REVISION 9a

Thomas Jefferson
National Accelerator Facility

Safety Assessment Document

April 2025

Prepared for the U.S. Department of Energy
under Contract DE-AC05-06OR23177

APPROVALS

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Associate Director Facilities Management and Logistics	______________________________ Kent Hammack	_____________ Date
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REVISION HISTORY

rev*	summary	approval	date
9a	• Added FM&L to signature page • Numerous edits to address opportunities for improvement and findings related to content and formatting from multiple reviews • Addition of RF testing as an operational mode in CEBAF, LERF, and UITF • Addition of links to controls summary for each accelerator	- ES&H Division Manager - FM&L Department Manager - Accelerator Division AD - Physics Division AD - Lab Director	

9	• updated
	  ○ title of document to Safety Assessment Document
	  ○ Appendix B, including descriptions and hazard assessments of accelerators operating at or below 10 MeV
	• formatting throughout
	• re-arranged content, relocated section 7.0 between 6.0 and Appendix A
		- ES&H Division Manager
		- Accelerator Division AD
		- Physics Division AD
		- Lab Director
			08/19/2024

8d	Changes to Sections 1 and 2 related to DOE O 420.2D definitions for accelerator and accelerator operations.	(minor update) - ES&H signoff - Accelerator signoff - Physics signoff	12/15/2023
8c	Refines links to NEPA process documents for bounding conditions. Changes administrative limit and operating envelope to 1.3 MW and 1.1 MW. Evaluates hazard and updates tables in Section 5 accordingly, updates description of Hall B beam termination points, corrections to references, org charts.	(minor update) - ES&H signoff - Accelerator signoff - Physics signoff	9/22/2022
8b	Updated Hall B tagger as acceptable beam destination under certain circumstances. Removed Hall C beam line Moeller Polarimeter Vent as Credited Control. Updated ODH section to reflect nitrogen generators use. Updated injector beamline designations to line-up with revised ASE. Added shielding Credited Control Designation to injector existing shielding. Removed BSY Dump. Add link to NEPA process documents for bounding conditions.	(minor update) - ES&H signoff - Accelerator signoff - Physics signoff	01/21/2022
Periodic Review	No changes as no positive USI that requires an update to the SAD.	n/a	10/07/2020
8a	Removed UITF BCM Credited Control requirement and updated UITF hazard assessment and controls. Made minor updates to CEBAF hazard assessments and controls. Revised format.	(minor update) - ES&H AD - Andre signoff	9/30/2019
8	Revised layout of SAD, added the UITF accelerator, updated hazard analysis, incorporated changes related to positive USIs since 7a.	see signature page	11/14/2018
7a	Updated organization chart, updated FEL to LERF and deleted reference to expired FELODS, added expanded hydrogen detonation hazard assessment, added North Linac helium vent penetration to hazard assessment to resolve USI, added electrical distribution infrastructure changes, corrected technical information for Hall D, and updated information based on the 2013 review year-end review.	see signature page	12/16/2014
7	CEBAF Upgrade to 12 GeV and SAD and ASE revised to comply with DOE-O-420.2C	see signature page	08/27/2012

* Major revisions, identified by whole numbers in this case, require full Jefferson Science Associates, LLC, (JSA) approval on a new signature page.

* Minor revisions (identified using a letter suffix), such as clarifications, corrections that do not change the intent of the document, and typographical corrections, require JSA approval by the Director or Associate Director of the affected division(s): Accelerator Operations, Research and Development, Experimental Nuclear Physics, or the Environment, Safety and Health Division. Approval of minor changes is indicated in the revision history.

Table of Contents

1. EXECUTIVE SUMMARY

In compliance with the requirements of the Department of Energy (DOE) Accelerator Safety Order (ASO), DOE O 420.2D, *Safety of Accelerators*,[1] this Safety Assessment Document (SAD) provides a qualified safety assessment of the hazards specific to the operation of accelerators at Jefferson Lab.

This document is focused on specific accelerator hazards. As such, it does not address standard industrial hazards that are managed under the Thomas Jefferson National Accelerator Facility (TJNAF or the lab) *Worker Safety and Health Program* or the *Radiation Protection Program*, both of which apply federal statutes, other DOE Orders, and consensus standards to the mitigation of standard industrial hazards present at Jefferson Lab. However, the analyses within evaluate industrial hazards that have the potential to initiate or contribute to postulated accelerator-specific accidents.

Included within is an overview of the TJNAF accelerators; an analysis of hazards associated with accelerator operations; and a description of the employed hazard mitigations. All of the hazards associated with the operation of accelerator facilities have been analyzed using worst-case assumptions associated with credible, hypothetical accident scenarios (including accidents initiated by natural phenomena). From these analyses, engineered and administrative controls, including limits on key operating conditions, were developed for each accelerator. The primary controls that ensure safe accelerator operations within the associated accelerator safety envelope (ASE) are identified and documented in the assessment and are approved by the DOE. Operation within the safety envelope provides adequate assurance for the safety of workers, the public, and the environment.

2. INTRODUCTION

Jefferson Lab is a national user facility for conducting frontier research in nuclear physics and medium-energy particle physics. TJNAF accomplishes this mission by providing unique, forefront research capabilities based on superconducting electron accelerators that produce continuous-wave, highly polarized electron beams.

Separate from its nuclear physics mission, Jefferson Lab also serves as the lead for a High Performance Data Facility Hub. This facility will be a resource for data analysis, networking, and data storage for the nation's research enterprise. This facility provides researchers with tools, methods and technologies to maximize the scientific value of data.

Jefferson Lab also utilizes the current technology in the nuclear physics program to develop technology for the next generation of accelerators, including high-brightness electron guns, high-gradient superconducting cavities, and energy-recovery linear accelerators.

TJNAF's mission includes:

- partnering with industry to identify, develop, and transfer commercially promising technologies and applications based on the lab's competency;
- implementing educational partnerships;
- capitalizing on strengths and assets to enhance motivation, interest, and literacy in science, math, and technology; and,
- continuing the lab's commitment to excellence in all aspects of its work, including ensuring a healthy staff, a safe workplace, and minimum impact to the environment.

The lab's nuclear physics mission is supported by its accelerators (and their operations), which are discrete devices that can be broadly grouped into two classes. The first class consists of relatively complex machines or accelerator component test facilities capable of accelerating particles above 10 MeV (million electron volts). These devices operate "in accordance with" (IAW) a DOE-approved ASE and are subject to all related requirements in the ASO. Typically, these machines operate within a shielded enclosure specifically designed and maintained exclusively for the operation of these devices. They employ control systems that receive input from operators, as well as systems and equipment for personnel protection. The second class of accelerators operate at or below 10 MeV and are not subject to certain elements of the ASO. This class of accelerator may include portable or comparatively simple devices operated IAW manufacturer's documentation or other procedures developed under the lab's Integrated Safety Management (ISM) System. In some cases, safety assessments and hazard controls for such devices may be documented as part of the operating procedures for the equipment (rather than in this SAD).

The Continuous Electron Beam Accelerator Facility (CEBAF), Low Energy Recirculator Facility (LERF), and LERF Gun Test Stand (GTS) accelerators are located within a fence boundary with a single point for routine access that is staffed around the clock by security guards. The fenced boundary designates a controlled area (CA), where training or escort is required for entry. These three accelerators share certain utilities and operational interfaces. An inventory of accelerators is continuously maintained and posted on an Environment, Safety, and Health Division web page for key accelerator program documents.

The operating limits for CEBAF and LERF accelerators (in terms of energy and current) are reflected in the administrative limits stated in this document that are a function of Environmental Assessments (EAs) conducted throughout the development of the facility and its capabilities. This administrative limit is coupled with a lower-power operational envelope that, together, provides clear bounding conditions for planning and conducting accelerator operations.

In January 1987, the potential environmental impact of CEBAF operations was evaluated in an initial EA (DOE/EA-0257),[2] which resulted in a *finding of no significant impact* (FONSI). Subsequently, several additional EAs, related to upgrades to the facility and CEBAF energy and current, were conducted. Each EA, including those subsequent to DOE/EA-0257, resulted in a FONSI: DOE/EA-1204[3] for CEBAF and FEL (Free-Electron Laser; now known as the LERF) in January 1997; and DOE/EA-1534[4] for the Jefferson Lab facility in 2007.

Environmental Assessment DOE/EA-1534 is of particular importance because it evaluated a proposal to increase the maximum beam energy of CEBAF from 8.0 GeV (billion electron volts) to 16.0 GeV and increase the beam power from 1 MW (megawatt) to a maximum of 2 MW in the recirculating linear accelerator (linac) sections of CEBAF, with a maximum beam power of 1 MW each at the high-power beam dumps for Experimental Halls A & C simultaneously.

Associated revisions of this SAD contained hazard analyses that support a total-power administrative limit and operating envelope to 1.3 MW and 1.1 MW, respectively. It is evident in the hazard analysis presented in Section 5 below, that the principal hazard conditions are most often a function of chronic beam loss and *not* accidental beam loss at full power. Therefore, the relationship between total beam power and hazard is not always strictly proportional, nor is it straightforward.

The potential environmental impact of the Upgraded Injector Test Facility (UITF) was addressed by a categorical exclusion (CX) (TJSO-SC-15-02).[5] The UITF accelerator is located outside the fence boundary; however, it is housed securely inside the Test Lab High Bay, a controlled area that has requirements for radiological safety training – otherwise, a trained escort is required for entry.

With this revision of the SAD, requirements of the ASO associated with accelerators operating above 10 MeV are applied to the Cryomodule Test Facility (CMTF) and the Vertical Test Area (VTA). The hazard analyses for these devices are updated and included in Section 5, along with the bases for their accelerator safety envelopes. Appendix B now contains descriptions and hazard assessments of accelerators operating at or below 10 MeV.

The information and analyses demonstrate that operation of Jefferson Lab's accelerators and associated experiments can be conducted in a manner that will produce minimal risks to the safety and health of personnel, visiting scientists, the public, and the environment. This SAD was prepared IAW the requirements of the ASO, DOE O 420.2D, and the guidance in the *Accelerator Facility Safety Implementation Guide*, DOE G 420.2-1A. It is supplemented by documents developed at other DOE facilities, as well as national and international consensus standards on accelerator safety.

2.1. Objective

The intention of this SAD is to describe the features of Jefferson Lab that:

- Collectively define the accelerator facility; and,
- Identify the hazards that are unique to Jefferson Lab as an accelerator facility; and,
- Evaluate operations and their support activities to provide an analysis of postulated operational events (hazards) that can lead to adverse consequences.

The SAD also identifies the complete collection of specific controls necessary to reduce the risks associated with these hazards to acceptable levels.

This document is further divided into the following sections:

- Section 3.0, *SITE DESCRIPTION AND RESOURCES*
- Section 4.0, *DESCRIPTION OF ACCELERATOR ORGANIZATION AND FACILITY*
- Section 5.0, *HAZARD ASSESSMENT AND MITIGATION*
- Section 6.0, *POST-OPERATIONS PLANNING*
- Section 7.0, *BIBLIOGRAPHY*
- Appendix A, *ACRONYMS AND ABBREVIATIONS*
- Appendix B, *HAZARD ANALYSIS FOR ACCELERATORS OPERATING AT OR BELOW 10 MEV*

2.2. Scope and Assessment Methodology

The scope of operations for each accelerator encompasses the production or utilization of accelerator beams; research and experimental activities utilizing accelerator beams; the handling, storage, and analysis of accelerator-induced radioactive components; and materials associated with the accelerator. The scope also encompasses the receipt, preparation, assembly, inspection, and installation of targets or samples into the accelerator beam; or removal, disassembly, handling (including packaging), storage, or transportation of such.

Although the hazards above are associated with accelerator operations, the programs that address those hazards may address similar hazards from other laboratory activities unrelated to accelerator operations.

The scope of the hazard assessment in the SAD includes hazards unique to the operation of Jefferson Lab's accelerators; therefore, it focuses on hazards in and around accelerator housings, enclosures, and associated support buildings, including above-ground control systems and activities that can affect any of these areas. The hazard assessment also includes the evaluation of any standard industrial hazard that, while safely managed under the provisions of Title 10, Code of Federal Regulations (CFR), Part 835 (10 CFR 835) and Part 851 (10 CFR 851), can serve as an initiator or contributor to an accelerator-specific postulated accident sequence. An accelerator-specific postulated accident sequence is referred to throughout the document as a hazard event.

