well as a get-lost tube (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; and;
- instrument PPS providing automatic access control interlocks; and
- 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 assure 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 (see 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 He-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 for maintenance of the helium environment.

The core vessel inserts are located at the boundary between the core vessel environment and the primary shutter region environment, and, 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. Due to the close proximity of the core vessel inserts to 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 located in 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 (see Section 4.2.1 of the *FSAD for Proton Facilities*[1]) to allow personnel access to the beamline sample area when closed. Additionally, the secondary shutters are interlocked with the instrument PPS.

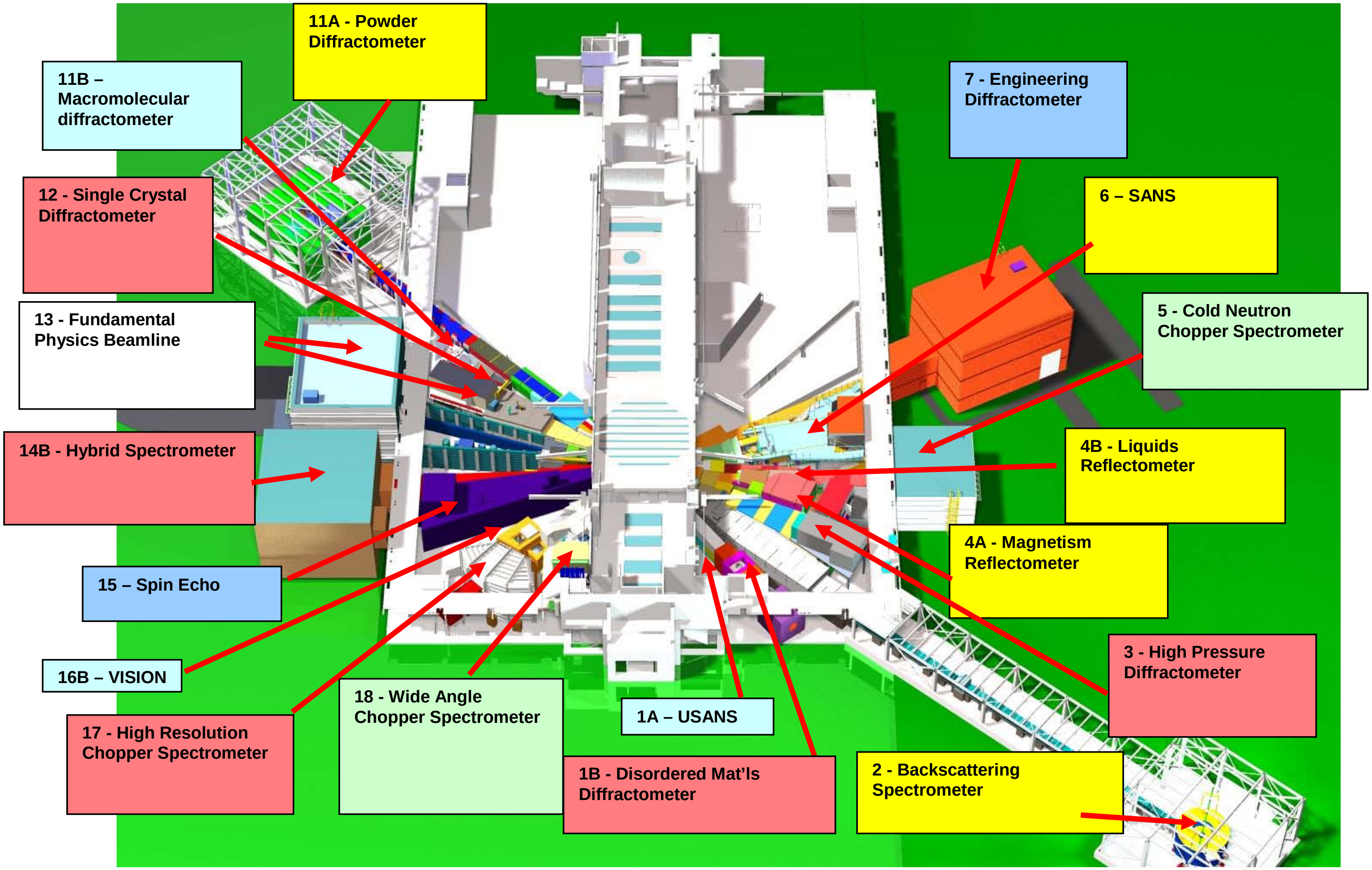


Figure 3.3.13.1-1 SNS Instrument Hall.

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 Ni, Ti, Co, and Fe. 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 He filled to minimize to air scattering. Most neutron guides have an external vacuum jacket to support the vacuum forces. Beam benders are multi-slit mirrors, 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 be operated in vacuum in order to minimize undesirable scattering of neutrons by air.

3.3.13.7 Neutron Beamline Shielding

The beamline shielding controls radiation levels 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 levels of radiation 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 quantity of hydrocarbon that is present. It should be noted that hydrocarbon neutron shielding is utilized in various locations where the low density and neutron stopping power provide a significant advantage. The fire hazard is in some cases minimal 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 hazard, as discussed below. The beamline shielding provides a nonflammable buffer between the monolith/target service bay area and hydrocarbon shielding materials present at the instrument stations.

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

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 (*Fire Accident Source Terms and Consequences*, SNS Document Number 102030102-R01, September 2003) particularly with regard to not exceeding 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 versus locations in satellite buildings. Unmitigated fires in satellite buildings are not capable of transporting significant heat into the monolith or target service bay; however, the hydrocarbon in them is still required to be encased for investment protection purposes and curbs or other design features are provided as needed to prevent molten hydrocarbon shielding from being able to flow 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 2000 lb inside the instrument hall shall be encased in steel or other approved material.
- Individual encasements shall not exceed 4000 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 life time 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 with more than 4000 lb of hydrocarbon require a documented hazard evaluation 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 document whether any additional measures need to 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 en route from the target/moderator to the instrument sample location. Three general types of neutron choppers utilized are the T0 neutron chopper, Fermi neutron chopper, and disk neutron chopper.

A T0 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 sub-thermal, neutrons to pass when they arrive. Two major types of T0 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 en route 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 T0 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.

As a result of their operation, 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 for beam verification and monitoring purposes. 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 is needed to support the cryogenic and furnace sample environments, as well as to reduce air scattering from the direct neutron beam. These chambers are small and have thin windows, so they typically are not designed to the_American Society of Mechanical Engineers (ASME) B&PV Code, Section VIII, Division I.[16] These sample chamber designs are required to meet any additional requirements identified by the Instrument Safety Committee.

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 have an enclosed volume of as much as 300 m^3, therefore, careful design planning is required to ensure worker safety. Since the pressure differential is less than 15 psi, these chambers are not required to meet the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section VIII, Division 1,[16] or to be code stamped. However, as good practice they are designed to meet the stress level requirement of the ASME Pressure Vessel Code. These vacuum vessel designs must also meet any additional requirements identified by the Instrument Safety Committee.

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 Pressure Vessel Code, but any oxygen deficiency hazards they may present must be analyzed and if necessary, mitigated.

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 ^{3}He 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. These 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 size of the enclosure 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 to limit 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 (SCE) and Hot Offgas (HOG) 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 is 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 for control of the instrument and for data collection. This equipment is typically located in a small modular hutch close to the instrument. Each such hutch also typically contains one or two desks and several chairs for instrument staff and users to use during the course of an experiment.

Most instruments also typically need some space near the instrument sample location for preparation of samples and for staging equipment. In some cases this space is in a second modular hutch, while in other cases it is a reserved area at the floor level or mezzanine level of the instrument. For some instruments certain chemical supplies need to be available for use in the sample preparation process. Chemical hazards are controlled following requirements in the ORNL SBMS. Radiological hazards associated with activated samples and components are controlled in accordance with the ORNL Radiological Protection Program. Individual instrument teams are responsible for control of 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 *Final Safety Assessment Document for Proton Facilities* (Reference 1).

Operation of the Neutron Instruments The Neutron Scattering Science Division (NSSD) is responsible for the safe operations and maintenance of neutron instruments. The NSSD organization includes the elements necessary for safe and efficient development and use of the neutron instruments. Groups for infrastructure support are provided and there is 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 lead scientist is assigned to each of the instruments. The lead scientist has responsibility for the operation of his or her designated instrument station including operations, safety, and functionality of the station. The lead scientist has, as needed, an assistant scientist and a Scientific Associate to aid in achieving safe and efficient scientific operations of the instrument station. The Instrument Support group provides support, oversight, and coordination of activities associated with maintaining operating instruments. The Instrument Hall Coordinators Team within the Instrument Support Group, provide as-needed support to the instrument scientists and users to facilitate safe and efficient conduct of research activities.

Operation of Target System The Research Accelerator Division is responsible for safe operation of the accelerator, target, and ancillary systems. A target systems group within the Research Accelerator Division (RAD) has the primary responsibility for safety operating and maintaining the target systems. Operation of the target systems is closely coordinated and integrated with accelerator and other site operations to ensure coordinated and safe operation of the entire SNS facility. Both the Proton Facilities and Neutron Facilities are operated from the integrated central control room (CCR) located in the CLO building. Target systems may also be operated from the auxiliary control room located in the target building basement. Only qualified personnel are allowed to operate target building equipment and systems.

The target systems group includes the Operations Shift Technician Team and the Target Support and Remote Handling Team, systems engineers, and other administrative and professional staff as necessary. The responsibilities of these specific members are described as follows.

The Group Leader for target systems is responsible for the safe and efficient operation and maintenance of the target and its support systems and functions as the manager of the group. The Group Leader is responsible for making sure that individuals within the operations group performing work are properly trained and equipped to safely and effectively accomplish the work at hand. In this capacity the Group Leader establishes the level of training required for particular job assignments.

The Operations Shift Technician (OST) Team is responsible for round-the-clock operation of the target and support systems. The team 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 and functions as a member of the SNS integrated control room staff. During target operations, a majority of this individual's time is typically spent operating systems and monitoring parameters from one of the control rooms, but this individual is also responsible for conducting rounds and troubleshooting system problems. The OSTs are properly trained to operate the integrated target systems and are certified to stand a shift by themselves.

The Target Support and Remote Handling Team consists of a team leader responsible for managing and coordinating the activities of team which include:

- Remote handling technicians perform the remote handling operations and maintenance required for the target and support systems
- Facility technicians conduct maintenance, preventative maintenance, troubleshooting, repairs, and replacements of target and support systems
- Bargaining unit personnel (matrixed or assigned) perform the craft work and maintenance activities

Systems Engineers are assigned to the specific systems. These engineers provide technical assistance to operations, assist in configuration management, evaluate ongoing system performance, recommend needed modifications and actions to correct problems, assist in development of test procedures and additional engineering activities associated with maintaining a system and improving performance. Some systems engineers are matrixed to the target systems group for this responsibility.

3.4.2 PROCEDURES

Operation of the target and support systems (e.g., mercury loop, cooling water loops, moderator systems, PCES, etc.) is performed in accordance with written operating procedures. Operating procedures are reviewed, approved, revised and controlled in accordance with 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 Credited Administrative Controls (CACs) in Chapter 5, operating procedures include internal operating procedures (both technical and administrative), operator aids, and guidance from technical manuals and industry standards.

Procedures are included site-wide in the *SNS Operating Procedures Manual* (OPM), which can be accessed through an SNS Web page.

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 such that revisions to an existing procedure will undergo appropriate review.

Emergency response procedures are used to assist the operations team to respond to unplanned events which could have a directly or indirect effect on 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.

In addition to 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* provides a team of personnel to respond to emergency situations. The team coordinates event response activities to ensure personnel safety while mitigating the impact to the target facility and the environment. The manual also provides a brief description of the facility population, operational processes, facility equipment and potential hazards. A list of key personnel to be notified, as well as response team training requirements are also included.

3.4.3 TRAINING AND QUALIFICATION

Operation of neutron scattering instruments is under the jurisdiction of the NSSD. 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, as determined by the Science Group Leader. Users (non-SNS employees) are trained for the activities they are allowed to perform and are supervised by assigned members of the NSSD (See Section 3.4.8).

The Training and Qualification Program for the target systems group is designed to ensure that all members of the group (OSTs, remote handling technicians, and support staff) are qualified to perform their routine duties, respond to abnormal events and mitigate their consequences.

The implementation of the training and qualification program is designed to ensure that work is performed safely by qualified workers in accordance with effective procedures. The program ensures that personnel performing work in the target building are qualified to perform their jobs. 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 target systems group training 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 personnel working in the facility are qualified to perform their job, are aware of relevant hazards, controls and work requirements, and understand the impact 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 Chapter 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 Chapter 5:

- Access to the Target Service Bay
- Access to the Transfer Cell
- 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 performance of an individual’s duties. Qualification requirements are based on industry standards and determined by the organization and its needs. An individual’s qualification is determined by comparing the individual’s education and experience to the needs of the job. When the deficiencies have been identified, training is provided to meet those requirements.

Line management is responsible for the training and qualification of 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 needs of the organization.

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

System-specific training combined with use of qualified personnel operating target systems and appropriately detailed and approved procedures ensure that risks associated with the operation of systems with significant hazard potential are minimized. This includes systems such as 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, hydrogen filling and hydrogen purging of the CMS require verbatim compliance to 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.

Training will be conducted for all OST team members 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.

3.4.4 CONFIGURATION CONTROL PROGRAM

Configuration control of CECs is assured 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 handled 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, or assigns a level of change control or approval that is commensurate with that safety function. Assessing for an Unreviewed Safety Issue (USI) is integral to the configuration control process.

This program assigns roles and responsibilities that involve the 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 with 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, etc. Review of changes to these systems is controlled by the USI determination process in conjunction with the engineering and work control related processes that ensure configuration control. Among changes or aspects of change evaluated include those that affect the required seismic qualification of CECs. This program assures that the appropriate seismic protection remains in place following normal maintenance or facility modification, as well as assure that the seismic protection is not lost based on component degradation or failure.

Passive design features that require control under the Configuration Control Program are identified below:

- 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 two-hour 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

Configuration Control of active CECs is maintained under approved OPM procedures. Control of safety related keys (e.g., TPS and TPPS) is the responsibility of the target systems OST Team. This includes keys required to enter Target and Instrument PPS controlled areas and keys for entry into the Transfer Bay. Key accountability, custody and custody transfer will be tracked via log book. Keys not in use will be placed in a lock box controlled by the on-duty Operations Shift Technician and Instrument Hall Coordinator. The key codes for these spares will be unique (not used by any existing key). If a key is lost, 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 Spallation Neutron Source Work Control document (SNS-108000000-PR0061), ensures that jobs are planned and approved based on their importance to safety and their potential impact 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 principals of integrated safety management (ISM) of (1) defining the work to be done and associated hazards; (2) developing and implementing appropriate hazard controls; (3) performing the work within the controls; and (4) providing feedback on the work to improve the process. The work control process also ensures that individuals working on systems are properly trained to safely carry out the required work.

Work on Credited Engineered Controls (CECs) requires a more rigorous routine than work on other components and systems and this is built into the work control process. Work planning on this type of system includes involvement of operations, maintenance (including individuals directly involved in accomplishing the work), and engineering design, 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. In addition, post maintenance 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. The Job Hazard Analysis facilitates this process at discussed in the Section 4.1.3 of FSAD-PF. Work involving systems with significant hazard potential require 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 includes the purging of hydrogen from the entire system if the work requires opening the hydrogen boundary. Because of the special nature of hazards associated with the CMS, special training and procedures will be required for work on hydrogen bearing portions of the system.

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 Instrument Systems Safety Committee reviews the initial design and proposed changes to instruments.

Each neutron beam instrument must satisfactorily undergo an Instrument Readiness Review (IRR) prior to operation of the instrument with neutron beam. This review is carried out by an expert Instrument Systems Safety Committee (ISSC) selected by and reporting to the SNS Operations Manager. Each such review is intended to verify that the instrument is safe to operate, and cover 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 covered in the review as appropriate to the specific instrument. The review also covers instrument operation and maintenance procedures and training of staff and users for instrument operation. Instrument reviews are repeated periodically as needed to keep up with changes. Experiments to be performed on the instruments may involve other hazards such as chemical, cryogenic, high pressure, and magnetic fields. 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 through 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

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

One of the expectations that SNS faces is 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 SNS 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 tracked in the user training records. Additional training may be needed for handling of samples and for operation of sample environment equipment and this 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, a large number of experimental samples in a variety of forms come to or are prepared at the SNS. 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 addressing the final disposition of the sample with the normal expectation that the sample will be returned 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 calculated. If this calculation yields an acceptably low level, confirmed by radiation detectors (process instrumentation) upon withdrawal from the sample location in the neutron beamline, handling of the sample or its container can be accomplished by the user (with appropriate training) in the near vicinity of the neutron scattering instrument. Minimal sample storage is maintained in a properly posted and controlled area in the near vicinity of each neutron scattering instrument, with the expectation that upon completion of a series of measurements, samples be transferred to a central storage area in the target building.

It is the responsibility of SNS staff to ensure 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 Radiation Control Technicians and either cleared for normal handling (following established procedures and guidelines) or else arrangements made for shipping as a radioactive material. Furthermore, users are only allowed to move uncleared irradiated samples 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. The handling of 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, TN, December 2010.
2. 10 CFR 835, "Occupational Radiation Protection," *Code of Federal Regulations*, U.S. Government Printing Office, Washington, DC.
3. *Spallation Neutron Source Shielding Policy*, SNS 102030000-ES0008, Oak Ridge National Laboratory, Oak Ridge, TN, 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-R1, Oak Ridge National Laboratory, Oak Ridge, TN, 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, U.S. Department of Energy, Washington, DC, Change Notice 1, January 1996.
9. *Natural Phenomena Hazards Performance Categorization Guidelines for Structures, Systems, and Components*, DOE-STD-1021-93, U.S. Department of Energy, Washington, DC.
10. *Natural Phenomena Hazards Characterization Criteria*, DOE-STD-1022-94, U.S. Department of Energy, Washington, DC, Change Notice 1, January 1996.
11. *Natural Phenomena Hazards Assessment Criteria*, DOE-STD-1023-95, U.S. Department of Energy, Washington, DC, 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, TN, March 2004.
13. *Safety of Accelerator Facilities*, DOE Order 420.2C, U.S. Department of Energy, Washington, DC, July 2011.
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, TN, 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.

4.0 HAZARD AND ACCIDENT ANALYSES

4.1 INTRODUCTION

This chapter 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 potential risks.

The hazard analysis (HA) assesses process-related, external, and natural phenomena hazard (NPH) events. Potential hazards have been identified and categorized as either standard industrial hazards (also referred to in this chapter as "common" hazards) that can be safely managed by the existing Oak Ridge National Laboratory (ORNL) institutional safety programs or as hazards that warrant additional controls to mitigate adequately.

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. Environmental protection is addressed in Section 4.6.

Credited Controls[1] selected to mitigate specific hazards are not the only layer of protection. The facility design, structured operational practices, and ORNL institutional safety programs are also key elements in providing extra layers of safety. Much of the initial hazard and accident analysis for SNS were completed prior to the issue of the more recent versions of the DOE accelerator safety order (e.g. DOE Order 420.2B[3] and 420.2C[60]) and implementation guide[4]. The decision was made to develop the initial safety documentation in accordance with DOE-STD-3009-94[2] which also greatly influenced safety related design decisions. After the initial hazard identification documentation, [35] the hazard identification tables served as a basis and historical document. The project relied on a periodic review and update process to maintain the validity and completeness of this evaluation.[36-40]

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

Requirements, Guidance and Standards

Requirements for performing the analyses presented in this chapter are contained in DOE Order 420.2C, *Safety of Accelerator Facilities*[60]. DOE Guide 420.2-1[4] presents guidance that has been followed for the hazard analysis. While not required, methodology presented in DOE-STD-3009[2] was used as a basis for performing the rigorous 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;[6] the threshold quantity listed in *Risk Management Programs for Chemical Accidental Release Prevention*, 40 CFR 68;[7] the reportable quantity listed in the *List of Hazardous Substances and Reportable Quantities*, 40 CFR 302.4;[8] or the threshold quantity listed in *Process Safety Management (PSM) of Highly Hazardous Chemicals*, 29 CFR 1910.[9] Neither 40 CFR 68 nor 29 CFR 1910 apply to metallic mercury. However, the SNS has target mercury is in excess of the 40 CFR 355 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 (~2MW). Beryllium is present as a reflector material but since it is encapsulated in an aluminum case, and no credible accidents were identified that could disperse the beryllium, it is not addressed further in the hazard analysis.

ORNL institutional safety programs as promulgated through the Standards Based Management System (SBMS) directly address chemical safety and are more than adequate to control risk associated with onsite chemical usage. The design basis criteria for natural phenomena are based on DOE Order 420.1A;[10] DOE-STD-1020-94, *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities;*[11] DOE-STD-1021-93, *Natural Phenomena Hazards Performance Categorization Guidelines for Structures, Systems, and Components;*[12] and DOE-STD-1022-94, *Natural Phenomena Hazards Characterization Criteria;*[13] DOE-STD-1023-95, *Natural Phenomena Hazards Assessment Criteria;*[14] and DOE-STD-1024-92, *Guidelines for Use of Probabilistic Seismic Hazard Curves at Department of Energy Sites for Department of Energy Facilities*.[15]

The NPH design requirements were applied to the structures, systems, and components required to meet PC-2 demand loads to assure 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 Chapter 3. The governing design codes and standards applicable to the SNS are specified in *Spallation Neutron Source Standards for Design and Construction of the Target Facility*.[16]

4.2 HAZARD ANALYSIS METHODOLOGY

This section presents the methodology used to perform the Hazard and Accident Analysis for the SNS target facility. 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 due to single or multiple failures. The analysis considers the potential for equipment failure and human error.

The Hazard Analysis (HA) includes a thorough, predominantly qualitative evaluation of the spectrum of risks to site workers, the public, and the environment due to accidents involving identified hazards. The HA, consistent with DOE guidance, [4] comprehensively address the following:

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

Informed, qualitative estimates of consequences and frequencies are performed in the HA such that attention can be focused on those scenarios of highest risk. Section 4.2.1 provides a description of 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 if an event required 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.*[19]

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 is based on DOE-STD-1027, *Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23*,[17] which states the following in Section 4.1: “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.” The use of the hazard identification tables provides a rigorous method of identifying hazards. The tables contain a list of hazardous energy sources that include the information listed in Table 4.2.1-1 below used to evaluate each system.

Except for hazards that could cause a worker to experience breathing air with oxygen concentration below 12.5 volume percent, screening was performed to eliminate material/energy types and quantities considered standard industrial or “common hazards.” Common hazards are required to 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 chapter. 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*.[18]

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 (see diagrams in Chapter 3 for orientation):

- Target Assembly
- Target Service Bay
- Basement Utility Vault
- High Bay
- Target Building Balance of Plant

Table 4.2.1-1 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/Decon Solvents • Gasoline • Flammable Liquids • Flammable Mixtures	• Explosive/Pyrophoric • Explosive Gas • Dynamite • Sodium • Hydrogen (batteries) • Primer Cord • Electric Squibbs • Nitrates • Dusts • Peroxides • Caps • Pu/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 • Ashyxiation • Ammonia and Compounds • Beryllium and Compounds • Chlorine and Compounds • Tricholorethelyene • 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 • Fork Lifts • 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 “paper” or 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 the SNS were reviewed with the HA team. The initial “paper walkdown” included review of facility-related documents listed in the reference section of Reference 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 to Reference 18. Since 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, the hazard was carried forward through the complete HE process.

Initial Conditions

Initial conditions within the HA were initially based on the National Spallation Neutron Source Conceptual Design Report,[20] the Construction and Operation of the Spallation Neutron Source—Final Environmental Impact Statement,[21] the Spallation Neutron Source Design Manual,[22] interviews with system designers, and analyst judgment. These were maintained current within the inputs and assumptions document that has been the basis for SNS hazard and accident analyses and with subsequent updates. Updated inputs and assumptions are contained in Reference 23. The initial conditions used in the HA are listed in the scenario summary for each system.

4.2.2 HAZARD EVALUATION

The purpose of HE is to ensure a comprehensive assessment of facility hazards and to focus attention on those events that pose the greatest risk to the workers, the public, and the environment.

The HE is presented in tabular form in Reference 19 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 is chosen such that facility section, system, or area is identified mnemonically. For example, the target 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 (as described below), followed by a sequence number. For example, event TC2-3 would indicate the target 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,[24] is used. The event category number is also included in the third alphanumeric position of the event number. This categorization scheme is used simply to label 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 4.2.2.1-1.

Table 4.2.2.1-1 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)
- Mercury Offgas Treatment, Vacuum, and Helium Systems (GW)
- Process Waste and Sanitary Waste Systems (PW)
- Contact Waste Handling and Decontamination Area (WH)
- Confinement Ventilation System (HV)
- Core Vessel General Area, Shielding/Reflectors/Shutters (SH)
- Target 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[2]-based lettering scheme given in Table 4.2.2.2-1. Sources of frequency information including generic initiator databases are 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.[25]

Table 4.2.2.2-1 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).	$f \geq 10^{-2}$
Unlikely (U)	Accidents that are not anticipated to occur during the life cycle of the facility. Natural phenomena of this probability class include the following: Uniform Building Code-level earthquake, 100-year (y) flood, maximum wind gust, etc.	$10^{-2} > f \geq 10^{-4}$
Extremely Unlikely (EU)	Accidents that will probably not occur during the life cycle of the facility. This class includes the DBAs.	$10^{-4} > f \geq 10^{-6}$
Beyond Extremely Unlikely (BEU)	All other accidents.	$f < 10^{-6}$

4.2.2.3 Unmitigated Consequences (and Risk Bin)

Unmitigated consequences are categorized in accordance with Table 4.2.2.3-1 for offsite and onsite receptor locations to assess health effects associated with the postulated event. Onsite receptors include workers inside of the facility (Onsite-1) and workers outside of the facility (Onsite-2).

Table 4.2.2.3-1 Radiological Consequence Evaluation Levels for Hazard Receptors

Consequence Level	Offsite Receptor	Onsite Receptor
High (H)	≥25 rem	≥100 rem
Moderate (M)	5 ≤ C < 25 rem	25 ≤ C < 100 rem
Low (L)	0.5 ≤ C < 5 rem	5 ≤ C ≤ 25 rem
Negligible (N)	<0.5 rem*	<5 rem

*Note: the Accelerator Facility Safety Implementation Guide[4] uses a value of 1 rem. Since the hazard analysis predates the guide, the final analysis has retained the lower value.

Offsite	Offsite receptors are individuals outside the reservation boundary and members of the public traveling on Bethel Valley Road.
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 at a distance of 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.[1]

Note that 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 open Bethel Valley Road to uncontrolled access by the public.

Risk Bins

Figures 4.2.2.3-1 and 4.2.2.3-2 are risk bin matrices for the three receptor locations (i.e., offsite and both Onsite-1, and Onsite-2) for radiological risk (see paragraph on page 4-12 for chemical 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 a previous version of the *SNS Policy for Selection of Safety Related Credited*

Frequency→ Consequence ↓	**Beyond Extremely Unlikely** $F < 10^{-6}$/y	**Extremely Unlikely** $10^{-6} \leq f < 10^{-4}$/y	**Unlikely** $10^{-4} \leq f < 10^{-2}$/y	**Anticipated** $f \geq 10^{-2}$/y
High	**10**	**7**	**4**	**1**
Moderate	**11**	**8**	**5**	**2**
Low		**9**	**6**	**3**
Negligible	**11**			

Figure 4.2.2.3-1 Unmitigated Risk Binning Matrix—Offsite Receptors (Radiological)

Frequency→ Consequence ↓	**Beyond Extremely Unlikely** $F < 10^{-6}$/y	**Extremely Unlikely** $10^{-6} \leq f < 10^{-4}$/y	**Unlikely** $10^{-4} \leq f < 10^{-2}$/y	**Anticipated** $f \geq 10^{-2}$/y
High	**10**	**7**	**4**	**1**
Moderate	**11**	**8**	**5**	**2**
Low		**9**	**6**	**3**
Negligible	**11**			

Figure 4.2.2.3-2 Unmitigated Risk Binning Matrix—Onsite Receptors (Inside and Outside Facility) (Radiological)

Controls.[1] The current policy (See Section 4.2.2.4-1) does not require a frequency component for selection of the first level of control. The policy requires 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 4.2.2.3-1 presents the unmitigated risk bin matrix for offsite receptors. The cross-hatched bins (i.e., 1, 4, 7, and 10) represent risk that exceeds the unmitigated HA screening criteria. Unmitigated events falling into these bins, along with bins 2 and 5, require further evaluation.

The four dark cross-hatched bins in Figure 4.2.2.3-1 (i.e., 3, 6, 8, and 9) fall below the offsite unmitigated HA screening criteria, yet, these events are considered “situations of concern” that are evaluated for possible identification as a subset of “representative” events needing further examination. Representative events bound a number of similar events of lesser risk (i.e., the worst fire for a number of similar fires). At least one event from each of the event types (i.e., fires, explosions) is considered representative; however, representative events are examined only to the extent that they are not bounded by unique events.

Figure 4.2.2.3-2 is the risk bin matrix for the onsite receptors. The cross-hatched bins (i.e., 1, 2, 4, 5, and 7) represent risk that exceeds the onsite hazardous material criteria for selection of credited controls. 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 (see Section 4.2.2.4) are frequency independent. Credible events that exceed the chemical criteria are evaluated for appropriate controls that provide protection for the public and workers irrespective of their initiating event frequencies as long as the frequencies are higher than the Beyond Extremely Unlikely frequency (10^{-6}/y). 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 one determined through hazard evaluation to be essential for safe operation directly related to the protection of personnel or the environment. The number of credited controls should be a limited subset of the total number of controls employed for overall facility operation[4]. Credited controls are assigned a higher degree of operational assurance than other controls.

The following criteria for selection of controls is established in the SNS Policy,[1] which satisfies the DOE accelerator safety order[3] requirement to ensure that unacceptable risks have been mitigated to acceptable levels through controls and/or limits on the operation of the facility:

1. If the unmitigated dose exceeds 25 rem to an off-site receptor, 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 rem and 25 rem to an offsite receptor with an estimated frequency above 10^{-4}/y, 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 hr for mercury vapor), 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 LOC 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 above the defined ERPG-3 level (4 mg/m^3 for mercury vapor) a level of control shall be identified.
5. If the unmitigated radiation dose to a worker outside the building exceeds 25 rem and occurs at an estimated frequency exceeding 10^{-4}/year, 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 volume percent and for which existing SBMS 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 those scenarios whose unmitigated consequences meet the control selection criteria, the controls are grouped into “levels of control.” A level of control (LOC), as defined in the *Spallation Neutron Source Policy for Selection of Safety Related Credited Controls*,[1] 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 “levels 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 HAZARDS ANALYSIS - POTENTIAL ONSITE IMPACTS AND CONTROLS

This section provides a discussion of identified hazards determined to pose significant risk to onsite workers at ORNL. This evaluation process resulted in the identification of 180 potential events involving credible hazards to the public, workers, and the environment. The results are based on the analyses presented in Reference 19. Of the 180 events, 53 were identified as potentially exceeding the criteria requiring credited controls. Evaluations of those events are presented in the subsections that follow. Those judged as potentially challenging the public radiological or hazardous chemical criteria were carried forward for a more detailed quantitative analysis of potential offsite impacts (see Section 4.4). The remaining events did not challenge the criteria for any of the receptors and, therefore, required no further analysis.

The following sections present the analysis of unmitigated event scenarios and the Credited Controls selected for workers protection.

4.3.1 TARGET SYSTEMS (TS) EVENT SCENARIO SUMMARY

In evaluating the target systems, several fire events, an explosion, 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.

TS Initial Conditions and Assumptions

a. The design proton beam power is 2 MW.
b. Normal mercury operating temperature is less than or equal to 125ºC.
c. The total volume of mercury in the mercury process 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 target service bay and/or core vessel.
d. Radionuclide inventory calculations assume the mercury is not replaced over the life of the facility.
e. 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.
f. Mercury loop doghouse shielding is normally in place when mercury is in the process loop. The purpose of the shielding is to reduce radiation levels surrounding the loop to less than 250 rem/h to minimize radiation damage to wiring insulation and to items such as TV cameras. Therefore, the shielding is required only when Hg is activated sufficiently to increase radiation levels surrounding the loop to >250 rem/h.

g. The walls surrounding the target service bay are designed to PC-3 seismic requirements and would provide a barrier after a seismic event to separate combustibles outside the target service bay from mercury inside the target service bay.

h. For purposes of the unmitigated analysis, automatic proton beam cutoff interlocks are not credited.

i. Mercury is drained from the system to the mercury storage tank prior to target module removal from the core vessel or target carriage.

j. The accumulation rate of spallation product hydrogen in the mercury process system has been determined to be insufficient for accumulation of a concentration greater than the lower flammability limit (LFL) for hydrogen gas in air.[26]

k. Cooling loop 1 water is cooled directly by the tower water cooling system.

l. Interstitial mercury in the Hg heat exchanger is normally at a higher pressure than both Loop 1 cooling water or mercury process loop pressures in the mercury heat exchanger.

m. Activation of the mercury process system cooling water (Loop 1) is negligible.

n. The heat exchanger that serves the mercury process system and cooling loop 1 is a robust double-walled heat exchanger design.

o. A helium-filled gap exists between the mercury containment and target shroud cooling water (cooling loop 2) containment within the target module. The helium layer within the gap is stagnant.

p. Leakage of mercury into the core vessel would not cause a hydrogen release due to rapid corrosion of the aluminum moderator vessels because liquid mercury would collect at the bottom of the core vessel and not be in contact with the moderator vessels. Tests conducted for SNS indicate that liquid mercury corrodes aluminum rapidly whereas mercury vapor does not (See Reference 25, Chapter 5).