Accelerator hazards often have unique aspects that are not fully addressed by a standardized approach to industrial safety; as such, they require an augmented approach. This approach includes the application of engineered safety systems and administrative controls as mitigation measures to reduce the likelihood or consequence of the postulated hazard event to acceptably low levels.

2.3. Safety Envelope

The entire set of engineered safety systems and administrative controls that serve as mitigation measures to reduce the likelihood or consequence of postulated hazard events for an accelerator or group of accelerators is called the ASE. Individual controls determined to be essential for safe operation of an accelerator are referred to as Credited Controls (CCs). When all operations are performed within the boundaries of the ASE, the risks associated with the hazards of accelerator operations, or the results of a particular hazard event, will be acceptable for protection of the facility staff, subcontractors, users, the public, and the environment. Other safety controls identified in this analysis are designated as defense-in-depth. These controls are often used in addition to CCs to provide further mitigation of hazard events (from *acceptable* to *low*, for example) and to increase the margin of safety.

The requirements specified in the ASE are binding for operations of applicable accelerators at Jefferson Lab. As a result, changes to an accelerator or its operations, or changes to the supporting facility that are inconsistent with the underlying basis of the ASE, *will require additional analysis*. This analysis is conducted through the Unreviewed Safety Issue (USI) process, which, in accordance with the ASO, is also applied to any discovered conditions having the potential to affect safe operation of an accelerator. Depending on the outcome of the USI process, changes to this document and to the ASE may result and thus require DOE approval.

2.4. Summary

The Safety Assessment Document identifies the accelerators at Jefferson Lab, analyzes their hazards, and identifies necessary controls to mitigate associated hazards and hazard events to an acceptable level (as defined in Section 5.0 below). As such, the SAD is the safety basis document for operation of the CEBAF, LERF, UITF, VTA, and CMTF. The hazard assessment for the GTS is also included in this document as Appendix B.

The necessary controls, identified within as Credited Controls (CCs), and any key requirements associated with these CCs, are incorporated into the ASE. An ASE is a separate document that lists the set of conditions that *must be met before* an accelerator delivers beam.

3. SITE DESCRIPTION AND RESOURCES

3.1. Location

The 221-acre site that includes TJNAF is located in the northern section of Newport News, Virginia. Newport News is bounded on the east by York County and the City of Hampton; on the north by James City County and the City of Williamsburg; on the west by the James River; and, on the south by the Hampton Roads waterway. The lab is located just east of Jefferson Avenue, a main thoroughfare, and is less than 1 mile to the west of Interstate 64. The general vicinity layout of Jefferson Lab is included as Figure 1, Jefferson Lab Vicinity Plan.

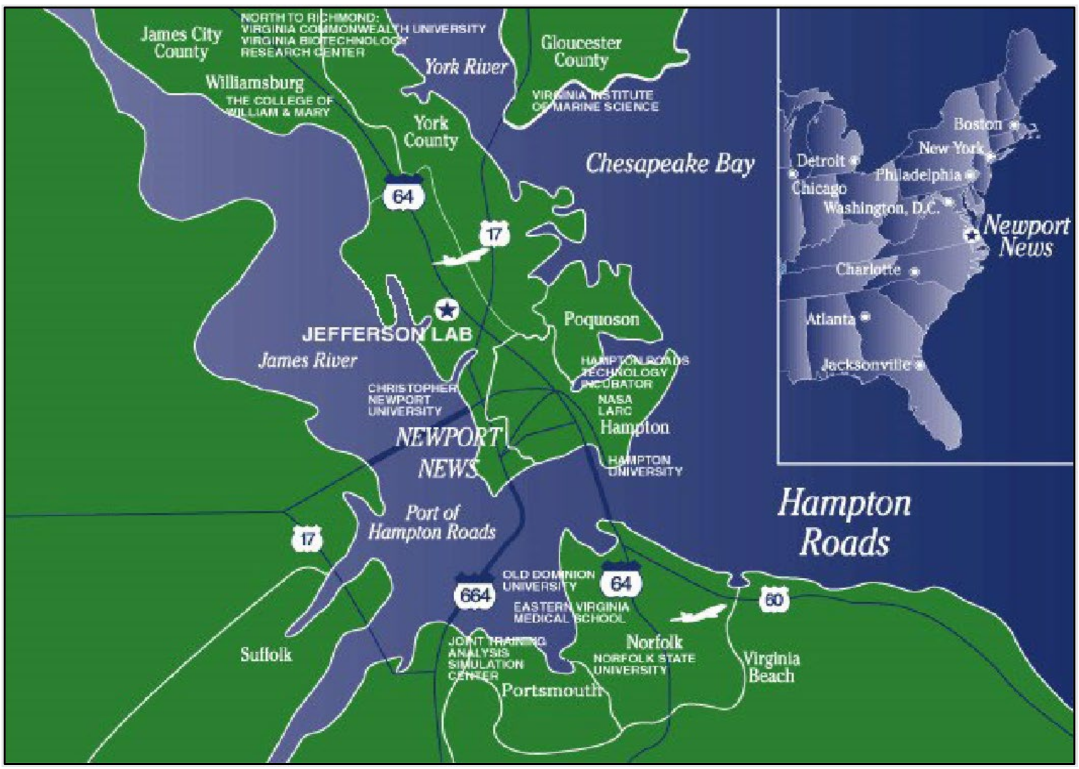

Figure 1. Jefferson Lab Vicinity Plan

Jefferson Lab is situated just north of the Oyster Point Industrial Park. Two schools and railroad tracks serving the local rail system are located within 1 mile of the site. The Newport News/Williamsburg International Airport (airport code PHF) is located 2 miles to the north. In addition to PHF, there is one additional commercial airport, two small aircraft airports, and three military airbases within a 30-mile radius of the facility.

Jefferson Lab is also situated near a former Boeing CIM-10 Bomarc Missile Base, which was active from September 1959 to October 1972 and is now owned by the City of Newport News.

The Bomarc site is a formerly utilized defense site and has residual groundwater contamination, principally benzene and chlorinated solvents in groundwater, extending toward the northeast area of the fenced portion of the Jefferson Lab site. This legacy groundwater contamination is not associated with lab operations; it is managed by the U.S. Army Corps of Engineers.

The federal government owns 179 acres as part of the TJNAF site. Portions of Jefferson Lab are built on what was the Space Radiation Effects Laboratory (SREL) site operated by the College of William & Mary for the National Aeronautics and Space Administration (NASA) in the 1960s. The Commonwealth of Virginia, in support of the administration's decision to build the SREL, developed the Virginia Associated Research Campus (VARC), which is now referred to as the Support Service Center (SSC). The SREL included a synchrocyclotron with a primary beam of 600 MeV protons and secondary beams of 400 MeV pions and muons produced to study the effects of radiation on materials planned for use in space. The synchrocyclotron was removed in 1980 when the SREL shut down – repurposing the remaining infrastructure was a key consideration in the selection of the site for construction of Jefferson Lab.

As mentioned above in Section 2.4 Summary, the campus is home to six accelerators. The CEBAF, LERF, and GTS accelerators are located on the 179-acre tract of land in the fenced area historically known as the Accelerator Site. The remaining three accelerators are located in what was the main SREL building, now called the Test Lab. Consequently, only portions of the campus are directly involved in or affected by accelerator operations. For the purposes of this document, however, the campus is treated as an *Accelerator Facility*.

3.2. Area and Demography

3.2.1. Population

The population of Newport News has steadily grown over the past 40 years. The U.S. Census Bureau estimated the 2020 population of Newport News at 186,247, an increase of 22% over the 1980 census number of 144,903. The metropolitan statistical area, which includes Norfolk, Virginia Beach, and Newport News, was estimated to have a population of 1,780,062 in 2020, up 33% from the 1,201,400 documented in the 1987 Environmental Assessment (EA).

3.2.2. Climate

The meteorology of the site is strongly affected by the nearby marine environment. The Chesapeake Bay moderates the climate and weather of the site, with land-sea breezes dominating the wind patterns during much of the year. Since 1887, the temperature for Richmond, Virginia (the nearest location with extensive records) in winter ranged from -12 °F (January 1940) to 94 °F (March 1907) with a mean of 37.9 °F. In the summer, temperatures ranged from 46 °F (August 1934) to 107 °F (August 1918) with a mean of 78.2 °F.

For the same location, mean annual precipitation is 43.58 inches spread approximately evenly throughout the year except for the period June through August, which has approximately one-third of the total. The minimum and maximum annual precipitation occurred in 1889 and 1941, respectively. Extreme precipitation events, caused by hurricanes or tropical cyclones, have deposited as much as 11.5 inches of rain in a 24-hour period. Mean snowfall is 12.6 inches, with a maximum of 38.9 inches (1962).

Because of the proximity of the Chesapeake Bay, fog is a common occurrence in the area, as well. Heavy fog, reducing visibility to less than 0.25 miles, occurs on an average of 23 days per year (d/y). Thunderstorms, and other similar severe weather, occur an average of 37 d/y.

Tornadoes are rare in coastal Virginia but may be spawned by severe thunderstorms or when associated with hurricane or tropical cyclone activity. On average, hurricanes make landfall less than once per year in Virginia but have caused both wind and flooding damage to the area in the last several hundred years of record.

3.2.3. Geology

Jefferson Lab is located in the coastal plain of the lower York-James Peninsula, which is characterized by a succession of plains and intervening scarps. The site, located on the Huntington Flat, is underlain by the Norfolk and Yorktown formations in an area of low seismic risk. The most recent earthquake widely felt in Virginia occurred on August 23, 2011, when a magnitude 5.8 quake, followed by a magnitude 4.5 aftershock, was centered near Mineral, Virginia, which is close to the eastern-most extension of the central Virginia Seismic Zone. Mineral is approximately 80 miles northwest of Jefferson Lab, and although the quake was noticed at the site, there was no adverse impact. No geologic hazards have been identified in the site area.

3.2.4. Surface Hydrogeology

The Peninsula is rather flat land, lying near sea level, that is well-drained by numerous small rivers and creeks. The James and York rivers, defining the Peninsula, are major connecting tributaries of the Chesapeake Bay. Rainfall on the Peninsula readily drains to the bay, and both tidal and wide-area flooding is of negligible likelihood. The potential for localized flooding within the Accelerator Site is discussed in the safety analysis in Section 5.0. The site has an average elevation of 34 feet above mean sea level, with an elevation range from approximately 29 to 35 feet (ft), which is above the 100-year floodplain level of 13 feet. Jefferson Lab is located in the Brick Kiln Creek watershed, which discharges into the Big Bethel Recreational Area (operated by the U.S. military).

Three major aquifers are present in the area:

- An unconfined water table aquifer, present in the Norfolk and Yorktown formations, has a low yield, with thicknesses ranging from 50 to 100 ft below the ground surface.
- An upper artesian aquifer underlies the water-table aquifer and lies in the Miocene-Eocene-age sediments.
- A principal artesian aquifer is present in sediments of the Cretaceous period.

3.2.5. Air Quality

Jefferson Lab is located in the Hampton Roads Intrastate Air Quality Control Region 223, which is an attainment area for all criteria pollutants (sulfur dioxides, nitrogen dioxide, total suspended particulates, carbon monoxide, ozone, and lead).

3.3. Public Services

3.3.1. Municipal Water Supply

The two water mains that supply the site are owned and operated by the City of Newport News. The one from the east runs under Canon Boulevard, and the other, from the west, runs under Jefferson Avenue.

The system has adequate capacity and pressure to serve the present and future needs of the site. The Newport News water system is equipped with modern filtration and purification plants and meets Environmental Protection Agency (EPA) standards for water quality.

The on-site water distribution system consists of a loop configuration sectionalized with shut-off valves at intersections. The maximum diameter of the distribution main is 12 inches. Fire hydrants are located within approximately 50 feet of major buildings and are connected to the main with 6-inch lines.

3.3.2. Publicly-owned Treatment Works

The site is served by the Hampton Roads Sanitation District (HRSD). All sewer discharges are routed through the western side of the site through four existing lines designated as A, BC, D, and EF lines. Most of the industrial wastewater discharges authorized by TJNAF's HRSD permit include: cooling tower blowdown, effluent from the Acid Waste Neutralization System, Ultra-pure Water System discharges (located adjacent to building 58), and batch discharges from CEBAF floor drain sumps and high-power beam dump cooling water systems. The permit requires pH monitoring of two existing industrial effluent lines (D and EF), along with flow meter volumes submitted monthly to HRSD. The permit also requires radionuclide analysis of discharges from the floor drain sumps, the high-power beam dump water disposal system, and Acid Waste Neutralization System.

3.3.3. Stormwater Management

The City of Newport News has developed a comprehensive stormwater drainage system at the Oyster Point Industrial Park (east of the site) and on Jefferson Avenue (southwest of the site). Onsite pipes, culverts, drainage channels, and storm-drain systems were designed to pass a 25-year frequency storm without surcharging the pipes or overtopping the off-site channels. Site drainage consists of existing channels and two stormwater retention ponds that flow to the Brick Kiln Creek Watershed in accordance with a U.S. Army Corps of Engineers deed restriction and requirements of the City of Newport News Engineering Department. Similar drainage channels exist on adjacent property leased by DOE from the Commonwealth of Virginia, the City of Newport News, and SURA.

TJNAF is authorized to discharge stormwater through the Municipal Separate Storm Sewer Systems (MS4) permit with the Virginia Department of Environmental Quality (DEQ). Several best management practices (BMPs) are utilized as part of the MS4 permit to prevent unauthorized non-stormwater discharges into Jefferson Lab's stormwater management system of ditches, drains, and ponds. These BMPs include:

- annual MS4 Report and Program Plan submittal to DEQ.
- monthly on-site self-inspections of MS4 under the *Illicit Discharge Detection and Elimination Program.*
- routine preparation and submittal of a *Chesapeake Bay Total Maximum Daily Load Action Plan* to account for proper management of nutrient loads in stormwater runoff.
- annual DEQ approval of *Annual Standards and Specifications for Stormwater Management/Erosion & Sediment Control.*

3.3.4. Electric and Natural Gas Power Supplies

Dominion Energy provides three independent, medium-voltage services to Jefferson Lab to meet power requirements.

Two substations located on the Accelerator Site, respectively 40 and 33 megavolt-amperes (MVA), are fed from the Dominion Warwick Substation via an overhead line.

A third, 22 MVA substation, primarily used to feed power to the campus part of Jefferson Lab, is powered by a separate feed coming from the Rock Landing Substation. Dominion provides additional electric service from the Rock Landing Substation to Buildings 13, 19, and 28, which are located away from the main campus.

Natural gas is supplied to the site by Virginia Natural Gas through a pipeline from Jefferson Avenue. Natural gas supplies boilers for heat and hot water while fueling several standby emergency power generators. Refer to Section 3.4.1, below, for a more detailed discussion of site power.

3.3.5. Telecommunications

The interface to the public-switched telephone network is provided using industry-standard primary rate interfaces. Local phone service comes into the lab at two locations to provide redundant connections. A second company provides most of the long-distance phone service via connection with the federal telephone service.

The primary internet service is provided by two direct connections to the DOE Energy Sciences Network (ESnet) that connects all DOE-related laboratories. The connections occur at two different locations at Jefferson Lab with one providing connectivity to ESnet in Washington, D.C. and the other providing connectivity to ESnet in Atlanta. There is a second, lower-speed backup circuit provided by another telecom company. To provide reliability, telecom and internet services are redundant; have automatic fail-over features; and are geographically diverse.

3.4. On-site Utilities

Seven utilities serve Jefferson Lab: electric power, computer networks, telecommunications, water, sanitary sewer, storm drains, and natural gas.

3.4.1. Site, Emergency, and Uninterruptable Power

As mentioned above, there are three sources of power to the lab. The first is a 40-MVA, 34.5/12.47-kilovolt (kV) Dominion *Jefferson Lab Industrial Substation* located on the Accelerator Site near the Central Helium Liquefier (CHL) and supplied by a 34.5-kV overhead circuit (pole line) from the *Dominion Warwick Substation* located on J. Clyde Morris Boulevard. The second is a 33-MVA, 34.5/12.47-kV Dominion *Jefferson Lab Industrial Substation* located on the Accelerator Site near the CHL and supplied by the same 34.5-kV overhead circuit (pole line) from the *Dominion Warwick Substation* located on J. Clyde Morris Boulevard. The third is a 22-MVA, 34.5/13.2-kV Dominion *Oyster Point Industrial Substation* that is located in the Central Material Storage Area (CMSA) and is supplied by a 34.5-kV overhead circuit from the Dominion *Rock Landing Substation*. This campus substation is cross-connected to the Accelerator Site substations so that power can be transferred from one Jefferson Lab substation to another when necessary.

Several on-site generators provide emergency power to critical systems and facilities when the electric utilities (identified in Section 3.3.4, above) experience power outages. Depending on their location, the generators use natural gas, diesel fuel, or liquid propane. The following is a partial list of generator locations and areas (buildings), along with a partial list of systems served. The complete list is managed by Facilities Management & Logistics (FM&L).

Generators

Location	Building #	System(s) serviced
Low Energy Recirculator Facility (LERF)	18	Sump pumps ODH alarms
Service Support Center (SSC)	28	Finance Main fire control system
Technology and Engineering Development (TED)	55	Life Safety
Test Lab	58	Life Safety ODH alarms Scrubber vent system Other equipment
Central Utility Plant	60	Pumps Equipment
Accelerator Emergency Loop	67	Pumps Equipment ODH alarms
Machine Control Center (MCC)	85	Accelerator controls Other equipment
Experimental Halls A, B, C Emergency Loop	101, 94, 96	Groundwater pumps ODH alarms Hall equipment support
Applied Research Center (ARC)		Life safety systems Fire pumps
CEBAF Center	12	Data Center
Security Post 2 (Accelerator Guard House)	51	Data communication Security equipment
Accelerator Maintenance Support	87	Phone switch system

In addition, uninterruptible power supplies (UPS) serve systems that have safety significance. For example, systems that monitor for oxygen-deficient atmospheres in potentially occupied locations are served by UPS systems to help avoid intermittent power outages and to maintain the system in an operational mode during a transition to standby power. During a complete power outage, the UPS will maintain power long enough for personnel to establish administrative controls for the related hazards.

3.4.2. Telecommunications

TJNAF utilizes several types of telecommunications services including landlines, mobile phones, and Voice over Internet Protocol (VoIP) services. A paging service is also used for rapid notification and text messaging.

Served by a wide area network connection provider (mentioned in 3.3.5 above), ESnet enables a scientist at Jefferson Lab to connect to virtually any network in the world. Local area networks (LAN) on-site are based on gigabit and fast ethernet technology, providing connectivity for computer systems, printers, VoIP telecommunications, and other network devices in all buildings.

The lab's computer networks, including those used for facility infrastructure and accelerator controls, are protected against unauthorized use and malicious intrusion by a layered defense model. This model includes:

- user education,
- vulnerability scanning,
- intrusion detection,
- network segregation and firewalls, and
- two-factor authentication.

These measures are identified in the Cyber Security Protection Plan.

Systems associated with the CEBAF accelerator operations are controlled and monitored by an Experimental Physics and Industrial Control System (EPICS). Software control for accelerator operations is managed by the Accelerator Control Group, which provides a structured and controlled software development and maintenance environment. Software QA for safety systems is managed by *AD-02-001 v1 PSS Configuration Management Procedure*. AD-02-001 is one of three documents developed by the Safety Systems Group that define requirements and processes for the complete Personnel Safety System (hardware, software, processes, etc.) throughout its lifecycle."

Conventional facilities control systems for buildings (access; heating, ventilation and air conditioning [HVAC], etc.), cooling towers and water supplies, cryogenic plants, clean rooms, and energy-management processes that support accelerator operations, do not share computer hardware. The controls are based on virtual machines running on isolated subnets. Vendors gain access to their devices through secure remote access using two-factor authentication.

3.4.3. Cryogenics

3.4.3.1. Central Helium Liquefier

There are two helium refrigerators at the Central Helium Liquefier (CHL1 and CHL2) (Building 8) that support 2- Kelvin and 35-Kelvin operations for the CEBAF and LERF accelerators via transfer-line systems. Both CHL1 and CHL2 are located on the surface between the North and South LINACS (NL and SL, respectively). CHL1 is normally configured to support the SL and LERF, while CHL2 is normally configured to support the NL and injector.

The CHL complex houses the refrigerators, compressors, warm-gas storage, liquid helium and nitrogen storage, purification systems, electrical panels, and motor controls.

The two compressor rooms have 5-ton bridge cranes and acoustic reduction treatments due to the high noise levels. There are three 20,000-gallon LN2 (liquid nitrogen) dewars on the south side of the CHL that are used to support the LN2 operations at the CHL, as well as at the End Station Refrigerators (ESR1 and ESR2) for the physics experimental halls. There are two 10kL helium dewars. Cooling water is supplied from cooling towers that are on the east side of the CHL. There are seven, 30,000-gallon helium gas tanks on the south side of the CHL that are used as buffer tanks and to support the recovery system at the CHL.

3.4.3.2. End Station Refrigerator

There are two helium refrigerators at the End Station Refrigerator complex (ESR1 (Building 102) and ESR2 (Building 104)) that support operations for Physics Halls A, B, and C.

The refrigerators are located near Halls A, B, and C within the west side of the fenced boundary, providing 4-Kelvin and 15-Kelvin gas to the three halls via a transfer-line system. Typically, only one ESR will be operated at a time. The ESR1 and ESR2 compressor rooms are high noise environments. The ESR2 compressor room has a bridge crane and the complex has two 10kL liquid helium storage dewars. The CHL is also capable of sending up to 20 grams/second of 4-Kelvin helium through a transfer line connecting the CHL to the ESR complex, when required. Cooling water is supplied from cooling towers that are on the west side of the North Linac service building.

3.4.3.3. Hall D Refrigerator

The Hall D Refrigerator (Building 201) is located at the Hall D Complex within the east side of the fenced boundary. It provides 4-Kelvin helium gas and liquid nitrogen to the Hall D magnet via a transfer-line system. A 6,000-gallon LN2 dewar and a 1,000-gallon liquid helium dewar are east of the building. Cooling water is supplied from cooling towers west of building, and one, 30,000-gallon warm helium gas tank is also on the west side of Building 201.

3.4.3.4. Cryogenic Test Facility

Building 57, the CTF (Cryogenic Test Facility) is located on the east side of the Test Lab, outside the accelerator site fence boundary. Two helium refrigerators at the CTF support 2-, 4-, and 35-Kelvin operations in the VTA, CMTF, and the UITF via transfer-line systems. A 13,000-gallon liquid nitrogen dewar and a 10,000 liquid liter helium dewar are north of the building. Cooling water is supplied from cooling towers on the north side of the CTF. Four, 30,000-gallon warm helium gas tanks are located on the south side of the building, as well.

3.4.4. Low-Conductivity Water

Low-conductivity water (LCW) is water that has been processed to remove impurities to lower or eliminate the conductive and corrosive properties of water used to cool electrically energized systems. There are four LCW systems: one in each of the NL and SL service buildings; one at experimental end stations (Halls) A, B, and C; and one near Experimental End Station (Hall) D. Each is served by nearby evaporative heat exchangers. Piping from each system delivers LCW to several locations around the CEBAF and LERF accelerators, as well as to the experimental end stations, where it is used in several important applications.

Low-conductivity water is principally used to cool magnet power supplies and radiofrequency tubes (klystron and inductive output tube amplifiers) that are located outside the accelerator enclosure. It is also used to directly cool magnets and certain radiofrequency cavities located inside the accelerator enclosure. LCW is also used to cool several types of accelerator components that directly intercept the beam, including low-power and tune-up dumps. Finally, LCW is used to indirectly cool intermediate power dumps and high-power dumps, as well as water-cooled experiment targets.

3.5. Local Emergency Response Resources

Emergency services are provided through the City's 911 system.

Regular exercises with the city emergency response services help to maintain readiness for lab-specific hazards. An updated hazard profile is routinely provided to emergency response services to aid first responders. Services include emergency medical response and transport; emergency *technical* rescue;

firefighting; and hazardous-material incident response.

These memoranda are kept on file with TJNAFs Emergency Manager and the City of Newport News Police and Fire Chiefs. TJNAF maintains regular, and mutually beneficial, interactions with local emergency response services in the form of planned exercises, training, and preplanned visits to the site. TJNAF also provides site-specific information to responders at the local fire stations.

The nearest emergency response station is located less than 1.5 miles from Jefferson Lab, at the City of Newport News Oyster Point Fire Station (Station 6). Riverside Regional Medical Center, a Level II Trauma Center, is located approximately 3.5 miles from the lab. Its Emergency Department is trained and equipped to treat injuries involving radiological complications and acid exposures that might result from chemicals used in acid-etching processes.