TS1 Fire Events

One of the fire events postulated included a small incipient fire (TS1-1) that originates in the target service bay but does not result in the release of mercury; therefore, no further analysis was performed.

Other postulated fire events related to the target systems include a medium fire (TS1-2) that originates outside the target service bay (e.g., the high bay) and propagates to the target service bay, a fire (TS1-3) that originates and becomes established in the target service bay, and two fire events (TS1-4 and TS1-6) that occur during maintenance activities. TS1-4 is a fire that occurs in the target service bay during maintenance activities while the core vessel, target service bay, transfer bay, and high bay could be open to a common airflow and the target mercury has been drained to the storage tank. TS1-6 is a fire that occurs in the target service bay during maintenance activities with a worker inside the transfer bay with the personnel door in the open position. The design of the ventilation system (air intake at floor level of decon room) minimizes hot gases that can be drawn into the target service bay and, therefore, contributes to the credited controls consisting of the two-hour fire barrier, combustible material control program, and mercury inventory control for charcoal adsorbers. Due to the limited mercury inventory in the adsorbers, the high temperature detection switches (one per adsorber) provided by the design, which complement the credited fire suppression system (FSS) outside the target service bay for postulated charcoal adsorber fires (subcategory under Event TS1-2), are not credited.

Since a fire in the vicinity of target mercury could hypothetically vaporize a significant amount of the target mercury, two levels of control are provided to protect workers outside the target building. For fire postulated to originate outside the target service bay (e.g., TS1-2) the credited controls either suppress/extinguish the fire or prevent it from spreading into the target service bay:

- FSS outside the target service bay—provides a means to suppress the maximum fire anticipated outside the target service bay to ensure the fire barrier is not challenged.

- Two-hour equivalent fire barrier—encloses the target service bay and the core vessel and performs the function of preventing migration of either combustibles or mercury across that barrier and ensures fires outside the core vessel would not propagate into the core vessel or target service bay (including bulk shielding liner drain termination point).
- Combustible Material Control Program (See Section 5.3.3) outside the target service bay—ensures the fire barrier is not challenged and that the fire would not cause gross building failure.

For fires postulated to originate inside the target service bay (TS1-3 and TS1-6), the credited controls either suppress the fire or ensure that it is small and not able to spread.

- FSS inside the target service bay—provides a means of reducing the frequency of a severe fire inside the target service bay and thereby limiting the release of mercury due to vaporization. If the mist system is in-operable, at least one of the following two mitigations shall be in place: (1) mercury loop steel shielding in place, or (2) mercury loop drained to the storage tank.
- Combustible Material Control Program inside the target service bay—limits allowable combustibles, fixed or transient, consistent with the maximum 1 MW-hr locally intense fire analyzed in the safety basis to ensure a fire could not challenge the primary mercury containment.

Various credited controls combine to protect workers initially inside the target building from being exposed to air potentially contaminated with target mercury from a target service bay fire.

- PCES design features: (1) backdraft dampers would close during a service bay fire as needed to prevent backflow from the target service bay in the event of a fire or loss of normal negative pressure, and; (2) flame retardant exhaust filters mounted in stainless steel housings discourage transmission of fire to charcoal adsorbers.
- Service bay differential pressure monitoring system—provides detection and alarm upon loss of negative pressure between the target service bay and adjacent areas. Complementary procedures and training for response to loss of negative pressure alarm—ensures workers evacuate areas adjacent to the target service bay upon loss of negative pressure alarm and subsequently evacuate the building and area outside of target building if required.

- Procedures and training for closure of personnel door—requires workers to close the Personnel Door upon evacuation of the transfer bay after hearing the loss of negative pressure alarm (TS1-6 only, helps ensure radiological and chemical protection of Onsite 3 Worker).
- Procedures and training—for evacuation of workers in event of fire during maintenance activities when the target service bay, transfer bay, and high bay are open to common air flow (TS1-4 only).
- Transfer Bay Access Control System— prevents inadvertent worker access to the interior of the target service bay.

Finally, for the specific case of a significant fire postulated to occur in the charcoal filter room (i.e., as one possible variant of TS1-2), an administrative monitoring program is credited for the charcoal adsorbers.

- Procedures for mercury inventory control—ensures each PCES charcoal adsorber is < 19.4 kg and the total PCES charcoal adsorber inventory is < 155.2 kg.

TS2 Explosion Events

Other than postulated explosions for cryogenic moderator hydrogen release (CM events, below), 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[26] of this event determined that only trace level amounts of hydrogen were involved, so the event did not require further analysis.

TS3 Loss of Confinement Events

Loss of confinement for TS events refers to a breach of the target mercury system. Several loss-of-confinement events involving damage to the target module or to the proton beam window as the result of beam misalignment (TS3-1), a malfunction of the beam expander mechanism (TS3-3), failure of mercury piping/components in the target service bay (TS3-5, TS3-6), a system breach and release of Loop 1 cooling water in the utility vault (TS3-20), did not exceed public or worker exposure criteria and, therefore, no additional analysis was performed.

Event TS3-6 involves leakage of shroud water into the interstitial space between shroud and target module. An instrument is provided to detect this condition so that the proton beam can be cut off before damage occurs. However, the hazard analysis assumes that the water boils and causes failure of water shroud and target module boundaries, making TS3-6 an initiator for a spill of mercury and cooling water into the core vessel (similar to event TS3-4).

Numerous loss-of-confinement events, primarily focusing on the release of mercury, were postulated to exceed the criteria for credited controls. These events include damage to the target module or proton beam window as the result of beam misalignment or excessively small focus area (TS3-2), release of mercury as the result of failure of the target module in the core vessel (TS3-4), failure of mercury piping/components in the target service bay (TS3-7, TS3-10), or overheating resulting from loss-of-mercury or cooling-water flow (TS3-11 through TS3-15 and TS3-22 through 27). An additional event related to the mercury loop postulates the effects of a breach in the mercury heat exchanger that allows Loop 1 cooling water to migrate to the mercury loop (TS3-9). Other loss-of-confinement events postulated include a loss of cooling to the intermediate cooling water loop (Loop 1 water) as the result of a loss of cooling tower water (TS3-16) and a breach of the mercury piping as the result of a dropped crane load inside the target service bay (TS3-18). The final loss-of-confinement events postulated include a release of mercury to the cooling tower water system (TS3-21) and a release of liquid mercury into the mercury offgas system during initial filling of the mercury pump tank (TS3-28). Except for Events TS3-7, TS3-10, and TS3-18, for the balance of the above events no controls are required for the Onsite 1 Worker immediately adjacent to the hazard because physical access to the core vessel is not credible.

The common credited controls selected for TS Loss-of Confinement Events TS3-12 through 16 and TS3-22 through 25 needed to either reduce the frequency or mitigate the radiological and chemical consequences are listed below:

- TPS proton beam cutoff on out-of-limits differential pressure across mercury pump or high mercury temperature—prevents excessive overheating due to inadequate mercury loop flow or cooling (Events TS3-12 and TS3-22 through 3-25).
- TPS proton beam cutoff on high mercury temperature—prevents mercury excessive overheating due to inadequate mercury loop flow or cooling (Events TS3-13 through TS3-16).

The common credited controls selected for Events TS3-4, TS3-6, TS3-7, TS3-8, TS3-10, TS3-11, TS3-18, TS3-26, and TS3-27) needed to either reduce the frequency or mitigate the radiological and chemical consequences are listed below:

- Primary confinement exhaust system (PCES) and associated ductwork—confine mercury-vapor-contaminated air within the target service bay following a spill (events involving mercury spill/leakage inside target service bay).
- 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 activated cooling water spills to allow decay of short-lived activation products of water (events involving mercury spill/leakage inside core vessel).
- Service bay differential pressure monitoring system—monitors and provides an alarm for loss of negative pressure between the target service bay and adjacent areas (events involving mercury spill/leakage inside target service bay).

- Transfer Bay Access Control System—prevents inadvertent worker access to the target service bay (Events TS3-7, TS3-10, TS3-18 only).
- Procedures and training for response to loss of negative pressure alarm—ensures evacuation of areas adjacent to the target service bay upon loss of negative pressure alarm (events that credited the negative pressure alarm function).
- Target service bay confinement of mercury—consists of a stainless steel liner configured and sloped to promote spilled mercury travel to the collection basin (events involving mercury spill/leakage inside target service bay).

The credited control selected for Event TS3-9 needed to mitigate the radiological consequences for workers within the occupied area consists of:

- Design of mercury heat exchanger—prevents failure of single wall from allowing radioactive mercury to escape from the target service bay via the mercury loop cooling water system.

The credited control selected for Event TS3-21 needed to mitigate the hazardous chemical consequences for the Onsite 1 and 2 Worker consists of:

- Design of mercury heat exchanger—prevents failure of single wall from allowing radioactive mercury to escape from the target service bay via the mercury loop cooling water system.

The credited control selected for Event TS3-28 needed to mitigate the radiological consequences for the Onsite 1 Worker consists of:

- Design of mercury pump tank exhaust line loop seal—prevents mercury pump tank overfill during system startup from leaking mercury outside the target service bay via the offgas system.

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 re-targeting activities (TS4-1 and TS4-2) and direct exposure to Loop 1 cooling water (TS4-3). Event TS4-3 resulted in negligible consequences and, therefore, no further analysis was performed. Event TS4-1 is an inadvertent actuation of the beam to the target service bay when the target carriage has been withdrawn from the core vessel for maintenance or target change out. This event is considered a proton beam accident and is addressed in the FSAD-PF.[27] The unmitigated consequences for this event were high to the Onsite 1 Worker. The following credited feature of the PPS prevents this accident as addressed in the Section 5.2.1 of the FSAD-PF[27], as listed below.

- Target PPS monitoring of target carriage position (requirements addressed in Section 5.2.1 FSAD-PF27)

- TPS prevents beam to target when target carriage is withdrawn (See Section 5.2.5)

- TPS prevents beam to target unless the mercury flow (differential pressure across the pump) is within operating limits because the mercury system must be disconnected in order to withdraw the target carriage (See Section 5.2.5).

Measured dose rates in the Manipulator Gallery during target change out activities confirm the adequacy of the thick shield walls and windows of the Target Service Bay; therefore direct radiation hazards are confined to within the Target Service Bay during target change out activities (TS4-2). The credited control selected for Event TS4-2 needed to protect the Onsite 1 worker consists of:

- Transfer Bay Access Control System—prevents inadvertent worker access to the target service bay, initiates alarm if intrabay shielding door not closed when Transfer Bay access door is open.

4.3.2 CRYOGENIC MODERATOR (CM) SYSTEM EVENT SCENARIO SUMMARY

Since the CMS uses hydrogen and spans a number of areas of the facility, it follows that fire (i.e., rapid deflagration) and explosion events, as a result of ignition of hydrogen released from a breached system, could be postulated. In the design phase of the CMS development, it was postulated non-mechanistically that fires and explosions could result from a breach in, and release of hydrogen from, the CMS piping in the core vessel, HUR, high bay, and shutter drive room (the space just above the core vessel under the shielding blocks). Combustion of hydrogen due to leakage of oxygen into the CMS was determine to be non-credible due to the ~ 13 bar normal pressure of the hydrogen in the CMS, the use of high purity VLSI 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 – see discussion in Section 3.3.3). One could postulate that, 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 due to 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. It was concluded that scenarios involving combustion of hydrogen inside the CMS were either non-credible and/or would not have consequences high enough to be evaluated further.

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 (see Section 3.3.3), hydrogen is vented from the CMS to the hydrogen safe vent system prior to cryogenic hydrogen system maintenance or inner reflector plug removal from the core vessel.
- The proton beam inner reflector plug design prevents direct proton beam view into the area of the moderator vessels.
- The CMS moderator and vacuum vessel are aluminum but are not significantly corroded by mercury in accidents because no accident scenarios result in their being submerged in liquid mercury (See discussion in 5.2.8.4 on aluminum corrosion by mercury).
- The hydrogen boundary is designed for a maximum acceptable working pressure of 19 bar absolute.

CM1 Fire Events

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

CM2 Explosion Events

Event CM2-1a is an explosion event with a follow-on fire caused by a breach (large leak) in the 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 similar to 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, moderate to the Onsite 2 worker, and the chemical consequences exceed the criteria 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 cause the system to be vented.[28] The credited controls needed to reduce the frequency of these events and to mitigate the radiological and chemical consequences consist of:

- Robust hydrogen barrier—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/externally protected hydrogen equipment that provides protection against impact and ensures the relief path remains unobstructed.
- Robust vacuum barrier—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/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 a significant adverse impact 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 involves a breach in the CMS piping in the core vessel (slow leak) (CM2-7) allowing hydrogen to escape to the vacuum vent system (followed by ignition). The unmitigated consequences for these events are either negligible or low to all receptors; therefore, no further analysis was performed.

CM3 Loss-of-Confinement Events

Several loss-of-confinement events were 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 resulting in a fire or explosion. The events postulate releases to such areas 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 over-pressurization or high temperature (CM3-5), system, and loss of power (CM3-6 through CM3-8).

A loss of confinement releasing H_2 outside the core vessel could be postulated to allow air to diffuse into the CMS inside the core vessel after the escape of H_2 depressurizes the CMS. Subsequently, an explosion inside the CMS would not be capable of vaporizing mercury because the robust H_2 boundary would contain the explosion without failure.

While it is presumed that the hydrogen and pre-moderator water in the CMS could contain trace quantities of tritium or other activation products or activated corrosion/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 pre-moderator water were well below criteria for all receptors and require no further analysis.

Oxygen deficiency due to leakage of hydrogen or helium was considered. The worst location (smallest volume) would be in the hydrogen utility room. However, the quantities of helium and/or hydrogen and buoyant nature of both gases prevent excessive oxygen displacement in breathable room air.

4.3.3 COOLING WATER (CW) LOOPS 2, 3, AND 4 EVENT SCENARIO SUMMARY

Hazards identified for Cooling Water Loops 2, 3, and 4 include a potential for fires, explosions, loss-of-confinement events, and events involving direct radiological exposure.

CW Events Initial Conditions and Assumptions

- Interstitial mercury in the Hg Heat Exchanger is at a higher pressure than both Loop 1 cooling water and mercury process loop operating pressures in the mercury heat exchanger.
- The operating pressure of Loop 1 cooling water is greater than the operating pressure in the mercury loop.
- Be-7 is assumed to be present as an activation product in water cooling systems exposed to direct proton beam radiation (cooling loops 2 and 3).
- The Loop 2 and 4 cooling systems are cooled by the de-ionized water isolation loops, which are, in turn, cooled by the tower water system. Loop 3 is cooled by a de-ionized water isolation loop which is cooled by the sensible chilled water system, which is, in turn, cooled by the tower water system.
- Pumps for the de-ionized water isolation loops are located in the basement of the target building.
- 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 Cooling Water Loops 2, 3, and 4 is lower than the pressure in the de-ionized 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 tank(s) into the system.
- Each cooling water (Loops 1, 2, 3, and 4) system loop includes 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 of shroud (Loop 2) cooling water release.

CW1 Fire Events

The fires postulated 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 explosion events postulated (CW2-1 and CW2-2) consider the possibility of H_2 explosions in gas/liquid separators located in a cavity the high bay area. Based on the inventory information available for the cooling water systems, 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

Loss-of-confinement events (CW3-1 through CW3-16) include a breach in cooling water system components resulting in a release of cooling water to the target service bay (target shroud cooling water [cooling loop 2]) (CW3-1 and CW3-2), core vessel (CW3-3, CW3-4, CW3-6, CW3-9 through CW3-11), bulk shielding liner and drain line (CW3-8 and CW3-15), high bay (CW3-14), basement utility vault (CW3-5, CW3-7, and CW3-12), central deionized water loop (through a breach in a heat exchanger) (CW3-13), and the manipulator gallery (by seepage through the building structure) (CW3-16). One event (CW3-9) postulates a major leak of cooling water into the core vessel (circulation pump continues to operate) filling the core vessel to a level above the proton beam. Assuming the beam stays on, the beam boils the water and subsequently produces steam, ruptures the core vessel rupture disk, and releases activated water vapor to the atmosphere through its vent system stack. Based on the radionuclide inventory in the cooling water systems, the consequences for all of these events are either negligible or low to all receptors; therefore, no further analysis was performed.

CW3-16 is a breach of cooling water (heavy water or light water) from Loop 2 (proton beam window only), 3 or 4 gas/liquid separators. Contaminated/tritiated water collects in gas/liquid separators concrete pit and migrates through porous concrete or cracks in the concrete into the manipulator gallery below, which may be occupied during operations. The breach can be caused by material defect, corrosion, fatigue from vibration, improper seal at system joints, heavy load drops in the high bay area into the gas/liquid separators pit, or rupture of the pit liner during seismic activity. Measured radiation dose rates in the delay tank and gas/liquid separator pits indicate that the radiological consequence associated with a heavy load drop would not rise to the level requiring credited controls[59]. A leak within the pits would be contained by the stainless steel pit lining. Even if failure of the liners is postulated, the radionuclide content of the water and end of life projected tritium concentrations would not pose consequences to the worker that would require credited controls[59].

CW4 Direct Exposure Events

As discussed in Section 3.3.8.3.1.8, acutely hazardous radiation levels are not expected (confirmed by operational measurements) in the basement utility vault or in the Shutter Drive Equipment Room.

Radiation measurements[59] 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/hr and up to about 10 R/hr at a location (ceiling area where pipe chase enters room) that requires a ladder to access. TLD measurements[59] in the shutter drive equipment room indicate that 2 MW dose rates would be well below 1 R/hr. 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. The initial analysis for this event (CW4-1) assumed that an individual remained in an assumed radiation field of 100 R/hr 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 minutes. As discussed above, measured dose rates in the basement utility vault and shutter drive equipment room are much lower than the initial assumption of 100 R/hr. Measured dose rates[59] indicate 2 MW dose rates on the order 60 R/hr in the delay tank pit and 20 R/hr 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 which requires evaluation of controls. The selected control needed to reduce the consequences to an acceptable level is provided by:

- 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 OFFGAS TREATMENT/CORE VESSEL VACUUM/CORE VESSEL HELIUM SYSTEMS (GW) EVENT SCENARIO SUMMARY

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

GW Initial Conditions and Assumptions

a. The mercury offgas system contains two gold adsorber beds, a CuO/molecular sieve system, and a liquid nitrogen-cooled charcoal bed to trap xenon, iodine, and residual mercury.
b. The offgas system is operated near atmospheric pressure.
c. The helium system pressurization equipment/storage tank is located external to the target building.

d. The vacuum system and offgas system are assumed to have no more than loose internal surface contamination.

GW1 Fire Events

The fire events postulated include one involving overheating of the copper oxide 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

The explosion events include one that assumes that hydrogen from a variety of sources is drawn into the vacuum system and is ignited. The event also (GW2-2) assumes that the explosion does not impact the mercury because it would be away from the core vessel or target 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 offgas treatment, vacuum, helium, and nitrogen systems were postulated. These include internal failures (GW3-1), leaks, or ruptures of offgas system components (e.g., mercury offgas treatment system) releasing tritium, mercury vapor, or other radioactive offgases (GW3-1 through GW3-5, GW3-8, GW3-11, GW3-14, GW3-16). Other loss-of-confinement events postulated include releases of radioactive material resulting from leaks or failure of such components as nitrogen purge gas (GW3-17 and GW3-18), offgas system exhaust fans (GW3-12), delay line (GW3-10), vacuum booster pumps (GW3-9 and GW3-14), and HEPA filters (GW3-13). All of 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 mercury offgas system within the target service bay resulting in a release of mercury vapor and/or offgas into the target service bay atmosphere. The unmitigated consequences for this event are negligible to the public; however, it is possible that airborne Hg 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:

- Transfer Bay Access Control System— prevents inadvertent worker access to the target service bay
- Service bay differential pressure monitoring system—monitors differential pressure to verify target service bay confinement
- Procedures and training to evacuate in response to Service bay differential pressure alarm.

GW4 Direct Exposure Events

Two direct radiological exposure events were postulated.

Event GW4-2 involves direct worker accidental exposure in the vicinity of the mercury offgas system (gold adsorber, zeolite beds). The unmitigated consequences for this event were negligible to the offsite public and low to the facility workers; therefore, no further analysis was performed.

4.3.5 PROCESS WASTE/SANITARY WASTE SYSTEMS EVENT SCENARIO SUMMARY

Process liquid waste for the target building drains to the process waste collection tank in the basement utility vault 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 low-level liquid waste (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 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 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 onsite hazardous material criteria. Therefore, no further analysis was performed and no credited controls were required.

4.3.6 CONTACT WASTE HANDLING (WH)/DECONTAMINATION AREA EVENT SCENARIO SUMMARY

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

WH Initial Conditions and Assumptions

- There may be as many as 20 spent ion exchanger resin columns stored in the contact waste handling and decontamination area awaiting processing.[23]
- 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/or replacement activities occur in the contact waste handling area.
- Drains from 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 out. Resins of low flammability are used and strong chemicals that would promote flammability upon dryout are not used.

WH1 Fire Events

A number of ignition sources were identified in Reference 19 along with the potential for combustibles to accumulate. On that basis, a fire in the general contact waste handling/decontamination area was postulated (WH1-1). It is assumed that several ion exchange columns containing spent resin could be stored within the area at any given time. In addition, it is assumed that the room has 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 offsite 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 out (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 offsite 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. At the time of this writing, SNS has no plans to regenerate resin onsite.

WH3 Loss-of-Confinement Events

Several loss-of-confinement events were postulated. These include spread of radiological material (general contamination) from the decontamination area through such means as 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 the above events do not result in doses that challenge offsite 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 of events resulting in a release of LLLW are small, including those for the facility worker. The unmitigated consequences resulting from this event are negligible to the offsite 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 provide assurance that exposures from this event are low.

4.3.7 CONFINEMENT VENTILATION (HV) 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

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

HV1 Fire Events

One event (HV1-1) was postulated for this scenario that resulted in negligible consequences to the offsite 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), mishandling, or confinement failure during replacement (HV3-5), and a failure of the gold adsorber beds (HV3-6). With the exception of HV3-5, all of the above events resulted in unmitigated consequences negligible to the offsite public and low or negligible to the facility workers; therefore, no further analysis was performed.

The unmitigated consequences from the postulated inhalation of radioactive material for HV3-5 are moderate to the Onsite 1 Worker, which requires evaluation of controls to reduce the consequences. The selected credited control is:

- 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 in the vicinity of the gold adsorber beds. The unmitigated consequences for both of these 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, SHIELDING/REFLECTORS/SHUTTERS (SH) EVENT SCENARIO SUMMARY

During the evaluation of the core vessel general, shielding/reflectors/shutters, fires, explosions, loss-of-confinement events, and an event involving direct radiological exposure were postulated.

SH Initial Conditions and Assumptions

a. Core vessel the inner reflector plug stainless steel clad and the lower aluminum section contains stainless steel and beryllium pieces. All beryllium pieces are encapsulated aluminum so that no credible accidents have been found that could cause the beryllium to become airborne. The reflector plug is cooled by heavy or light water.
b. The core vessel and bulk shielding liner and drain line area has no more than loose surface contamination.
c. The core vessel and bulk shielding liner and drain line areas have highly activated system components.
d. Shielding material outside the core vessel is steel or concrete and is sufficient to prevent excessive radiation exposure to workers in adjacent occupied spaces.
e. The core vessel atmosphere may be a helium blanket or a rough vacuum.

f. The core vessel is pressure protected by a rupture disk to the hydrogen safe vent stack. The rupture disk ruptures at approximately 7 psig internal pressure.
g. The core vessel and monolith drain lines are normally closed (by closed valve or blank flange cap).
h. The area directly above the core vessel is accessible from the high bay and is exhausted by the PCES.

SH1 Fire and SH2 Explosion Events

A potential exists for a fire involving the hydraulic shutter drives (in the general vicinity above the core vessel). The unmitigated consequences for this event (SH1-2) are negligible to the offsite public and low or negligible to the facility workers; therefore, no further analysis was performed. Other fire and explosion events that could 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/or liquid as the result of a breach in the core vessel (SH3-1), a neutron beam window (SH3-2), or target module/core vessel seals (SH3-3). The unmitigated consequences for these events are negligible to the offsite 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 such mishaps as misalignment of the target module (allows radiation "streaming") (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 offsite public. As reported in Chapter 7 for completed instruments with chopper, beamline, and instrument enclosure shielding in place, instrument PPS interlocks would shut off the beam in the event of inadvertent shutter opening that would expose workers to excessive radiation levels. Worker 1 could potentially be exposed to high radiation for operations when chopper, beamline or enclosure shielding is not installed and the primary shutter is open (SH4-3). Requiring the primary shutter to have its locking pin installed and locked into place with a radiation safety (RS) hold in accordance with the approved operations procedures adequately prevents this scenario. RS Holds are described in Section 4.2.1.2 *Moveable Shielding* of the FSAD-PF[27]. For event SH4-3 with shielding not installed the credited control for worker protection is:

- Radiological Protection Program - provides a means of controlling the radiological exposure received by facility workers when shielding is not in place by ensuring that each applicable primary shutter is locked in place with approved RS hold.

Chipmunks, placed in the monolith/chopper vicinity in locations specified by the Radiation Safety Officer, provide an extra level of safety for event SH4-3 by providing an automatic proton beam trip in the event of unusual radiation levels.

Event SH4-1 is a direct radiological exposure event involving misalignment of the target module, or misaligned proton beam window plug assembly, or core vessel inner plug assembly (with moderator vessels), which results in radiation into the high bay area. This event was postulated prior to beam operations. High power surveys have confirmed adequate shielding performance. This event is none-the-less being retained to cover situations that may evolve involving significant changes in placement of shielding associated with these components. The consequences of this event are high to the Onsite 1 Worker and require evaluation of controls. The selected credited control for the Onsite 1 Worker is:

- 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 involving breaches or cracks in the concrete shielding assumes that a worker, unaware of the condition, receives exposure over a prolonged period of time. This event was postulated prior to 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 1000 rad/h for five minutes. 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 selected credited control for the Onsite 1 Worker includes:

- Radiological Protection Program—provides a means of controlling the radiological exposure received by facility workers by ensuring that periodic radiation surveys take place (SH 4-2).
- Radiological Protection Program-enforces the use of RWPs with required approvals commensurate with potential hazard. Need for RCT coverage is considered for each RWP.

4.3.9 TARGET SERVICE BAY GENERAL AREA EVENT (TC) SCENARIO SUMMARY

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

TC Initial Conditions and Assumptions

a. The target service bay, maintenance support area, and transfer bay portions of the interior service bay structure within the target building are capable of withstanding a surface vehicle impact originating from outside the building, small external fires/explosions, or a tornado missile without a significant release of radiological materials.
b. Target service bay shielding material is concrete and steel and is sufficient to prevent excessive radiation exposure to workers in adjacent occupied spaces.
c. The shield door separating the maintenance bay from the transfer bay is normally closed. Personnel are not allowed in the transfer bay during beam on conditions unless, the intrabay door is closed.
d. Normal operations in the target service bay are accomplished remotely.
e. The loop 2 shroud water cooling system delay tanks for the target shroud are contained within the target service bay, and the delay tank for the proton beam window cooling water and the gas/liquid separators are contained in a high bay cavity.
f. The target service bay and transfer bay have loose surface contamination.
g. The target service bay contains highly activated system components.
h. Any hydrogen leaked into the atmosphere of the high bay would become sufficiently diluted so as to result in a concentration less than the LFL for hydrogen in air prior to being drawn into the target service bay ventilation supply intake.[30]
i. Natural gas is not piped to the target building. Any natural gas released into the atmosphere external to the target building would become sufficiently diluted so as to result in a concentration less than the LFL for natural gas in air prior to being drawn into the target service bay ventilation supply intake.[29]

TC1 Fire Events

See Events TS1-1, TS1-3, and TS1-4 in Section 4.3.2.

TC2 Explosion Events

Event TC2-2 involves a breach of hydrogen piping in the CMS, allowing hydrogen to escape to the high bay. The hydrogen cloud is then drawn into the PCES ventilation ductwork via the air intake, is ignited in the target service bay, and explodes releasing mercury. A similar event (TC2-3) postulates that an explosive gas external to the facility 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 target service bay where it explodes as in the previous event. Both explosion events involving an accumulation and ignition of hydrogen or other explosive gas in the target service bay would be expected to result in radiological doses that would challenge the offsite public exposure guidelines and onsite hazardous material criteria for all receptors. However, both of these events have been determined to be non-credible based on the assumption that any hydrogen leaked into the atmosphere of the high bay would become sufficiently diluted so as to result in a concentration less than the LFL for hydrogen in air prior to being drawn into the PCES ventilation supply intake[30] and the fact that the target building does not have natural gas service.[29] Therefore, no further analysis is required.

TC3 Loss-of-Confinement Events

One of the loss-of-confinement events involves a breach in the target service bay confinement barrier (releasing contamination including 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 Hg concentrations based on measured airborne Hg in the Target Service Bay indicate that consequences associated with a loss of service bay confinement would not rise to the level of requiring credited controls[59]. None-the-less, controls associated with the original analysis are retained. The controls selected to reduce the consequences for the Onsite 1 Worker include:

- Service bay differential pressure monitoring system—detects and alarms on loss of negative differential pressure between the target service bay and adjacent locations.
- Procedures and training for response to loss of negative pressure alarm—ensures evacuation of areas adjacent to the target 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 target 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, controls were selected for protection of the workers within the occupied area. These consist of:

- Transfer Bay Access Control System—prevents inadvertent worker access to the target service bay
- Service bay differential pressure monitoring system—detects and alarms on loss of negative differential pressure between mercury containing areas and adjacent occupied areas (chemical protection for the worker within the occupied area).
- Procedures and training for response to loss of negative pressure alarm-ensures evacuation of areas adjacent to target service bay upon loss of negative pressure alarm.

Event TC3-3, involving movement of the target carriage while mercury is being circulated, has the potential to release significant quantities of mercury. The unmitigated radiological consequences for TC3-3 are high to the Onsite 1 Worker and moderate to 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 selected controls consist of:

- Transfer Bay Access Control System—prevents inadvertent worker access to the target service bay (Onsite 1 Worker).
- Target service bay confinement of liquid mercury design—consists of a stainless steel liner configured and sloped to promote spilled mercury travel to the collection basin (Onsite 1 and 2 Workers).
- PCES and associated ductwork—confine mercury-vapor-contaminated air within the target service bay following a spill (Onsite 1 and 2 Workers).
- Service bay differential pressure monitoring system—detects and alarms on loss of negative differential pressure between mercury containing areas and adjacent occupied areas.
- Procedures and training for response to loss of negative pressure alarm-ensures evacuation of areas adjacent to target 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 steel intrabay shielding door is opened while workers are present in the transfer bay. The unmitigated consequences are high to the Onsite 1 Worker and require evaluation of controls. The controls selected to reduce the consequences of this event consist of safety functions provided by the transfer bay access control system.

- Transfer bay access control system a) prevents opening of the transfer bay personnel door if the steel intrabay shielding door (located between the maintenance bay and transfer bay) is not closed and b) sounds an alarm if the intrabay shielding door is not closed when the personal access door is open.

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

- Transfer Bay Access Control System—prevents inadvertent worker access to the target service bay
- Radiological Protection Program—provides a means of controlling the radiological exposure received by facility workers, radworker training enables workers to understand shielding value of thick windows and thus, to evacuate should they break.
- Hoisting and Rigging Program—ensures safe operation and proper certification and preventive maintenance of the target service bay crane and gantry crane robotic arm.

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

- Design of mercury heat exchanger—robust design prevents failure of single wall from allowing radioactive mercury to escape from the target 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 target service bay atmosphere. The number has been left intact for traceability to the historical hazard analyses. The unmitigated consequences for event TC4-4 are Moderate to the Onsite 1 worker in the transfer bay, which requires evaluation of controls. The selected controls consist of:

- Service bay differential pressure monitoring system—detects and alarms on loss of negative differential pressure between mercury containing areas and personnel locations.
- Procedures and training for evacuation of the transfer bay and areas adjacent to the service bay in response to loss of negative pressure alarm.

4.3.10 HIGH BAY AREA EVENT (HB) SCENARIO SUMMARY

During the evaluation of the high bay area, fires, explosions, loss-of-confinement events, and an event involving direct radiological exposure were postulated.