4. DESCRIPTION OF ACCELERATOR ORGANIZATION AND FACILITY

4.1. General Description

The Jefferson Lab campus consists of buildings and grounds supporting the operation of three accelerators located inside a fenced boundary, and three accelerators outside the fenced boundary in a multi-purpose building called the Test Lab.

There are 53 buildings inside the fenced boundary and 71 buildings in total on the campus. There are four buildings in which space is leased, one building adjacent to the campus and three others off-site. The lease arrangements change depending on the needs of the laboratory. The buildings consist of office and laboratory spaces, equipment storage buildings, and various other support structures.

The campus is partially located on previously disturbed land and previously used structures associated with SREL as mentioned in the *Site Description*. The multi-purpose building that houses three accelerators contains low-level residual radioactivity that remains embedded in concrete shielding in a few locations. For purposes of DOE O 420.2D, *Safety of Accelerators*, the campus is generally considered the "accelerator facility." The inventory of all real property is officially retained in the DOE Facilities Information Management System.

Jefferson Lab staff includes in-house nuclear scientists and engineers who are specialists in accelerator operation, technology development including research activities in accelerator physics, superconducting radiofrequency (SRF) technology, physics detector research and development, data acquisition, and high-performance computing. Jefferson Lab staff also provides management, administrative, logistical, and safety support. Jefferson Lab serves an international user community of approximately 1,900 scientists. On any given day, there are approximately 900 employees and up to 100 visiting scientists.

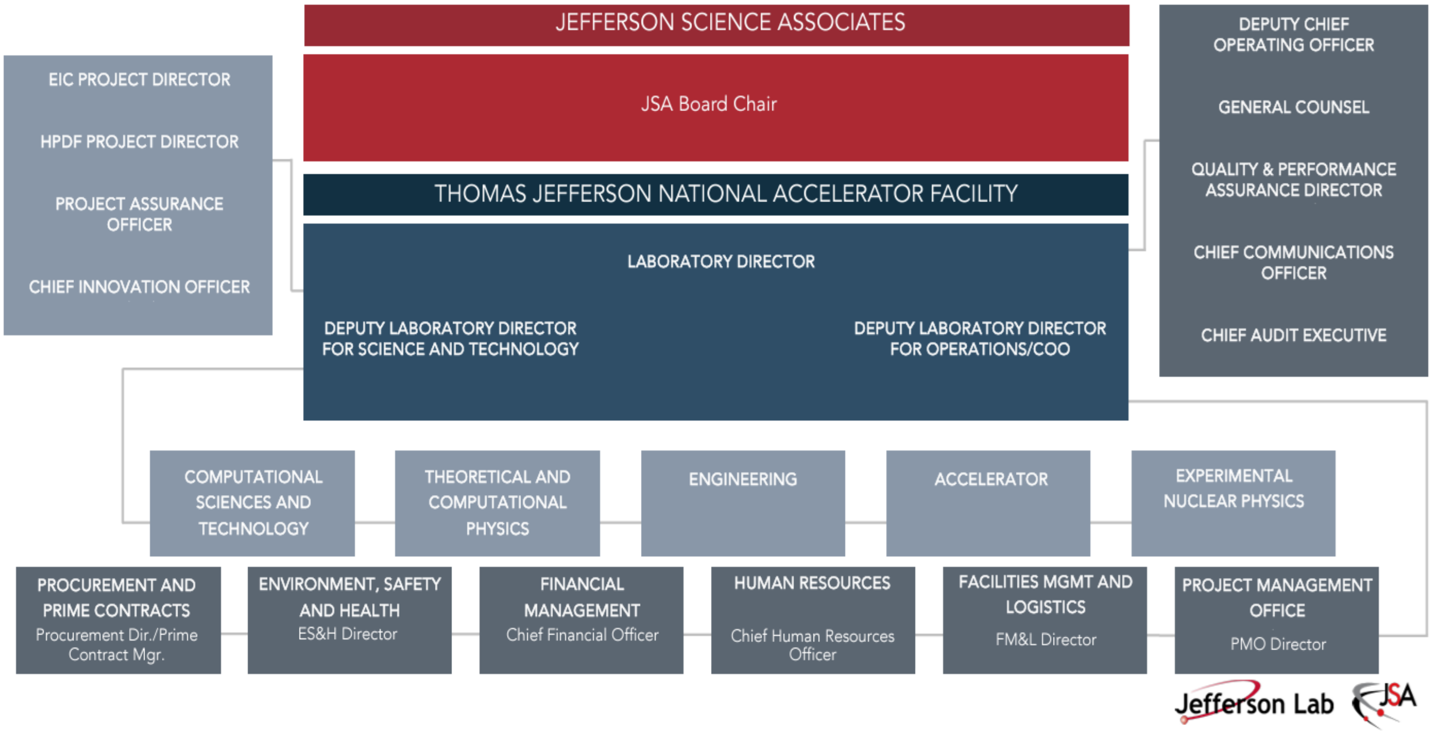

Figure 2. TJNAF Organization

4.2. Accelerator Safety Support Processes by Organization

Safe operation of the accelerators for the conduct of nuclear physics research is supported by engineered safeguards and processes, and administrative programs, processes, and procedures maintained by organizational units throughout Jefferson Lab shown above in Figure 2. The following sections focus on the contribution for safe accelerator operation provided by specific organizational units.

4.2.1. Accelerator Operations, Research, and Development

The Accelerator Operations, Research, and Development Division (commonly referred to as the "Accelerator Division") provides the personnel, procedures, and processes for safe and efficient operation of Jefferson Lab accelerators and associated technical areas used to research, develop, test, and refine accelerator component performance. The Accelerator Division manages accelerator repair and maintenance activities performed by division staff and other laboratory organizations. This is discussed in more detail below. The division is also home to the Accelerator Engineering Systems (AES) Safety Systems Group (AESSAF). Its expertise extends to risk and reliability analysis, fail-safe design, programming techniques, and development of standards and practices. The AESSAF manages the Personal Safety System (PSS), Machine Protection Systems (MPS), and Oxygen Deficiency Hazard (ODH) monitoring systems on the accelerator site.

4.2.1.1. Accelerator Governing Processes and Procedures

Accelerator Division develops and maintains the Accelerator Operations Directives (AOD), the LERF Operations Directives (LOD), the UITF Operations Directives (UOD), Testing Operations Directives (TOD), and VTA Operations Directives (VOD) which govern accelerator operations for CEBAF and LERF accelerators, the UITF accelerator, the Cryomodule Test Facility, and the Vertical Test Area respectively. These directives describe how safety is integrated into the execution of the respective accelerator programs and establish acceptable conduct of operations by governing how each program is defined and executed. These directives outline how configuration management standards and work practices are applied as part of accelerator operations and specify how the accelerator programs are carried out, including the safety responsibilities of the control room staff and the role of safety organizations.

The Operations Directives (ODs) describe the planning, scheduling, and coordinating of maintenance and repair activities to maintain and improve accelerator availability, integrate projects, and interface with the conduct of physics experiments. The ODs define the operational interfaces (both processes and hardware) between the Accelerator and Physics Divisions and provide the framework for accelerator operation within the ASE – verification of proper configuration of the safety-related controls by the Director of Operations before authorizing operation.

The ODs are linked to the USI process. The USI process provides for the review and evaluation of planned or discovered conditions that may be inconsistent with the safety basis in the SAD or the ASE requirements. These documents also specify a set of Operational Restrictions that list administrative limits and operating parameters for specific accelerator systems or areas and require the use of Beam Test Plans – formal plans that are submitted when a system expert wishes to test specific accelerator operating parameters or gather test data during normal accelerator operations. Beam test plans require thorough pre-task planning and undergo an internal review/approval process.

Accelerator maintenance is scheduled and performed during routine, planned, shutdowns. Short-term Maintenance Days are scheduled throughout experimental nuclear physics programs and a longer-term Scheduled Accelerator Maintenance (SAM) is scheduled at the end of experimental nuclear physics operations. This is a period of scheduled, dedicated time during which all accelerator systems are recovered, and exercised. A process called Hot Checkout is used to systematically check systems and verify them as ready for operation in the System Readiness Manager subsequent to the SAM. At the end of a SAM, Accelerator Division uses a tool called the Jefferson Lab Authorization Manager (JAM) is used to document the condition of accelerator components and systems.

Nuclear physics experiments in the end stations A, B, C, and D are governed by the Physics Division Associate Director using the Experiment Readiness Review (ERR) process found in ES&H Manual Chapter 3120 and identified in Section 4.2.2.1, Physics Governing Processes and Procedures. At the discretion of the Accelerator Division Associate Director with concurrence from the Physics Division Associate Director, the Experiment Readiness Review (ERR) process identified in ES&H Manual Chapter 3120, may also be applied to proposed activities outside the experimental end stations.

However, the CEBAF Experiment Review Process, in ES&H Manual Chapter 3120, is typically used in a graded approach to assess activities proposed for the CEBAF beam enclosure or the LERF and UITF accelerators. The Accelerator Division Associate Director will determine whether Environment, Safety, and Health (ES&H) Manual Chapter 3130 applies, and the Director of Operations shall determine the scope and scale of the review methodology.

Work Control Documents (WCDs) are developed when a task involves assembly and fabrication, maintenance, diagnostics, repair, and R&D (research and development). See *ES&H Manual 3240 Work Planning, Control, and Authorization Using ePAS*.

4.2.1.2. Accelerator Training and Personnel

The Accelerator Division trains Accelerator Operators and Crew Chiefs to operate systems that tune, control, and direct the electron beam to specific destinations while minimizing beam loss and maintaining beam quality. Accelerator Operators are trained to establish conditions for safe access to the accelerator enclosure, and they are trained to recognize and properly react to off-normal conditions and emergencies that can occur on the accelerator site. Accelerator Operations staff provides Tunnel Awareness Training; this training familiarizes workers with the hazards and mitigations associated with access to the accelerator tunnel.

The AOD and LOD address training of division personnel who operate or Crew Chiefs who supervise those who operate the accelerators. Accelerator Operators and Crew Chiefs are trained as Safety System Operators (SSO). An SSO is trained in the theory and operation of the CEBAF and LERF PSS to the point that they can operate the PSS of each respective accelerator.

For CEBAF and LERF, AESSAF trains and certifies Accelerator Operators in PSS function and operation. These trained operators referred to as SSOs, operate the PSS, oversee sweeps from the Control Room, and facilitate Controlled Access in PSS segments. Accelerator operators are trained to operate and respond to alarms from the ODH monitoring system.

The presence of a minimum number of trained operations' staff in the CEBAF and LERF is considered a Credited Control in the ASE.

The training requirements for the UITF are addressed in the UOD that governs UITF operation. Training on the operation of the UITF is done by the UITF Facility Manager.

Training requirements for VTA and CMTF are addressed in the respective operations directives.

The operation, maintenance, repair, and certification (or calibration) of the ODH monitoring system and the PSS is limited to AESSAF staff who are specifically trained and qualified on that equipment and the requirements for maintaining proper operational configuration.

4.2.1.3. Accelerator Engineered Safety Systems

4.2.1.3.1. Accelerator Engineering PSS

Personnel protection from prompt ionizing radiation at Jefferson Lab relies on a reasoned combination of active and passive engineered and administrative safeguards. The active engineered safeguards are collectively referred to as the Personnel Safety System, or PSS. The PSS is a comprehensive, redundant, fail-safe system used to provide employee protection from prompt ionizing radiation.

Because of the radiation levels associated with beam transport, personnel are excluded from the accelerator enclosure and experimental halls when they are configured to receive beam.

The PSS design follows the *Beam Containment and Access Control Policy* requirement to keep "beam away from people and people away from beam." To achieve a high level of performance, the PSS includes multiple (redundant) and diverse safety functions that minimize the likelihood of common-cause failures. The PSS also includes sensors that independently monitor the status of devices and incorporates logic that compares the monitored status to the command status. PSS component failures are mitigated by the redundant and fail-safe nature of the PSS design, which assures that, in the event of a PSS failure, the accelerator will default to a predetermined (fail-safe) condition.

The CEBAF PSS is designed as a segmented system. A segmented system allows beam delivery in part of the accelerator while other parts of the accelerator are accessible to personnel. The nine logical segments of the PSS are illustrated below in Figure 3 – Segments of the CEBAF PSS.