HB Initial Conditions and Assumptions

a. Use of forklifts in the high bay is subject to regulation by the Combustible Materials Control Program outside the target service bay.
b. Electric-hydraulic robots may operate in the high bay.
c. The Loop 2 (proton beam window cooling), 3, and 4 gas/liquid separators are contained within a shielded pit within the high bay floor covered by shielding directly above the manipulator gallery during operations.
d. The high bay area may have no more than loose surface contamination.
e. The steel biological shielding assembly surrounding the core vessel and the inner and outer reflector plugs are in place during operations. This includes the "birthday cake" shielding of carbon steel above the core vessel as shown in Figure 3.3.2-1.

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 of the two 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 result in 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 both event HB1-1 and HB1-2 do not challenge the radiological guidelines or criteria for any receptor group and, 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 drop of a crane load onto the core vessel. During the design phase of the project, it was assumed the impact caused sufficient displacement of the inner reflector plug assembly to breach the cryogenic moderator vessels and the mercury target, spilling hydrogen and mercury within the core vessel. In this case, released hydrogen was assumed to ignite and explode within the core vessel, thus dispersing the spilled mercury. In reality, the core vessel, and hence the inner reflector plug, is protected from significant deflection by the massive steel biological shielding installed both above and around the core vessel. The internals of the core vessel 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 conceivably be crushed, trapping hydrogen in the core vessel. The trapped hydrogen could be released inside the core vessel with bounding consequences similar to the CM explosion events (Section 4.3.2). The unmitigated radiological consequences for HB2-2 are high to the onsite receptors, which require evaluation of controls. The radiological consequences to the offsite receptor are Low based on the operational requirement to have bulk radiation shielding during operating conditions. In addition, 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 covered by the ORNL SBMS hoisting and rigging safety program). The selected controls needed to prevent the explosion consist of:

- Seismically qualified (PC-3), restrained/externally protected hydrogen equipment in high bay—provides protection against impact and ensures the relief path remains unobstructed.
- High bay crane design per ASME NOG-1[31]—ensures the 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 performed by trained personnel in accordance with approved lift plans and procedures; restricts crane lifts over core vessel and Hg process system unless beam to target is terminated and Hg is drained to the mercury storage tank.

- High bay floor design—provides ability to withstand load drops permitted by Hoisting and Rigging Program to pass above the core vessel when the loop 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 guidelines/criteria and, therefore, no further evaluation was performed. These 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 is a release due to crane failure or operator error from the high bay crane dropping a transfer cask (causing the cask to leak). The unmitigated consequences for event HB3-2 are Moderate to the Onsite 1 Worker which requires evaluation of controls. The selected controls needed to reduce the frequency of this event and to protect the Onsite 1 Worker consist of:

- High bay crane design per ASME NOG-1[31] 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 the load being dropped on the target service bay. It is assumed that the dropped item penetrates the high bay floor (which serves as the target service bay roof) and damages the mercury loop, releasing mercury. The unmitigated consequences for event HB3-3 are Negligible to the Offsite Public and High to the Onsite 1 and 2 Workers, which require evaluation of controls to protect the onsite workers. The selected controls needed to reduce the frequency and consequences consist of:

- Transfer Bay Access Control System—prevents inadvertent worker access to the target service bay.
- High bay crane design per ASME NOG-1[31] 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 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 result in significant damage to the adjacent transfer bay and remote waste handling area in the target service bay. The unmitigated consequences for event HB3-6 are Negligible for the Offsite Public and Low to the Onsite 2 Worker but high for the Onsite 1 Worker. This requires evaluation of controls. The selected controls needed to reduce the consequence to the Onsite 1 Worker consist of:

- Transfer bay access control interlock prevents opening of the transfer bay personnel door if the steel intrabay shielding door (located between the maintenance bay and transfer bay) is not closed.

Event HB3-7 is highly similar to HB3-2 but the load is assumed to be dropped on the core vessel. If the steel shielding that forms the monolith above and surrounding the core vessel were not in place, it would be reasonable to postulate that this event could cause an impact sufficient to displace the target inner plug assembly 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 and it would prevent significant displacement of the target inner plug assembly and thus prevent significant leakage. None-the-less, it is conservatively assumed that damage to the target module does occur. Accordingly, the target module mercury boundary and the water cooled shroud are assumed to subsequently 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 offsite receptor, Low to the Onsite 2 Worker, and High to the Onsite 1 Worker. The unmitigated chemical consequences are below offsite criteria but exceed onsite criteria. Physical access to the target service bay is not credible for the worker in the immediate vicinity of the hazard. Therefore, an evaluation of controls is required for worker within the occupied area of the hazard. The selected controls consist of:

- High bay crane design per ASME NOG-1[31]—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 (radiological and chemical).
- Hoisting and Rigging Program—provide[s] regular inspection and maintenance of equipment; crane lifts performed by trained personnel in accordance with approved lift plans and procedures (radiological and chemical).

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 could occur in the vicinity of 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 due to 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 monolith shutter drive access room, the target service bay, and the cooling water delay tank and gas-liquid separation pits. Prevention of potential direct radiation exposure due to inappropriate movement of shielding follows Section 4.2.1.2 “Movable Shielding” of the *FSAD for Proton Facilities*.[27] Following the approach described in this reference, the Radiological Protection Program controls access to radiological areas and controls placement of shielding that mitigates dose and prevents worker access.

4.3.11 COMPRESSED AIR SYSTEM EVENT (CA) SCENARIO SUMMARY

During the evaluation of the compressed air system, a fire, explosion, and a loss-of-confinement event were postulated.

CA Initial Conditions and Assumptions

Configuration of the compressed air lines makes it unlikely there could be significant back-leakage of air out of the target service bay. When the air is not connected to the device(s) it powers, installed quick disconnects act like a cutoff valve. When connected, the air-powered device would prevent or restrict backflow.

Instruments, valves, or other components controlled by instrument air are designed to fail in the safest position on a loss of compressed air.

CA1 Fire Events

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

CA2 Explosion Events

Event CA2-1 is an over-pressurization 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, it is assumed the rupture does not 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 instrument air supply to the facility. This event assumes that the loss of instrument air does not affect processing equipment such that radiological material is released. It assumes any equipment that relies on instrument air for control is designed to fail (from loss of air supply) in the safest position and is not adversely affected by failure of the air system. The event does not involve release of any radiological material, and the event is considered a common hazardous event.

4.3.12 FIRE DETECTION AND SUPPRESSION SYSTEM EVENT (FS) SCENARIO SUMMARY

During the evaluation of the fire detection and suppression system, fires, an explosion, and a loss-of-confinement event were postulated.

FS Initial Conditions and Assumptions

The FSS inside the target service bay utilizes a UL-listed or 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 there to be combustibles on or immediately adjacent to the system, it is postulated that a fire could be initiated in the system. Assuming the fire involves only the electrical wiring or components on the fire suppression and detection system, it can be considered a common hazardous event since the system is not likely to contain any contamination. It is recognized that, if left unattended, the fire could ultimately propagate to areas of the facility that contain radiological material, although this is unlikely to occur due to 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 FSS could include cylinders containing CO_2 or N_2. Also, it is assumed that the rupture of the cylinder does not result in any impact to processing equipment and no radiological material is released. As a result, 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 there is a potential for internal flooding as a result of the breach. 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 offsite public and Low to the onsite workers and, therefore, no further evaluation was performed.

4.3.13 TRUCK BAY AND UTILITY VAULT GENERAL AREA EVENT (UV) SCENARIO SUMMARY

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

UV Initial Conditions and Assumptions

a. The basement utility vault area has no more than loose surface contamination.
b. The cooling system components in the basement utility vault have highly activated cooling water during operations and some long-lived particulates following shutdown.
c. Road vehicles have access to the truck bay in the target building basement.
d. Sumps in the basement utility vault drain, or are pumped, to the LLLW tank or process waste system depending on radioactivity content.
e. 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 general area. The designation as a general area fire is based on the identification of a number of ignition sources along with the potential for combustibles to accumulate. It is assumed the area may have surface contamination that is released during the general area fire and, 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. In addition, this event is assumed to be confined to the immediate area of the truck bay. Again, the material released is assumed to be general surface contamination and, therefore, no further evaluation was performed.

UV2 Explosion Events

Event UV2-1 is a small explosion such as one that would involve hydrogen released from forklift batteries or from a battery charging station and 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 impact 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 areas such that large quantities of highly radioactive material (e.g., mercury) are released. In both events, unmitigated consequences are Negligible or Low to all receptors and, 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 include release of radiological material (general contamination) from the basement utility vault general area or truck bay through such means as 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 (UV3-2) acid is evaluated in Event CW3-7 in Section 4.3.3.1.4. The event involving the truck impact (UV3-3) assumes there is no fire or explosion following the impact. Also, while it is assumed the vehicle penetrates the wall at the end of the truck bay, the radiological impact is small. The unmitigated consequences for both UV3-1 and UV3-3 are Negligible or Low to all receptors and, 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 and, therefore, no further evaluation was performed.

4.3.14 TARGET BUILDING GENERAL (BG) EVENT SCENARIO SUMMARY

The evaluation of target building general events focuses on evaluation of the events that could affect the general SNS target facility or multiple systems contained within the facility. This includes events that occur within the facility, external events that adversely impact the target building, and natural phenomena events.

BG Initial Conditions and Assumptions

a. Electric forklifts and associated charging stations are used on the experiment floor level of the target building.
b. Facility workers have the ability to react to obvious hazardous conditions and evacuate unless injured as a result of the hazardous event.
c. No fissionable material, which could cause an inadvertent criticality, is available in the target building.
d. The SNS facility is located 1.5 kilometers or more from the nearest uncontrolled public access.
e. Surface vehicles have access to roadways or parking lots in areas immediately adjacent to the target building.
f. 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 program for chemical safety. Any beryllium in the reflector is encapsulated in aluminum.
g. 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.
h. The walls surrounding the target service bay are designed to PC-3 seismic requirements and would provide a barrier after a seismic event to separate combustibles outside the target service bay from mercury inside the target service bay.
i. Mercury loop steel shielding is normally in place when mercury is in the process loop. This is operationally required only when Hg is activated to 250 rem/h (design goal to protect electronics within the service bay). Mercury loop shielding is designed to PC-2 seismic accelerations.
j. Combustible material is available in each section of the building.

BG1 Fire Events

Event BG1-1 is a full-facility fire. This event is assumed to involve all of the areas in the facility and releases significant quantities of mercury. The unmitigated radiological consequences for BG1-1 are high to onsite receptors and the unmitigated chemical consequences exceed hazardous chemical criteria. This requires evaluation of controls for radiological and chemical protection for all receptors. The selected controls needed to reduce the event frequency and consequences include:

- Two-hour equivalent fire barrier—encloses the target service bay and core vessel and prevents migration of either combustibles or mercury across that barrier and ensures fires outside the service bay or monolith would not propagate into the core vessel or target service bay (including bulk shielding liner drain termination point) (public and worker protection).

- Combustible Material Control Program outside target service bay—ensures the fire barrier is not challenged and precludes gross building structural failure (public and worker protection, see Section 5.3.3).
- PCES (Design feature, location of air intake).
- FSS outside target service bay—provides an additional means to suppress the maximum fire anticipated outside the target service bay to ensure the fire barrier is not challenged (Onsite 2 Worker protection only).
- Transfer Bay Access Control System—prevents inadvertent worker access to the target service bay (protection for the worker in the immediate area of the hazard only).
- Procedures for mercury inventory control—ensures each PCES charcoal adsorber is < 19.4 kg and the total PCES charcoal adsorber inventory is < 155.2 kg. (chemical protection for the worker outside of the target building).

BG3 Loss-of-Confinement Events

Event BG3-1 involves a leak in the helium or liquid nitrogen supply piping. This could occur at essentially any location in the building. The event assumes a potential for asphyxiation only and also assumes that it does not involve a release of radiological material (although loss of liquid nitrogen supply to the mercury offgas charcoal bed would reduce the bed's ability to remove contaminants from the offgas stream). Subsequent design changes removed liquid nitrogen supply piping in the target building. Nitrogen piping only supplies dewar fill stations external to the building. The nitrogen supply to the offgas charcoal bed is provided by dewars. This event is considered a common industrial hazardous event; therefore, no further evaluation was performed.

BG6 External Events

The external events postulated include impact to the facility as the result of a major loss of power (BG6-1), explosions near the target facilities (BG6-4 through BG6-6), and impacts by aircraft, vehicles, or dropped crane loads (BG6-7 through BG6-11). The external fire events include a fire in the experiment hall (outside the target service bay and support equipment boundary) (BG6-3) and a fire that originates outside the target building (such as a forest fire) (BG6-2). The external explosions postulated include one in the laboratory facilities (BG6-4), explosions involving natural gas (BG6-5), and an explosion involving a vehicle carrying explosive material (such as a gasoline truck) (BG6-7). Event BG6-5 is not considered credible as natural gas is not piped into the building. In addition, any natural gas released into the atmosphere external to the target building would become sufficiently diluted so as to result in a concentration less than the LFL for natural gas in air prior to being drawn into the target service bay ventilation supply intake.[29] 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 and, therefore, no further evaluation was performed for these events. Events BG6-8 and BG6-9 are external aircraft impact events. A specific evaluation of aircraft impact risk was performed for the SNS target building utilizing the methodology of DOE-STD-3014-96, *Accident Analysis for Aircraft Crash into Hazardous Facilities*.[32] The results[33] show that, despite conservative assumptions, the frequency of potentially damaging aircraft impact is below 10 ^{6}/y. Therefore, aircraft impacts are not considered as a credible external man-made hazard to the SNS site and were not evaluated further.

Event BG6-11 involves an external crane drop over the target building resulting in a release of radiological material. The unmitigated radiological consequences are Low to the Offsite Public, thereby not requiring credited controls. The unmitigated radiological consequences for event BG6-11 are High to the Onsite 1 Worker and Moderator to the Onsite 2 Worker, and the chemical criteria are exceeded for both worker groups and the Offsite Public. The selected controls needed to reduce the frequency and consequences of this event include:

- Hoisting and Rigging Program—controls external crane lifts over the target building (public and worker protection).
- Emergency response procedures and training requiring evacuation—ensure notification and evacuation of Onsite 2 Worker in event of external crane drop resulting in release.

BG7 Natural Phenomena Events

The natural phenomena events postulated that do not challenge public or worker evaluation criteria and require no further analysis include: tornado or high straight winds (BG7-5) that impact the target building directly causing damage or resulting in damage to other structures (such as a stack) that subsequently collapse onto the target building; lightning (BG7-6); flooding (BG7-7); and roof collapse resulting from heavy snow, ice load (BG7-7), and freezing weather (BG7-8).

Event BG7-1 is an earthquake with a subsequent fire or explosion. Fire or explosion is 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 onsite receptors, Low to the Offsite receptor, and the hazardous chemical criteria are exceeded for all receptors. Therefore, an evaluation of controls is required for public (chemical only) and worker protection. The selected controls consist of:

- Two-hour equivalent fire barrier enclosing target service bay and core vessel—prevents migration of either combustibles or mercury across that barrier and ensures fires outside the core vessel would not propagate into the core vessel or target service bay (including bulk shielding liner drain termination point) qualified to PC-2.

- Procedures for mercury inventory control—ensure each PCES charcoal adsorber is < 19.4 kg and the total PCES charcoal adsorber inventory is < 155.2 kg.
- Robust hydrogen barrier 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/externally protected hydrogen equipment that provides protection against impact and ensures the relief path remains unobstructed.
- Combustible Material Control Program outside target service bay—ensures the fire barrier is not challenged and precludes gross building structural failure (See Section 5.3.3).
- Combustible Material Control Program inside target service bay—limits allowable combustibles, fixed or transient, consistent with the maximum 1 MW/1 h locally intense fire analyzed in the safety basis inside the target service bay to ensure a fire in the service bay could not challenge the primary mercury containment (fire inside core vessel not credible).
- Target 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 outside two-hour fire barrier—limits ignition sources in the instrument hall (and elsewhere outside of the target service bay and monolith, See Section 5.3.4).
- Target service bay confinement of mercury - Mercury loop steel shielding normally installed (designed to withstand PC-2 seismic accelerations).

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. This requires evaluation of controls. The selected controls needed to reduce the consequences to the onsite workers consist of:

- Target service bay and monolith seismically qualified structure—ensure confinement of mercury following a PC-2 seismic event.

Procedures and training are not necessary to ensure evacuation of areas adjacent to the target service bay upon loss of negative pressure because instinctive human behavior in earthquakes makes evacuation a virtual certainty.

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 offsite receptor is not required based on the assumed initial condition of radiation shielding required to be in place during normal operating conditions for equipment protection and worker ALARA considerations. The selected controls needed to reduce the consequences of this event include:

- Robust hydrogen barrier 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/externally protected hydrogen equipment that provides protection against impact and ensures the relief path remains unobstructed.

- Robust vacuum barrier 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/externally protected vacuum equipment that provides protection against impact and ensures the relief path remains unobstructed.
- Target service bay and monolith seismically qualified structure—ensures confinement of mercury following a PC-2 seismic event.

Event BG7-4 is a tornado or high winds with missiles that result in damage to the target building with subsequent release of radiological material. Further analysis of the radiological consequences to the off-site receptor is not required based on the assumed initial condition of radiation shielding that 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 offsite 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[1] because the initiating frequency of this event is Extremely Unlikely (below 10^{-4}/y).

4.3.15 SUMMARY OF HAZARD ANALYSES AND REQUIRED CREDITED CONTROLS

Of the 180 hazard events initially identified, the hazard analysis indicates that 53 require Credited Controls for worker protection. Analyses for these events are summarized in the Controls Matrix presented in Appendix A. Credited Engineered Controls identified in the hazard analysis for worker protection are listed in Table 4.3.15-1. Credited Administrative Controls are listed in Table 4.3.15-2. It should be noted that the analysis of impacts to the offsite public (presented in Section 4.4) shows that credited controls identified for worker protection are sufficient to protect the public. Therefore the Credited Controls listed in the tables below represent the comprehensive set of Credited Controls for SNS.

Table 4.3.15-1 Summary of Credited Engineered Controls

	Credited Engineered Controls	Applicable Events
1	CMS Robust Hydrogen Boundary (includes seismically qualified , restrained/externally protected Relief Path)	CM2-1a, CM2-1b, BG2-2, BG7-1, BG7-3
2	CMS Robust Vacuum Boundary	CM2-1a, CM2-1b, BG7-3
3	Service Bay/Core Vessel Fire Barrier: • Isolation Function • Two-Hour Equivalent Fire Barrier Function	BG7-1, TS1-2, TS1-3, BG1-1, TS1-2, TS1-3, BG1-1
4	Target Protection System	TS3-12, TS3-13 thru TS3-16, TS3-22 through 25
5	FSS Inside the Service Bay	TS1-3, TS1-6, BG1-1
6	FSS Outside the Service Bay	TS1-2, BG1-1
7	Core Vessel with Rupture Disk and Neutron Beam Windows – Confinement Function	TS3-4, TS3-6, TS3-8, TS3-11, TS3-26 and TS3-27
8	Target Service Bay and Monolith — Confinement of Mercury [includes mercury loop steel shielding (PC-2) for event BG7-1]	TS3-7, TS3-10, TS3-18, TC3-3, BG7-1, BG7-2, BG7-3
9	Primary Confinement Exhaust System (includes associated ductwork, and backdraft dampers)	TS1-2, TS1-3, TS1-6, TS3-7, TS3-10, TS3-18, BG7-1
10	High Bay Crane Design per ASME NOG-1	HB3-2, HB3-3, HB2-2
11	High Bay Floor Design	HB2-2
12	Robust Mercury Heat Exchanger	TS3-9, TS3-21, TC4-3
13	Service Bay Differential Pressure Monitoring System (SBDPMS)	TS1-3, TS1-4, TS1-6, TS3-7, TS3-10, TS3-18, TC3-1, TC3-2, TC3-3, TC4-4, GW3-2
14	Mercury Pump Tank Exhaust Line Loop Seal	TS3-28
15	Transfer Bay Access Control System	TS1-3, TS3-7, TS3-10, TS3-18, TS4-2, GW3-2, TC3-2, TC3-3, TC4-1, TC4-2, HB3-3, HB3-6, BG1-1
16	Target and Instrument PPS	See Chapter 7

Table 4.3.15-2 Summary of Credited Administrative Controls

	Credited Administrative Control	Applicable Events
1	The Radiological Protection Program – provides a means of controlling the radiological exposure received by facility workers by controlling the planning, approval, monitoring, and execution of radiological work.	CW4-1, TC4-2, SH4-1, SH4-2, SH4-3, SH4-4, HV3-5
2	The Chemical Safety Program provides protection against inadvertent exposure to mercury or mercury vapor during initial facility startup (chemical protection, was applicable only during initial facility startup) – No Longer Applicable	Not Applicable
3	The Combustible Materials Control Program inside and outside of the target service bay	TS1-2, TS1-3, BG1-1, BG7-1
4	The Hoisting and Rigging Program • Restricts Crane Lifts in high bay • Restricts External Crane Lifts Over Target Facility • Addresses Certification and Preventive Maintenance for Service Bay Crane and Gantry Crane Robotic Arm. •	TC4-2, HB2-2, HB3-2, HB3-3, HB3-7, BG6-11
5	Procedures and training are required for the following: • To ensure proper response to loss of negative pressure alarm • To ensure workers close the transfer bay personnel door when evacuating in response to negative pressure alarm • To ensure awareness of vulnerability of window and safe operation of Target Service Bay Crane and Gantry Robotic Arm • To control Hg inventory on charcoal adsorbers	For corresponding bullet at left: • See Table 4.3.15-1, SBDPMS events • TS1-6 • TC4-2 • TS1-2, BG1-01, BG7-1
6	Emergency Response Procedures are required for the following: • Fire with worker(s) in the transfer bay and the personnel door in the open position • Evacuation of Workers outside target building as required in response to an external crane load drop on the target building resulting in a release • Evacuation of Workers in event of fire during maintenance activities when the target service bay, transfer bay and high bay are open to common air flow	For corresponding bullet at left: • TS1-6 • BG6-11 • TS1-4

4.3.16 IDENTIFICATION OF EVENTS WITH POTENTIAL OFFSITE IMPACTS

Hazard event scenarios analyzed for onsite impacts above were reviewed to identify accidents that may potentially have an impact on the offsite public. Events initially placed in offsite public risk bins 1 through 9 during qualitative hazard analysis were selected for offsite impact analysis. Based on the approach taken in DOE-STD-3009-94,[2] 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" that resulted in a subset of "representative events" for further examination.

The number of events needing accident analyses was reduced by grouping similar events that could conservatively be bounded 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 since to purpose of the quantitative accident analysis is to determine bounding consequences and not to characterize small differences between similar accidents. As the chemical consequence analysis followed the radiological analysis, accident selection for chemical evaluation made use of the existing radiological analysis.

Events selected for offsite impact accident analysis are presented below:

1. Target Service Bay Fire (TS1-3, TS1-6)
2. Medium Fire (TS1-2)
3. Full Facility Fire (BG1-1)
4. CMS Hydrogen Explosion with Follow-On Fire (CM2-1a)
5. Hydrogen Explosion without Follow-On Fire (CM2-1b)
6. Loss of Confinement (Service Bay) (TS3-7, TS3-10)
7. Loss of Confinement (Core Vessel – Helium Inerting Operation) (TS3-4, TS3-6, TS3-8, TS3-11)
8. Loss of Confinement (Core Vessel – Vacuum Operation)
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. Crane Load Drop, Service Bay (TS3-18)
13. Crane Load Drop, High Bay onto Service Bay (HB3-3)
14. Crane Load Drop (High Bay Crane) onto Core Vessel (No Hydrogen Explosion) (HB3-7)
15. Crane Load Drop (High Bay Crane) onto Core Vessel with Hydrogen Explosion (HB2-2)
16. External Load Crane Drop (BG6-11)
17. Natural Phenomena (Seismic) Including H2 Explosion and Follow-On Fire (BG7-1)

18. Natural Phenomena (Seismic) Event Including Follow on Fire (no H2 Explosion) (BG7-2)
19. Natural Phenomena (Seismic) Including Follow-On H2 Explosion (No Fire) (BG7-3)

Accident analyses for impacts to the offsite public are present in Section 4.4 below.

4.4 ANALYSIS OF EVENTS WITH POTENTIAL OFFSITE IMPACTS

This section presents the quantitative assessment of accident scenarios that have a postulated radiological or toxicological impact 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[2]. An overview of methodology including source term, meteorological dispersion, and dose calculations is provided in Section 4.4.1.

Bounding consequences to the offsite 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 prior to operations, served to identify certain design features and other controls needed to ensure protection of the offsite 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 was done to highlight the important safety role of these features and to provide input into the design process. For instance, the important safety role of the Service Bay walls (e.g. confinement of airborne Hg and protecting the Hg 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 take into account passive robust structures and design features but take no credit for active controls or administrative controls. The as-constructed analysis incorporates updated information based on operational experience that simply was not available during the pre-operational phase of the project. Assumptions associated with the as-constructed analyses are described with the various accident scenarios in Section 4.4.2. In several instances, where the unmitigated analysis consequences were well below crediting thresholds, no "as-constructed" analysis was performed and consequences were simply assumed equal to the unmitigated consequences.

It should be noted that functions provided by passive structures with no credible failure mode may be accounted for in determining unmitigated consequences. The definition of unmitigated consequences from *SNS Policy for Selection of Safety Related Credited Controls*[1] is 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 results of the unmitigated analyses, performed prior to operations, were used to determine the need for credited controls to protect the offsite public. Consequences associated with the unmitigated analyses were compared with the criteria for the selection of credited controls (Section 4.2.2.4) to determine if credited controls were needed for public protection.

Accident analyses are typically carried out only to the point where the conservative assessment confirms that the calculated consequences of the event satisfy the *SNS Policy for Selection of Safety Related Credited Controls*[1] for radiological and chemical exposures. Mitigated analyses[34] have been performed 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 where 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, follow-up analyses were performed either 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, no further analyses were performed and the results presented to demonstrate that criteria were not challenged.

This approach, while considered cost effective, causes the degree of conservatism in the analysis to vary from event to event. Because of this, the calculated consequences are not intended to be representative of expected doses if the accident were to occur and 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, etc.) and examined to identify the bounding event for each specific type, where such identification is possible solely by inspection, with no detailed quantitative analysis. This examination concludes that, in many instances, the bounding hazardous material release consequences for events listed in Section 4.3.16 are determined to be 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 that 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 public consequence[34]. Offsite consequences associated with the "as-constructed" analysis were all below crediting thresholds.

Engineering calculations describing processes employed to develop the source term and consequence analysis are provided in References 34, 41, 42 and 59.

4.4.1 METHODOLOGY FOR OFFSITE IMPACT ANALYSIS

This section describes the basic methodology used for the accident analysis assessment of the SNS target facility.

4.4.1.1 Assumptions and Input

The assumptions and inputs used for hazard and accident analyses are documented in Reference 23 and/or other reference documents. 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 deal with:

- 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 facility personnel have the ability to control or change. Those critical assumptions and inputs that preserve the validity of the safety analyses and that 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:

1. The maximum temperature of the mercury in the hot leg of the target system during normal operations is 125°C.
2. The maximum mercury system pressure during normal operations is 105 psig (at the pump outlet).
3. 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.
4. The maximum ambient temperature in the target service bay is 50°C, and the maximum ambient temperature in the core vessel is 60°C.
5. Radioactive inventories are based on those that would exist after 40 y of operations (5000 h/y) at 2 MW with an uncertainty multiplier 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.
6. The total hydrogen mass in the cryogenic moderator system is 7 kg.
7. No natural gas service in the target building.
8. In unmitigated assessments, no credit is generally taken for a beam cutoff function to stop the beam from continuing to transfer energy to the mercury system. An exception is the analyses of seismic events that rely upon the 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 ~ 300-m-long accelerator to provide the proton beam.[43,44]

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 to allow for instrument uncertainty and operational variability. For example, the 125ºC, initial hot leg temperature is well above the 90ºC nominal hot leg temperature expected at 2 MW proton beam power. These assumed parameter values were used in the quantitative accident analyses.

Features of the facility configuration and operating conditions credited in the analyses are protected against function-altering modification through the work control process.

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 both those specific events that were carried forward for both control selection and those that did not require credited controls. This is because even “unmitigated” assessments assume certain basic control functions (e.g., if there is no upper bound on the quantity of material that can be present in the facility at any one time, then there is, in principle, no upper bound on the consequences of certain postulated scenarios). Thus, a control on the inventory, or material at risk (MAR), is always required. This 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 based on 5000 h operation per year for 40 y at the maximum beam power of 2 MW. An uncertainty factor of 1.575 is applied to the predicted activity levels to account for uncertainty in the predicted values.[23]

In addition to the facility-related assumptions discussed above, the following physical phenomena assumptions are employed for all analyses:

1. Radioactive decay during plume transport has been ignored for simplicity.
2. The unmitigated receptor exposure is assumed to end in eight hours.[1]
3. Passive cooling is adequate to remove decay heat from stagnant mercury in the primary loop after the proton beam is shut off.[45]
4. All non-condensable gases are assumed to escape.

Additional specific event assumptions used are described below.

4.4.1.2 Source Term

The basic methodology used for quantitatively determining 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.[46]

The source term (ST) is the quantity of hazardous material that is released airborne in respirable form. It is determined using the following equations:

For a short-duration (or instantaneous) release:

$$\text{ST [kg or Ci]} = (\text{MAR [kg or Ci]})\,(\text{DR})\,(\text{ARF})\,(\text{RF})\,(\text{LPF}) \qquad \text{(Equation 1)}$$

For a constant release rate:

$$\text{ST [kg or Ci]} = (\text{MAR [kg or Ci]})\,(\text{DR})\,(\text{ARR} \times t)\,(\text{RF})\,(\text{LPF}) \qquad \text{(Equation 2)}$$

where:

MAR = Material at Risk—the radioactive material (Ci) or hazardous material (kg of mercury) available to be acted upon by a given physical stress.

DR = Damage Ratio—the fraction of MAR actually impacted by accident-generated conditions (pure number).

ARF = Airborne Release Fraction—the fraction of MAR impacted by accident conditions that is suspended in air as an aerosol due to the physical stresses from a given accident and thus available for airborne transport (unitless quantity).

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 time^{-1}, normally h^{-1} 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 quantity).

LPF = Leak Path Factor—the fraction of radionuclides in air that is not removed through confinement, deposition, or filtration mechanisms during transport to the exterior of the facility (unitless quantity).

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 elevated temperature 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*.[1]

Several essential precursor conceptual engineering analysis steps are necessary to select the parameters used in the source term equations. These steps include: (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 or consequential effects and events that can be triggered by the initiating event, so they can be included in the source term analysis.

The MAR consists of the process mercury that includes the radionuclide inventory generated by the spallation process. For hazardous material analysis, the MAR is expressed in terms of mercury mass (units of kg) 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 builds up in the mercury is very small relative to the amount of mercury present. Therefore, mitigating the chemical toxicity effects of the mercury provides adequate protection against the other toxic spallation products. The MAR for radiological impact analysis consists of an extensive table of radionuclide inventories[47] calculated to be present in the process mercury and activated cooling water. The source term analysis determines releases of mercury as both a vapor and an aerosol and tracks these releases separately since the radiological composition of each release form are different.

For some scenarios, the analysis conservatively assumes that the entire radioactive inventory can be subjected to the accident stresses. Therefore, a DR value of 1.0 is specified for these events. 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 in Reference 46 and results of the precursor engineering analysis described above.

In general, the primary methods of preventing respirable material that has become airborne within a facility from escaping are: (1) to remove the material from air and other gases exiting the facility (such as by filtration for particles and condensation for vapor) and/or (2) to prevent the atmosphere in the building from exiting (such as by use of confinement structures without forced exhaust). Since the analysis does not credit such systems, a LPF of 1.0 is used.

Equations 1 and 2 can be simplified by the introduction of the Respirable Release Fraction (RRF) defined as the ratio of (ST)/(MAR). Equations 1 and 2 can then be expressed as:

$$ST_i = (MAR)_i \times (RRF)_i \qquad \text{(Equation 3)}$$

where the subscript “i” has been introduced to denote a particular radionuclide 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 Reference 34 and are based on analyses from References 41 and 42. Unmitigated RRFs for the various events are presented in Table 4.4.1.2-2. Note that for the hydrogen explosion (no fire) event, source terms are given separately for the detonation case and deflagration case

4.4.1.2.1 Material at Risk

The total mercury (Hg) inventory of 18,000 kg (from Table 1 of Reference 23) and the radionuclide inventory contained within represent the MAR. This value represents the minimum mass of mercury in the mercury loop. It represents 95% of the nominal mass of mercury in the system (i.e., 18,950 kg from Table 1 of Reference 23). With the radionuclide inventory determined in Reference 47 taken to reside within the mercury, use of the minimum mercury mass results in a more concentrated radionuclide inventory (i.e., more activity per unit mass of Hg). The conservatism of this approach is apparent when a fixed amount of Hg is exposed to the accident stress (i.e., DR less than 1.0) or when the analysis determines only a fixed amount 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 40 y of operations (5000 h/y) at 2 MW beam power. An uncertainty factor of 1.575 is applied to these values to represent the MAR to account for uncertainty in the predicted activity levels.