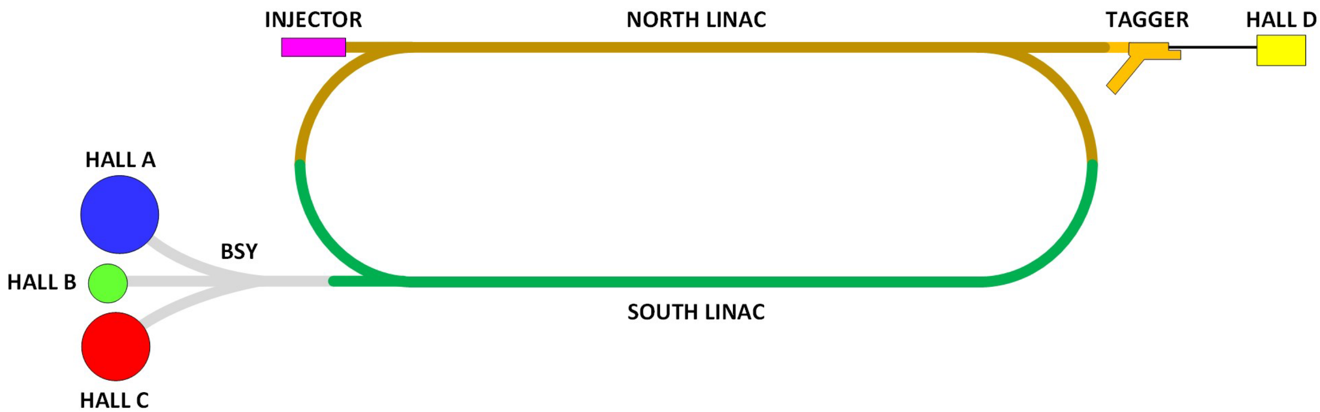

Figure 3. Segments of the CEBAF PSS

Every access point in a segment of the accelerator enclosure configured to accept beam, including exit stairs, service elevators, and crane hatches, is redundantly monitored and interlocked by the PSS. Any unauthorized access to an interlocked segment will cause the PSS to shut off the beam and other potentially hazardous devices within a beam enclosure. The PSS is designed to prevent beam transport to a particular segment unless all conditions necessary for transport are satisfied.
The PSS in each accelerator includes features that facilitate "sweeps" to ensure all personnel have exited the segment prior to establishing a configuration that makes beam transport to the segment possible. Once excluded, personnel are prevented from entering these areas when they are configured to receive beam. The sweep procedure is developed by AESSAF in concert with Accelerator Operations. Sweep patterns are incorporated into the PSS logic such that operators performing a sweep must follow a precise, pre-planned path.

The PSS in CEBAF and LERF also provides for access to already swept areas by a limited number of personnel for troubleshooting and repair while preventing beam delivery to access areas. This entry procedure is referred to as the Controlled Access procedure. Under the Controlled Access procedure, each entrant is processed by an SSO; the entrant takes a unique key from a key bank and is allowed through a set of doors controlled by the SSO. This allows limited access without the need to repeat a sweep.

The PSS functions to ensure that people cannot enter an area configured to receive beam:

- Shut off of beam (and other devices) when interlocked physical barriers are breached;
- Signal unsafe conditions by means of visual and audible indicators;
- Deter unauthorized entry during Controlled Access by means of magnetically locked physical barriers; and
- Inhibit radiation-generating devices when radiation dose rates in occupied areas exceed Jefferson Lab limits.

For the CEBAF accelerator, a segmented system, the PSS functions ensure that the beam cannot enter an occupied area:

- Three devices using diverse technologies such as a combination of beam blocks and beam steering devices.

The PSS is maintained by AESSAF within the Accelerator Division. Other staff may be assigned to work with AESSAF on an as-needed basis. However, the AESSAF is considered to be the systems and subject matter expert for the PSS and its suite of equipment, software, and processes.

For the purposes of this SAD, a PSS failure is characterized by an event where:

- The PSS system fails to function in the manner in which it was designed (e.g., the loss of one of the two redundant interlock chains fails to terminate beam delivery to affected areas);
- Both PSS devices in a redundant pair of devices fail to function in the manner in which they were designed (e.g., both interlocks in a redundant pair on an exit stair door fail to terminate beam delivery to affected area); or
- Two of a set of three devices designed to prevent beam transport to an occupied area in a segmented accelerator fail to function as designed while providing protection.

PSS failures are promptly evaluated by the AESSAF and the Safety Configuration Management Board (SCMB) to determine whether the failure violates the ASE conditions or represents a hazard condition that has not been fully evaluated.

The PSS functionality is certified annually by physical testing of the system. PSS failures detected during certification are not ASE violations but shall be evaluated by the AESSAF and the SCMB to determine whether the failure represents a hazard condition that has not been fully evaluated.

The PSS is a Credited Active Engineered Control and is listed in each ASE.

Any access to a segment that is configured in an exclusion state will also cause the PSS to render safe other potentially hazardous devices within the accelerator enclosure. The PSS serves to integrate numerous safety functions that are not Credited Controls but serve as defense-in-depth. For example, the PSS receives trip signals from the Controlled Area Radiation Monitors (CARMs). CARMs monitor gamma and neutron levels at locations beyond the installed shielding and, through the PSS, terminate the beam if preset thresholds set by the Radiation Control Department (RCD) are exceeded.

The PSS will not allow RF power supplies to be energized in an RF zone where waveguides will not hold air pressure. This eliminates RF leakage from waveguides. In addition, the PSS access control system (ACS) may be used to control access temporarily as a means of limiting access to a hazardous condition (e.g., a High Radiation Area with a whole-body dose rate above 100 mrem/h).

4.2.1.3.2. Accelerator Engineering MPS

The MPS is a hardware-based system used to shut off the electron beam in cases where sustained beam, or energy directly related to the electron beam, could damage components. MPS inputs include variables such as target motion, beam loss, and superconducting cavity arcs or quenches.

The backbone of the MPS system is the Fast Shutdown (FSD) system, which has the ability to shut off the beam (in accelerators with a beam source) from anywhere in the accelerator in less than 100 µs. MPS subsystems include beam-loss monitors, the FSD system, and, in CEBAF, the beam-loss accounting system. The CEBAF MPS includes an active engineered system that turns off the accelerated beam when the beam current reaches a user-specified threshold for a specific destination.

The CEBAF beam-loss accounting system consists of beam-current cavity monitors and associated electronics. The system accommodates multiple, simultaneous beam destinations and is intended to trip the beam before reaching beam-current limits. Each cavity generates a signal proportional to the beam intensity. One of these cavities is located at the exit point of the injector, and the remaining cavities are located at different beam locations around the accelerator. The signals are compared continuously. A loss greater than 2 µA of beam instantaneously or an integrated fractional beam loss greater than 15,000 µA-µsec will interrupt beam delivery.

In addition, the Beam Envelope Limit System (BELS) ensures that the CEBAF accelerator does not exceed the total power administrative limit of 1.3 MW. BELS can be used to alert operations staff and to turn off the beam before preset limits are exceeded. This system measures the beam energy and current for each end station and the beam switchyard, combines the results, and alerts the control room staff when beam power reaches an operating envelope of 1.1 MW.

Beam shutoff capability is provided by the FSD system. The FSD system uses a high-frequency permission signal connected to the injector hardware responsible for beam generation and is capable of terminating the beam with a response time short enough to prevent equipment damage. The FSD system interfaces MPS hardware and many accelerator systems, including vacuum/valve status, beam-dump cooling systems status, radiator status, as well as providing experiment-specific inhibitors.

Certain features of the MPS serve as defense-in-depth protection and are not included in an ASE.

4.2.1.3.3. Accelerator Engineering ODH

ES&H Manual Chapters 6540, Oxygen Deficiency Hazard Control Program, and *6550, Cryogenic Safety Program*, serve as the basis for the TJNAF ODH management program.

These requirements apply to each accelerator and technical area where the uncontrolled release of compressed and/or liquefied gases can result in cryogenic burns and lead to a reduction in the concentration of available oxygen in the work area, creating an ODH. Potentially serious health effects are associated with exposure to decreased oxygen concentrations.

Areas where an ODH may be present are classified and posted according to risk. ODH risks are mitigated by a combination of both passive and active safeguards and administrative controls. Passive engineered safeguards include lintels and helium-removal vents situated in key locations. Administrative controls include training, specialized Personal Protective Equipment (PPE), and monitoring equipment. Active controls include engineered safeguards such as floor- and ceiling-mounted ODH monitors, which are part of a monitoring system that results in workplace audible and visual alarms and, in some cases, can initiate high-volume air exchange to mitigate ODH conditions.

For the purposes of this SAD, an ODH System failure is characterized by an event where:

- The ODH System is operated with less than the minimum number of ODH monitors in the required monitor location(s) as specified in the most current ODH Assessment for the location(s); or
- The ODH System cannot detect or locally alarm in a potentially occupied and monitored location where the oxygen content is 19.5% or lower.

ODH System failures are promptly evaluated by the AESSAF and the SCMB to determine whether the failure violates the conditions of the ASE or represents a hazard condition that has not been fully evaluated.

Accelerator ODH System functionality is certified every two years by physical testing of the systems. ODH System failures detected during calibration are not ASE violations but shall be evaluated by AESSAF and the SCMB to determine whether the failure represents a hazard condition that has not been fully evaluated.

ODH monitoring systems in the CEBAF, LERF, UITF and CMTF accelerators are considered Credited Active Engineered Controls.

4.2.1.4. Other Accelerator Engineered Systems

4.2.1.4.1. Accelerator and Beam Dumps

The Accelerator Division is responsible for the proper configuration, maintenance, and operation of the accelerator from the injector to the experiment hall targets. The configuration of high-power beam dumps is maintained by the Engineering Division. The Physics Division is responsible for the beamline from the alcove shield wall to the target assembly. There is a shared responsibility for certain beamline components within experimental halls, such as magnets and associated power supplies, and diagnostics. FM&L is responsible for the cooling system hardware associated with high-power beam dumps and other sources of cooling water, as well as pressure-related utilities.

4.2.1.4.2. Accelerator Computer Controls System

The systems that constitute the accelerator controls are managed and monitored by EPICS. Computer hardware and software are managed by the Accelerator Controls Group. They provide a structured and controlled software development and maintenance environment.

Software for EPICS is developed using standard methods that include planning, testing, documenting, and managing configuration.

Channel Access Security is an active engineered system that establishes a security protocol limiting the ability of individuals to access electronic process variables used to control the accelerator.

As identified in Section 3.4.2 Telecommunications, the lab's computer networks, including those used for facility infrastructure and accelerator controls, are protected against unauthorized use and malicious intrusion by a layered defense model. These measures are identified in the *Cyber Security Protection Plan*. Note that the EPICS control system is not a safety system. Software QA for safety systems is managed by *AD-02-001 v1 PSS Configuration Management Procedure*.

4.2.2. Experimental Physics Division

The Experimental Nuclear Physics Division (commonly referred to as the Physics Division) is responsible for the design, installation, commissioning, operation, and maintenance of the equipment required to conduct the experimental physics program and the coordination of the research program with the user community. The Physics Division oversees staff scientists and domestic and international visiting scientists (users) at Jefferson Lab as they design, conduct, and interpret results from experiments using the Jefferson Lab accelerators and the advanced particle-detection and ultrahigh-speed data acquisition equipment in four experimental halls.

4.2.2.1. Physics Governing Processes and Procedures

A Readiness Certificate is developed and ensures that roles and responsibilities for hazard control and safe conduct of operations are clearly identified. There is effective coordination between Accelerator operations and experimenters, meaningful metrics on operational reliability for accelerator and experimental equipment are provided. The Readiness Certificate is the authorization for a particular experiment to run.

Experiment proposals are reviewed for merit, and approved experiments are subject to the CEBAF Experimental Readiness Review (ERR) process. The ERR process analyzes potential hazards in proposed experiments that could result in accelerator-specific accidents and determines effective mitigations, which are then included in the design of the experiment. The review team determines whether additional provisions for safety must be made before the proposal can be approved. This process is described in *ES&H Manual Chapter 3130, Accelerator Experiment Safety Review Process*. Note that while the ERR process is primarily used for experiments that use CEBAF and take place in the experimental halls, it can also be applied to nuclear physics experiments that might take place at other facilities at Jefferson Lab.

The ERR process provides a progressive review of an experiment, from the proposal stage through to the installation and checkout, and its effect on the environment, and worker safety and health.