4.4.1.2.2 Respirable Release Fractions

Inventory radionuclides are grouped according to volatility characteristics. The radionuclides released to the atmosphere during a postulated accident are taken to consist of three main components consisting of:

- Group I—volatile radioactive products;
- Group II—radioactive mercury vapor; and
- 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 in Reference 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 entirety during an accident (i.e., RRF equal to 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 the arsenic oxide (As_2O_3) isotopes. It has lower volatility than mercury. The same RRF is conservatively applied to As_2O_3 isotopes as is applied to the Group II and Group III mercury isotopes.
- Group IA-4 (conditionally-formed volatile oxides) consists of oxides of osmium, ruthenium, technetium, rhenium isotopes that form 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 to be further heated so that the potentially volatile oxides can begin forming. If this condition is met, the same RRF is applied to these

radionuclides as applied to mercury isotopes. If this condition is not met, the same RRF is applied to these radionuclides as applied to the nonvolatile spallation products (i.e., the Group III).

- Group IB (gaseous nuclides in cooling water) consists of gaseous tritium and nitrogen and oxygen isotopes that are present in the activated cooling water. If the accident scenario involves a breach of radioactive cooling water loops, the entire inventory is assumed to be released (RRF equal to 1). Otherwise, the RRF is assured 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 due to accident conditions that promote evaporation or boiling of the liquid mercury. Mercury boiling can occur due to 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.[41, 42]

Group III

- Group III consists of mercury isotopes plus the nonvolatile spallation products contained within the mercury. This group represents mercury released in aerosol form due 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.[41, 42]

Table 4.4.1.2.2-1 summarizes the RRF specifications for the various inventory groups. The accident analyses documented in References 41 and 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.

Table 4.4.1.2.2-1 Summary of Respirable Release Fraction Specifications

Volatility Group	Vapor RRF	Aerosol RRF	Total RRF
IA-1	1.0	0	$RRF_{IA-1} = 1.0$
IA-2	RRF_{II}	RRF_{III}	$RRF_{IA-2} = RRF_{II} + RRF_{III}$
IA-3	RRF_{II}	RRF_{III}	$RRF_{IA-3} = RRF_{II} + RRF_{III}$
IA-4	= RRF_{II} if Hg boiled dry = 0 if Hg not boiled dry	RF_{III}	$RRF_{IA-4} = (RRF_{II}$ or $0) + RRF_{III}$
II	RRF_{II}	NA	RRF_{II} {from analysis[41,42]}
III	NA	RRF_{III}	RRF_{III} {from analysis[41,42]}
IB	0 or 1.0	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 Equation 3. Recall that the subscript "i" in Equation 3 denotes a particular radionuclide and that each radionuclide belongs to a volatility group as discussed above. 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 Hg isotopes released in vapor form (the aerosol RRF component for Group II is thus not applicable by definition). Group III includes Hg 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 125ºC for event scenarios that do not involve a temperature excursion. This 125ºC conservatively represents the hot leg temperature of the mercury process system. The vapor pressure is only about 1.3×10^{-3} atm at 125^{o}C and is 1 atm of 357^{o}C.

Because of the vapor pressure, any accidental release of mercury from the target module or associated mercury loop piping will result in the formation of airborne (and respirable) mercury vapor. Mercury vapor formation is assumed to continue until the accident is stabilized. 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 be formed during certain accidents. Droplets can be formed from a pressurized spray release and by forces exerted on the fluid during events where 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 as it mixes with air. Droplets formed by condensation would have the same radioactive inventory as mercury vapor (i.e., not contain nonvolatile spallation products). Since 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 might be formed by condensation, are modeled to be carried out of the facility on air currents and transported by wind without removal by deposition mechanisms. It should be noted that this is an unrealistic, but conservative treatment of the hazardous material release in droplet form.

ARF and RF values from Reference 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 from Reference 46 have been developed for aqueous solutions and slurries containing radioactive uranium and plutonium. Additional evaluations have been performed to identify factors to adjust the airborne respirable aerosol values from Reference 46 based on aqueous solutions to correspond to mercury properties and SNS accident conditions.

For several types of postulated events, the accident analysis employs fairly 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 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 over 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, based on information found in standard textbooks such as *Heat and Mass Transfer*,[49] is described below.

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, 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:

$$\dot{m} = h\ A\ (M\ \Delta p\ /\ (R_u\ T)) \qquad \text{(Equation 4)}$$

where (units listed for background information only):

$\dot{m}$ = 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]
R_u = universal gas constant [0.08314 bar-m^3/kg-mole-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 there is no net mass transfer from the liquid phase to the vapor phase.

The gas-phase partial pressure is taken to be zero for simplicity, 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:

$$h = \frac{D}{d}(0.037\mathrm{Re}^{0.8})\mathrm{Sc}^{1/3} \qquad \text{for Re} \geq 5 \times 10^5 \qquad \text{(Equation 5)}$$

where:

d = pool diameter, [m]
D = diffusion coefficient of the volatile compound in air, [m^2/s]
Re = Reynolds number, and
Sc = Schmidt number.

The Reynolds and Schmidt numbers are defined as:

$$\mathrm{Re} = \frac{du\rho_a}{\mu_a} \qquad \text{(Equation 6)}$$

$$\mathrm{Sc} = \frac{\mu_a}{D\rho_a} \qquad \text{(Equation 7)}$$

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 covers the maximum possible fall from a leak at any piping location. For scenarios involving a release from a pressurized pipe, a geyser effect is postulated that increases the effective release height. The basic spill scenario is intended to cover 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 where mercury evaporation is significant include the following:

1. The cooling of mercury spills is assumed to occur only by evaporation and forced convection from the airflow across the upper surface of the spilled material. Conduction to the floor of the facility is neglected.
2. Air velocity across the spill is assumed to be 2.5 m/sec. This value is greater than typical 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 application of mechanical or kinetic energy stresses on the liquid mercury that promote the formation of respirable-size 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. In addition, 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-size droplets. The RRF_{III} value to represent the droplet formation from these stresses is derived from the ARF, ARR, and RF values summarized in Reference 46.

RRFs for Mercury Vaporization during Fire Accidents

Three fire scenarios are considered with a fire starting in one of three locations: (1) target service bay; (2) target building outside the target service bay (referred to as Medium Fire); and (3) external to the 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 primary purpose of the shielding is to extend 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).[42] The analysis of Reference 42 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, it is possible that a fire could vaporize minor quantities of residual mercury that could accumulate in out-of-the-way places (the analysis assumes 19.4 kg of mercury immediately adjacent to the fire to demonstrate the potential for mercury vaporization due to miscellaneous mercury accumulation outside the shielding panels).

During the commissioning of the target loop and early operations before mercury becomes significantly radioactive to warrant protective shielding, part of the steel shielding may be left temporarily uninstalled to support loop integrity checks. For this reason, 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 with mercury spilling either as a result of the impact of falling structural components or from the fire itself. In the analyses of these 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 Reference 50).

The mitigated 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 are assessed not to 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 allow the fire to be close to 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 external to the target service bay), the bounding fire is one that propagates to the target service bay. Another scenario considered involves the fire postulated to occur in, or propagate to, the basement room housing the charcoal adsorbers and conceivably vaporizes radioactive mercury residing on the sulfur-impregnated charcoal. To bound releases from this mercury, 19.4 kg of such 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. (It should be noted that measured accumulation on the adsorbers after five years of operations indicates that a maximum of only 7.6 kg mercury would accumulate on all adsorbers over the life of the facility.[59]) The mercury on the filters would have been transported there as a vapor that formed under low temperature conditions in the target service bay (prior to 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 where a hydrogen leak (from the cryogenic moderator system) 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 ignites. Both detonations and deflagrations are considered to determine which type of explosion produces the bounding release.

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.[46] 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 leaving 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., $RRF_{III} = RRF_{II}/10$).[42,50]

The energy output of a hydrogen explosion in terms of the equivalent mass of TNT (M_{TNT}) is given by:

$$M_{TNT} = \frac{M_{H_2} \cdot E}{E_{TNT}}, \qquad \text{(Equation 8)}$$

where

M_{H_2} = mass of liquid hydrogen;
E = heat of combustion of hydrogen (1.2E5 kJ/kg); and
E_{TNT} = specific energy of TNT (4520 kJ/kg).

The hydrogen assumed to be involved in the explosion is the mass of liquid hydrogen in the moderator systems, assumed to be 7 kg[23] 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.[59]

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, which allows 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 to below the lower flammability limit 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 prior to the explosions. This analytical approach ensures that the analysis bounds a situation where the force of explosion can both damage the mercury-containing process vessels and cause vaporization or aerosolization of mercury released from the damaged vessel.

In the unmitigated assessments of both 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 is in contact with 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 is in contact with the pooled mercury there.

For deflagrations, the fraction of the radiant energy deposited in the mercury pool is determined from geometric considerations. In the core vessel, the exposed mercury is assumed to be pooled at the bottom of the core vessel in the ullage volume. Since the ullage volume is about 2.5 m^3 and the total core vessel free volume is about 7.5 m^3, only 1/3 of hydrogen combusting inside the core vessel would be able to vaporize the exposed mercury.[42] 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 as a result of the hydrogen deflagration above it 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. Inherent in this recipe is the assumption that the deflagration is very rapid such that only the top surface of the puddle is heated. Thus 100% of the thermal energy is assumed to be used for the creation of Hg 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 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. Failure of the target module and water-cooled shroud allows mercury to depressurize into the core vessel. Flashing of mercury occurs 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 comes in contact with this hot mercury.

The formula used to calculate the flash fraction (F_f) of a mass of pressurized mercury is for an adiabatic expansion process in which the energy to vaporize mercury is supplied by cooling the mercury liquid.

$$F_f = \frac{C_p \cdot (T_o - T_b)}{H_{fg}}, \tag{Equation 9}$$

where

C_p = specific heat of liquid mercury (135.6 J/kg/K);
T_o = initial saturation temperature of pressurized mercury in target module;
T_b = boiling point of mercury at atmospheric pressure (357°C); and
H_{fg} = heat of vaporization (295 J/g).

The F_f value from the above equation 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 surrounding liquid mercury (flash atomization). The contribution to the RRF_{III} term is based on experimental data summarized in Reference 46 for flashing sprays modified as explained in Reference 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 Reference 56 this entrainment is modeled assuming conservatively that steam bubbles through mercury prior to escaping from the core vessel.

RRFs for Loss of Mercury Flow Accidents

Analysis is performed for scenarios in which mercury flow completely stops, as well as scenarios in which the mercury flow drops to a very low level. These accidents involve similar types of failure of the target module due to boiling phenomena as the loss of heat sink accidents. As a result, the same methodology is used to calculate the mercury vapor and aerosol releases from flashing, flash atomization, steam-flow entrainment, and pool evaporation. Less mercury, however, is released in comparison with the loss of heat sink accidents. A greater percentage of the mercury is heated to boiling or near boiling conditions with the loss of heat sink accidents since 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 such that 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., if 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. Recall that 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.[41]

Summary of RRFs

Table 4.4.1.2.2-2 presents a summary of RRFs calculated for the pre-construction 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 due to the receptor being immersed in a semi-infinite cloud of the radionuclide at the plume ground level concentration.

The committed effective dose equivalent (CEDE) from inhalation is calculated using the following equation:

$$CEDE = \sum_i ST_i \cdot DCF_i \cdot \chi / Q \cdot BR \qquad \text{(Equation 10)}$$

where:

CEDE [rem] = 50-y committed effective dose equivalent from inhalation
ST_i [Ci] = source term for airborne radiological release for radionuclide *i*
DCF_i [rem/Ci] = inhalation dose conversion factor for radionuclide *i*
χ/Q [s/m^3] = atmospheric dispersion factor
BR [m^3/s] = breathing rate

Source Term (ST) determination was discussed in Section 4.4.1.2 above. At a given downwind distance, the ratio of the time-integrated centerline concentration (units of kg-s/m^{3}or Ci-s/m^3) to the source term release quantity (kg) or activity (Ci) defines the parameter χ/Q (units of s/m^3). This parameter is a measure of the dilution of the plume during atmospheric transport. The calculations that were performed 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 only a small fraction (0.75%) of the internal dose as documented in previous SNS accident consequence studies[50]. Therefore the Total Effective Dose Equivalent is calculated as follows:

$$TEDE = CEDE \times 1.075 \qquad \text{(Equation 11)}$$

Table 4.4.1.2.2-2 Summary of Unmitigated Respirable Release Fractions for Accident Scenarios

Event	Respirable Release Fraction For Volatility Group (groups are defined in Section 4.4.1.2.2)						
	IA-1	**IA-2**	**IA-3**	**IA-4**	**IB**	**II**	**III**
1. Target Service Bay Fire — with shields/without shields	1.0	1.2E–03	1.2E–03	1.2E–03	0	1.1E–03	1.1E–04
	1.0	2.7E–02	2.7E–02	2.7E–02	0	2.5E–02	2.5E–03
2a. Medium Fire, General	See Target Service Bay Fire Results Above						
2b. Medium Fire (in Charcoal Adsorber Room)	0	0	0	0	0	1.1E–03	0
3. Full-Facility Fire	1.0	3.4E–02	3.4E–02	3.4E–02	1.0	4.0E–02	3.1E–03
4. H_2 Explosion (No Fire) Detonation/Deflagration	1.0	1.0E–02	1.0E–02	1.1E–02	1.0	7.0E–04	1.0E–02
	1.0	2.5E–02	2.5E–02	2.5E–02	1.0	2.3E–02	2.3E–03
5. H_2 Explosion w/ Fire	Bounded by Seismic Event w/ H_2 Explosion and Fire						
6. Loss of Confinement (Target Service Bay)	1.0	5.4E–04	5.4E–04	3.6E–05	0	5.0E–04	3.6E–05
7. Loss of Confinement (Core Vessel — He Inerting)	1.0	7.4E–04	7.4E–04	3.6E–05	1.0	7.0E–04	3.6E–05
8. Loss of Confinement (Core Vessel — Vacuum Operation)	1.0	3.5E–03	3.5E–03	3.6E–05	0	3.5E–03	3.6E–05
9. Partial Loss of Hg Flow	1.0	3.6E–03	3.6E–03	1.1E–03	1.0	2.5E–03	1.1E–03
10. Complete Loss of Hg Flow	1.0	1.3E–03	1.3E–03	1.1E–03	1.0	1.1E–03	1.7E–04
11. Loss of Heat Sink	1.0	4.9E–03	4.9E–03	2.2E–03	1.0	2.7E–03	2.2E–03
12. Target Service Bay Crane Load Drop	1.0	5.6E–04	5.6E–04	6.3E–05	1.0	5.0E–04	6.3E–05
13. High Bay Crane Load Drop onto Target Service Bay	1.0	8.7E–04	8.7E–04	3.7E–04	1.0	5.0E–04	3.7E–04
14. High Bay Crane Load Drop onto Core Vessel (No Explosion)	1.0	1.1E–03	1.1E–03	3.7E–04	1.0	7.0E–04	3.7E–04
15. High Bay Crane Load Drop w/ H_2 Explosion	Bounded by Seismic Event w/ H_2 Explosion and Fire						
16. External Crane Load Drop	1.0	6.8E–03	6.8E–03	6.3E–03	1.0	5.0E–04	6.3E–03
17. Seismic w/ H_2 Explosion and Fire	1.0	4.5E–02	4.5E–02	4.5E–02	1.0	3.2E–02	1.3E–02
18. Seismic w/ Fire (No Explosion)	Bounded by Seismic Event w/ H_2 Explosion and Fire						
19. Seismic w/ H_2 Explosion (No Fire)	Bounded by Seismic Event w/ H_2 Explosion and Fire						

For toxicological consequence analysis, 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 [Hg] in the plume at a given downwind location for an accidental release of mercury over an assumed duration.

$$[\mathrm{Hg}] = (\mathrm{ST}_{\mathrm{Hg}} \times \chi/\mathrm{Q}) / \Delta t \qquad \text{(Equation 12)}$$

where (units listed for background information only):

$[\mathrm{Hg}]\ (\mathrm{mg/m^3})$ = centerline concentration of mercury in the plume

$\Delta t\ [\mathrm{s}]$ = assumed duration over which the Hg release occurs

$\mathrm{ST}_{\mathrm{Hg}}\ [\mathrm{mg}] = \mathrm{MAR}_{\mathrm{Hg}}\ [\mathrm{kg}] \times 10^6\ [\mathrm{mg/kg}] \times (\mathrm{RRF}_{\mathrm{II}} + \mathrm{RRF}_{\mathrm{III}})$ (Equation 13)

where:

$\mathrm{MAR}_{\mathrm{Hg}}$ = 18,000 kg

4.4.1.3.1 Meteorological Dispersion

The Environmental Protection Agency recommended Industrial Source Complex Short-Term (ISCST3) air dispersion model[51] was used to estimate χ/Q values for the onsite worker at 100-m and the maximally-exposed offsite individual (MOI). ISCST3 uses the steady-state Gaussian plume algorithm. Key elements of the χ/Q calculations (References 52 and 53) are summarized below.

- Per DOE guidance,[2] the statistical treatment of calculated χ/Q values as described in regulatory position 3 of USNRC 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 taking into account variations in distances to the site boundary as a function of direction.
- Meteorological data recorded for each hour over a five-year period from the Oak Ridge National Laboratory 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). Six years of data (1996–2001) were analyzed initially. Because the year 2000 contained the largest number of missing or invalid hours, that year was eliminated from the analysis. The resulting dataset included a total of 40,939 hours of valid data.
- A large number of receptors were carried in the calculation to allow positive identification of the MOI receptor. These include receptors at locations along, or outside of, the reservation boundary and on Bethel Valley Road. A radial receptor grid was created centered on the SNS facility. Terrain elevations, obtained from the U.S. Geological Survey DEM (digital elevation model) 10-m database, were included for the source and receptors (modeled locations). It is important to note that 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 with the direction toward which the wind was blowing during that hour. The receptors extend outward from the Oak Ridge Reservation (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. Altogether 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 one-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 Reference 52). For the worker at 100 m, the 95th-percentile χ/Q value is 7.4×10^{-4} s/m^3.[53]
- Building wake effects were not included. Ignoring building wake effects is conservative since 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 due to condensation deposition leads to conservatively higher downwind concentrations of mercury.

4.4.1.3.2 Inhalation Dose Conversion Factors

Of the 768 radionuclides identified for the SNS inventory, the inhalation DCFs for 500 radionuclides are taken from ICRP Publication 68.[54] 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 in Reference 55 to estimate the inhalation DCFs for radionuclides not addressed by ICRP publications. In addition, even though ICRP publications document inhalation DCFs for mercury vapor, revised DCFs were developed in Reference 55 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 offsite consequences. Bounding consequences are presented for the “unmitigated” and for the “as-constructed” accident scenarios as described in Section 4.4.

In all cases, the credited controls identified as providing protection for the workers also provide protection for the public. The list of accidents that potentially impact the offsite public were identified in the accident selection process (Section 4.3.16).

Details of the unmitigated radiological and toxicological consequences analysis are presented in Reference 34. Details of the bounding consequence analysis for the as-constructed facility are presented in Reference 59. 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 H_2 explosions, the higher of the two consequence values between the detonation case and deflagration case are given. The analysis of Reference 34 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).

As will be shown, none of the offsite radiological consequences associated with the unmitigated analysis exceed levels that would require credited controls; however, some of the events had associated offsite 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. As will be shown, no additional credited controls, beyond those already identified in Section 4.3 for worker protection, are required to mitigate impacts to the public. Offsite consequences associated with the "as-constructed" analyses were all below crediting thresholds.

Accident scenarios with unmitigated radiological and toxicological consequences well below the offsite 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 are found or referenced in References 34, 41 and 59.

4.4.2.1 Seismic Event Including Follow-on Explosion and Follow-On Fire

This section addresses the natural phenomena (seismic) event including follow-on explosion and follow-on fire. The results of this analysis served 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 due to 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 as a result 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 since 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, Performance Category 1 [(PC-1)] create a disturbance that would upset the crucial alignment necessary for the ~ 300-m-long accelerator to provide the proton beam and, thus, automatically shut down the beam).[43,44]

The unmitigated analysis considers the possibility of both 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.

Scenario for Seismic Event with Explosion and Fire

The unmitigated scenario for this event is as follows:

A. 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.
B. A seismic event takes place, causing damage that leads to breaks in: (1) the hydrogen–filled moderator vessels (and/or associated piping); (2) the water filled moderator vessel (and/or associated piping of cooling loop 3); (3) the shroud (and/or associated piping of cooling loop 2); (4) the target module (and or associated piping/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/air mixture in this region); and (3) leakage of water (coolant).
C. Accelerator physics shut down the proton beam in response to the seismic disturbance, stopping the transfer of energy from the beam to the mercury.
D. Airborne droplets of mercury (and dissolved spallation products) are formed due to splashing and (possibly) pressurized release.
E. Mercury vapor is formed due to evaporation of spilled hot mercury.
F. Mercury droplets are formed due to metal/water reactions as hot mercury falls into the colder water.
G. Airborne water droplets (containing spallation activation products) are formed from cooling water spilling from coolant piping.
H. An ignition source causes the flammable hydrogen-air mixture to explode (deflagrate or detonate).
I. 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 target service bay.
J. Hydrogen not consumed in the initial explosion migrates into the target service bay via the damaged seals.
K. The hydrogen mixes with the air inside the target service bay to form a second flammable hydrogen-air mixture.
L. An ignition source causes the flammable hydrogen-air mixture to explode (deflagrate or detonate).

M. The explosion in the target 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.

N. 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 mechanism contribute to the source term: (1) evaporation (boiling) of some liquid mercury at the upper surface of the liquid due to heat from the explosion over the gas/liquid interface (this 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 due to liquid surface motion caused by blast effects.

O. A fire starts in the target building (or spreads into the target building from some source external to the building).

P. The heat from the fire causes the temperature of the mercury to increase. 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.

Q. The heat from the fire causes failures of the process equipment due 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).

R. Mercury evaporates due to the heat of the fire until combustibles are consumed.

S. 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 4.4.2.1-1.

Table 4.4.2.1-1 Summary of Respirable Release Fractions for Seismic Event Including Follow-On Explosion and Follow-On Fire

Volatility Group	Vapor RRF	Aerosol RRF	Total RRF
IA-1, highly volatile	1.0	0	1.0
IA-2, moderately volatile	3.2E–02	1.3E–02	4.5E–02
IA-3, moderately volatile oxides	3.2E–02	1.3E–02	4.5 E–02
IA-4, conditionally formed volatile oxides	3.2E–02	1.3E–02	4.5E–02
II, Hg vapor	3.2E–02	n/a	3.2E–02
III, Hg droplets with nonvolatile solids	n/a	1.3E–02	1.3E–02
IB, activation products in cooling water	1.0	0	1.0

Note: The RRF_{II} and RRF_{III} values are from the analysis of Reference 34, which combines the contributions from the explosion and fire release mechanisms determined in Reference 42 with the contributions from the mercury spill release mechanisms determined in Reference 41. The other RRF specifications are derived from the RRF_{II} and RRF_{III} values using the scheme outlined in Table 4.4.1.2.2-1 of Section 4.4.1.2.2. The accident analysis of Reference 42 shows the bounding consequences occur with the detonation instead of the deflagration for the follow-on explosion. Since the mercury may boil dry in this scenario, the vapor component of $RRF_{IA\text{-}4}$ is set to the RRF_{II} value. This scenario can involve a breach of the cooling water system, so RRF_{IB} is set equal to 1.0.

The 3.2E–02 RRF_{II} value corresponds to approximately 569 kg of Hg vapor release that is the result of the following components:

- direct radiative heat transfer from the fire (556 kg), and
- 8-h evaporation (13 kg).

The RRF_{III} value of 1.3 E–02, equivalent to approximately 234 kg of Hg, 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 (177 kg), and
- aerosolization from agitation of the pool surface from bubbling phenomena during the fire (56 kg).

The total respirable mercury release fraction is calculated using the sum of RRF_{II} and RRF_{III} (Table 4.4.1.2.2-2) equal to 4.5E–02 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 3.9 rem with an associated toxicological consequence at 4.9 times 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 to be the Maximum Credible Incident (MCI) for the unmitigated analysis.

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 that 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 target service bay, through combustible material control programs and two-hour equivalent fire barrier enclosing the target service bay and core vessel.

The as-constructed analysis accounts for the following passive design features: (1) the presence of radiation shielding covering piping and other process vessels that are required for normal operation, (2) target service bay confinement of mercury features: (i) the sloped floor of the target service bay; (ii) drainage channels in 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 and (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 offsite consequences[59] associated with the as-constructed facility are bounded at 0.11 Rem with an associated toxicological consequence at 0.18 times ERPG-2.

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 serve to 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 through seven sub-channels at the bottom into an annular passage at the front of the target module to cool the inner walls of the target window (portion of the vessel structure within the proton beam). The outer walls of the target window are cooled by water, resulting in its designation as the “water cooled shroud.” The mercury used to cool the inner walls of the target window merges with the main mercury flow inside the target module for the return to the cooling loop. The heat is removed from the mercury by cooling loop 1 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 water flow/cooling 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 density. 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, along with entrained droplets, is released to the air, and mercury liquid and water spill into the core vessel.

Scenario for Loss Heat Sink

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 up until the mercury reaches boiling conditions. After several circuits of the mercury process system, the mercury in the loop approaches the boiling point of mercury. At this elevated temperature, the pump in the mercury process system may cavitate, which reduces its effectiveness in causing the mercury to circulate. This can increase 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.
- Flashing of mercury occurs during the depressurization resulting in radioactive mercury vapor and aerosol formation. Much of this mercury vapors 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, after this point, the proton beam would pass through the emptied target module and dissipate its energy into the massive shielding steel of the target cart. This 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 the Table 4.4.2.2-1, below. The 2.7E–03 $\mathrm{RRF}_{\mathrm{II}}$ value corresponds to approximately 49 kg of Hg vapor release that is the result of the following components:

- flashing (36 kg) and
- 8-h evaporation (13 kg).

The $\mathrm{RRF}_{\mathrm{III}}$ value of 2.2E–03, equivalent to approximately 40 kg of Hg, 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), and

- steam flow entrainment (1.5 kg).

Table 4.4.2.2-1 Summary of Respirable Release Fractions for Loss of Heat Sink Accident

Volatility Group	Vapor RRF	Aerosol RRF	Total RRF
IA-1, highly volatile	1.0	0	1.0
IA-2, moderately volatile	2.7E–03	2.2E–03	4.9E–03
IA-3, moderately volatile oxides	2.7E–03	2.2E–03	4.9E–03
IA-4, conditionally-formed volatile oxides	0	2.2E–03	2.2E–03
II, Hg vapor	2.7E–03	n/a	2.7E–03
III, Hg droplets with nonvolatile solids	n/a	2.2E–03	2.2E–03
IB, activation products in cooling water	1.0	0	1.0

Note: The RRF_{II} and RRF_{III} values are from the analysis of Reference 34, which combines the contributions from the flashing and steam-entrainment mechanisms determined in Reference 42 with the contributions from the mercury spill release mechanisms determined in Reference 41. The other RRF specifications are derived from the RRF_{II} and RRF_{III} values using the scheme outlined in Table 4.4.1.2.2-1 of Section 4.4.1.2.2. Since the mercury does not boil dry in this scenario, the vapor component of RRF_{IA-4} is set to zero This scenario can involve a breach of the cooling water system, so RRF_{IB} is set equal to 1.0.

The 2.7E–03 RRF_{II} value corresponds to approximately 49 kg of Hg vapor release that is the result of the following components:

- flashing (36 kg) and
- 8-h evaporation (13 kg).

The RRF_{III} value of 2.2E–03, equivalent to approximately 40 kg of Hg, 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), and
- steam flow entrainment (1.5 kg).

The total respirable mercury release fraction is calculated using the sum of RRF_{II} and RRF_{III} equal to 4.9E–3.

Consequence of Loss of Heat Sink

The unmitigated radiological consequence to the public is calculated to be 0.52 rem for this event. The unmitigated toxicological consequence to the public is calculated to be a factor of ~2 below the Credited Control Criterion for ERPG-2 (2 mg/m^3 for 1 hour). Unmitigated consequences were well under thresholds requiring credited controls.

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 cutoff upon detection of a high mercury temperature in the mercury cold leg before the mercury temperature increases to a value where it could cause boiling. 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 analysis.

Required Controls for Loss of Heat Sink

No CECs or CACs are required for the protection of 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 Number CM2-1a. CM events are described in Section 4.3.2.

During the pre-construction design process, the analysis assumed non-mechanistically that spontaneous failure of the cryogenic moderator system (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 lead to the passive seismically qualified design features that make up the robust hydrogen barrier which includes a separate seismically qualified vacuum barrier (see Section 5.2).

The analysis for the unmitigated scenario focuses on a postulated situation where a hydrogen leak (from the cryogenic moderator vessels or associated piping) mixes with air to form a flammable hydrogen/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. There are also evaporative mercury releases until the event is stabilized. Both detonations and deflagrations are considered. Detonation is less likely than deflagration because it can take place 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/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 target service bay, where a second explosion takes place.

The analysis postulates that mercury has spilled into the bottom of the core vessel or target service bay at the time of each explosion. This analytical approach ensures that the analysis bounds a situation where the force of explosion can both 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:

A. The system is running normally, with the mercury in the mercury process system at the upper normal operating limits for pressure, temperature, and inventory.
B. A catastrophic hydrogen leak develops in a cryogenic hydrogen moderator system inside the core vessel.
C. The hydrogen mixes with the air to fill the open space inside the core vessel to form a flammable hydrogen-air mixture. [Note: 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 atmosphere.]
D. An ignition source causes the flammable hydrogen-air mixture to explode (deflagrate or detonate).
E. The explosion in the core vessel creates a blast wave that: (1) damages the target module (causing liquid mercury to spill); (2) provides stresses to the spilled liquid; and (3) damages seals separating the core vessel from the target service bay.
F. Hydrogen not consumed in the initial explosion migrates into the target service bay via the damaged seals. No credit was taken for venting through the core vessel rupture disk/vent line.
G. The hydrogen mixes with the air inside the target service bay to form a second flammable hydrogen-air mixture.
H. An ignition source causes the flammable hydrogen-air mixture to explode (deflagrate or detonate).
I. The explosion in the target 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.
J. 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 mechanism contribute to the source term: (1) evaporation (boiling) of some liquid mercury at the upper surface of the liquid due to heat from the explosion over the gas/liquid interface (this 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 due to liquid surface motion caused by blast effects. These mechanisms are in addition to releases (similar to 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.

K. A fire, which is initiated by one or both of the explosions, starts in the target building.

L. The heat from the fire causes the temperature of the mercury to increase. 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.

M. The heat from the fire causes failures of the process equipment due to reduced piping integrity at the high temperatures or to failures of seals, gaskets, and/or o-rings at high temperatures.

N. Mercury evaporates due to the heat of the fire until combustibles are consumed.

O. 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 that is presented above (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.

As explained above, this scenario provided input that lead to the credited robust seismically qualified design of the double walled hydrogen barrier. As built, the passive design provides credited protection to ensure 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. Since the explosion is the initiator for the follow-on fire, preventing the explosion also prevents the fire. With the entire scenario prevented by the passive credited design, there are no consequences associated with the as-constructed analysis.

Although spontaneous failure of the hydrogen barriers of the as-constructed system is considered unrealistic, other scenarios do consider impacts 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/vacuum barrier design) as described in Section 4.3.2 for this event also serve to 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 Number CM2-1b. CM events are described in Section 4.3.2. The analysis for the unmitigated scenario is the same as the Hydrogen Explosion with Fire event described above except that there is no follow-on fire.

Scenario for Hydrogen Explosion

The unmitigated scenario for this event is the same as that documented above, except there is no follow-on fire.

Unmitigated Source Term for Hydrogen Explosion

The total respirable mercury release is calculated using the sum of RRF_{II} and RRF_{III} as shown in Table 4.4.1.2.2-2 (Section 4.4.1.2.2) for this event (Note that a higher total respirable mercury release occurs with the deflagration case in comparison with the detonation case.). This sum is equal to 2.5E–02.

Consequence of Hydrogen Explosion

The completely unmitigated bounding toxicological consequence to the public calculated for this event assuming a spontaneous leak of hydrogen into a large volume assumed to explode over a large puddle of mercury is exceeds ERPG-2 by a factor of 2.8. 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 1.4 rem.

As explained above, this scenario provided input that lead to the credited robust seismically qualified design of the double walled hydrogen/vacuum barrier. As built, the passive design provides credited protection to ensure spontaneous failure of the boundaries is beyond credible. Therefore, the as-constructed design of the system prevents hydrogen from escaping from the cryogenic moderator system into the core vessel. With the entire scenario prevented by the passive credited design, there are no credible toxicological or radiological consequences from this event.

Although spontaneous failure of the hydrogen barriers of the as built system is considered unrealistic, other scenarios do consider impacts 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/vacuum barrier design) as described in Section 4.3.2 for this event also serve to 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 HE Event Numbers 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 by definition range from slight to a near-total loss of mercury flow. If the loss reduces flow from the normal range (in the neighborhood of 380 gpm for 2 MW beam power) to below 31 gpm, then bulk boiling could occur, as addressed below. Events TS3-22 through 3-25 could credibly reduce total loop flow to below 31 gpm. Flow blockage events TS3-26 and TS3-27 are not addressed in the analysis described below because occurrence of credible blockage would reduce total loop flow only to about 100 gpm[59]. Although a partial loss of flow event involves a less severe flow reduction than a complete loss-of-flow event, as discussed in Reference 42, this does not necessarily mean that the consequences are less severe than a complete loss of flow for an unmitigated scenario. The reason for this is 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 (such as 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)—TS3-23, TS3-24, and TS3-25. It is also possible to have a localized or partial flow blockage, such as from a foreign object in the piping or a system component that becomes loose within the piping system—TS3-26 and TS3-27. In most cases, flow blockage accidents would involve blockage of one flow path, while 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. The reason for this temperature increase is that 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 is reduced (relative to normal conditions). Therefore, each unit of mercury mass absorbs proportionately more heat, which results in an increased mercury temperature in the target module and in the hot leg of the mercury system. This is somewhat offset by the reduction in cold leg temperature at the mercury heat exchanger approaches the inlet cooling water temperature.

A key factor in the event scenario is if the increased temperature is sufficient to cause boiling of the mercury in the target module. If there were boiling in the target module, it would increase flow resistance, causing a further reduction in the system flow. Because of this, 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, similar to 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 along with entrained droplets is 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:

A. 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.
B. The system's bulk mercury flow drops to a very low level (less than 10% of normal mercury flow but not all the way to zero flow).
C. 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.
D. The proton beam continues to heat the target.
E. The mercury in the target module begins to boil resulting in reduced heat transfer from the metal body of the target module to the mercury, which normally cools this metal.
F. The mercury in the annulus and bulk flow region of the target continues to heat up until enough vapor is produced at the outer annulus (window) wall of the target module that it restricts the supply of mercury to the hot wall to below what is necessary to adequately cool it.

G. 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.
H. 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.
I. 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 using the sum of RRF_{II} and RRF_{III} as shown in Table 4.4.1.2.2-2 (Section 4.4.1.2.2) for this event. This sum is equal to 3.6E–03.

Consequence of Partial Loss of Mercury Flow

The unmitigated offsite radiological consequence is conservatively bounded at 0.3 Rem with an associated toxicological consequence at 0.39 ERPG-2.

In the mitigated accident analysis, credit is taken for the TPS proton beam cutoff on out of limits differential pressure across mercury pump. The proton beam would be cut off on a TPS signal from differential pressure across the mercury pump. This 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 analysis takes no credit for the TPS because it is an active system. Because the original unmitigated consequences were well under thresholds 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 for the protection of the public.

4.4.2.6 High Bay Crane Load Drop Accident with Follow-On Hydrogen Explosion

This section addresses mercury release and a hydrogen release from the cryogenic moderator system due to 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. The analysis of crane drop events in Reference 41 showed that only the scenario involving a follow-on hydrogen explosion may potentially challenge offsite criteria (specifically, the toxicological criteria).

The specific scenario assessed in this section is Event Number HB2-2. As discussed in Section 4.3.10, the core vessel and CMS inside the core vessel are actually protected by massive monolith steel shielding in place above and around the core vessel. Nevertheless, it is postulated that the CMS transfer lines (all 3) are 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 H2 within the core vessel explodes, causing release of mercury vapor.

Scenario for High Bay Crane Drop with H_2 Explosion

The unmitigated scenario assumed in the pre-construction design phase for this event is as follows:

A. The system is running normally, with the mercury in the mercury process system at the upper normal operating limits for pressure, temperature, and inventory.
B. 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).
C. The lift is of a load that is 50% heavier than the nameplate rating of the crane.
D. 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).
E. Liquid mercury is ejected from the mercury process system through the failed component due to the difference in pressure 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.
F. Droplets of mercury are formed due to aerosolization as the pressurized liquid mercury moves through the orifice in the target module or mercury process system.
G. Hydrogen leaks from the cryogenic hydrogen moderator system or the associated piping.
H. The hydrogen mixes with the air to fill the open space inside the core vessel to form a flammable hydrogen-air mixture.
I. An ignition source causes the flammable hydrogen-air mixture to explode (deflagrate or detonate).
J. The explosion in the core vessel creates a blast wave that: (1) damages the target module (causing liquid mercury to spill); (2) provides stresses to the spilled liquid; and (3) damages seals separating the core vessel from the target service bay.
K. Hydrogen not consumed in the initial explosion migrates into the target service bay via the damaged seals.
L. The hydrogen mixes with the air inside the target service bay to form a second flammable hydrogen-air mixture.
M. An ignition source causes the flammable hydrogen-air mixture to explode (deflagrate or detonate).
N. The explosion in the target service bay creates a blast wave that (1) damages piping and other process vessels inside the target service bay (causing liquid mercury to spill) and (2) provides stresses to the spilled liquid.

O. 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 mechanism contribute to the source term: (1) evaporation (boiling) of some liquid mercury at the upper surface of the liquid due to heat from the explosion over the gas/liquid interface (this 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 due to liquid surface motion caused by blast effects.

P. 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 H_2 Explosion

The unmitigated source term for this event was simply 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 H_2 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 $mg/m^3$and therefore requires one level of control.

The credited control set for the high bay crane drop scenario includes (1) the high bay crane design; (2) the protective barrier features that protect the CMS from external impact, and as a second layer of safety; (3) the Hoisting and Rigging program that 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 and, therefore, prevent damage that could lead to the hydrogen explosion (Note: 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 there are no consequences.

Since 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), it is expected that the Hoisting and Rigging Program will only rarely (if ever) restrict operations with the pedestal manipulator.

The as-constructed analysis[59] takes into account the massive steel shielding that surrounds the core vessel which 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 inch thick steel plug that sits above the core vessel and is supported by the monolith 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. Since the core vessel is protected from being crushed, it is very unlikely that any of the process components would be damaged by such a load drop. None-the-less, the as-constructed analysis conservatively assumes the load drop leads to breaches of both the CMS and mercury systems.

Additionally, the as-constructed analysis takes into account 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 some time after the event, eventually assumed to result in combustion. The analysis accounts for mercury vaporization by this delayed hydrogen combustion. The offsite consequences[59] associated with the as-constructed facility are bounded at 0.084 Rem with an associated toxicological consequence at 0.14 times ERPG-2.

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 due to 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 Number 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:

A. The system is running normally, with the mercury in the mercury process system at the upper normal operating limits for pressure, temperature, and inventory.
B. A lift is in progress. The external crane carries the load over the target service bay (e.g., an operator error or malfunction causes the load to pass over this location).
C. The lift is of a load that is 50% heavier than the assumed 300 ton rating of the crane.

D. When the load is over the target 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).

E. Liquid mercury is ejected from the mercury process system through the failed component due to the difference in pressure 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.

F. Droplets of mercury are formed due to aerosolization as the pressurized liquid mercury moves through the orifice in the target module or mercury process system.

G. The liquid mercury falls to the floor or the target service bay forming a pool of hot liquid mercury (droplets are assumed to be formed at this step due to entrainment because a jet or stream of liquid breaks up while falling and/or splashing).

H. 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 (there is some internal heat generation in the spilled mercury due to decay heating from the radioactive atoms in the mercury).

I. 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 is calculated using the sum of RRF_{II} and RRF_{III} as shown in Table 4.4.2-1 (Section 4.4.2) for this event. This sum is equal to 6.8E–03.

Consequence of External Crane Load Drop

The unmitigated consequences to the public calculated for this event were 1.3 Rem and 0.74 of the ERPG-2. The unmitigated consequences are below thresholds 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 lift loads did not exceed 50 tons. Therefore, the as-constructed 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 should a second target station be constructed. The resulting as-constructed consequences are 0.43 Rem and 0.25 ERPG-2.

The mitigation strategy for this event is to prevent the load drop through 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 there are no consequences.

Credited Controls for External Crane Load Drop

Credited controls established for worker protection as described in Section 4.3.14 for this event also serve to 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 Target Service Bay Fire

This section addresses the fire event that originates in the target service bay of the SNS target facility. The specific scenario assessed is HE Event Number TS1-3 (also TS1-2 medium fire that migrates into Service Bay). The primary concern from a target service bay fire were the consequences that could result if the fire occurred during commissioning/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. The steel shielding is required once significant radioactivity builds up in the target loop to protect electronic equipment within the Service Bay. This scenario was developed prior to initial operations when schedule delays threatened to delay the delivery of the shielding until after commissioning. The shielding was in fact delivered and installed prior to 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 in the future with Hg in the loop is expected to be insignificant with respect to the 40 year 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). None-the-less, this event is retained and illustrates the important role of the loop shielding.

Scenario for Target Service Bay Fire

The unmitigated scenario for this event is as follows:

A. 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 loop.
B. A fire starts in the target service bay.
C. The heat from the fire causes failure of the exposed portion of the mercury loop piping system due to (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.
D. A portion of the spilled liquid mercury is directly exposed to radiant heat from the fire and vaporizes.

E. Respirable droplets of mercury form and are entrained in the vapor leaving the liquid surface during boiling.
F. The mercury vapor and airborne mercury droplets are transported away from the building by natural air currents.

Unmitigated Source Term for Target Service Bay Fire

The total respirable mercury release for the unmitigated service bay fire without mercury loop shielding in place is calculated using the sum of RRF_{II} and RRF_{III} as documented in Reference 34 for this event. This sum is equal to 2.7E–2 and 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 1.4 Rem with an associated bounding toxicological consequence at 2.4 times ERPG-2. The unmitigated toxicological consequence to the public exceeds the credited control threshold, a single level of control is required per the selection of credited controls criteria presented in Section 4.2.2.4.

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 Hg in the loop is expected to be insignificant with respect to the 40 year 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 analysis assumes the mercury loop shielding to be in place with associated consequences bounded at 0.07 rem and 0.1 ERPG-2.

In the mitigated accident analysis, credit is taken for fire detection and suppression inside the target service bay that would suppress a fire consistent with the combustible material program for inside the target service bay and the two-hour equivalent fire barrier. Thus there would be no mercury release and no radiological or toxological consequences onsite or offsite.

Credited Controls for Target 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 HE Event Numbers BG1-1, discussed in Section 4.3.14. The primary concern 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 and that the spilled mercury is exposed to the heat flux from the fire.

Scenario for Full Facility Fire

The unmitigated scenario for this event is as follows:

A. The system is running normally, with the mercury in the mercury process system at the upper normal operating limits for pressure, temperature, and inventory.
B. A fire external to the building propagates to the target building and into the target service bay.
C. Falling structural components damage a portion of the mercury loop piping system leading to breaks that spill liquid mercury.
D. A portion of the spilled liquid mercury is directly exposed to radiant heat from the fire and vaporizes.
E. Respirable droplets of mercury form and are entrained in the vapor leaving the liquid surface during boiling.
F. 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 4.4.1.2.2-2 (Section 4.4.1.2.2) for this event. This sum is equal to 4.3E–02 and equivalent to approximately 780 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 which was thought to be a credible scenario during commissioning/early operations as was discussed for the Target Service Bay fire (refer to Section 4.4.2.8). The resulting unmitigated radiological consequence to the public is conservatively bounded at 2.1 Rem with an associated toxicological consequence at 1.2 times 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.

The as-constructed analysis assumes that the fire spreads into the target service bay despite the seismically qualified two-hour equivalent fire barrier of the service bay but assumes the mercury loop steel shielding is in place when mercury is in the target loop (see discussions in Section 4.4.2.8), while no credit was taken for the active fire detection/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/suppression system, the as-constructed analysis[59] assumes the full facility fire also leads to a release of all of the mercury contained in the PCES charcoal adsorbers (conservatively estimated at 7.6 kg based on measured accumulation[59]) located in the basement of the facility. The associated bounding consequences are 0.08 rem with an associated toxicological consequence at 0.14 times ERPG-2.

Consequences are mitigated by crediting the NFPA-13 compliant building fire detection/suppression system and a combustible material program for outside the target service bay to ensure that the fire barrier is not challenged. These prevent the fire from progressing into the target service bay.

Credited Controls for Full Facility Fire

Credited controls established for worker protection as described in Section 4.3.14 for this event also serve to protect the public. No new credited controls are required to protect the public.

4.4.2.10 Accident Analysis Summary

A summary of offsite bounding consequences for credible postulated accidents associated with both the unmitigated and as-constructed analyses is provided in Table 4.4.2.10-1.

Unmitigated offsite radiological consequences were all found to be below the threshold requiring credited controls. Associated unmitigated toxicological consequences exceeded the toxicological threshold (ERPG-2) and thus required credited controls:

- Target Service Bay fire (TS1-3, TS1-6, TS1-2)
- Full Facility Fire (BG1-1)
- H_2 explosion with/without follow-on fire (CM2-1a and CM2-1b)
- Seismic event with follow-on H_2 explosion and/or fire
- High Bay crane load drop (HB2-2)
- Seismic Event (BG7-1, BG7-2, BG7-3)

In all cases, credited controls established for worker protection in Section 4.3 also effectively serve to protect the public [As noted in Section 4.4.1.3.1, 4th bullet, the bounding exposure to workers located onsite 100-m from the target building is a factor of about 20.4 greater than the bounding offsite exposures discussed in this section]. No new credited controls beyond those identified for worker protection are needed.

The unmitigated 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 affect on accident progression has been assessed. A summary of the post-construction bounding credible postulated offsite consequences assuming all active controls and administrative controls fail is presented in Table 4.4.2.10-1.

In several instances, the unmitigated consequences were well below thresholds 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 4.4.2.10-1. Bounding Offsite Consequences for Postulated Accidents

	Unmitigated (input for design)		As-Constructed Facility[b]	
Event (HE designation)	**Rad Dose (rem)**	**ERPG-2 Ratio**	**Rad Dose (rem)**	**ERPG-2 Ratio**
1. Target Service Bay Fire (TS1-3, TS1-6)	1.4	2.4	0.066	0.1
2a. Medium Fire, Spreads into the Target Service Bay from anywhere in target building (TS1-2)	1.4	2.4	0	0
2b. Medium Fire Charcoal Filter Room (TS1-2)	0.038	0.1	0.0019	0.0049
3. Full Facility Fire (BG1-1)	2.1	1.2	0.081	0.14
4. Hydrogen Explosion without Follow-On Fire (CM2-1b)	1.4	2.8	0	0
5. Hydrogen Explosion with Follow-On Fire (CM2-1a)[a]	≤3.9	≤4.9	0.	0.
6. Loss of Confinement (Service Bay) (TS3-7, TS3-10)	0.026	0.05	0.026	0.05
7. Loss of Confinement (Core Vessel – He Inerted) (TS3-4, TS3-6, TS3-8, TS3-11)	0.034	0.07	0.034	0.07
8. Loss of Confinement (Core Vessel – Vacuum Operation)	0.12	0.08	0.12	0.08
9. Partial Loss of Mercury Flow (TS3-22, TS3-23, TS3-24, TS3-25)	0.3	0.39	0.3	0.39
10. Complete Loss of Mercury Flow (TS3-22)	0.07	0.14	0.07	0.14
11. Loss of Heat Sink (TS3-13, TS3-14, TS3-15, TS3-16)	0.52	0.53	0.52	0.53
12. Crane Load Drop, Service Bay (TS3-18)	0.033	0.05	0.033	0.05
13. Crane Load Drop, High Bay onto Service Bay (HB3-3)	0.093	0.08	0.093	0.08
14. Crane Load Drop (High Bay Crane) onto Core Vessel (No Explosion) (HB3-7)	0.1	0.1	0.034	0.07
15. Crane Load Drop (High Bay Crane) with Hydrogen Explosion (HB2-2)[a]	≤3.9	≤4.9	0.084	0.14
16. External Load Crane Drop (BG6-11)	1.3	0.74	0.43	0.25
17. Natural Phenomena (Seismic) Including H_2 Explosion and Follow-On Fire (BG7-1)	3.9	4.9	0.11	0.18
18. Natural Phenomena (Seismic) Event Including Follow-on Fire (no H_2 Explosion) (BG7-2)[a]	≤3.9	≤4.9	≤0.11	≤0.18
19. Natural Phenomena (Seismic) Including Follow-On H_2 Explosion (No Fire) (BG7-3)[a]	≤3.9	≤4.9	≤0.11	≤0.18

[a] Consequences conservatively assumed to be bounded by Accident 17, Natural Phenomena (Seismic) Including H_2 Explosion and Follow-On Fire (BG7-1).

[b] The ‘as-constructed analyses take into account passive robust structures and design features but take no credit for active controls or administrative controls.

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 in instances where postulated unmitigated accident scenarios lead to unacceptable onsite or offsite consequences. The Credited Controls identified for SNS are listed in the summary tables of Section 4.3.15.

Section 4.3 focused 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 focused 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 serve to mitigate the release of hazardous materials from the facility. As such, the Credited Controls serve to protect not only the onsite workers, but also the offsite public and the environment.

Appendix A presents the “SNS Controls Matrix,” which provides a summary Credited Controls identified for each event. Each column listing credited controls makes up one level of control (see discussion in Section 4.2.2.4).

Chapter 5 provides information about the design and functional requirements for each designated credited control which serves as the basis for the ASE.

4.6 ENVIRONMENTAL PROTECTION

The potential for large radioactive or toxic material releases is minimized by the credited engineered and administrative controls identified in this chapter. These controls protect the worker outside the facility and the public by mitigating atmospheric releases from the facility. Those CECs and CACs that provide protection for either the onsite workers or the public also inherently provide protection for 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*.[21]

4.7 REFERENCES

1. Spallation Neutron Source Policy for Selection of Safety Related Credited Controls, SNS 102030100-ES0005-R00, Oak Ridge National Laboratory, Oak Ridge, TN, March 2005.
2. Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Safety Analysis Reports, DOE-STD-3009-94, Change Notice 2, U.S. Department of Energy, Washington, DC, April, 2002.
3. Safety of Accelerator Facilities, DOE Order 420.2B, U.S. Department of Energy, Washington, DC, July, 2004.
4. Accelerator Facility Safety Implementation Guide for DOE O 420.2B, Safety of Accelerator Facilities, DOE Guide 420.2-1, U.S. Department of Energy, Washington DC, July 2005.
5. This reference deleted but the number retained for continuity in numbering of references.
6. Emergency Planning and Notification (TPQ), 40 CFR 355, Appendices A and B, U.S. Environmental Protection Agency, Washington, DC, revised June 1993.
7. Chemical Accident Prevention Provisions, 40 CFR 68, Risk Management Programs for Chemical Accidental Release Prevention, Environmental Protection Agency, Washington, DC, revised January 1999.
8. List of Hazardous Substances and Reportable Quantities, 40 CFR 302.4, Environmental Protection Agency, Washington, DC, revised July 1997.
9. Process Safety Management (PSM) of Highly Hazardous Chemicals, 29 CFR 1910.119, Labor, U.S. Occupational Safety and Health Administration, Washington, DC, revised July 1992.
10. Facility Safety, DOE Order 420.1A, U.S. Department of Energy, Washington, DC, May 2002.
11. Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities, DOE-STD-1020-94, U.S. Department of Energy, Washington, DC, Change Notice 1, January 1996.

12. Natural Phenomena Hazards Performance Categorization Guidelines for Structures, Systems, and Components, DOE-STD-1021-93, U.S. Department of Energy, Washington, DC, Change Notice 1, January 1996.
13. Natural Phenomena Hazards Characterization Criteria, DOE-STD-1022-94, U.S. Department of Energy, Washington, DC, Change Notice 1, January 1996.
14. Natural Phenomena Hazards Assessment Criteria, DOE-STD-1023-95, U.S. Department of Energy, Washington, DC, Change Notice 1, January 1996.
15. Guidelines for Use of Probabilistic Seismic Hazard Curves at Department of Energy Sites for Department of Energy Facilities, DOE-STD-1024-92, U.S. Department of Energy, Washington, DC, Change Notice 1, January 1996.
16. Spallation Neutron Source Standards for Design and Construction of the Target Facility, SNS 102030102-ES0012-R02, Oak Ridge National Laboratory, Oak Ridge, TN, September 2001.
17. Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23, Nuclear Safety Analysis Reports, DOE-STD-1027-92, U.S. Department of Energy, Washington, DC, Change 1, September 1997.
18. 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).
19. SNS Target Facility Hazard Identification and Evaluation, SNS 102030102-ES0017-R00, Oak Ridge National Laboratory, Oak Ridge, TN, October 2005.
20. National Spallation Neutron Source Conceptual Design Report, NSNS/CDR-2/V1 and V2, Oak Ridge National Laboratory, Oak Ridge, TN, May 1997.
21. Construction and Operation of the Spallation Neutron Source—Final Environmental Impact Statement, DOE/EIS-0247, U.S. Department of Energy, Office of Science, Washington, DC, April 1999.
22. Spallation Neutron Source Design Manual, Oak Ridge National Laboratory, Oak Ridge, TN, September 1998.
23. 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 SC, August 2005.

24. C. H. Blanton and S. A. Eide, “Nonreactor Nuclear Facilities: Standards and Criteria Guide,” DOE/TIC-11603, Rev. 1, Science Applications International Corp., LaJolla, CA, September 1986.
25. 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, U.S. Nuclear Regulatory Commission, February 1999.
26. 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, SC, October 11, 1999.
27. Spallation Neutron Source Final Safety Assessment Document for Proton Facilities, SNS 102030103-ES0018-R02, Oak Ridge National Laboratory, Oak Ridge, TN, June 2010.
28. J. A. Crabtree personal communication of Calculation of Hydraulic Impedance of CM Transfer Lines, August 2005.
29. Calculation of Atmospheric Dispersion of Natural Gas Releases, SNS 102030102-ES0004 R00, Oak Ridge National Laboratory, Oak Ridge, TN, February 2000.
30. Hydrogen Concentration after Release to the High Bay, SNS 102030102-ES0009 R01, Oak Ridge National Laboratory, Oak Ridge, TN, March 2002.
31. Rules for Construction of Overhead and Gantry Crane, ASME NOG-1-2002.
32. Accident Analysis for Aircraft Crash into Hazardous Facilities, DOE-STD-3014-96, U.S. Department of Energy, Washington, DC, October, 1996.
33. R. Lux, Aircraft Impact Risk for the Spallation Neutron Source Target Facility, WSMS-OR-0000015, August 24, 2000.
34. 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, TN, August 2005.
35. Spallation Neutron Source Preliminary Safety Analysis Report, SNS 102030102-ES0001-R00, Oak Ridge National Laboratory, Oak Ridge, TN, December 1999.
36. Spallation Neutron Source Preliminary Safety Analysis Report Update Report, SNS 102030102-ES0008-R00, Oak Ridge National Laboratory, Oak Ridge, TN, March 2001.

37. Spallation Neutron Source Preliminary Safety Analysis Report Update Report, SNS 102030102-ES0008-R02, Oak Ridge National Laboratory, Oak Ridge, TN, May 2002.
38. Spallation Neutron Source Preliminary Safety Analysis Report Update Report, SNS 102030102-ES0008-R03, Oak Ridge National Laboratory, Oak Ridge, TN, August 2003.
39. Spallation Neutron Source Preliminary Safety Analysis Report, SNS 102030102-ES0001-R02, Oak Ridge National Laboratory, Oak Ridge, TN, December 2003.
40. Spallation Neutron Source Preliminary Safety Analysis Report, SNS 102030102-ES0001-R01, Oak Ridge National Laboratory, Oak Ridge, TN, August 2000.
41. C. C. Fields, Master Engineering Calculation for Accident Analyses Supporting Revised PSAR, WSMS-OR-03-0006, Rev. A, Westinghouse Safety Management Solutions LLC, Aiken, SC, December 2003.
42. 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, TN, August 2006.
43. 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, TN, July 2005.
44. K. Davis and J. Delayen, SNS SRF LINAC Earthquake Response Testing at 4K, SNS 102030102-TR0009-R00, Oak Ridge National Laboratory, Oak Ridge, TN, July 2005.
45. M. W. Wendel, Thermal-Hydraulic Analysis of the SNS Mercury Target, SNS 106010101-DA-0005-R01, February 2006.
46. Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities, Volume 1 — Analysis of Experimental Data, DOE-HDBK-3010-94, Change Notice 1, U.S. Department of Energy, Washington, DC, March 2000.
47. P. Ferguson, Radionuclide Inventory of the SNS Mercury Target, SNS 106100200-DA0014-R00, Oak Ridge National Laboratory, Oak Ridge, TN, July 2005.
48. 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, TN, March 2005.

49. E. R. G. Eckert and R. M. Drake, Heat and Mass Transfer, McGraw-Hill, New York, 1959.
50. R. M. Harrington, Fire Accident Source Terms and Consequences, SNS 102030102-CA0001-R01, Oak Ridge National Laboratory, Oak Ridge, TN, September 26, 2003.
51. USEPA, User’s Guide for the Industrial Source Complex (ISC3) Dispersion Models, EPA-454/B-95/003a, Research Triangle Park, NC.
52. 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, TN, August 2003.
53. A. L. Sjoreen and R. L. Miller, Onsite Dispersion Coefficient, SNS 102030102-CA0013-R00, Oak Ridge National Laboratory, Oak Ridge, TN, September 2003.
54. ICRP, Dose Coefficients for Intakes of Radionuclides by Workers, ICRP Publication 68, International Commission on Radiological Protection, Pergamon Press, Oxford, 1994.
55. R. W. Leggett, Determination of Inhalation Dose Coefficients for SNS Accident Analysis, SNS 102030102-TR0006-R00, Oak Ridge National Laboratory, Oak Ridge, TN, May 2005.
56. C. F. Weber, Mercury Aerosol Production in a Postulated SNS Loss of Heat Sink Accident, SNS 102030102-TR0070-R00, March 2006.
57. Setpoint Definition for Low-Speed Mercury Pump Operations, SNS-106010200-DA0003-R05, September 2005.
58. American Industrial Hygiene Association, Emergency Response Planning Guidelines for Mercury Vapor, December 2003.
59. Addendum to Master Engineering Calculation in Support of the FSAD-NF Rev 3 Update, SNS 102030102-CA0024-R00, July 2011.
60. Safety of Accelerator Facilities, DOE Order 420.2C, U.S. Department of Energy, Washington, DC, July, 2011.

5.0 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 Chapter 4. Identified credited engineered controls (CECs) and credited administrative controls (CACs) are described in detail below. For each control, the means by which the safety function of the control is maintained is given. The continued operability or safety function of Credited Controls is assured by various means including Accelerator Safety Envelope Coverage, Operational Envelope Coverage, Configuration Management, and Operating Procedures. Accelerator Safety Envelope coverage constitutes the most rigorous control and forms the basis for accelerator safety envelope (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 provide an understanding of the safety function of CECs that prevent or mitigate the consequences of potential accidents. A listing of the 16 CECs may be found in Table 4.15-1 (Section 4.3.15). This section provides the safety function(s), system description, functional requirements, system evaluation, and ASE bases, where applicable, for each CEC.

Safe operation requires that CECs be able to 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. CECs with passive functions are generally more appropriately covered by the configuration control program or in the Operations Envelope because they are generally design features that are able to 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 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 Target Service Bay and for the Target Building in general (outside of the Service Bay) are covered in SBMS and therefore no additional requirements are needed to ensure operability. The configuration control program ensures that all CECs remain as described in this chapter.

Natural phenomena hazard (NPH) qualification requirements are listed only where the CEC is specifically credited in performing its safety function for an NPH event. Therefore, only the Performance Categories (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 DOE-STD-1020[2] and DOE-STD-1021-93.[3] As provided by DOE-STD-1021-93,[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. The CECs that have a seismic safety function are specifically called out below.

Design codes and standards applicable to the 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 items such as: (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 safety function of the cryogenic moderator system (CMS) hydrogen boundary is to prevent hydrogen leakage into the core vessel due to breaches of the system. The adjacent CMS vacuum boundary provides the credited backup to the hydrogen boundary (see 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 provides cooling to the supercritical hydrogen using circulators and a helium-cooled heat exchanger located in the hydrogen utility room (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 pump module and heat exchanger module. 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 (referred to as “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 referred to as 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 (i.e., of each of the three CMS subsystems) is protected by a rupture disc in the HUR that relieves to an inert gas-purged line that discharges above the roof level. If the cryogenic hydrogen inside the core vessel begins heating up, pressure of the hydrogen would increase and the rupture disc would actuate if pressure increases to 19 bar (275.5 psia). No hydrogen would escape to the vacuum layer unless the hydrogen boundary failed. The rupture disc is part of the credited relief path. The design also includes a spring-loaded relief valve actuating at 18 bar (261 psia) and discharging to the atmosphere through the same inerted relief path. This spring-loaded relief 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 disc ⇨ 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 disc and the core vessel. Protection is provided for internally generated missiles, operator error, equipment failure, etc., and is qualified to perform this function during and following a PC-3 NPH event.

5.2.1.4 System Evaluation

The design and fabrication of all piping meet the requirements of ASME B31.3[5] and the design and fabrication of the moderator vessels meet the requirements of ASME Section VIII[6]. 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 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 disc actuation pressure and flow capacity certified per ASME by the vendor, ensure adequate relief to maintain the hydrogen boundary within acceptable stress levels during heat-up events including loss of vacuum. If cryogenic conditions are not maintained, 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 location of the leak. Since the vacuum regions are interconnected, this 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.

An analysis[7] was prepared to demonstrate the PC-3 seismic capability of the hydrogen barrier. The hydrogen barrier components and lines are supported in accordance with criteria developed for a PC-3 level seismic event with respect to the above 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 and, therefore, does not require ASE coverage. The Configuration Control Program ensures safety features of the design are maintained.

Operations Envelope coverage is required for operability of the rupture discs requiring periodic inspections for deformation or other visual damage and replacement whenever the CMS pressure at the inlet to a rupture disc rises to the rupture disc deformation pressure, whenever the rupture disc safety head is disassembled, or at least once every five years. In addition, the relief path requires periodic surveillance requirements to ensure the rupture disc discharge path remains open. 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 damaging the vessels due to overheating. The limiting proton beam power for non-cryogenic conditions is pre-established in an approved design analysis calculation.

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 barriers preventing 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 barrier 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 location of the leak. Since the vacuum regions for the moderator vessel and transfer line are interconnected, this 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 due to 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 internally generated missiles, operator error, equipment failure, etc., and is qualified to perform this function during and following a PC-2 NPH event.

5.2.2.4 System Evaluation

The design and fabrication of all piping meet the requirements of ASME B31.3, [5] and the design and fabrication of the pressure vessels meet the requirements of ASME Section VIII[6]. These design features, combined with the high vacuum that must be maintained for normal operation of the CMS, ensure integrity of the vacuum boundary.

A fragility study[7] has been completed demonstrating the PC-3 seismic capability of the vacuum barrier. In addition, Calculation 106020200-DA-0002-R01, *Vacuum Vessel Venting Analysis following Hydrogen Moderator Failure,* [8] evaluates the ability of the moderator vacuum barrier to withstand a rupture of the moderator vessel that releases hydrogen into the vacuum region and concludes the pressure inside the vacuum vessel immediately after a failure of the hydrogen moderator is only about 0.68 bar (9.9 psia). Once the vacuum rupture disc fails, the vent line 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).

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 design features important to safety are maintained and able to perform their safety functions.

Operations Envelope coverage is required for operability of the rupture discs requiring periodic inspections for deformation or other visual damage and replacement whenever the CMS pressure (i.e., in one of the three CMS subsystems) at the inlet to a rupture disc rises to the rupture disc deformation pressure, whenever the rupture disc safety head is disassembled, or at least once every five years. In addition, the relief path requires periodic surveillance in accordance with the surveillance requirement to ensure it remains open downstream of the rupture disc.

5.2.3 TARGET SERVICE BAY/CORE VESSEL FIRE BARRIER—ISOLATION FUNCTION

5.2.3.1 Safety Function

The isolation safety function of the target service bay/core vessel fire barrier is to provide a physical barrier between the mercury inside the target service bay/core vessel and combustibles that may be located outside the target service bay/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/or steel structures comprise the fire barrier surrounding the target service bay and the core vessel:

1. The concrete and steel structure and steel shielding that surround the core vessel and the bulk shielding liner drain cavity
2. The concrete walls of the target service bay and transfer bay
3. Target service bay floor and Hg collection basin
4. High bay floor over the target service bay

Of the four features listed above, the first protects the core vessel and the others protect the target service bay.

5.2.3.3 Functional Requirements

The barrier shall prevent additional combustibles that may be located outside of the target service bay from entering the target service bay. Additionally the barrier shall prevent significant quantities of mercury from being transported out of the target service bay or core vessel. The barrier, including the foundation, floor, walls, and ceiling (high bay floor) of the target 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 separately.

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 target service bay. The target building contains combustible materials in electrical wiring, instrumentation cables, etc., to an extent typical for an industrial or other similar type facility, distributed throughout the facility, inside and outside the target service bay. However, the major combustible material hazard of the target building 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 in the high bay above the target service bay.