From this process, a number of key documents are developed:

- Conduct of Operations Document, which defines directly, or by flow-down to lower-level documents, typical experiment-running procedures and unique requirements of the particular experiment. The Conduct of Operations Document specifies organization and administrative responsibilities; duties, operation, procedures, and safety requirements; and includes qualifications and training requirements.
- Experiment Safety Assessment Documen*t*, which provides a safety analysis of the specific equipment design. It identifies safety issues for the specific equipment as operating in the planned experiment (including tests and commissioning) and incorporates hazard mitigation measures.
- Radiation Safety Assessment Document (RSAD), which provides an estimate of the site-boundary dose for each experiment and reviews specific radiation hazards associated with the experiment, including operation and maintenance of physics targets unique to that experiment, and identifies responsibilities for custody and eventual disposal of radioactive materials associated with that target.
- Emergency Response Guidelines, which address emergency response requirements and emergency egress routes for a given specific experiment and identifies the locations of major

potential hazards and emergency systems.

The ERR process is scalable, and the scope and intent of its application for a given experiment is ultimately determined by the Associate Director for Physics.

Work Control Documents (WCDs) are developed when a task involves production (e.g., assembly and fabrication), maintenance, repair, and R&D (research and design). WCDs are used to operate new equipment installed in experimental halls for equipment commissioning and initial operation. Routine operation of equipment in an experimental hall is governed by the respective Equipment Manual and is not subject to the ERR process.

The ERR process determines whether an experiment can function safely within the context of the safety assessment and controls identified in the SAD. As mentioned in Section 4.2.5.2, *ES&H Subcommittees*, the SCMB is responsible for maintaining this Safety Assessment Document and the ASE. A standing member of the SCMB is the Radiation Control Manager (RCM) who reviews each RSAD. Any hazard that is not identified in the SAD or requires controls that are not represented in the ASE is considered a positive USI and actions necessary for that experiment to run are evaluated and documented using the ASE Violation and USI Review Process before the experiment is run. In that sense, the ERR process serves a key configuration management role consistent with the requirement of 420.2D.

Successful completion of an ERR is a prerequisite for beam delivery for the purposes of conducting a nuclear physics experiment and is considered an Administrative Credited Control in the ASE.

4.2.2.2. Physics Training and Personnel

The Physics Division provides the personnel and procedures for personnel who operate and maintain the equipment in each of CEABF's four experimental halls. The requirements for safe operation of the basic equipment in each experimental hall are identified in the hall's operations manual and WCDs.

To ensure close coordination between Jefferson Lab and external users on operational and ES&H issues, the Physics Division assigns a Liaison Physicist or a Division Safety Officer (DSO) for each scheduled experiment. This individual is responsible for coordinating interactions between the lab and the experimenters with particular emphasis on equipment staging and installation in the hall, and on the completion of the necessary ES&H reviews of the equipment and procedures that will be used for the experiment.

The Physics Division provides Hall Awareness Training; this training familiarizes workers with the hazards and mitigations unique to and associated with each experimental hall. This training is required for all experimenters participating in the staging and running of experiments in the hall.

4.2.2.3. Physics Engineered Systems

The Physics Division works with the Accelerator and Engineering Divisions to ensure the functionality of the beamline hardware from the alcove shield wall to the target assembly. Services (power, cooling water, etc.) for beamline elements in this area may be provided by either the Physics Division or Accelerator Division. The Physics Division is responsible for the physics target design, fabrication, assembly and functionality, as well as the electrical distribution, cooling-water distribution, vacuum, and pressure-related utilities provided by the FM&L Division, and the vacuum and pressure systems, power supplies, and control systems associated with experimental equipment in the halls.

4.2.3. Engineering Division

The Engineering Division provides technical services including mechanical engineering, cryogenic engineering, operations of cryogenic production facilities, engineering support services, and fabrication support. The division also provides survey and alignment, document control, magnetic measurements, fabrication, and machine shop services.

4.2.3.1. Engineering Governing Processes and Procedures

The Engineering Division maintains the *Conduct of Engineering Manual* (COEM). This manual identifies Configuration Management requirements on the basis of mission support and safety using a graded approach. Configuration Management is managed per policy and procedure outlined in the COEM Section 5.0: Configuration Management. The COEM specifies four levels; Level 1 has the most stringent Configuration Management requirements – these systems are critical to mission/operation and have high safety impact. The basis for the application of Level 1 Configuration Management systems is discussed in COEM Section 5.0: Configuration Management. The Level 1 Configuration Management systems determined to be critical to protect workers, users, contractors, the public, and the environment include:

- Listed Active Credited Controls
- Listed Passive Credited Controls

COEM Section 5: Configuration Management also discusses the basis for the application of Credited Controls and the programs and procedures in place to ensure their functionality and integrity. All aspects of PSS functionality are certified annually for each accelerator. Certification involves a multiday, procedure-driven process performed by Accelerator Operations and Safety Systems Group (AESSAF) staff, which verifies the functionality of all PSS devices and tests the functionality of all PSS segments as well as the entire system function as a whole. For CEBAF and LERF, Accelerator Crew Chiefs verify the functionality of the PSS from the MCC while the AESSAF (and other staff) create conditions that test the functionality of individual Critical Devices installed in the accelerator or at access points to the accelerator enclosure. The Crew Chief's role in this process is fulfilled by the facility manager or their trained designee at the UITF, CMTF and VTA. A duplicate process is used to verify the functionality of critical devices in other accelerators.

4.2.3.2. Engineering Training and Personnel

The Engineering Division provides design and operational expertise for cryogenic, vacuum, and pressure systems that support and make up accelerator hardware. The Engineering Division also provides for the design and operation of electron beam dumps. Training is managed through TJNAF's Learning Management System.

4.2.4. Human Resources (HR)

4.2.4.1. HR Governing Processes and Procedures

The HR Department is responsible for the Administrative Manual. The Administrative Manual is a comprehensive policy document that addresses human resources, finances, facilities, procurement, etc. The Administrative Manual also clearly states laboratory ES&H Policy.

4.2.4.2. HR Training and Personnel

Proper training and qualifications are necessary for personnel performing roles that are key to the safe operation of Jefferson Lab accelerators and the conduct of nuclear physics experiments. Training requirements are specified in relevant sections of the Administrative Manual and the ES&H Manual. All laboratory staff, visiting scientists (users), and subcontractors must undergo the basic Jefferson Lab orientation training. The employee's supervisor, sponsor, or student mentor, using a Job Task Analysis, then determines the specific training required for each laboratory employee, user, or student. Within HR, the Learning and Development Office provides the tools necessary for supervisors to conduct a Job Task Analysis to develop a Skill Requirements List for each employee. The Human Resources Department supports the development and assists with scheduling, of training for staff for various required skills.

4.2.5. Environment, Safety, and Health (ES&H)

The ES&H Division provides the program and processes whereby Jefferson Lab staff, users, and contractors understand and meet their responsibility to perform their work safely and in an environmentally sound manner, in an atmosphere of continuous improvement. Jefferson Lab has developed and implemented administrative programs and procedures to comply with federal, state, and local laws, along with DOE requirements (including DOE rules and orders applied to Jefferson Lab by the management and operating contract).

Fundamental to this system is the commitment that line management bears primary responsibility for ES&H issues in their areas of operation. Consequently, the ES&H effort is accomplished programmatically by line managers. Most of the safety professionals at Jefferson Lab are in the ES&H Division, which serves as a resource for the lab as a whole by providing industrial safety, industrial hygiene, health physics, radiation control, environmental management, and occupational medicine. The ES&H program extends to visiting researchers, subcontractors, and the public through all divisions and offices.

4.2.5.1. ES&H Governing Processes and Procedures

Jefferson Lab's ES&H Program is implemented through the Integrated Safety Management System, which is an integral part of Jefferson Lab's ES&H Program and incorporated into the ES&H Manual. The ES&H Manual is intended to provide clear and uniform ES&H guidance to Jefferson Lab staff, users, and visitors.

It is available to staff, users, subcontractors, and visitors on the Jefferson Lab intranet and is accessible throughout the Jefferson Lab campus. The ES&H Division also manages the lab's safety-related assessment, recording, and reporting functions, and provides policy and guidance for the lab's quality assurance program.

Jefferson Lab's principal administrative safety programs are Worker Safety and Health, Radiation Protection, and the Environmental Management System.

4.2.5.1.1. ES&H Worker Safety and Health

The Jefferson Lab *Worker Safety and Health Program* defines a program that satisfies the requirements of 10 CFR 851, Worker Safety and Health Program, and ensures industrial worker safety and health. ES&H policies for industrial hazards are contained in the ES&H Manual. Work control documents are required by Jefferson Lab policy for all operations where a significant potential health, safety, or environmental hazard can be identified and for which specific authorization or guidance is required. During the preparation of these procedures, potential hazards are identified, mitigation measures are developed, and specific controls are established for conducting the proposed activities. The WSHP principally addresses standard industrial hazards associated with an operating accelerator. These are not otherwise addressed in the SAD, which focuses on industrial hazards that are specific to accelerators or have the potential to initiate or contribute to postulated accelerator-specific accidents.

4.2.5.1.2. ES&H Radiation Protection

The Jefferson Lab Radiation Protection Program (RPP) defines the program that satisfies the requirements of 10 CFR 835 and addresses radiological worker safety and health. The RPP defines requirements for the management of doses to personnel from radioactive materials and machine-generated radiation. The RCD implements the RPP using the Radiation Control Manual. The RPP flows down its requirements into procedures and controls including Radiation Work Permits and Radiation Control Operating Procedures.

Unique hazards associated with intense, prompt ionizing radiation from high-power accelerator operations are addressed by the *Beam Containment and Access Control Policy* and the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001)*. The Beam Containment Policy and Access Control Policy provides the basis for a reasoned combination of active and passive controls to manage personnel exposure to prompt ionizing radiation by keeping beam away from people and people away from beam. The principal passive control is shielding. The *Shielding Policy for Ionizing Radiation (RCD-POL-14-001)* addresses the design, performance testing, and management of shielding used to limit exposure to prompt ionizing radiation. The RCD manages monitoring systems (described in Section 4.2.5.1.2, *ES&H Radiation Protection*) that are typically located outside shielding.

Shielding is identified as a Credited Passive Engineered Control in an ASE. The RCD is responsible for verifying, at least every five years, that the earth shielding berms over the accelerator enclosures for the CEBAF and LERF accelerators meet the minimum specified requirements. Then RCD is responsible for preoperational visual checks on earth shielding berms on a more routine basis. Movable credited shielding (shielding that can be altered by non-destructive means) must have configuration controls applied and be inspected semiannually or prior to operations for the movable shielding that serves as Credited Controls. Operational radiological controls and monitoring systems, such as CARMs, serve as Defense-in-Depth Controls.

4.2.5.1.3. ES&H Environmental Management System

The Jefferson Lab Environmental Management System governs the environmental management practices of the lab, provides oversight and monitoring of operations that could have environmental impacts, and ensures compliance with the various federal, state, and local regulations that apply to the facility and all operations. The RPP is coordinated with the Environmental Management System to ensure the protection of the environment and the public. ES&H publishes an *Annual Site Environmental Report*, available to the public, presenting the results of monitoring processes conducted by Jefferson Lab.

4.2.5.2. ES&H Subcommittees

A number of ES&H subcommittees function under the ES&H Director. One particular subcommittee, the SCMB, provides a measure of independent oversight and review for systems and activities that ensure safe accelerator operations.

The SCMB is chartered by the Lab Director and operates under the oversight of the AD, ES&H, to address accelerator-specific safety issues. As such, the SCMB is charged with:

- Maintain a current listing/inventory of accelerators;
- Review relevant events at Jefferson Lab and other facilities for potential application to systems and processes within the scope of the SCMB charter, such as the Final Safety Assessment Document (SAD), Credited Controls, and the Accelerator Safety Envelope (ASE);
- Charter ad hoc shielding review teams as needed and approve shielding design for medium shielding design projects as part of the RCD Shielding Design and Review process;
- Provide guidance on the development and implementation of the Accelerator Readiness Review (ARR) process associated with commissioning and operations;
- Screen safety concerns pertaining to accelerator operations and determine whether they are Unreviewed Safety Issues (USI), deficiencies in Jefferson Lab policies or the implementation thereof, or ASE violations;
- Refer positive USI determinations and any known or suspected ASE violations to the Reporting Officer upon discovery;
- Review and approve changes to the Credited Controls defined in the ASE and to other systems or processes that can impact the effectiveness of the Credited Controls;
- Review the SAD and the ASE in a timely manner to ensure they remain current, make recommendations regarding approval to the Lab Director through the ES&H Director;
- Review matters pertaining to compliance with the Accelerator Safety Order (ASO) DOE 420.2D and subsequent revisions as may be incorporated in the DOE contract, and make recommendations to the Lab Director through the ES&H Director;
- Review proposed changes to the Accelerator Safety Order and participate in the DOE review process to protect the interests of Jefferson Lab; formal submissions to the review process are coordinated with the ES&H Director;
- Recommend training to ensure awareness of matters affecting the safety of accelerator operations and compliance with the ASO and related Jefferson Lab policies.