As discussed in Section 4.4, the seismic event is the most severe because it potentially combines assumed mechanical/structural failures with potential target service bay hydrogen explosion and the worst-case combustible loading in the target service bay and instrument hall. The CMS hydrogen barrier design prevents hydrogen explosions, and the structural design of the fire barrier maintains separation of combustibles inside and outside the target 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 non combustible (e.g., concrete and steel) neutron beamline shielding provides a buffer between the hydrocarbon-based neutron shielding instrument enclosures and the target service bay. The mercury process system piping and vessels are not credited against leakage during or after a seismic event. Spilled mercury in the target service bay is assumed.

The fire barrier between the combustible shielding in the instrument hall and the mercury inside the target 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.[9] The portions of the fire barrier provided by the target service bay ceiling (high bay floor) and the walls of the target service bay and monolith must survive the PC-3 event such that they preclude combustibles on the outside of the target service bay from migrating into the target service bay as a result 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 target service bay) has been completed[10]. 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.

Performance of the fire barrier with regard to retention of mercury spilled inside the target service bay is satisfied by the PC-3 design of target 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 regard 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-gallon 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 target 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.

5.2.4 TARGET SERVICE BAY/CORE VESSEL FIRE BARRIER—TWO-HOUR EQUIVALENT FIRE BARRIER FUNCTION

5.2.4.1 Safety Function

The function of the target service bay/core vessel fire barrier enclosing the target service bay and the core vessel is to prevent a fire outside the core vessel or the target service bay from propagating into the core vessel or the target service bay for a two-hour equivalent fire.

5.2.4.2 System Description

The fire barrier function is to prevent transmission of fire from outside the target service bay to inside the target service bay. By contrast, the safety function of the fire barrier isolation function (Section 4.3.2) is to maintain structural integrity in an earthquake so as to prevent additional combustibles from entering the target service bay and to prevent mercury from being transported from the target service bay to the basement.

The following concrete and/or steel structures comprise the fire barrier surrounding the target service bay and the core vessel:

- The concrete and steel structure and steel shielding that surrounds (around and above) the core vessel (functions as a fire barrier separating the core vessel from the instrument hall, high bay, ring-to-target beam transport (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)
- Outer walls of the target service bay (functions as a vertical fire barrier separating the target service bay from the manipulator gallery, decontamination room, and service gallery)
- Target service bay floor (functions as a horizontal fire barrier separating the target service bay from the basement)
- High bay floor and removable concrete floor beams over the target service bay
- Doors, hatches, through-penetrations, etc., 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 target service bay fire barrier shall meet National Fire Protection Association (NFPA) and/or Factory Mutual (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.

5.2.4.4 System Evaluation

The credited fire barriers and penetrations are designed based on existing approved two-hour Underwriters Laboratories (UL)—listed or FM—approved configurations or shown by calculation to have equivalent performance. Applicable standards include the *Standard Building Code* (SBC),[43] NFPA-801, *Standard for Fire Protection for Facilities Handling Radioactive Materials*[11] and NFPA-251, *Standard Methods of Tests of Fire Endurance of Building and Construction and Materials*.[12]

As noted in Section 5.2.1, a hydrogen barrier prevents leakage of hydrogen and, therefore, explosions damaging the fire barrier walls are prevented. Construction and design fire barrier requirements and maintenance of this configuration through the Configuration Control Program ensure the worker protection function would be provided in the event of a fire. Structural analysis[7] 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 two-hour equivalent fire barrier is considered a design feature and, therefore, does not require ASE coverage. The Configuration Control Program ensures the safety features of the design are maintained.

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 the two-hour equivalent fire barrier is capable of performing 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 integrity of the fire barrier.

5.2.5 TARGET PROTECTION SYSTEM

5.2.5.1 Safety Function

The TPS cuts off the proton beam, when necessary, to prevent overheating of mercury due to inadequate mercury loop flow or cooling. An additional credited safety function is to provide an automatic prevention of beam on target when the target carriage is in the withdrawn configuration. This additional safety function backs up the Personnel Protection System function that prevents beam on target based on sensing target carriage withdrawal using position switches.

5.2.5.2 System Description

The three process inputs to the TPS are differential pressure across the mercury pump (indicative of mercury flow), power utilization by the mercury pump (also indicative of flow), and mercury temperature at the mercury heat exchanger outlet. 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 causes a beam cutoff when power to the pump is below the established set point.

The TPS also includes a manual cutoff in the Central Laboratory and Office (CLO) control room, target control room, 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 the diagram below (Figure 5.2.5.2-1):

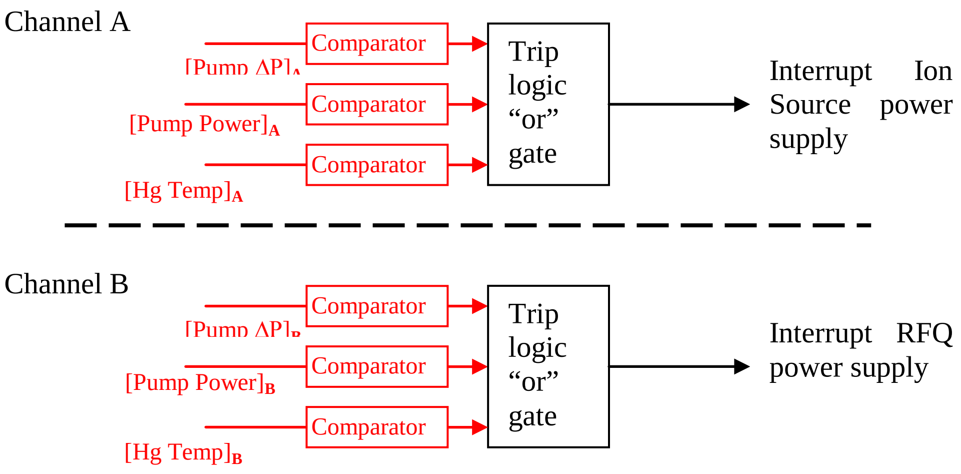


Figure 5.2.5.2-1 1 TPS 2-Channel 1-out-of-2 Architecture

Proton beam trip 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 and other features provide the fail-safe design concept of the target protection system.

On receipt of a low pump differential pressure , high temperature, or a loss of power to the pump signal, 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 2100 VAC 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.[1] Using these two diverse cutoff mechanisms helps ensure reliability.

A mode select feature for the TPS allows operations personnel in the central control room to select the “bypass” mode when it is desired to perform accelerator tuning with proton beam “upstream” of the target when the target has no mercury flow, or during retargeting when the mercury has been drained and the target carriage withdrawn. Although referred to as a “bypass” mode the TPS is active and continues to provide automatic protection for the target (it could also be called the “dump” mode since the beam is directed to a beam dump instead of to the target when in this mode). While in the “bypass” mode the TPS is not able to trip the beam on low mercury pump power, differential pressure or mercury temperature. However, the TPS actively monitors that the proton beam is not being sent to the target using permissives on the contactors that direct the proton beam to the target or extraction dump. Closing the AC power or DC power disconnects to the bending magnet (DH-13) automatically transfers the TPS back into its normal mode (i.e., beam-on-target mode) in which it is then automatically able to trip the beam based on the behavior of the TPS mercury process input variables. This operating bypass is implemented by monitoring permissives on the AC and DC disconnects to the 15° bending magnet (identified as RTBT DH-13) between the ring and the ring extraction dump. Magnet DH-13 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 protons are 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

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[1] 106080000-DA0001 R00, John Staples, “Security of Front End Cutoff Devices,” 09/07/2000.

power supply, and Channel B monitors the position of the disconnect in the dc output of 15° bending magnet power supply. The TPS performs the additional safety function of preventing beam on target when the target carriage is in the withdrawn configuration by the following actions: if either AC or DC power is supplied to DH-13, the bypass mode is automatically terminated and the TPS reverts to normal mode which initiates proton beam trip since mercury flow is zero when the carriage is in the withdrawn state.

The bypass mode is actuated manually from the CLO control room after both disconnects are opened. The opened disconnects actuate permissives that allow an operator to close the momentary, "bypass-enable" key switches in each channel. The independent TPS channels go into bypass mode separately. In order for a TPS channel to go into bypass mode, its channel disconnect permissive must indicate bending magnet power "off," and the "bypass-enable" keyswitch 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" keyswitch automatically removes the trip bypass for the selected channel. That is, any one of four conditions—a permissive for either disconnect or a bypass-disable switch in either channel—not satisfied would change one TPS channel 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 permissives are fail-safe 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 became disconnected or severed, or a short circuit occurred in one channel, a proton beam cutoff would be initiated by that channel. Since 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 and discharge piping.

The TPS includes status indicators in the target and central control rooms that indicate the status of each TPS channel. These provide positive indication to 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 the experimental physics and industrial control system (EPICS). The isolation devices prevent a malfunction in the non-safety system from propagating into the TPS system. The outputs of the isolation devices connected to EPICS are not part of any credited engineered control. They are used for Machine Protection System (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 located in the front end building and the klystron gallery, the trip bypass equipment is located in the RTBT service building and the bypass-enable and bypass-disable key switches in the CLO control room, the operator indicators and manual shutdown switches are on panels located in the main and target control rooms, and the TPS process modules for Channel A are located in the target control room 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 due to a natural phenomena event 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 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.

The TPS system is designed with the intent that all redundant input signals shown in the diagram above are functional. However, the TPS may be still be considered operational in instances where 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 that ensure reliability of both the temperature and flow related trip functions are maintained at design levels.

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.[14] The TPS design also follows the *Implementation Guide for Non-Nuclear Safety Design Criteria and Explosives Safety Criteria*.[15] 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.*[16] 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 IEEE 379, *Application of the Single Failure Criterion to Nuclear Power Generating Station Class 1E Systems.*[17] These design features and the permissive-based design (both channels must remain energized in order for the TPS not to trip) allow the TPS to provide protection even if any credible single failure is assumed.

A set point analysis ensures that the cutoff set points account for instrument error and drift and transient effects. The set point analysis for mercury temperature, circulation pump power, and circulation pump pressure difference ensures the set points selected provide an adequate amount of overlap to cover the full spectrum of credible partial loss-of-mercury flow or 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 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 (CEBAF) superconducting cavities, extension of that experience to the comparably sensitive SNS and measurements on the SNS cavities, [18, 19] an observable ground tremor would cause immediate beam termination and operating through 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 due to 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 cause beam cutoff 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 being required to operate the full accelerator at 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

The ASE requires that the TPS be operable whenever beam in excess of 5.6 kW-hours in any 24 hour period is directed onto the target. This limit ensures that the mercury temperature in the target module cannot reach boiling even when the mercury is not being pumped and is not cooled. Annual certification is required to ensure continued operability.

5.2.6 FIRE SUPPRESSION SYSTEM INSIDE THE TARGET SERVICE BAY

5.2.6.1 Safety Function

The FSS inside the target service bay shall detect and suppress a fire in the target service bay.

5.2.6.2 System Description

The FSS inside the target service bay is a water-based suppression system, referred to below as the mist system. It uses a mist-type water spray that absorbs heat, displaces oxygen, and/or blocks radiant heat to control, suppress, or extinguish fires and is compliant with NFPA Standard 750, *Standard on Water Mist Fire Protection Systems.*[20] Very Early Smoke Detection Apparatus (VESDA™) smoke detectors provide the signals 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*, as well as NFPA 750.[20] The system is divided into two zones of operation. Suppression Zone 1 covers the process and maintenance bay portion of the Service Bay. 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, 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 consisting of two VESDA™ air sampling detectors to 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 are provided to 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 hours 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.[20]

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 fire hazards analysis;[13] and,
2. continue to be operable after a loss of building or site power for a period of 8 hours.

5.2.6.4 System Evaluation

A NFPA-750-compliant[20] system design and construction ensure the system can fulfill its safety function. Inspection, testing, and monitoring of the system, per NFPA-750, [20] ensure the availability and reliability of the mist system, thereby reducing the frequency of an unchecked fire in the target service bay.

If the mist system were to actuate in the process bay during or after a mercury spill, it is possible that water would contact spilled mercury on the floor while draining or in the collection basin (where all floor drainage in the process bay is routed). This would not affect the fire suppression function of the mist system. 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 Chapter 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 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.[20] ASE coverage provides consistency with other SNS active CECs.

This system is required to be operable at any time that the Hg is not drained to the storage tank or mercury loop steel shielding is not fully installed (note: steel shielding is normally in place) unless appropriate compensatory actions are implemented.

The following surveillance is required to ensure operability:

- Inspection, testing, and maintenance of the target service bay water mist fire protection system per NFPA Standard 750[20]

The Combustible Material Control Program controls amounts, types, and configurations of combustible materials in the target service bay.

5.2.7 FIRE SUPPRESSION SYSTEM OUTSIDE THE TARGET SERVICE BAY

5.2.7.1 Safety Function

The FSS outside the target service bay shall automatically initiate sprinkler flow to control a fire that develops in areas directly adjacent to the service bay, in the high bay, instrument hall, or target building basement area.

5.2.7.2 System Description

A FSS is provided to control a fire that initiates outside of the target service bay. The FSS outside the target service bay is a wet-pipe sprinkler system designed and installed in accordance with NFPA Standard 13, [21] *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, target service bay service gallery, decontamination room, and the manipulator gallery. The detection needed for automatic initiation is a local function provided by the design of the NFPA-compliant sprinkler heads which reacts to the thermal effects of the fire to initiate local sprinkler flow.

The wet-pipe sprinkler system outside the target service bay is fed from a combined water service distribution loop supplied by a 300,000 gallon elevated gravity tank. Approximately 170,000 gallons in the elevated gravity tank are reserved for fire suppression purposes. This reserve capacity is designed to provide approximately two hours of firewater flow at the maximum anticipated demand. The combined water service distribution mains are designed to meet the general requirements of NFPA 24.[22] The elevated gravity tank is designed to meet the general requirements of NFPA 22.[23]

5.2.7.3 Functional Requirements

The wet-pipe sprinkler system outside the target 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 target service bay based on the anticipated combustible loading and occupancy classifications of the areas as defined in the FHA.[13] Successful fire control shall protect the credited fire barrier (Section 5.2.4) and prevent challenges to the structural integrity of the building.

5.2.7.4 System Evaluation

A system designed and constructed in accordance with NFPA 13[21] 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 WSS ensure the availability and reliability of the sprinkler system, thereby reducing the frequency of an unchecked fire outside the target service bay. Design and construction of the elevated gravity-flow water tank and the main water distribution loop in accordance with NFPA-24[22] and NFPA-22[23] 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, [21] reduce the frequency of improper isolation valve positioning due 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 of the wet-pipe sprinkler systems in the target building per the ORNL SBMS Fire Protection, Prevention and Control subject area.

The Combustible Material Control Program (see 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 CORE VESSEL (W/RUPTURE DISK) 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.

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. This limits the surface area for evaporation of the mercury, providing mitigation of the unmitigated mercury spill events analyzed in Chapter 4. A drain line is provided to allow drainage of any liquid accumulation in the core vessel to a drain line that terminates in a standpipe with a blind flange to ensure closure and contamination control as described in Chapter 3.

The core vessel contains the target, neutron reflectors, neutron moderators, and passively and actively cooled shielding elements. The 316 stainless steel vessel is designed and fabricated to meet the intent of ASME, *Boiler and Pressure Vessel (B&PV) Code*, Section VIII[6] requirements with all welded connections.

The lower vessel has 20 ports: 18 neutron beam ports, a proton beam port, and a target port. The neutron and proton beam ports do not provide 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 with a double metal vacuum gasket, o-ring, seal. 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 target 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 disc 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 gallons
- Provide overpressure relief by a rupture disc [nominal actuation pressure 1.5 bar absolute (22 psia)]
- All parts of the pressure boundary shall be able to withstand an atmosphere contaminated with mercury vapor for at least eight hours

5.2.8.4 System Evaluation

The designed-in ruggedness provided to meet the intent of ASME B&PV Section VIII[6] design and fabrication ensures that the core vessel can perform its safety function. The neutron beam inserts and inner windows are designed and fabricated to applicable ASME B&PV Section VIII[6] 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. Tests at ORNL[25] have shown, however, that the corrosion due to mercury vapor exposure is slow enough to support the minimum eight-hour mission time for the windows in a mercury spill event. Since liquid mercury drains by gravity to the bottom of the vessel, the windows are not in a liquid mercury environment in a mercury spill event.

The core vessel rupture disc is sized to prevent failure of the neutron beam windows or core vessel boundary in the event of hypothetical hydrogen release due to multiple CMS boundary failures inside the core vessel. This provides a greater relief capacity than required for the mercury spillage/leakage events for which vapor/gas retention is required since these events do not involve coincident failure of the CMS. The 1.5 bar 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 target service bay is a standpipe configuration with normally closed top that is above the level that mercury could fill the core vessel to in the event of a leak. This 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.

Operations Envelope coverage is required for the periodic inspection/replacement of the rupture disc and the relief path to ensure operability.

5.2.9 TARGET SERVICE BAY AND MONOLITH – CONFINEMENT OF MERCURY

5.2.9.1 Safety Function

Provide confinement of liquid mercury and mitigate the airborne mercury source term following a mercury spill event by retaining 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 target service bay and monolith. Robust construction includes the concrete floors and walls surrounding mercury-containing components in the target service bay and the concrete and steel structures that surround the monolith.

The target 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 so as to not trap excessive mercury. The liner in the target service bay process bay is sloped to direct the flow of mercury to the collection basin located below the target 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 Chapter 3.

The interface between the target service bay and monolith occurs at the core vessel (see Figure 5.2.9.2-1). The target 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, the leakage is routed to the target service bay collection basin by the system of sloping floors since the target tunnel floor is sloped underneath the carriage tracks toward the process bay (i.e., east). 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, it would drain through the bulk shielding (steel blocks), into the bulk shielding drain line, and 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 ~ 2 in.) that is in place normally and removed very infrequently. The steel shielding not only controls radiation levels inside the target service bay but also would minimize the range of a spraying leak from the mercury loop. It would also help minimize mercury vaporization in the event of a fire in the vicinity of 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.

Target Service Bay

All areas of the target 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 target service bay liner and collection basin shall be qualified to perform the safety function after a PC-2 seismic event.

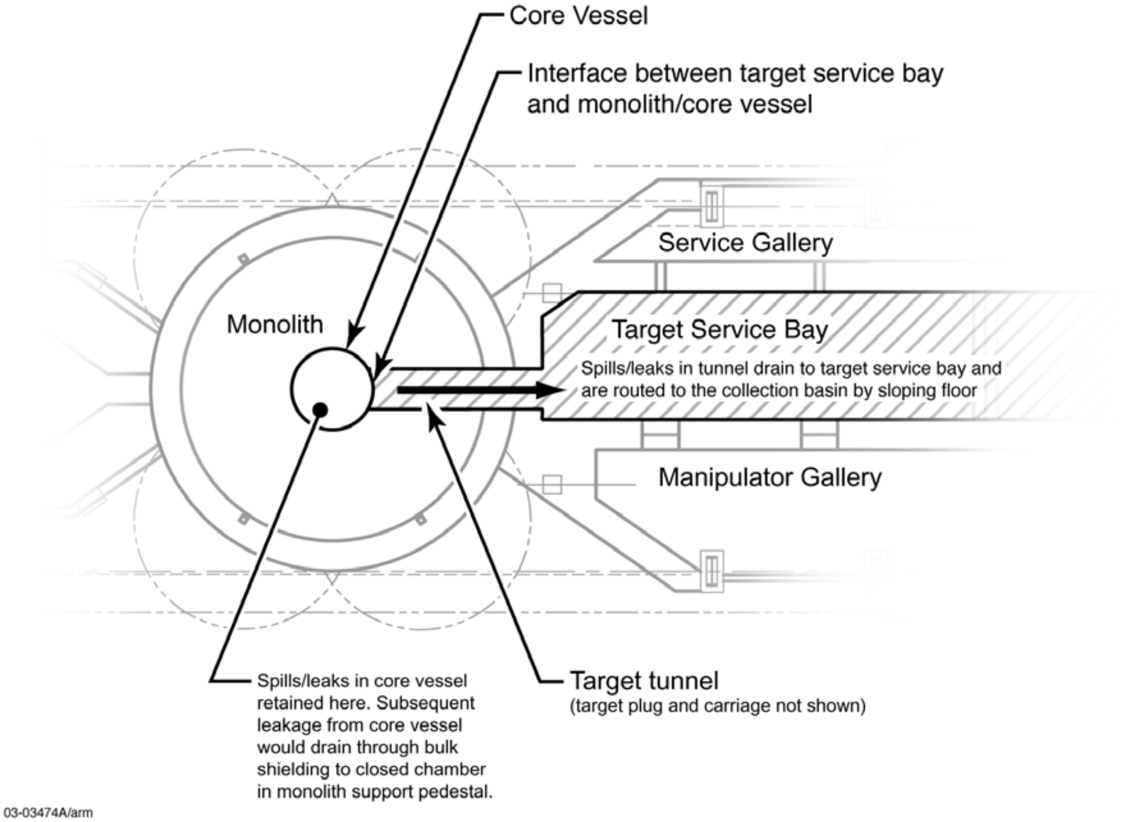

Figure 5.2.9.2-1 Schematic Illustration-Interface between Monolith/Core Vessel and Target Service Bay

5.2.9.3 Functional Requirements

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-2, or higher, seismic level.

5.2.9.4 System Evaluation

Target Service Bay

This feature reduces 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 provided at high reliability. Experiments performed in 1999[26] show that mercury flows freely on stainless steel at angles as small as 0.5 degrees. The target service bay liner slope in the process bay is greater than 0.5 degrees. The nominal design requirement is for a one-degree slope.

The locations of penetrations are such that even if passage to the collection basin were blocked, spilled mercury would not escape from the target service bay.

The target 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 drain pipe into the closed chamber in the support pedestal. The support pedestal and chamber liner and access hatch are designed to withstand PC-3 accelerations because they perform part of the fire barrier 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 the design features important to safety are maintained and able to perform their safety functions.

5.2.10 PRIMARY CONFINEMENT EXHAUST SYSTEM

5.2.10.1 Safety Function

Spill events: minimize escape of mercury-vapor-contaminated air from the target service bay to other parts of the target building.

Fire outside target service bay: minimizes hot gas intake to target service bay.

Fire inside the target service bay: prevents flow reversal in primary confinement exhaust system (PCES) target service bay intake duct.

5.2.10.2 System Description

The PCES routes target service bay exhaust via stainless steel ductwork to exhaust filtration stages that perform the ALARA function of reducing airborne radioactivity released to the exhaust stack in the event of a mercury-spill event. Operation of the PCES blowers maintains target service bay pressure sufficiently negative to direct in-leakage 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 ALARA function of the PCES. The core vessel vacuum pumps exhaust through the sulfur-impregnated charcoal adsorbers assuring filtration of any mercury vapor leaked into the core vessel.

The atmosphere in the 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. A high efficiency particulate air (HEPA) filtration stage is provided directly downstream from the charcoal adsorbers; however, the HEPA filters are not credited in the accident or HA. Additionally, while the exhaust stack that serves the PCES would elevate any release, the reduction in consequence due to the stack elevation feature is also not credited.

The exhaust portion of the PCES extends from where the PCES exhaust duct connects to the target service bay through the exhaust side of the charcoal adsorbers. Specification TS0883R06, Section 15895, *Stainless Steel High Pressure Ductwork and Accessories (Certified Materials),*[30] describes the PCES ductwork as stainless steel piping having welded seams and joints for systems operating up to 5,000 fpm and 0 to minus 60 in. 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 PCES inlet. The PCES inlet portion extends between the inlet to the upstream backdraft damper to where the inlet line connects to the target 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.*[31]

Although not credited, HEPA filtration is also provided on the intake side of the PCES. HEPA filters are provided to remove particulate matter that could enter the target service bay and become contaminated in the target 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 particulate into the PCES ductwork.

Fire in the charcoal adsorber units is very unlikely due to 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 postulated charcoal adsorber fire, allowing the fire department to isolate an affected unit and add water as needed.

5.2.10.3 Functional Requirements

The PCES is required to operate during and following 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:

- PCES ductwork provides confinement and direction of target 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 target service bay.
- Supply side backdraft dampers minimize the potential for reversal of airflow from the target service bay in the event of a target service bay fire or loss of normal negative pressure.
- Design features discourage transmission of fire from the service bay to the charcoal adsorbers. These features include: (1) floor level location of the exhaust ports in the service bay; (2) stainless steel filter housings that protect the filters at the exhaust ports, and (3) use of fire retardant filter medium in the filter housings.

The PCES is not required to operate during or after a seismic event. Since the PCES acts in conjunction with other features to provide defense-in-depth and since a power outage does not lead to significant mercury release, it is not required to have safety-related backup power supply.

5.2.10.4 System Evaluation

The PCES stainless steel ductwork is of welded construction that complies with ASME-N509[28] including the supply side target 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 target service bay up to the sulfur-impregnated charcoal adsorber is maintained regardless of whether the PCES fans continue to operate during an event. If the fan(s) continues to operate, there would be a forced flow into the target service bay and out to the filters. If the fans stop, there would not be enough motive force except during the early stages of a fire event to move significant quantities of hazardous material out of the target 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 target 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 target 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/alarm system and Section 5.3.5 addresses proper response to a loss of negative pressure alarm.

Locating the target service bay air intake close to the floor minimizes the amount of hot gases that would be drawn into the target service bay in the event of a fire in the fire zone that includes the decontamination room (located just outside the transfer bay part of the target service bay). The decontamination room is part of the fire zone that also includes the Service and Manipulator galleries.

5.2.10.5 Assurance of Continued Operability

The PCES ductwork between the service bay and the charcoal adsorbers are considered a design feature and, therefore, do not require ASE coverage. The Configuration Control Program ensures the design features important to safety are maintained and able to perform their safety functions.

Testing/inspection of the backdraft dampers are addressed in the Operations Envelope to ensure operability.

5.2.11 HIGH BAY CRANE

5.2.11.1 Safety Function

Reduce the probability of breaching the high bay floor or core vessel due to a failure of the crane that could result in the load being dropped. Either scenario is a safety concern when mercury is in the loop (i.e., the loop mercury inventory is not drained into the storage tank). When mercury is drained into the storage tank, it is in a protected location, and a crane drop onto the core vessel or mercury loop would not cause a significant airborne mercury source term.

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. The crane is used to lift loads such as the core vessel inner plug assembly within a shielding cask, a neutron beam shutter within a shielding cask, and the concrete shielding beams located above the core vessel, as well as smaller maintenance or housekeeping parts/containers. Accordingly, it is capable of delivering 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,* [32] 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.*[33] 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.*[34]

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 with dropping a suspended load in the intended service.

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, includes operational and impact loads specified in Crane Manufacturers Association of America (CMAA) Specification, 70-1994,[35] 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.[34]

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.

5.2.12 HIGH BAY FLOOR

5.2.12.1 Safety Function

Maintain structural integrity to prevent a dropped load (consisting of the maximum load and height above floor allowed by administrative controls) from contacting the interior of the target service bay process bay or core vessel. (Service Bay fire barrier and isolation functions of 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 are: (1) the floor directly above the target service bay process bay and (2) the removable shine shield beams above the core vessel.

Figure 3.3.5.1-1 shows the target service bay in cross section and shows the removable roof "Ts" 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 target service bay (including the removable beams) is designed for a static loading of approximately 4,000 lb/ft^2.

Figure 3.3.4-1 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 500 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 target 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 Hoisting and Rigging Program.

5.2.12.4 System Evaluation

Shielding and cask weights dictate a thick, robust floor design. A load-drop analysis[36] was performed to determine the live and dead loads for the high bay over the target service bay resulting in a 200 inch-ton drop load criteria for load paths that approach the center of the target service bay ceiling:

Example Limits for 200 inch-ton Load Drop Over the Center of the Target Service Bay Ceiling Accommodated within the Elastic Limit

Height of Drop	Drop Load
4 in.	50 Tons
5 in.	40 Tons
10 in.	20 Tons
20 in.	10 Tons

The floor beams that cover the core vessel are thinner than the target service bay ceiling and have a greater span. They can only accommodate much smaller 20 inch-ton load drops for load paths that approach the center of the monolith:

Example Limits for 20 inch-ton Load Drops Over the Center of the Monolith Shine Shield Accommodated within the Elastic Limit

Height of Drop	Drop Load
4 in.	5 Tons
5 in.	4 Tons
10 in.	2 Tons
20 in.	1 Ton

The above limits pertain to paths that approach the center of the applicable spans; other limits may be justified for other load paths with appropriate, documented engineering calculations. Should planned load movements over the target service bay process bay or monolith exceed the applicable envelope (e.g., tables above), the mercury process system must be drained to the storage tank prior to the movement taking place.

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 target 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.

In general, maximum loads, lift heights, and safe lift paths above the floor are limited by administrative controls described under the Hoisting and Rigging Program. Conditions that prohibit lifts exceeding 200 inch-tons and 20 inch-tons (See Section 5.2.12.4) are specified in the Operations Envelope.

5.2.13 MERCURY HEAT EXCHANGER

5.2.13.1 Safety Function

Prevent failure of single wall from allowing radioactive mercury to escape from the target service bay via the mercury loop cooling water system.

5.2.13.2 System Description

The mercury-to-intermediate cooling loop 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 provided in Section 3.3.1.3. The design includes a double tube sheet with stagnant mercury in the interstitial space pressurized to a pressure higher than either the main mercury loop or the cooling water loop. 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 that is connected to the mercury between the tubes. Approximately 20 gallons of interstitial mercury is required. The interstitial mercury is essentially unirradiated; it is recognized that 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 mercury into the intermediate cooling water system
- Provide a means for detection of failure of a single boundary

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[6] and all materials used in the construction of the heat exchanger vessel are grade 304L or 316 L 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 100% 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*.[37]

The pressure of the interstitial mercury is maintained by a trapped volume of helium. It 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. Since the heat exchanger is of 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 leak location determined (i.e., into the intermediate cooling water system or into the mercury loop) before action is taken. 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.

5.2.14 TARGET SERVICE BAY DIFFERENTIAL PRESSURE MONITORING SYSTEM

5.2.14.1 Safety Function

The target service bay differential pressure monitoring system (SBDPMS) shall provide: (1) a means of monitoring differential pressure between the target service bay and adjacent occupied areas, (2) an alarm for evacuation of adjacent areas upon loss of target service bay negative pressure, and (3) an alternate alarm mode based on target service bay PCE system exhaust air flow. The alternate alarm mode is for when workers have opened the service bay personnel access door for entry into the transfer bay, causing differential pressure to be too low to be useful as an indication of adequate target service bay confinement.

5.2.14.2 System Description

The target service bay differential pressure monitoring system alarms are initiated by a programmable logic controller (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 need 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 the two highest occupancy areas adjacent to the target service bay: (1) differential pressure between the target service bay and the manipulator gallery and (2) differential pressure between the target service bay and decontamination room. If either of these areas has inadequate differential pressure, the target service bay differential pressure monitoring system initiates the evacuation alarm in the six areas that could potentially be occupied by workers and affected by loss of target service bay vacuum: (1) manipulator gallery; (2) service gallery; (3) decontamination room; (4) bottom loading hatch room (basement); (5) high bay area above target service bay process bay; and (6) high bay area above accelerator tunnel.

The target service bay differential pressure monitoring system interfaces with non-safety instruments, but the design includes provisions to protect the target service bay differential pressure monitoring system from faults in the systems to which it is interfaced.

The alternate alarm mode is implemented on a single 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 administratively but limited by a 24-hour timer in the PLC that reverts automatically to differential pressure mode if the operators do not reset the timer prior to timing out.

5.2.14.3 Functional Requirements

The target service bay differential pressure monitoring system shall: (1) provide measurement of differential pressure between the target service bay and the manipulator gallery and between the target service bay and the decontamination room and (2) automatically sound audible evacuation (subject to an approximate 10 second time delay) in the potentially affected areas in the target building when the negative pressure of the target service bay is inadequate to ensure inflow from the manipulator gallery and the decontamination room into the target service bay.

5.2.14.4 System Evaluation

The target service bay differential pressure monitoring system monitors target service bay pressure with respect to the surrounding areas. The adjacent areas include 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 PCES, along with continued operation of the secondary confinement exhaust system (SCES), would reverse the differential pressure and could cause airflow from the target 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 PCES backdraft dampers (see Section 5.2.10) would prevent reversed flow of target service bay air through the PCES ductwork to the decontamination room (i.e., the target service bay air intake is located in 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 would not be a significant hazard unless it occurred during an event involving unusual airborne mercury inside the target service bay. It 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 air tight and workers in the area could be exposed to potentially contaminated air. An automatic cutoff of the operating SCES blower in response to loss of the PCES provides a defense-in-depth function to minimize the potential spread of contamination.

Design estimates[38] and operational measurements indicate that the concentration of mercury in the target 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 one hour), but this cannot be assured for the life of the facility. Therefore, adjacent areas are evacuated if target service bay negative pressure is lost. The target service bay differential pressure monitoring system 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[39] , 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*[40] the PCES was analyzed to determine the areas to monitor that would detect loss of negative pressure in the target service bay with respect to any surrounding occupied area. The analysis determined that if the target service bay pressure were negative with respect to the manipulator gallery and with respect to the Decontamination area, it would be negative with respect to other surrounding occupied areas. Therefore, the logic of the target service bay differential pressure monitoring system is to sound the evacuation alarms if the target service bay pressure is not negative with respect to either of these two areas. A set point 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 target service bay differential pressure monitoring system[40] 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 (note: the transfer bay personnel door remains open when the transfer bay is being occupied for periodic maintenance), parts of the high bay above the target service bay, and parts of the basement that are occupied and below the target 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 during entry into the transfer bay. The 24-hour period allowed for the alternate alarm mode of operation (normally when a port to the Service Bay is open that decreases the differential pressure) is acceptable because the probability of an accident requiring PCES mitigation based on differential pressure rather than flow occurring during this period combined is negligible.

5.2.14.5 Assurance of Continued Operability

The ASE addresses service bay differential pressure monitoring system operability requirements that apply when the transfer bay personnel access door is open. 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

Prevent mercury pump tank overfill during system startup from leaking mercury outside the target service bay via the offgas system.

5.2.15.2 System Description

The line that connects the offgas system to the pump tank is routed above the normal level of the mercury in the pump tank before looping down to connect into the offgas system components in the target service bay. A simplified schematic is provided in Figure 3.3.7-2. 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 the pump tank. 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 causing mercury to escape from the target service bay during the pump tank filling operation. During the fill operation, the circulation tank level is monitored by the operator. 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 provides the credited last level of defense against mercury escaping from the target service bay through the offgas system.

5.2.15.3 Functional Requirements

Liquid mercury is prevented from escaping from the target service bay in the event that the following multiple failures occur: (1) helium pressure regulator failure supplies 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% uncertainty allowance); (2) helium supply interlock on high pump tank level fails; and (3) operators fail to notice the overfill condition.

5.2.15.4 System Evaluation

The top of the loop seal is sufficiently high, and the inert gas pressure used in the mercury storage tank is insufficient to force liquid mercury up to the top of the loop. 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 offgas system during the loop refilling 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 the design features important to safety are maintained and able to perform their safety functions.

5.2.16 TRANSFER BAY ACCESS CONTROL SYSTEM

5.2.16.1 Safety Function

The safety function of this system is to protect workers from excessive radiation and/or airborne Hg vapor by preventing access to the transfer bay when either intra-bay shield door is not closed.

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 intra-bay shielding door (both upper and lower segments) is not closed. If workers are accessing the transfer bay (transfer bay access door is open), the system sounds an alarm if the intra-bay shielding door begins to open. A bypass may be used to allow worker access past the intra-bay door in accordance with strict administrative control.

5.2.16.4 System Evaluation

This system is a single channel system built to safety integrity level SIL-1 per ISA standard ISA S84.01.[39] This is an adequate reliability level since this system supplements the stringent administrative controls that are in place and a noncredited trap-key system that 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 target service bay.

5.2.16.5 Assurance of Continued Operability

The ASE requires that the TBAC system be operable when the transfer bay personnel door is not locked in the closed position. 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 this system is to prevent potentially injurious radiation exposure to prompt radiation in specific target PPS controlled areas and in the general target building occupied areas (chipmunk type radiation sensors).

5.2.17.2 System Description

The system, as described in Section 3.3.8.3.3, “Target Personnel Protection System,” is an arm of the PPS described in the FSAD for Proton Facilities (Ref. 42). It is an automatic electronic system designed to the same standard as the PPS implemented in the proton facilities. Since the target PPS is a “downstream” arm of the proton facilities PPS it uses the PPS critical devices in the Front End when needed to interrupt the proton beam to protect workers. The target PPS performs a safety function for the instrument PPS.

The target PPS monitors the instrument PPS status output (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 and for others it trips the proton beam if the primary shutter fails to close after a predetermined time interval. The 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 (see Section 4.3.3). Access control to these areas will not be considered a credited function of the PPS system until such time that 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 performs its protective function by cutting off the proton beam.

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. Annual certification is required to ensure continued operability.

5.2.17.5 Assurance of Continued Operability

The ASE requires that the target PPS to be operable whenever the accelerator is putting beam on target or is capable of putting beam on target.

5.2.18 INSTRUMENT PERSONNEL PROTECTION SYSTEM

5.2.18.1 Safety Function

The safety function of this system is to prevent potentially injurious radiation exposure to prompt radiation in instrument enclosures.

5.2.18.2 System Description

The system is described in Section 3.3.8.3.2, “Instrument Personnel Protection System.” The IPPS is downstream of the TPPS much like TPPS is downstream of the proton facilities PPS. The instrument PPS comprises parallel instrument packages with one instrument package serving each neutron instrument. The instrument PPS packages installed on different instruments operate independently as dictated by conditions in the individual instruments or instrument enclosures.

5.2.18.3 Functional Requirements

The instrument PPS performs its protective function by cutting off the proton beam when the situation cannot be corrected by closing the appropriate neutron beam shutter.

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

The ASE requires that instrument PPS for each instrument be operable whenever the primary shutter is open or is capable of being opened. Annual certification is required to ensure continued operability.

5.3 CREDITED ADMINISTRATIVE CONTROLS

CACs identified in Chapter 4 are described in the following subsections. As explained below, 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 to particular operations. Administrative Controls that are SNS specific are covered by the Operations Envelope and/or Operations Procedure Manual as needed to assure the safety functions are maintained. When the identified Credited Administrative Controls 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 that assures 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 Chapter 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 Chapter 4 events that credit the program.

- Event HV3-5 is an inhalation overexposure due to a mishap during HEPA filter change out. Work in Radiological Areas involves planning through work packages that include Radiological Permits (RWPs) requiring approvals commensurate with the predicted hazards. Need for personnel protective equipment (PPE), protective clothing, and RCT coverage is considered for each RWP.
- Event SH4-2 involves overexposure due to voids/cracks in shielding concrete. The Radiological Protection Program enforces regular area surveys in selected occupied areas carried out in accordance with an approved schedule.
- Event SH4-4 involves excessive radiation exposure due to 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 RCT coverage is considered for each RWP.
- Event TC4-2 postulates excessive radiation exposure after violent breakage of a target service bay viewing window due to a service bay crane load handling accident. Workers who routinely perform tasks in the manipulator gallery have radworker 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 which would prevent worker access.

- Event SH4-3 postulates worker exposure due to 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 RS hold).

- Event SH4-1 postulates worker exposure in the high bay due to misaligned target module, proton beam window, or core vessel. The Radiological Protection Program ensures radiation surveys take place as appropriate after replacement of shielding associated with these components.

- HB4-3 postulates inadvertent removal of shielding in the high bay area resulting in worker exposure. The Radiological Protection Program controls access into radiological areas and controls placement of shielding which would prevent worker access.

Controlling workers exposure to the radiological hazards of mercury includes prevention of exposure to airborne mercury products which also effectively protects against the toxicological hazards of mercury. During the early phases of the project, prior to 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 as of this writing are such that controls provided by the ORNL Radiological Protection Program serve to 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.

5.3.2 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 institutional 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 relative 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.

5.3.3 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 target service bay from challenging the fire barrier surrounding the target service bay and core vessel or causing gross building structural failure and limiting the combustible loading inside the target service bay to reduce the frequency and intensity of a fire in that location, thereby protecting the onsite workers as well as the public.

Combustible Materials outside the Target Service Bay

The Combustible Material Control Program is credited with providing a means of ensuring that any fire that could challenge the two-hour equivalent fire barrier outside the core vessel or target service bay would not exceed the equivalent two-hour fire barrier function of the target service bay/core vessel fire barrier. The potential impact of all combustible materials outside the service bay is considered. The combustible material outside the target service bay is controlled through the ORNL SBMS on *Fire Protection, Prevention and Control,* as 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 has provisions to ensure that the following design requirements for the hydrocarbon configuration and encasement on the instrument floor (See 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 2000 lb inside the instrument hall shall be encased in steel or other approved material.
- Individual encasements shall not exceed 4000 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 either be left open or be provided with rupture disks, depending on the hydrocarbon used and the overall configuration, orientation, and structural integrity of the encasement.
- For instrument stations with 4000 lb or more of hydrocarbon, additional design measures may be needed as documented in a documented hazard evaluation to ensure instrument hall fire protection goals are achieved.
- Instrument stations with more than 4000 lbs of hydrocarbon require a documented hazard evaluation to ensure that instrument hall fire protection goals are met.

Combustible Materials inside the Target Service Bay

The Combustible Material Control program is credited with providing a means of ensuring that a fire in the target service bay is limited in effective duration and intensity. The quantity of combustible material in the target service bay during normal operations is limited to an equivalent 3600 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 on Fire Protection, Prevention, and Control and, therefore, no further coverage is required. Requirements specific to the target building are promulgated through the Operations Envelope and/or the Operation Procedure Manual.

5.3.4 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: SBMS Subject Area *Electrical Work*, the SBMS for *Fire Protection, Prevention and Control* and the SBMS Subject Area *Welding, Burning, and Hot Work*. SNS implements ORNL SBMS programs. The SNS instrument halls are intended to host numerous diverse experiments over the facility life and some of them may utilize one-of-a-kind equipment that is not UL-listed. The purpose of the Ignition Control Program as credited in the SNS hazard analysis is to ensure 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 NSSD experiment safety review process. [This 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

As explained above, the ORNL institutional SBMS programs provide and maintain fire protection and minimize ignition likelihood; therefore, no further coverage is required. Reviews of experiment configuration are administered through the approved NSSD experiment review process.

5.3.5 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.

5.3.5.1 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 *High Bay Floor*) 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.

These floor sections are above the target service bay T-beams (in the area directly above the mercury loop), above the monolith T-beams (directly over the core vessel). The Operations Envelope integrates these geographic, weight, and height limitations into an acceptable restrictive envelope.

The beam-to-target is terminated, and Hg drained to the storage tank prior to load movements in excess of the applicable load height and weight limits over the core vessel region or the mercury process system portion of the target service bay.

5.3.5.2 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 (or an approved equivalent). 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 onsite workers. Conducting lifts in accordance with the ORNL SBMS Hoisting and Rigging Program provides a high degree of assurance 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.

5.3.5.3 Certification and Preventive Maintenance for the Target Service Bay Crane and Gantry Crane Robotic Arm

The appropriate level of certification and preventative maintenance for the target service bay crane and crane robot are maintained under a routine preventative maintenance program by trained service personnel.

5.3.6 PROCEDURES AND TRAINING

The analysis presented in Chapter 4 identified several instances where procedures and training for specific items are required as CACs. These items are discussed in the subsections below. The overall procedures and training programs for the SNS Neutron Facilities are described in Section 3.4. It is essential for operational safety that procedures are capable of being modified readily as process knowledge matures or modified operations are undertaken. Approved procedures that fulfill the credited safety functions discussed below are maintained in the OPM. Workers are trained as needed to ensure effective execution of the procedures.

5.3.6.1 Response to Target Service Bay Differential Pressure Alarm

Procedures and training are provided to workers to ensure proper response to the service bay differential pressure alarm to include: (1) worker evacuation of the service/transfer bay; (2) closing of 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 to ensure that they meet their credited safety function. These procedures are required to be applicable in all modes and control access appropriately according to the mode.

5.3.6.2 Control of Mercury Inventory on the 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 Chapter 4. Specifically, mercury loading on each charcoal adsorber is limited to 19.4 kg, and the total mercury loading on all of the charcoal adsorbers is limited to 155.2 kg.

5.3.6.3 Emergency Response Procedures

The following three Emergency Response Procedures identified as CACs in the safety analyses (Chapter 4) require OPM coverage to ensure they exist and meet the credited functions:

- Response to a service bay fire with worker(s) in the transfer cell and the personnel door in the open position (close personnel door upon evacuation);
- Evacuation of worker(s) in event of a service bay fire during maintenance activities when the target service bay, transfer cell, and high bay are open to common air flow; and
- Response to an external crane load drop on the target facility impacting the mercury.

5.4 REFERENCES

1. Spallation Neutron Source Policy for Selection of Safety Related Credited Controls, SNS 102030100-ES0005-R00, Spallation Neutron Source, Oak Ridge, TN, March 2005.
2. Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities, DOE STD-1020-2002, U.S. 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, TN, October 2002.
5. Process Piping, American Society of Mechanical Engineers, ASME B31.3, 1996.
6. Boiler and Pressure Vessel Code, ASME, Section VIII, American Society of Mechanical Engineers.
7. SNS Hydrogen Transfer Line Seismic Evaluation, SDE-18-03-C-001, May 2003.
8. Vacuum Vessel Venting Analysis following Hydrogen Moderator Failure, 106020200-DA-0002-R01, July 2003.
9. N. E. Stone, SNS Target Building Seismic Ruggedness Study, Design Analysis Calculation, Rev. 0, BWXT Y-12, LLC, June 2002.
10. R. M. Harrington, Fire Accident Source Terms and Consequences, SNS 102030102-CA0001-R01, Oak Ridge National Laboratory, Oak Ridge, TN, September 26, 2003.
11. Facilities Handling Radioactive Materials, NFPA 801, National Fire Protection Association 1998.
12. Standard Methods of Tests of Fire Endurance of Building Construction and Materials, NFPA-251, National Fire Protection Association, 1999 Edition.
13. 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.
14. Facility Safety, DOE Order 420.1, U.S. Department of Energy, Washington, DC, Change 2, October 1996.

15. Implementation Guide for Non-Nuclear Safety Design Criteria and Explosives Safety Criteria, DOE G 420.1-X, U.S. Department of Energy, Washington, DC.
16. 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.
17. Application of the Single Failure Criterion to Nuclear Power Generating Station Class 1E Systems, IEEE 379, Institute of Electrical and Electronics Engineers, Inc.
18. 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, TN, July 2005.
19. K. Davis and J. Delayen, SNS SRF LINAC Earthquake Response Testing at 4K, SNS 102030102-TR0009-R00, Oak Ridge National Laboratory, Oak Ridge, TN, July 2005.
20. Standard on Water Mist Fire Protection Systems, NFPA-750, National Fire Protection Association, 1996.
21. Standard for the Installation of Sprinkler Systems, NFPA-13, National Fire Protection Association, 1996.
22. Standard for the Installation of Private Fire Service Mains and Their Appurtenances, NFPA-24, National Fire Protection Association.
23. Standard for Water Tanks for Private Fire Protection, NFPA-22, National Fire Protection Association, 1996.
24. Standard for Inspection, Testing, and Maintenance of Wet-Pipe Sprinkler Systems, NFPA-25, National Fire Protection Association.
25. 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, SC, USA (May 19-24, 2002).
26. S. J. Pawel, “Draining Hg from Tubes,” E-Mail Transmitted to D. Lousteau, April 1999.
27. ASME N 509, “Adsorbers,” Specification TS072R01, Section 15475, Rev. 1, American Society of Mechanical Engineers, June 2002.
28. Nuclear Power Plant Air-Cleaning Units and Components, ASME N 509, American Society of Mechanical Engineers, 1989.

29. Code on Nuclear Air and Gas Treatment, ASME AG-1, American Society of Mechanical Engineers, 1996.
30. Stainless Steel High Pressure Ductwork and Accessories (Certified Materials), Specification TS0883R06, Section 15895, October 2001.
31. Testing of Nuclear Air Treatment Systems, ASME N 510, American Society of Mechanical Engineers, 1989.
32. Rules for Construction of Overhead and Gantry Cranes, ASME NOG-1-2002, American Society of Mechanical Engineers.
33. 50-Ton NOG-1 Crane, Specification TS0025R02, Section 14631, May 2002.
34. Single-Failure-Proof Cranes for Nuclear Power Plants, NUREG 0554.
35. Crane Manufacturers Association of America (CMAA) Specification CMA 70-1994.
36. Target Building Structural Notes, Abbreviations & Symbols, S0.10.30, Rev. 3, Knight Advanced Technology, March 2002.
37. Specification for the Design, Fabrication, and Erection of Steel Safety-Related Structures for Nuclear Facilities, ANSI/AISC N690.
38. 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, TN, October 2001.
39. Application of Safety Instrumented Systems for the Process Industries, ANSI/ISA S84.01-1996.
40. J. R. Devore, Setpoint Analysis for the Target Service Bay Differential Pressure Monitoring System, 108030700-DA0006-R00, March 2006.
41. SNS Operations Procedure Manuel, Procedure No. 2.J-3, Target Building Combustible Controls.
42. Spallation Neutron Source Final Safety Assessment Document for Proton Facilities, SNS 102030103-ES0018-R02, Oak Ridge National Laboratory, Oak Ridge, TN, December 2010.
43. Standard Building Code (SBC), Southern Building Code Congress 1997.
44. Target Building Facility Use Agreement, FUA-CRC_8700.

6.0 INTERFACE BETWEEN PROTON AND NEUTRON FACILITIES

Interfaces between the Neutron Facilities and the Proton Facilities are described in Chapter 6 of the FSAD-PF (*Spallation Neutron Source Final Safety Assessment Document for Proton Facilities*, SNS 102030103-ES0018-R02, December 2010).

7.0 INSTRUMENT SYSTEMS HAZARDS

Instruments at the Spallation Neutron Source (SNS) involve a diverse array of research activities. Presence of scientific users is discussed in Section 3.4.7. Hazards range from radiation hazards to standard industrial and laboratory hazards. SNS implementing the Oak Ridge National Laboratory (ORNL) Standards-Based Management System (SBMS) to provide guidance for the mitigation or prevention of hazards and hazardous materials, and this applies to instrument system hazards. Hazard mitigation requirements for standard industrial and laboratory hazards and other hazards are promulgated through the SBMS system and SNS policies and procedures. The instrument review process is described in Section 3.4.6. The instrument review ensures hazards not addressed by SBMS controls are reviewed and adequate hazard mitigation provided.

Experiments performed on SNS instruments require an experiment safety review to identify any hazards associated with a particular experiment and to make sure the hazards are appropriately mitigated. All experiments must be approved through the SNS experiment review process, which involves screening of all proposed experiments.

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 provides control over the types and volume of chemicals stored and used in work areas. Access to material safety data sheets (MSDSs) is required for all chemicals in use. Personnel handling these materials are required to receive adequate training in specific chemical handling procedures and proper use of MSDSs. 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 as mentioned above and, in addition, are subject to the experiment review process. This ensures that hazardous materials concerns associated with experiments are identified and handled appropriately. Since 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 Occupational Safety and Health Administration (OSHA)-compliant (e.g., 29 CFR 1910.1200 and 29 CFR 1910.1450)[1] SBMS chemical and hazard communication (HAZCOM) 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. See Section 7.7 for discussion of 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 Underwriters Laboratories Inc. (UL) listed and/or factory mutual (FM) approved or requires approval by the appropriate SNS safety review committee. All personnel performing service on equipment are required to receive training in, and to adhere to, SNS ORNL lockout/tagout (LO/TO) policies (see Sections 4.2.4, “Electrical Safeguards” and 4.2.5, “Lockout/Tagout” of the *Final SAD for Proton Facilities*[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 de-energized. Such individuals are capable of working safely on energized circuits and are familiar with the proper use of special precautionary techniques, personal protective equipment (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 being followed. Users will be restricted from most activities where 70 E might apply and will follow 70 E for allowed activities where 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 through the application of 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 used are of magnitude great enough to justify concern from both a conventional fire protection point of view as well as from the point of view of preventing potential release of hazardous material due to 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 is capable of providing protection for a two-hour duration 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 utilized 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. The locations of any regions with fields greater than 0.5×10^{-3} T (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 due to 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 for servicing of 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 are capable of containing rotor components in the event of a failure. When this is not the case, 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 planning. With 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, the mitigated risk due to chopper rotating masses is made extremely low.

Positioning of beamline and instrument components requires the use of forklifts, overhead cranes, and specialized lifting equipment. 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

It is an SNS safety goal 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. In the event that 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. SBMS policies and procedures supplemented by SNS policies such as the *Safety for Cryogenic Operations at SNS*[3] ensure that any needed mitigation features, e.g., safety interlocks or alarms, are employed and that CECs are designated, where appropriate, in accordance with the *SNS Policy for Selection of Safety Related Credited Engineered Controls*.[4] The Instrument Safety Committee reviews these determinations. Appropriate protection, training, and procedures are required to ensure the hazard is appropriately mitigated in all phases of design and operation.

Each instrument is designed in depth to handle its own inventory of potential ODH gasses (documented for each specific case). Once outside enclosed areas specific to the individual instruments, the light gasses such as helium and hydrogen will quickly rise to the upper parts of the target building or instrument satellite building, and the total inventory would be diluted below a level that causes ODH when dispersed over this volume. Gases such as nitrogen and argon will remain near floor level in the target building or satellite building before mixing and could potentially lead to an ODH condition locally. At most only ~3 adjacent instruments could contribute to any such a condition, since contributions from other instruments would be local to a different area. If the gases spread out beyond the local area, even the maximum inventory would quickly disperse to below ODH levels. As explained above, oxygen deficiency hazard analyses are done for each instrument before it comes on line and are reviewed by the Instrument Safety Committee.

7.8 RADIATION HAZARDS

Radiation limits for the instrument hall have been set in compliance to 10 CFR 835[5] and the *SNS Shielding Policy*[6] to ensure shielding is adequate to reduce radiation to ALARA levels. As discussed in Section 4.2.1.1.1 of the *Final Safety Assessment Document for Proton Facilities,*[2] 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. Beamline and other shielding necessary to meet these guidelines are 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 7.8-1, 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 7.8-1 analysis is generic in nature and assumes "worst case" in beam/area dose rates. It is recognized that some or the instruments may incorporate features (e.g. robust passive design 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. Generally, it is not physically feasible for a person to insert their whole body into the beam. This 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.). At a one foot radius from the sample (excluding the incident and transmitted beam), the dose rate typically falls off to levels on the order of ~1–10 rem/h. These risks must be mitigated with 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 may be required. These may include 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, 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 7.8-1 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 Prior to Mitigation				
Note: Refer to Figure 4.1.1-1 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 Following Mitigation				
Consequence	( ) High	( ) Medium	(X) Low	( ) Extremely low
Probability	( ) Anticipated High	( ) Anticipated Medium	(X) Unlikely	( ) Extremely Unlikely
Risk Category	( ) High Risk	( ) Moderate	( ) Low Risk	**(X) Extremely Low**
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. Since the pressure differential is less than 15 psi, these chambers are not required to meet the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section VIII, Division 1,[16] or to be code stamped. However, as good practice they are designed to meet the stress level requirement of the ASME Pressure Vessel 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 only 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, 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, LO/TO 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 of the scattering chambers and all of the sample chambers are intended to be vacuum only. In cases where there is any perceived possibility that these chambers could become pressurized, they will have pressure relief valves or rupture disks installed. A few of the scattering chambers contain argon gas at roughly atmospheric pressure. For those cases, there will be pressure relief valves and appropriate venting of the argon.

7.10 OTHER HAZARDS

Other hazards are evaluated as the need arises under the ORNL SBMS Work Control process which provides procedures and guidelines for implementing ISM and safely evaluating and controlling hazards associated with proposed neutron beamline activities. For example, the use of flammable hydrogen has been reviewed by the Instrument Review Committee (with ORNL Fire Protection engineer participating) and approved for the Beam Line 13 NPDγ experiment. In addition, an Unreviewed Safety Issue Determination was conducted and it was concluded that this use of hydrogen did not constitute an unreviewed safety issue due to the nature of the experiment, the limited quantity of hydrogen involved, the location outside the building of the hydrogen supply cylinders and the use of a flow limiting device to limit the rate at which gaseous hydrogen could flow into the Instrument Beam Line 13 experiment enclosure (Reference: *USID for NPD-Gamma Liquid Hydrogen Target*, SNS 102030102-ES0029-R01, September 2008).

7.11 REFERENCES

1. Code of Federal Regulations, Title 29, “Labor,” Part 1900, U.S. Government Printing Office, Washington, DC.
2. Spallation Neutron Source Final Safety Assessment Document for Proton Facilities, SNS 102030103-ES0018-R02, Oak Ridge National Laboratory, Oak Ridge, TN, December 2010.
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, TN, June 2005.
4. SNS Policy for Selection of Safety Related Credited Engineered Controls, SNS 102030100-E0005-R00, Oak Ridge National Laboratory, Oak Ridge, TN, March 2005.
5. Code of Federal Regulations, Title 10, “Energy,” Part 835, “Occupational Radiation Protection,” U.S. Government Printing Office, Washington, DC.
6. Spallation Neutron Source Shielding Policy, SNS 102030000-ES0008, Oak Ridge National Laboratory, Oak Ridge, TN, November 2005.
7. ASME Boiler and Pressure Vessel Code, AMSE, Section VIII, American Society of Mechanical Engineers.

8.0 QUALITY ASSURANCE

Quality assurance (QA) at the SNS is addressed in the *Final Safety Assessment Document for Proton Facilities* (SNS 102030103 ES0018-R02, December 2010).

9.0 POST OPERATIONS PLANNING

9.1 INTRODUCTION

This chapter describes provisions that facilitate post operations of the Spallation Neutron Source (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

A number of laws, regulations, and Department of Energy (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 (NEPA), the Resource Conservation and Recovery Act (RCRA), and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Requirements under the Clean Air Act (CAA) and National Emission Standards for Hazardous Air Pollution (NESHAP), Clean Water Act (CWA), Occupational Safety and Health Administration (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 (TDEC), the U.S. Environmental Protection Agency (EPA), and the DOE, may apply to post operations activities as well. An important requirement that applies to SNS is DOE Order 430.1, *Life Cycle Asset Management*. Its implementation guides provide project management, environment, safety, and health (ES&H) 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 a number of 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. Establishing the expected baseline conditions of the facility at the end of its operating life can be accomplished 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 to include 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 be used in performing 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 over the life of the facility will provide the necessary records to help establish the baseline to facilitate post-operational 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 comprised 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 because they form the basis for other specific goals and activities that must take place. The goals for the HC and safety basis of the deactivated facility will be established, and determination will be made of defense-in-depth protection measures.

   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. It is assumed that institutional control will remain in place under federal oversight for a number of years after completion of 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 consideration of 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, while 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

   A number of the orders actually cover two or more of the categories, so there are often overlapping requirements across categories. Sound planning for interacting with the regulatory agencies, and compliance with these regulatory requirements, is 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 as low as reasonably achievable (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, and other parts will require a short decay period to achieve contact-handled levels of activation, while other parts of the facility will be remote handled for many years. Additionally, while decontamination is not a large part of the SNS post operations, certain areas and equipment that become contaminated during operation, or contaminated during post operations activities, will have surface decontamination techniques applied. Therefore, a variety of techniques and removal methods will be analyzed to select the approach that accomplishes the goals and optimizes safety to the workers and the environment, as well as efficiency.

7. Evaluate treatment requirements and disposal options for the wastes remaining from operations as well as those generated by the post operations activities.

There will be multiple waste streams to be managed during post operations. Some could be treated and/or disposed of locally, while 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 (P2) 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. It is known that 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 for the dismantlement of the SNS facility after cessation of operations and shutdown of the facility have been conducted.[1] The study provides recommendations of actions that could be taken during the design phase to reduce post operations costs, as well as exposure of personnel during post-operations activities.

The baseline alternative established in the study is decontamination of the entire facility since it would allow for the entire facility to be demolished and removed from the site. All of the SNS material will be contact handled except for the target and its associated components, the maintenance bay, and the beam dump copper targets and can be removed by conventional methods. 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. Dismantlement of the SNS facility will require a combination of standard techniques and specialized use of equipment to handle unusual conditions.

The general approach applied in the study for dismantlement of the front-end facility and user-support facilities is to use conventional methods. These can be applied since the facilities are aboveground, are not activated or contaminated except for the two 10,000-sq-ft areas in the technical support and service buildings, and are mostly standard equipment and structures. Dismantlement of the accelerator systems, from the LINAC tunnel to the target building, will require the use of 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 present-day techniques. Therefore, considerable effort will have to be placed on 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 accomplishing dismantlement of the facilities, while meeting required criteria.

9.5 REFERENCES

1. *Spallation Neutron Source Decontamination and Decommissioning Study,* SNS 102030200TR0002R00, Oak Ridge National Laboratory, Oak Ridge, TN, November 1999.

APPENDIX A THE CONTROLS MATRIX

Table A-1 presents the “Controls Matrix” for the 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 are grouped into columns which represent “levels of control”. As described in Section 4.2.2.4, a level of control (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 *level of control* 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 level of control while in other instances, a single control suffices as the entire level of control.

The controls Matrix shows credited controls that protect three different worker groups as defined below:

- WG1 includes worker nearest the hazard.
- WG2 includes workers inside the building but not in the immediate vicinity of the hazard.
- WG3 includes workers outside the building.

Terminology changes have occurred 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 Chapter 4 analysis; however, the three worker group categories (i.e. WG1, WG2, and WG3) are retained in the Controls Matrix because they offer a more detailed definition of impacts 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	Event Description	Public Evaluation			Worker Evaluation						
		Radiological		Chemical	Radiological				Chemical		
		CEC (1a, 1b) Primary or 2^{nd} level of control*	CEC/CAC lvl of control (5<C<25 rem) (2)*	CEC/CAC(3)*	Worker Group 1	Worker Group 2	Worker Group 3		Worker Group 1	Worker Group 2	Worker Group 3
					CEC/CAC (4 or 5)*	CEC/CAC (4 or 5)*	CEC/CAC (4 or 5)*	CEC/CAC 2^{nd} level of control (5)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*
		*NOTE: Numbers in parentheses correspond to criteria for selection of credited controls as outlined in SNS Policy for Selection of Safety Related Credited Controls (Section 4.2.2.4)									
Target Systems											
TS1-2	Medium Size Fire- Fire starts outside of the Target Service Bay and propagates to Transfer Cell and Target Service Bay (Air intake for the Transfer and Target Service Bay is located in the Decon Room.) Release of Hg and activated water from the systems in the Target Service Bay caused by the fire.	Not Required	Not Required	*Radiological controls for WG 3 are adequate for chemical protection of public	*Fire detection / suppression system (NFPA-13) outside fire barrier	*Fire detection / suppression system (NFPA-13) outside fire barrier	*2-hour fire barrier enclosing the Target Service Bay and core vessel. *Combustible Material Control Program outside the Target Service Bay. *PCES [Design Feature]. *Mercury inventory control on PCES charcoal adsorbers (for medium fire in charcoal adsorber room).	*Fire detection / suppression system (NFPA-13) outside fire barrier	*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	Target Service Bay Fire: Release of Hg and coolant inventory due to a fire in Target Service Bay [during Startup when shielding may not be in place] breaching the Hg Process System and Shroud Cooling System boundaries.	Not Required	Not Required	Radiological controls for WG 3 are adequate for chemical protection of public	*Transfer Bay Access Control (TBAC) System prevents inadvertent worker access to target service bay	*DP detect / alarm on loss of negative pressure between Target Service Bay and adjacent areas. *Procedures and training for evacuation of adjacent areas.	*2-hour equivalent fire barrier enclosing the Target Service Bay and core vessel. *PCES Design (backdraft damper, flame retardant exhaust filters) *Combustible Material Control Program for Target Service Bay interior.	*Fire Detection / Suppression System inside Target Service Bay or mercury loop steel shielding in place (or Hg drained from loop to Hg storage tank).	*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 during maintenance activity when the Target Service Bay, Transfer Cell, and High Bay are all open to a common air flow and mercury is drained to the storage tank.	Not Required	Not Required	Not Required	*DP detection / alarm on loss of negative pressure between Target Service Bay and adjacent areas. *Emergency Response Procedures (evacuation)	*DP detection / alarm on loss of negative pressure between Target Service Bay and adjacent areas. *Procedures and training (evacuation of adjacent areas).	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.
TS1-6	Fire during maintenance/other activity with worker in Transfer Cell and personnel door in the open position.	Not Required	Not Required	Not Required	*Same as TS1-3	*Same as TS1-3	*Same as TS1-3, with following addition: *Procedures and training (evacuation of Transfer Bay and close personnel access door upon evacuation).	*Same as TS1-3	*Same as TS1-3	*Same as TS1-3	*Same as TS1-3

Event	**Event Description**	**Public Evaluation**			**Worker Evaluation**						
		Radiological		**Chemical**	**Radiological**				**Chemical**		
		CEC (1a, 1b) **Primary or 2nd level of control***	**CEC/CAC lvl of control (5<C<25 rem) (2)***	**CEC/CAC(3)***	**Worker Group 1**	**Worker Group 2**	**Worker Group 3**		**Worker Group 1**	**Worker Group 2**	**Worker Group 3**
					CEC/CAC (4 or 5)*	**CEC/CAC (4 or 5)***	**CEC/CAC (4 or 5)***	**CEC/CAC 2nd level of control (5)***	**CEC/CAC (4)***	**CEC/CAC (4)***	**CEC/CAC (4)***
		***NOTE: Numbers in parentheses correspond to criteria for selection of credited controls as outlined in SNS Policy for Selection of Safety Related Credited Controls (Section 4.2.2.4)**									
TS3-4 and TS3-6	Release of Hg and activated shroud cooling water into Core Vessel due to catastrophic failure of target module caused by loss of material integrity.	Not Required	Not Required	Not Required	*Physical access within Core Vessel not credible w/ systems operational.*	*Confinement function of core vessel and neutron beam windows.	Not Required	Not Required	*Physical access within Core Vessel not credible w/ systems operational.*	Radiological controls for WG 2 are adequate for chemical protection	*Not required.
TS3-7	Loss of Hg (Small Break or Leak): Release of Hg inside the Target Service Bay from various locations.	Not Required	Not Required	Not Required	*Transfer Bay Access Control (TBAC) System prevents inadvertent worker access to target service bay	*Target Service Bay confinement of mercury. *PCES and associated ductwork. *DP detection / alarm on loss of negative pressure between Target Service Bay and adjacent areas. *Procedures and training (evacuation of adjacent areas).	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 Hg (Small Break or Leak): Release of Hg inside the Core Vessel due to a leak or a break from loss of material integrity.	Not Required	Not Required	Not Required	*Physical access within Core Vessel not credible w/ systems operational.*	*Confinement function of core vessel and neutron beam windows.	Not Required	Not Required	*Physical access within Core Vessel not credible w/ systems operational.*	Radiological controls for WG 2 are adequate for chemical protection.	*Not required.
TS3-9	Release of Intermediate Cooling Water into the Hg Process System due to a break in the Mercury Heat Exchanger leads to Hg release in core vessel.	Not Required	Not Required	Not Required	*Physical access within Core Vessel not credible w/ systems operational.*	*Robust design of Hg / Intermediate Cooling Loop Heat Exchanger.	Not Required	Not Required	Not Required	Radiological controls for WG 2 are adequate for chemical protection.	Not required.