The SCMB is responsible for maintaining this Safety Assessment Document and the ASE.

4.2.5.3. ES&H Training and Personnel

The ES&H Director is the authority for Jefferson Lab for identifying hazards, assessing the Risk Level of the hazards, and applying effective hazard mitigations. The Electrical Safety Subject Matter Expert (SME) in the ES&H Division has been delegated by the Thomas Jefferson Site Office (TJSO) to serve as the electrical “Authority Having Jurisdiction,” or EAHJ.

Training, to obtain the industrial safety skills in a Skill Requirements List, is provided by SMEs in the ES&H Division and in the line organizations that have responsibility for certain accelerator-specific hazard controls. ES&H maintains SMEs, certified by their respective professional organizations, to provide professional advice, hazard mitigation techniques, and training for a wide range of industrial hazards.

Training associated with accelerator-specific hazards provided by ES&H includes ODH Training and Radiation Worker Training, including the process for making a Controlled Access.

Radiation Worker Training and ODH Training are considered Defense-in-Depth Controls.

4.2.5.4. ES&H Engineered Systems

The RCD calibrates, maintains, and operates a series of CARMs in radiologically controlled areas (on the site boundary, these are called Radiation Boundary Monitors, or RBMs).

CARMs are high-reliability devices with sensitive detectors that measure prompt ionizing radiation from accelerator operation. CARMS have internal data-logging features, provide workplace audible and visual alarms, and can be used to shut off the devices for which they are deployed.

CARMs, interlocked to the respective PSS, are mounted in areas accessible to personnel adjacent to accelerator enclosures. The data and alarms that CARMs provide are monitored centrally through EPICS and are available to the operations staff of each accelerator. In addition, CARMs may be deployed at radiation-generating devices (RGDs), and are operated according to procedures associated with operating such RGDs. CARMs are considered Defense-in-Depth Controls.

RBMs are located at the Jefferson Lab site boundary in the vicinity of the security fence, in areas accessible to the general population. RBMs use more sensitive detectors that measure very low levels of radiation and are not interlocked. RBMs have a centralized display for Accelerator Operators and data-logging for RCD staff.

Hydrogen gas monitoring systems, maintained, calibrated, and operated by ES&H are deployed inside buildings that house high-power beam-dump cooling system components. These buildings act as radiation shielding for radioactivity circulating in high-power beam-dump cooling water and as containment against potential leaks from these systems. The hydrogen gas monitors detect elevated hydrogen gas concentration and provide a centralized alarm for Accelerator Operators at levels well below the lower explosive level for hydrogen in the air.

The hydrogen gas monitors are considered Defense-in-Depth Controls for the buildings that house high-power beam-dump cooling system components.

4.2.6. Contractor Assurance System and Quality Assurance Program

The Contractor Assurance System (CAS) is designed to enable mission accomplishment; to protect workers, the public, and the environment; and to ensure the efficient and effective functioning of operational, facility, and applicable contract requirements. CAS outcomes are intended to consistently provide DOE with a reasonable level of confidence, or assurance, that objectives are being met in a compliant, efficient manner. Jefferson Lab uses a Tri-Party CAS Engagement Model: DOE provides performance expectations and feedback; JSA oversees and holds Jefferson Lab management accountable for laboratory performance; and Jefferson Lab uses an integrated management system to ensure the broad range of contract requirements are properly addressed, performance measured, outcomes understood and adjusted where necessary. The CAS includes structured reviews for DOE O420.2d compliance for the operation of each accelerator.

The Quality Assurance (QA) Program Description is an element of the Contractor Assurance System (CAS) Program, and thus the Lab Management System, and is managed by Performance Assurance. Jefferson Lab's policy is to integrate "quality and self-assessment into all activities for continuous improvement." As part of the Jefferson Lab Contractor Assurance System (CAS), quality-management activities are based on a graded approach that ensures appropriate controls and feedback commensurate with the scope and associated risk for each activity. Performance Assurance plans and facilitates performance assessments (Management Self- Assessment and Independent Assessment) that address cross-functional laboratory performance with respect to its goals and oversight requirements. The Jefferson Lab *QAP Description* is the primary mechanism for implementing and maintaining the quality management system and associated procedures, and it describes how the applicable criteria are implemented at Jefferson Lab. The QAP also facilitates implementation of DOE O 420.2D, incorporating requirements into Integrated Safety Management where possible and providing functional oversight for other key activities that include the Accelerator Readiness Review and USI process.

Accelerator-specific safety aspects of the Jefferson Lab QAP include:

- Calibration and testing of radiation-monitoring instruments as specified by the RPP;
- Coordination and recordkeeping of operational activities and system maintenance, which are managed through the experiment scheduling process; electronic logs of operations activities; and the "Accelerator Task List" and similar database tools that are used to manage maintenance activities throughout the accelerator site; and

4.2.7. Information Technology (IT)

The CST (Computational Sciences and Technology) Division provides information services to all areas of the organization, including the scientific computing services that support the theoretical and experimental programs of the lab. Within CST, the Computing and Networking Infrastructure (Computer) Center is the home of the Security Group. The Security Group, within the Computing and Networking Infrastructure (CNI) group, manages cyber security for Jefferson Lab.

4.2.7.1. IT Governing Processes and Procedures

CNI operates according to the Cyber Security Plan and provides policies and guidelines for users to protect the lab computing environment and its users.

4.2.7.2. IT Training and Personnel

CNI provides cyber security infrastructure for the lab and supports cyber security for accelerator operations computers and networks. CNI provides training on reporting suspected cyber security issues and maintains a Help Desk during business hours to resolve concerns regarding cyber security for computer users.

4.2.7.3. IT Engineered Systems

CNI installs, operates, and maintains the computer firewall systems that are the backbone of cyber security at the lab.

4.2.8. Facilities Management & Logistics (FM&L)

The FM&L Division provides facility maintenance, construction, security, property management, and utility services throughout the lab.

4.2.8.1. FM&L Governing Processes and Procedures

FM&L is responsible for the buildings and utilities on the Jefferson Lab site. The FM&L Site Security Department provides integrated security management ensuring the protection of laboratory assets, including physical and intellectual property, and establishes programs for cyber security, export control, and counterintelligence. Security management is implemented on the Jefferson Lab campus by executing Site Security Plans, which include both a roving guard service throughout the campus and a continuous guard presence at the access control point to the site security fence. This access control point is manned continuously to ensure only personnel with the required training and authorization are permitted entry to the Controlled Area that circumscribes the CEBAF, LERF, and GTS accelerators.

Facility conditions including the integrity of shielding and the high-power beam-dump cooling buildings' (Buildings 91 and 95) structural integrity are verified at least every five years. Facility integrity, including shielding material (depth, thickness, etc.) is verified by FM&L and is tracked in the Condition Assessment Information System (CAIS) at least every five years.

FM&L administers the Dig, Blind Penetration Permit in *ES&H Manual Chapter 3320, Temporary Work Permits*, which is identified in each ASE as Management and Surveillance for Permanent Shielding.

4.2.8.2. FM&L Training and Personnel

FM&L maintains a wide range of SMEs who manage electrical utilities, heating, ventilation, and air-conditioning utilities, LCW cooling systems, and the division provides professional engineering advice on construction, maintenance, materials handling, and fall protection. FM&L staff provide the SME for the high-power beam- dump cooling system operation and performance.

The Technical Representative, who is responsible for evaluating subcontractor training, determines training requirements for subcontracted activities.

4.2.8.3. FM&L Engineered Systems

FM&L is responsible for the maintenance and operation of the high-power beam-dump cooling system. FM&L maintains the integrity of radiation shielding and the structural integrity of the high-power beam-dump cooling buildings.

Permanent shielding integrity and structural integrity of the high-power beam-dump cooling buildings is identified in the ASE as a Credited Passive Engineered Control.

4.3. Accelerators Within the Fence

A security fence exists around the three accelerators at the Accelerator Site. Inside the security fence are the following accelerators and related facilities:

- CEBAF Accelerator with the associated Experimental Halls A, B, C, and D;
- LERF Accelerator; and
- LERF Gun Test Stand (GTS).

Both the CEBAF and LERF accelerators are also used as testbeds for an advanced accelerator physics research & development program. The techniques and models developed are used to advance the state-of-the-art electron source and superconducting accelerator technology.

Figure 4, Accelerator Site Plan Within the Fence, shows the location of roadways and surface buildings that support accelerator operations. The CEBAF beam enclosure is located below grade or under soil berms, which contribute to the shielding that attenuates radiation produced during accelerator operations. Power and controls for the accelerator are housed in service buildings on the surface directly above the accelerator tunnel. The CHL supplies cryogenic helium to the CEBAF and LERF linacs and is centrally located on the surface between the CEBAF linacs.

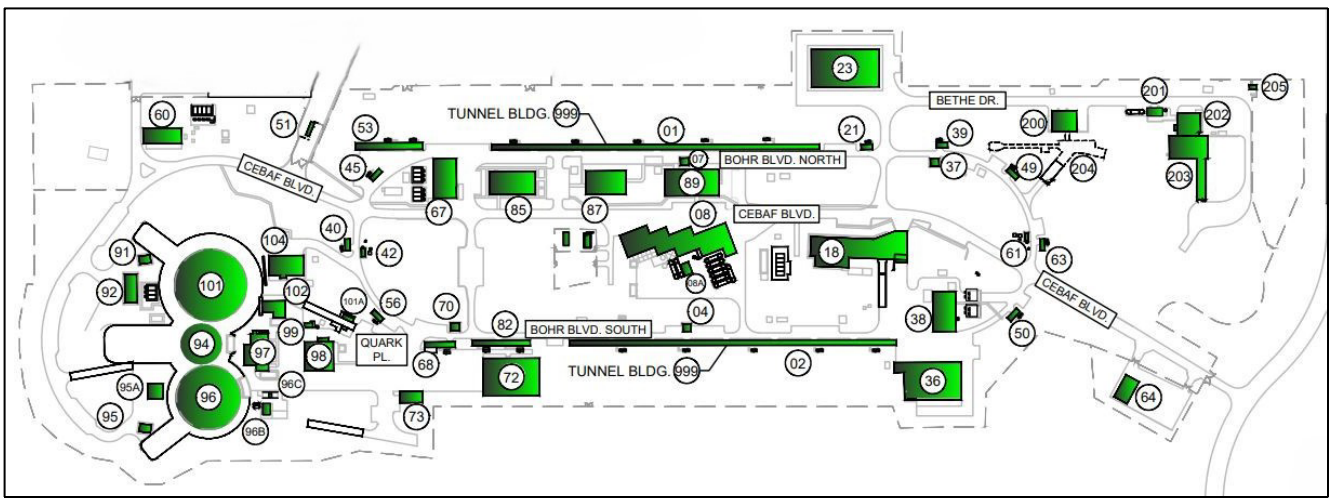

Figure 4. Accelerator Site Plan Within the Fence

The description of the accelerators is organized along the following lines:

- Brief Description
- Beam Generation and Transport
- Experimental Areas
- Beam Termination
- Hazard Summary

4.3.1. CEBAF Accelerator

The CEBAF accelerator consists of an electron injector, two parallel linear accelerators, 10 separate recirculation arcs – each with a series of bending magnets – and four experimental end stations. CEBAF is capable of delivering one or more (up to four) simultaneous CW beams of electrons with a maximum energy of 12 GeV to Experimental Hall D and 11 GeV to Experimental Halls A, B, and C.

The beam current to any experimental hall is also limited by the power rating on the physics target and beam dump for that experimental hall. Experimental Halls A and C are capable of 1.3 MW. There is a beam envelope limiting system (BELS) and an operations tool called Max Juice which provides operator controls over beam parameters. The electron beam current to each hall is independently controlled, and the beam energies to each hall are available at fixed ratios depending on the energy of the linear accelerators.

Individual segments of the accelerator and individual experimental halls may be isolated from beam transport and made accessible to personnel while beam is transported in other segments. The PSS described in Section 4.2.1.3.1, *Accelerator Engineering PSS*, provides the beam containment and access controls necessary for segmented operations.