Event	Event Description	Public Evaluation			Worker Evaluation						
		Radiological		Chemical	Radiological				Chemical		
		CEC (1a, 1b) Primary or 2nd level of control*	CEC/CAC lvl of control (5<C<25 rem) (2)*	CEC/CAC(3)*	Worker Group 1	Worker Group 2	Worker Group 3		Worker Group 1	Worker Group 2	Worker Group 3
					CEC/CAC (4 or 5)*	CEC/CAC (4 or 5)*	CEC/CAC (4 or 5)*	CEC/CAC 2nd level of control (5)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*
		***NOTE: Numbers in parentheses correspond to criteria for selection of credited controls as outlined in SNS Policy for Selection of Safety Related Credited Controls (Section 4.2.2.4)**									
TS3-10	Loss of Hg (Large Break): Release of Hg inside the Target Service Bay due to a large break in the Hg Process Loop.	Not Required	Not Required	Not Required	*Transfer Bay Access Control (TBAC) System prevents inadvertent worker access to target service bay	*Target Service Bay confinement of mercury. *PCES and associated ductwork. *DP detection / alarm on loss of negative pressure between Target Service Bay and adjacent areas. *Procedures and training (evacuation of adjacent areas).	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 Hg Flow: Release of Hg and Shroud Cooling Water inventory due to overheating of Target Plug caused by partial loss of Hg Flow from a dislodged object blocking the flow path to the window region or installing the wrong orifice.	Not Required	Not Required	Not Required	*Physical access within Core Vessel not credible w/ systems operational.*	*Confinement function of core vessel and neutron beam windows.	Not Required	Not Required	*Physical access within Core Vessel not credible w/ systems operational.*	Radiological controls for WG 2 are adequate for chemical protection.	Not required.
TS3-12	Full Loss of Hg Flow: Release of Hg and Shroud Cooling Water inventory into Core Vessel due to overheating of Target module caused by loss of Hg Flow.	Not Required	Not Required	Not Required	*Physical access within Core Vessel not credible w/ systems operational.*	*Beam cut-off upon out of limits differential pressure across the mercury pump.	*Beam cut-off upon out of limits differential pressure across the mercury pump.	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.
TS3-13	Loss of Heat Sink: Release of Hg and Shroud Cooling Water inventory into the core vessel due to overheating of Target Carriage caused by loss of cooling to Hg due to failure in the Intermediate Cooling Water system.	Not Required	Not Required	Not Required	*Physical access within Core Vessel not credible w/ systems operational.*	*Beam cut-off upon high mercury temperature.	*Beam cut-off upon high mercury temperature.	Not required.	*Physical access within Core Vessel not credible w/ systems operational.*	Radiological controls for WG 2 are adequate for chemical protection.	Radiological controls for WG 3 are adequate for chemical protection.

Event	Event Description	Public Evaluation			Worker Evaluation						
		Radiological		Chemical	Radiological				Chemical		
		CEC (1a, 1b) Primary or 2^{nd} level of control*	CEC/CAC lvl of control (5<C<25 rem) (2)*	CEC/CAC(3)*	Worker Group 1	Worker Group 2	Worker Group 3		Worker Group 1	Worker Group 2	Worker Group 3
					CEC/CAC (4 or 5)*	CEC/CAC (4 or 5)*	CEC/CAC (4 or 5)*	CEC/CAC 2^{nd} level of control (5)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*
		*NOTE: Numbers in parentheses correspond to criteria for selection of credited controls as outlined in SNS Policy for Selection of Safety Related Credited Controls (Section 4.2.2.4)									
TS3-14	Loss of Heat Sink: Release of Hg and Shroud Cooling Water inventory into the core vessel due to overheating of Target Carriage caused by loss of cooling to Hg due to flow blockage in the Intermediate Cooling Water Loop 1.	Not Required	Not Required	Not Required	*Physical access within Core Vessel not credible w/ systems operational.*	*Beam cut-off upon high mercury temperature.	*Beam cut-off upon high mercury temperature.	Not required.	*Physical access within Core Vessel not credible w/ systems operational.*	Radiological controls for WG 2 are adequate for chemical protection.	Radiological controls for WG 3 are adequate for chemical protection.
TS3-15	Loss of Heat Sink: Release of Hg and Shroud Cooling Water inventory due to over heating of Target Module caused by loss of cooling to Hg due to failure in the Intermediate (Cooling Loop 1) system.	Not Required	Not Required	Not Required	*Physical access within Core Vessel not credible w/ systems operational.*	*Beam cut-off upon high mercury temperature.	*Beam cut-off upon high mercury temperature.	Not required.	*Physical access within Core Vessel not credible w/ 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 Hg and Shroud Cooling Water inventory into core vessel due to over heating of Target Module caused by loss of cooling to Hg due to Intermediate (Cooling Loop 1) System.	Not Required	Not Required	Not Required	*Physical access within Core Vessel not credible w/ systems operational.*	*Beam cut-off upon high mercury temperature.	*Beam cut-off upon high mercury temperature.	Not required.	*Physical access within Core Vessel not credible w/ 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 Hg inventory into the Target Service Bay due to heavy load drop by the Target Service Bay Crane.	Not Required	Not Required	Not Required	*TBAC system prevents inadvertent worker access to target service bay	*DP detection / alarm on loss of negative pressure between Target Service Bay and adjacent areas. *Procedures and training (evacuation of adjacent areas). *PCES and associated ductwork. *Target Service Bay confinement of mercury.	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	Event Description	Public Evaluation			Worker Evaluation						
		Radiological		Chemical	Radiological				Chemical		
		CEC (1a, 1b) Primary or 2^{nd} level of control*	CEC/CAC lvl of control (5<C<25 rem) (2)*	CEC/CAC(3)*	Worker Group 1	Worker Group 2	Worker Group 3		Worker Group 1	Worker Group 2	Worker Group 3
					CEC/CAC (4 or 5)*	CEC/CAC (4 or 5)*	CEC/CAC (4 or 5)*	CEC/CAC 2^{nd} level of control (5)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*
		*NOTE: Numbers in parentheses correspond to criteria for selection of credited controls as outlined in SNS Policy for Selection of Safety Related Credited Controls (Section 4.2.2.4)									
TS3-21	Release of Hg to the cooling tower due to breach in the Hg / HX while operating with an existing breach in the Cooling Loop 1/ Tower water HX. Hg contamination of tower water occurs.	Not Required	Not Required	Not Required	Not Required	Not Required	Not Required	Not Required	*Robust design of Hg / Intermediate Cooling Loop Heat Exchanger.	*Robust design of Hg / Intermediate Cooling Loop Heat Exchanger.	Not required
TS3-22	Partial Loss of Hg Flow: Release of Hg and Shroud Cooling Water inventory due to continuous reduction of Hg flow over time and subsequent overheating of Target Module from worn or failing component.	Not Required	Not Required	Not Required	*Physical access within Core Vessel not credible w/ systems operational.*	*Beam cut-off-upon out of limits differential pressure across the mercury pump.	*Beam cut-off upon out of limits differential pressure across the mercury pump.	Not Required	*Physical access within Core Vessel not credible w/ systems operational.*	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection.
TS3-23	Partial Loss of Hg Flow: Release of Hg and Shroud Cooling Water inventory due to immediate partial loss of Hg flow and subsequent overheating of Target Module	Not Required	Not Required	Not Required	*Physical access within Core Vessel not credible w/ systems operational.*	*Beam cut-off upon out of limits differential pressure across the mercury pump.	*Beam cut-off upon out of limits differential pressure across the mercury pump.	Not Required	*Physical access within Core Vessel not credible w/ 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 Hg Flow: Release of Hg and Shroud Cooling Water inventory due to immediate partial loss of Hg flow and subsequent overheating of Target Module from pump failure.	Not Required	Not Required	Not Required	*Physical access within Core Vessel not credible w/ systems operational.*	*Beam cut-off upon out of limits differential pressure across the mercury pump.	*Beam cut-off upon out of limits differential pressure across the mercury pump.	Not Required	*Physical access within Core Vessel not credible w/ systems operational.*	Radiological controls for WG 2 are adequate for chemical protection	Radiological controls for WG 3 are adequate for chemical protection.

Event	Event Description	Public Evaluation			Worker Evaluation						
		Radiological		Chemical	Radiological				Chemical		
		CEC (1a, 1b) Primary or 2^{nd} level of control*	**CEC/CAC lvl of control (5<C<25 rem) (2)***	**CEC/CAC(3)***	**Worker Group 1**	**Worker Group 2**	**Worker Group 3**		**Worker Group 1**	**Worker Group 2**	**Worker Group 3**
					CEC/CAC (4 or 5)*	**CEC/CAC (4 or 5)***	**CEC/CAC (4 or 5)***	**CEC/CAC 2^{nd} level of control (5)***	**CEC/CAC (4)***	**CEC/CAC (4)***	**CEC/CAC (4)***
		***NOTE: Numbers in parentheses correspond to criteria for selection of credited controls as outlined in SNS Policy for Selection of Safety Related Credited Controls (Section 4.2.2.4)**									
TS3-25	Partial Loss of Hg Flow: Release of Hg and Shroud Cooling Water inventory due to partial loss of Hg flow and subsequent overheating of Target Module from motor speed controller failure.	Not Required	Not Required	Not Required	*Physical access within Core Vessel not credible w/ systems operational.*	*Beam cut-off upon out of limits differential pressure across the mercury pump.	*Beam cut-off upon out of limits differential pressure across the mercury pump.	Not Required	*Physical access within Core Vessel not credible w/ 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 Hg Flow: Release of Hg and Shroud Cooling Water inventory due to partial loss of Hg flow and subsequent overheating of Target Module from obstruction in line.	Not Required	Not Required	Not Required	*Physical access within Core Vessel not credible w/ systems operational.*	*Confinement function of core vessel and beam windows	*Confinement function of core vessel and beam windows	Not Required	*Physical access within Core Vessel not credible w/ 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 Hg Flow: Release of Hg and Shroud Cooling Water inventory due to partial loss of Hg flow and subsequent overheating of Target Module from foreign material left in system during maintenance.	Not Required	Not Required	Not Required	*Physical access within Core Vessel not credible w/ systems operational.*	*Confinement function of core vessel and beam windows	*Confinement function of core vessel and beam windows	Not Required	*Physical access within Core Vessel not credible w/ 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 Hg into the mercury target off-gas system during initial filling of the mercury pump tank.	Not Required	Not Required	Not Required	*Mercury pump tank exhaust line loop seal.	*Mercury pump tank exhaust line loop seal.	Not Required	Not Required	*Not Required*	Not Required	Not required
TS4-1	Inadvertent beam on target when the Target carriage is in the withdrawn position, e.g., for maintenance or re-targeting.	Not Required	Not Required	Not Required	PPS prevents Beam Permit mode based on target carriage position switch status.	PPS prevents Beam Permit mode based on target carriage position switch status.	PPS prevents Beam Permit mode based on target carriage position detector switch.	TPS prevents beam to target when target carriage withdrawn (based on out of limits differential pressure across mercury pump).	Not Required	Not Required	Not Required

Event	Event Description	Public Evaluation			Worker Evaluation						
		Radiological		Chemical	Radiological				Chemical		
		CEC (1a, 1b) Primary or 2nd level of control*	CEC/CAC lvl of control (5<C<25 rem) (2)*	CEC/CAC(3)*	Worker Group 1	Worker Group 2	Worker Group 3		Worker Group 1	Worker Group 2	Worker Group 3
					CEC/CAC (4 or 5)*	CEC/CAC (4 or 5)*	CEC/CAC (4 or 5)*	CEC/CAC 2nd level of control (5)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*
		***NOTE: Numbers in parentheses correspond to criteria for selection of credited controls as outlined in SNS Policy for Selection of Safety Related Credited Controls (Section 4.2.2.4)**									
TS4-2	Direct radiological exposure from residual Hg during target changeout activity in the Target Service Bay.	Not Required	Not Required	Not Required	*TBAC system prevents inadvertent worker access to target service bay.	*TBAC system initiates evac alarm if intrabay shielding doors not closed when Transfer Bay access door open.	Not Required	Not Required	Not Required	Not Required	Not required
					Cryogenic Moderator System						
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. Follow-on fire results.	Not Required	Not Required	*Radiological controls for WG 3 adequate for chemical protection of public	*Physical access within Core Vessel not credible w/ systems operational.*	*Robust hydrogen barrier design including relief path.	*Robust hydrogen barrier design including relief path.	*Robust vacuum barrier design including relief path.	*Physical access within Core Vessel not credible w/ 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	Not Required	*Radiological controls for WG 3 adequate for chemical protection of public	*Physical access within Core Vessel not credible w/ systems operational.*	*Robust hydrogen barrier design including relief path.	*Robust hydrogen barrier design including relief path.	*Robust vacuum barrier design including relief path.	*Physical access within Core Vessel not credible w/ systems operational.*	*Radiological controls for WG 2 are adequate for chemical protection.	Radiological controls for WG 3 are adequate for chemical protection.

Event	Event Description	Public Evaluation			Worker Evaluation						
		Radiological		Chemical	Radiological				Chemical		
		CEC (1a, 1b) Primary or 2^{nd} level of control*	CEC/CAC lvl of control (5<C<25 rem) (2)*	CEC/CAC(3)*	Worker Group 1	Worker Group 2	Worker Group 3		Worker Group 1	Worker Group 2	Worker Group 3
					CEC/CAC (4 or 5)*	CEC/CAC (4 or 5)*	CEC/CAC (4 or 5)*	CEC/CAC 2^{nd} level of control (5)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*
		*NOTE: Numbers in parentheses correspond to criteria for selection of credited controls as outlined in SNS Policy for Selection of Safety Related Credited Controls (Section 4.2.2.4)									
Cooling Water Loops 2, 3, & 4											
CW3-16	Breach of cooling water (heavy water or light water) from Cooling Loop 2 (proton beam window only), 3 or 4 gas/liquid separators. Contaminated/tritiated water collects in gas/liquid separators concrete pit and migrates through porous concrete or cracks in the concrete into the manipulator gallery below from material defect, corrosion, fatigue from vibration, improper seal at system joints, heavy load drops in the High Bay area into the gas/liquid separators pit, or rupture during seismic activity.	Not Required	Not Required	Not Required	Not required	Not required	Not Required	Not Required	Not Required	Not Required	Not required.

Event	Event Description	Public Evaluation			Worker Evaluation						
		Radiological		Chemical	Radiological				Chemical		
		CEC (1a, 1b) Primary or 2nd level of control*	CEC/CAC lvl of control (5<C<25 rem) (2)*	CEC/CAC(3)*	Worker Group 1	Worker Group 2	Worker Group 3		Worker Group 1	Worker Group 2	Worker Group 3
					CEC/CAC (4 or 5)*	CEC/CAC (4 or 5)*	CEC/CAC (4 or 5)*	CEC/CAC 2nd level of control (5)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*
		*NOTE: Numbers in parentheses correspond to criteria for selection of credited controls as outlined in SNS Policy for Selection of Safety Related Credited Controls (Section 4.2.2.4)									
CW4-1	Direct Radiological exposure of personnel to activated cooling water loops 2, 3, or 4. Personnel in direct line-of-sight and in immediate vicinity of cooling systems in basement utility vault, target 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	Not Required	Radiological Protection Program (control of access to vaults, control of placement of shielding)	Radiological Protection Program (control of access to vaults, control of placement of shielding)	Not Required	Not Required	*Not Required*	Not Required	Not required.
Mercury Offgas Treatment, Vacuum, and Helium Systems											
GW3-2	Leak or breach of mercury offgas system within the Target Service Bay resulting in release of mercury vapor and/or offgas into the Target Service Bay atmosphere.	Not Required	Not Required	Not Required	*TBAC system prevents inadvertent worker access to target service bay	Not Required	Not Required	Not Required	Radiological controls for WG 1 are adequate for chemical protection	Service Bay Differential Pressure Monitoring System. *Procedures and training (evacuation of adjacent areas)	*Not required.
Contact Waste Handling and Decontamination Area											

Event	Event Description	Public Evaluation			Worker Evaluation						
		Radiological		Chemical	Radiological				Chemical		
		CEC (1a, 1b) Primary or 2nd level of control*	CEC/CAC lvl of control (5<C<25 rem) (2)*	CEC/CAC(3)*	Worker Group 1	Worker Group 2	Worker Group 3		Worker Group 1	Worker Group 2	Worker Group 3
					CEC/CAC (4 or 5)*	CEC/CAC (4 or 5)*	CEC/CAC (4 or 5)*	CEC/CAC 2nd level of control (5)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*
		*NOTE: Numbers in parentheses correspond to criteria for selection of credited controls as outlined in SNS Policy for Selection of Safety Related Credited Controls (Section 4.2.2.4)									
WH2-2	Release of radiological material due to explosion involving ion exchange resin in the Contact Waste Handling and Decontamination Area.	Not Required	Not Required	Not Required	Not Required	Not Required	Not Required	Not Required	Not Required	Not Required	Not required.
Confinement Ventilation											
HV3-5	Breach of HEPA filter confinement package from mishandling or defect results in release of radiological material (during replacement).	Not Required	Not Required	Not Required	*Radiological Protection Program.	*Radiological Protection Program.	Not Required	Not Required	Not Required	Not Required	Not required.
Core Vessel General Area, Shielding/Reflectors/Shutters											
SH4-1	Misaligned target module results in radiation streaming into the Target Service Bay and the adjacent operating/service galleries. Misaligned proton beam window plug assembly or core vessel inner plug assembly (with moderator vessels) results in radiation streaming into the high bay area.	Not Required	Not Required	Not Required	*Radiological Protection Program.	*Radiological Protection Program.	Not Required	Not Required	Not Required	Not Required	Not required.
SH4-2	Voids/cracks in concrete shielding result in abnormally high radiation levels in occupied areas of Target Building.	Not Required	Not Required	Not Required	*Radiological Protection Program.	*Radiological Protection Program.	Not Required	Not Required	Not Required	Not Required	Not required.

Event	**Event Description**	**Public Evaluation**			**Worker Evaluation**						
		Radiological		**Chemical**	**Radiological**				**Chemical**		
		CEC (1a, 1b) **Primary or 2^{nd} level of control***	**CEC/CAC lvl of control (5<C<25 rem) (2)***	**CEC/CAC(3)***	**Worker Group 1**	**Worker Group 2**	**Worker Group 3**		**Worker Group 1**	**Worker Group 2**	**Worker Group 3**
					CEC/CAC (4 or 5)*	**CEC/CAC (4 or 5)***	**CEC/CAC (4 or 5)***	**CEC/CAC 2^{nd} level of control (5)***	**CEC/CAC (4)***	**CEC/CAC (4)***	**CEC/CAC (4)***
		***NOTE: Numbers in parentheses correspond to criteria for selection of credited controls as outlined in SNS Policy for Selection of Safety Related Credited Controls (Section 4.2.2.4)**									
SH4-3	Inadvertent shutter opening during operations when beamline shielding not in place.	Not Required	Not Required	Not Required	*Radiological Protection Program.	Not Required	Not Required	Not Required	Not Required	Not Required	Not required.
SH4-4	Direct radiological exposure to worker during shutter removal.	Not Required	Not Required	Not Required	*Radiological Protection Program.	*Radiological Protection Program.	Not Required	Not Required	Not Required	Not Required	Not required.
Target Service Bay General Area											
TC3-1	Loss of confinement from Target Service Bay allows leakage of Hg vapor and other radiological material to occupied areas (crediting assumes loss of PCES ventilation of target service bay during transfer bay access).	Not Required	Not Required	Not Required	*DP detection and alarm on loss of negative pressure between Target Service Bay and adjacent areas. *Procedures and training (evacuation).	*DP detection and alarm on loss of negative pressure between Target Service Bay and adjacent areas. *Procedures and training (evacuation of adjacent areas).	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	Event Description	Public Evaluation			Worker Evaluation						
		Radiological		Chemical	Radiological				Chemical		
		CEC (1a, 1b) **Primary or 2^{nd} level of control***	**CEC/CAC lvl of control (5<C<25 rem) (2)***	**CEC/CAC(3)***	**Worker Group 1**	**Worker Group 2**	**Worker Group 3**		**Worker Group 1**	**Worker Group 2**	**Worker Group 3**
					CEC/CAC (4 or 5)*	**CEC/CAC (4 or 5)***	**CEC/CAC (4 or 5)***	**CEC/CAC 2^{nd} level of control (5)***	**CEC/CAC (4)***	**CEC/CAC (4)***	**CEC/CAC (4)***
		***NOTE: Numbers in parentheses correspond to criteria for selection of credited controls as outlined in SNS Policy for Selection of Safety Related Credited Controls (Section 4.2.2.4)**									
TC3-2	Target drive mechanism drives target module liner into core vessel colliding with the core vessel. Alternately, target drive mechanism drives target module into Target Service Bay during module removal for retargeting. The target module carriage collides with Target Service Bay components. Residual mercury remaining in the module is spilled into the Target Service Bay.	Not Required	Not Required	Not Required	*TBAC system prevents inadvertent worker access to target service bay.	*DP detection / alarm on loss of negative pressure between Target Service Bay and adjacent areas. *Procedures and training (evacuation of adjacent areas).	Not Required	Not Required	Radiological controls for WG 1 adequate for chemical protection	Radiological controls for WG 2 adquate for chemical protection	Not required.
TC3-3	During beam on operations, target module drive mechanism activates, driving target module and shielding plug out of core vessel while the module is filled with mercury. Mercury jumper piping and shroud cooling water jumper piping are attached. Jumper piping and/or seals deform (or break) allowing mercury and shroud cooling water at nominal operating temperature to spill into the Target Service Bay from both supply and return lines. Beam stays on and mercury pump continues to pump until pump tank level is below impeller suction.	Not Required	Not Required	Not Required	TBAC system prevents inadvertent worker access to target service bay.	*Target Service Bay confinement of mercury. *PCES and associated ductwork. *DP detection / alarm on loss of negative pressure between Target Service Bay and adjacent areas. *Procedures and training (evacuation of adjacent areas).	Not Required	Not Required	Radiological controls for WG 1 adequate for chemical protection	Radiological controls for WG 2 are adequate for chemical protection.	*Not required.

Event	**Event Description**	**Public Evaluation**			**Worker Evaluation**						
		Radiological		**Chemical**	**Radiological**				**Chemical**		
		CEC (1a, 1b) **Primary or 2nd level of control***	**CEC/CAC lvl of control (5<C<25 rem) (2)***	**CEC/CAC(3)***	**Worker Group 1**	**Worker Group 2**	**Worker Group 3**		**Worker Group 1**	**Worker Group 2**	**Worker Group 3**
					CEC/CAC (4 or 5)*	**CEC/CAC (4 or 5)***	**CEC/CAC (4 or 5)***	**CEC/CAC 2nd level of control (5)***	**CEC/CAC (4)***	**CEC/CAC (4)***	**CEC/CAC (4)***
		***NOTE: Numbers in parentheses correspond to criteria for selection of credited controls as outlined in SNS Policy for Selection of Safety Related Credited Controls (Section 4.2.2.4)**									
TC4-1	Inadvertent opening of intrabay shield door between Transfer Bay and Maintenance (hot) Cell while personnel are working in Transfer Cell from worker error or drive motor short results in excessive worker exposure.	Not Required	Not Required	Not Required	*Transfer Bay Access Control System	*Transfer Bay Access Control System	Not Required	Not Required	Not Required	Not Required	Not Required
TC4-2	Load suspended from Target Service Bay crane swings during sudden lateral movement of crane trolley. Load swings into shielded viewing window, partially or fully shattering the window. Personnel in the operating gallery are exposed to direct radiation from the Target Service Bay or maintenance cell.	Not Required	Not Required	Not Required	TBAC system prevents inadvertent worker access to target service bay.	*Hoisting and Rigging Program *Radiological Protection Program (radworker training)	Not Required	Not Required	Not Required	Not Required	Not Required
TC4-3	Direct exposure to radioactive Hg due to a breach in the Hg/Cooling Loop 1 heat exchanger.	Not Required	Not Required	Not Required	*Robust design of Hg / Intermediate Cooling Loop Heat Exchanger.	*Robust design of Hg / Intermediate Cooling Loop Heat Exchanger.	Not Required	Not Required	Not Required	Not Required	Not Required
TC4-4	Direct radiological exposure to worker performing maintenance/other activity in Transfer Cell with personnel door in the open position from mercury vapor due to loss of ventilation (see also event TC3-1).	Not Required	Not Required	Not Required	*DP alarm on loss of ventilation in Target Service Bay. *Procedures and training (evacuation).	*DP alarm on loss of ventilation in Target Service Bay. *Procedures and training (evacuation of adjacent areas).	Not Required	Not Required	Not Required	Not Required	Not Required

Event	**Event Description**	**Public Evaluation**			**Worker Evaluation**						
		Radiological		**Chemical**	**Radiological**				**Chemical**		
		CEC (1a, 1b) **Primary or 2nd level of control***	**CEC/CAC lvl of control (5<C<25 rem) (2)***	**CEC/CAC(3)***	**Worker Group 1**	**Worker Group 2**	**Worker Group 3**		**Worker Group 1**	**Worker Group 2**	**Worker Group 3**
					CEC/CAC (4 or 5)*	**CEC/CAC (4 or 5)***	**CEC/CAC (4 or 5)***	**CEC/CAC 2nd level of control (5)***	**CEC/CAC (4)***	**CEC/CAC (4)***	**CEC/CAC (4)***
		***NOTE: Numbers in parentheses correspond to criteria for selection of credited controls as outlined in SNS Policy for Selection of Safety Related Credited Controls (Section 4.2.2.4)**									
High Bay Area											
HB2-2	Release of radiological material (Hg) from the core vessel as the 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	Not Required	Radiological controls for WG 3 are adequate for chemical protection..	*Physical access within Core Vessel not credible w/ systems operational.*	*High Bay crane design. *Hoisting and Rigging Program. *Robust, externally protected hydrogen barrier design in high bay.	*High Bay crane design. *Hoisting and Rigging Program. *Robust, externally protected hydrogen barrier design in high bay.	*High Bay Floor Design *Procedures and training prohibiting crane lifts that exceed floor capacity over Core Vessel unless beam is shut down and mercury is drained from the target module system into mercury storage tank.	*Physical access within Core Vessel not credible w/ 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	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 on Target Service Bay results in release of radiological material (Hg) from Target Service Bay. No explosion.	Not Required	Not Required	Not Required	* TBAC system prevents inadvertent worker access to target service bay	*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.	*High bay crane design *Hoisting and Rigging Program
HB3-6	Dropped transfer cell shielding door from failure of suspension system or operator error results in release of radiological material.	Not Required	Not Required	Not Required	*Transfer Bay Access Control System	*Transfer Bay Access Control System	Not Required	Not Required	Not Required	Not Required	Not required.

Event	**Event Description**	**Public Evaluation**			**Worker Evaluation**						
		Radiological		**Chemical**	**Radiological**				**Chemical**		
		CEC (1a, 1b) **Primary or 2nd level of control***	**CEC/CAC lvl of control (5<C<25 rem) (2)***	**CEC/CAC(3)***	**Worker Group 1**	**Worker Group 2**	**Worker Group 3**		**Worker Group 1**	**Worker Group 2**	**Worker Group 3**
					CEC/CAC (4 or 5)*	**CEC/CAC (4 or 5)***	**CEC/CAC (4 or 5)***	**CEC/CAC 2nd level of control (5)***	**CEC/CAC (4)***	**CEC/CAC (4)***	**CEC/CAC (4)***
		***NOTE: Numbers in parentheses correspond to criteria for selection of credited controls as outlined in SNS Policy for Selection of Safety Related Credited Controls (Section 4.2.2.4)**									
HB3-7	Release of radiological material (Hg) from the core vessel as the 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	Not Required	*Physical access within Core Vessel not credible w/ systems operational.*	*High Bay crane design. *Hoisting and Rigging Program	Not Required	Not Required	*Physical access within Core Vessel not credible w/ systems operational.*	Radiological controls for WG 2 are adequate for chemical protection.	*High bay crane design *Hoisting and Rigging Program
HB4-3	Excessive exposure to radiation due to inappropriate removal of movable shielding in the high bay area, e.g. by use of the high bay crane.	Not Required	Not Required	Not Required	Radiological Protection Program (control of access to radiological areas and the placement of shielding)	Radiological Protection Program (control of access to radiological areas and the placement of shielding)	Not Required	Not Required	Not Required	Not Required	Not Required
Target Building General											
BG1-1	Facility wide fire results in release of hazardous material (fire originates outside the target service bay).	Not Required	Not Required	Radiological controls for WG 3 are adequate for public chemical protection	TBAC system prevents inadvertent worker access to target service bay	*2-hour equivalent fire barrier enclosing the Target Service Bay and core vessel *Combustible Material Control Program outside the Target Service Bay *PCES [Design Feature, location of air intake]	*2-hour equivalent fire barrier enclosing the Target Service Bay and core vessel *Combustible Material Control Program outside the Target Service Bay *PCES [Design Feature, location of air intake] *Mercury inventory control on PCES charcoal adsorbers (assumes fire reaches charcoal adsorber room).	*Fire Detection / Suppression System (NFPA-13) outside Target Service Bay.	Radiological controls for WG 1 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	Event Description	Public Evaluation			Worker Evaluation						
		Radiological		Chemical	Radiological				Chemical		
		CEC (1a, 1b) Primary or 2nd level of control*	CEC/CAC lvl of control (5<C<25 rem) (2)*	CEC/CAC(3)*	Worker Group 1	Worker Group 2	Worker Group 3		Worker Group 1	Worker Group 2	Worker Group 3
					CEC/CAC (4 or 5)*	CEC/CAC (4 or 5)*	CEC/CAC (4 or 5)*	CEC/CAC 2nd level of control (5)*	CEC/CAC (4)*	CEC/CAC (4)*	CEC/CAC (4)*
		*NOTE: Numbers in parentheses correspond to criteria for selection of credited controls as outlined in SNS Policy for Selection of Safety Related Credited Controls (Section 4.2.2.4)									
BG6-11	External crane drops load on Target Building or impacts building resulting in release of radiological material (Hg).	Not Required	Not Required	Radiological controls for WG 3 are adequate for public chemical protection	*Hoisting and Rigging Program for external crane.	*Hoisting and Rigging Program for external crane.	*Hoisting and Rigging Program for external crane.	*Emergency Response Procedures and training for external crane load 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
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	Not Required	Radiological controls for WG 3 adequate for public chemical protection	*N/A (instinctive worker evacuation of the target building in a severe seismic event).	*N/A (instinctive worker evacuation of the building in a severe seismic event).	*2-hour equivalent fire barrier enclosing the Target Service Bay and core vessel (includes bulk shielding liner drain termination point) qualified to PC-2 *Combustible Material Control Program outside the Target Service Bay. *Combustible Material Control Program inside the Target Service Bay. *Robust hydrogen barrier design (PC-3) *Seismically qualified / restrained / protected hydrogen equipment to PC-3. *Mercury Inventory Control on the PCES charcoal adsorbers	*Target Service Bay confinement of mercury (drain, slope, liner, and mercury loop steel shielding seismically qualified to PC-2). *Ignition Control Program outside Target 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
BG7-2	Structural damage to Target Building from earthquake results in release of radiological material. No explosions or fires.	Not Required	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 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.	*Target service bay confinement of mercury (interior cell structures seismically qualified to PC-2)
BG7-3	Structural damage to system components and Target Building from earthquake followed by hydrogen explosion results in release of radiological material.	Not Required	Not Required	Radiological controls for WG 3 adequate for public chemical protection	*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).	*Robust hydrogen and barrier design (PC-3) *Seismically qualified / restrained / protected hydrogen equipment to PC-3. *Robust vacuum barrier design including relief path. qualified to PC-2	*Target Service Bay confinement of mercury (drain, slope, liner seismically qualified to PC-2).	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.