4.3.1.1. Beam Generation and Transport

The CEBAF injector is located on the West side of the accelerator enclosure and contiguous to the CEBAF accelerator tunnel. This injector uses a laser-driven photoelectron source, referred to as the source gun, designed to provide spin-polarized electron beams which can be accelerated and directed simultaneously to different experimental end stations. In the injector, the electron beam is shaped by a number of warm RF components and accelerated by one booster cryomodule and two full cryomodules before it is injected into the North Linac. The injector may be used to test accelerator components and unique configurations for future upgrades or, in some cases, for low energy nuclear physics experiments. Changes to the configuration of the injector are managed by the USI process. Low energy experiments are governed by the ERR process described in Governing Processes and Procedures for Accelerator and for Physics. The ERR Process is a Credited Administrative Control.

The source gun's photocathode is biased using a 350kV, 4.5mA Glassman high-voltage DC power supply. The power supply uses sulfur hexafluoride (SF6) as an insulating gas. If the CEBAF high-voltage power supply failed, the UITF high-voltage power supply can be installed in the CEBAF Injector. Both high voltage power supplies are capable of providing nominal operating voltage for beam operations, as well as greater voltages for field emission conditioning. The photocathode's lifetime, and integrity of the photoelecton source in general, is negatively impacted by field emission, and so high voltage conditioning is performed with the goal of no observable field emission when at beam operations settings.

There are five CEBAF Beam Modes, M0 through M4, in addition to an RF-only mode. These modes are configured through the PSS such that personnel cannot access a PSS segment where there is, or there is the potential for, beam or RF hazards. At the same time, the other PSS segments can be configured for safe personnel access.

The operational modes, which are linked to the PSS segments shown in Figure 3, are given in Table 1.

Table 1. CEBAF Operational Modes

Beam	Mode	Location within CEBAF	Beam Destination
OFF	RF Only	Injector, North Linac, South Linac	None
ON	M0	Injector	1D Spectrometer Dump
ON	M1	Injector, North Linac	In-line Dump
ON	M2	North Linac, South Linac, BSY	2kW Dumplettes
ON	M3	Halls A, B & C	Halls A, B & C Dumps
ON	M4	Hall D & HD Tagger	Hall D & HD Tagger Dumps

The beam off RF-only Mode applies when RF power >100 W is used to drive superconducting cavities in the Injector, North Linac, or South Linac, without injection of a bunched electron beam from an external source.

The first beam mode, Mode M0, has a maximum energy of the Injector source gun voltage. Beam is bent into 1D Injector spectrometer and terminated in a stationary shielded dump. In this beam mode, access to the Injector PSS segment is precluded. The North Linac, South Linac, Beam Switchyard, Halls and Hall D Tagger PSS segments can be safely accessed.

The second beam mode, Mode M1, is referred to as straight-ahead mode. Beam can travel as far as the inline dump, but can also be diverted into one of the Injector spurs. These are the 2D spectrometer, 3D Mott polarimeter, 5D experimental line, and 4D spectrometer. Each of these spurs has a shielded stationary beam dump termination point. The inline dump is also shielded, but is not stationary. It can be inserted or retracted from the beamline. It is physically located in the North Linac PSS segment, but operationally is considered the end of the CEBAF Injector.

In beam mode M1 beam can also be delivered to Faraday Cup #2 in the main beamline. This is an insertable device located in the Injector-NL PSS gate that physically divides the two segments. The Faraday Cup is shielded.

When beam is setup to the 2D, 3D, 5D spurs, or Faraday Cup #2, it passes through the booster cryomodule. The booster cryomodule was installed in 2023 and replaced a warm capture accelerating cavity and a 2-cavity quarter cryomodule. When beam is setup to the 4D spectrometer or inline dump, in addition to passing through the booster, it will pass through two full 8-cavity cryomodules.

In beam mode M1, access to the Injector and North Linac PSS segments is precluded. The South Linac, Beam Switchyard, Halls and Hall D Tagger PSS Segments can be safely accessed.

The North Linac and South Linac are each comprised of 25 superconducting cryomodules cooled to 2K by liquid helium supplied by CHL1 and CHL2. Each cryomodule has 8 multi-cell superconducting niobium cavities. Each cavity is powered by a klystron that provides 1497-megahertz (MHz) RF radiation, producing an accelerating gradient up to 30 MV/m. Each cavity can be independently adjusted. RF power, along with power for steering magnets, controls, and diagnostics, is supplied from an equipment gallery in a series of above-ground service buildings. In both the North and South Linac, as much as 1.1 GeV of energy is imparted to the electron beam each time the linac is traversed.

After each linac is a magnetic vertical spreader region that separates out beams based on energy. Then, there are magnetic horizontal arcs that bend the beam 180 degrees. Following the arcs are magnetic vertical recombiner regions that recombine beams from the arcs before entering the successive linac. On both the East and West sides of CEBAF there is a spreader, five arcs, and a recombiner. At the end of each of the ten arcs, there are 2kW shielded beam termination points referred to as beam dumplettes.

The electron beam is injected from the West into the North Linac, where is can be recirculated up to six times through the North Linac, and five times through the South Linac. The beam travels clockwise through the accelerator. Coming out of the South Linac, the beam can be extracted on the West side to Halls A, B, and C after it passes through both linacs from one to five times. Additionally, the beam can be extracted on the East side to Hall D tagger after it travels a sixth time through the North Linac. There are four additional 2kW beam dumplettes in the A, B, and C extraction lines, as well as in the Hall D Tagger extraction line.

In Beam mode M2, the Injector, North Linac, South Linac, and BSY PSS Segments are configured to preclude personnel access. The Halls and Hall D Tagger can be configured for access. Beam is terminated at any one of the fourteen 2kW beam dumplettes (one in each of ten arcs, one in front of each experimental Hall).

In beam mode M3, in addition to the segments listed for beam mode M2, at least one of Halls A, B, or C is configured to receive beam. Access is precluded to that Hall if it is configured to receive beam. Halls not configured to receive beam can be safely accessed.

In beam mode M4, in addition to the segments listed for beam mode M2, Hall D and Hall D tagger are configured to preclude personnel access and allow beam delivery.

Beam modes M0, M1, and M2 are mutually exclusive. Beam modes M3 and M4 are not. The PSS can be configured for M3 alone, M4 alone, or M3 and M4.

4.3.1.2. Experimental Areas

Experiments performed in Halls A, B, and C can independently utilize an electron beam that has completed one or more (up to five) passes representing five different electron beam energies up to 11 GeV. For Experimental Hall D, the electron beam makes an additional pass through the North Linac before being transported to the Hall D Photon Tagger. Thus, experiments in Hall D utilize photons from an electron beam that has completed 5½ passes and has a beam energy of approximately 12 GeV.

Certain general features are common to experimental halls:

- Halls A, B and C, the three halls capable of receiving an electron beam, are large cylindrical structures with a domed concrete roof and earth coverage that provides radiation shielding. Hall D, which only receives photons, is a rectangular steel building with radiation shielding to match the much lower radiological conditions of a photon beam.
- Each contains large magnets, cryogenic equipment, large detector systems, significant amounts of detector cabling, power distribution systems, and large overhead cranes. In Halls A and C, the magnet-supporting structures are capable of changing position in the hall. In Halls B and D, the magnets and detectors surround the target and are stationary.
- All experiments are fixed-target experiments where the electron or photon beam interacts

with a solid, liquid, or gaseous target near the center of the hall and then continues to a shielded beam dump. Physics targets may be standardized targets available as part of the conventional equipment in the hall. Targets can also pose unique challenges depending on the material, construction, chemical, isotopic, and possibly radioisotopic composition.

- Halls A and C are designed to receive high-power electron beam, Hall B is configured to receive low-power electron beam, and Hall D is configured to receive low-power photon beam.

The specific features in each hall are uniquely tailored to research areas identified by the nuclear physics community.

The convention for the following discussion of experimental end stations is that the electron beam on the figures below travels the beamline from left to right.

4.3.1.2.1. Experimental End Station – Hall A

Hall A instrumentation is designed to perform high-resolution, high-luminosity experiments (see Figure 5, Experimental Hall A). Instruments include two high-resolution spectrometers (HRSs) with a maximum momentum capability of 4 and 3.1 GeV. Both have a momentum resolution of 1 part in 10000. The spectrometers and hall were designed so that the Left-HRS can be positioned at any angle between 12.5 to 150 degrees with respect to the beam. The angular range of the Right-HRS is 12.5 to 130 degrees. Both spectrometers have a large solid angle and target acceptance (6 millisteradian and +/- 5 centimeter).

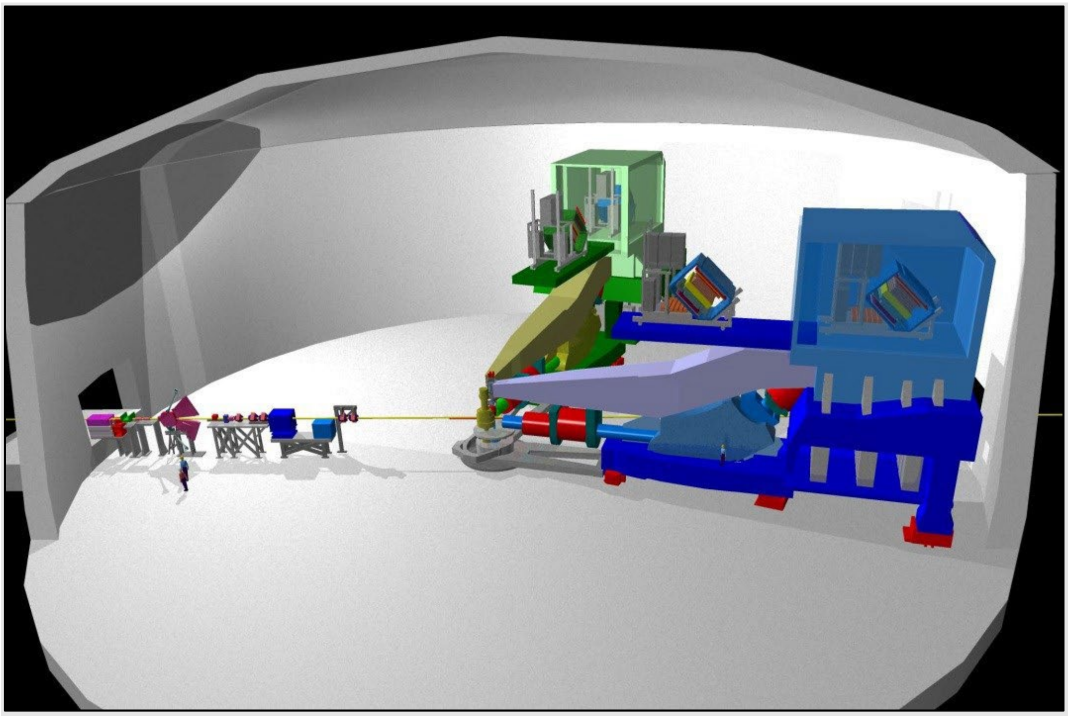

Figure 5. Experimental Hall A

Figure 5 shows the Left-High Resolution Spectrometer (green) and the Right-High Resolution Spectrometer (blue). The electron beam travels from left to right. The devices visible at the left of the figure are the last magnet of the Compton Polarimeter chicane (purple, used to measure beam polarization) and a Moller Polarimeter (another way to measure beam polarization). Several “large installation” experiments such as Moller and SoLID use detectors that are installed in Hall A as part of a particular experiment.

4.3.1.2.2. Experimental End Station – Hall B

Hall B has a bremsstrahlung tagging spectrometer located in an enlarged tunnel section at the entrance of the hall and can use electron or photon beams of relatively low power.

While Hall B can be configured for electron beams of up to 11 GeV for experiments, only electron beams of up to 6.2 GeV can be used with the tagger.

Experimental data are collected by the CEBAF Large Acceptance Spectrometer (CLAS12) shown schematically in Figure 6, Experimental Hall B. The CLAS12 torus and solenoid magnets produce the magnetic fields used to analyze the momentum of the particles produced in a collision. Various detector systems are shown: The Silicon Vertex Tracker (SVT), the Central Time-of-Flight (CTOF), the High-Threshold Cherenkov Counter (HTCC), various layers of Drift Chambers (DC), the Low-Threshold Cherenkov Counter (LTCC), the Forward Time-of-Flight (FTOF) and the calorimeters (PCAL/EC).

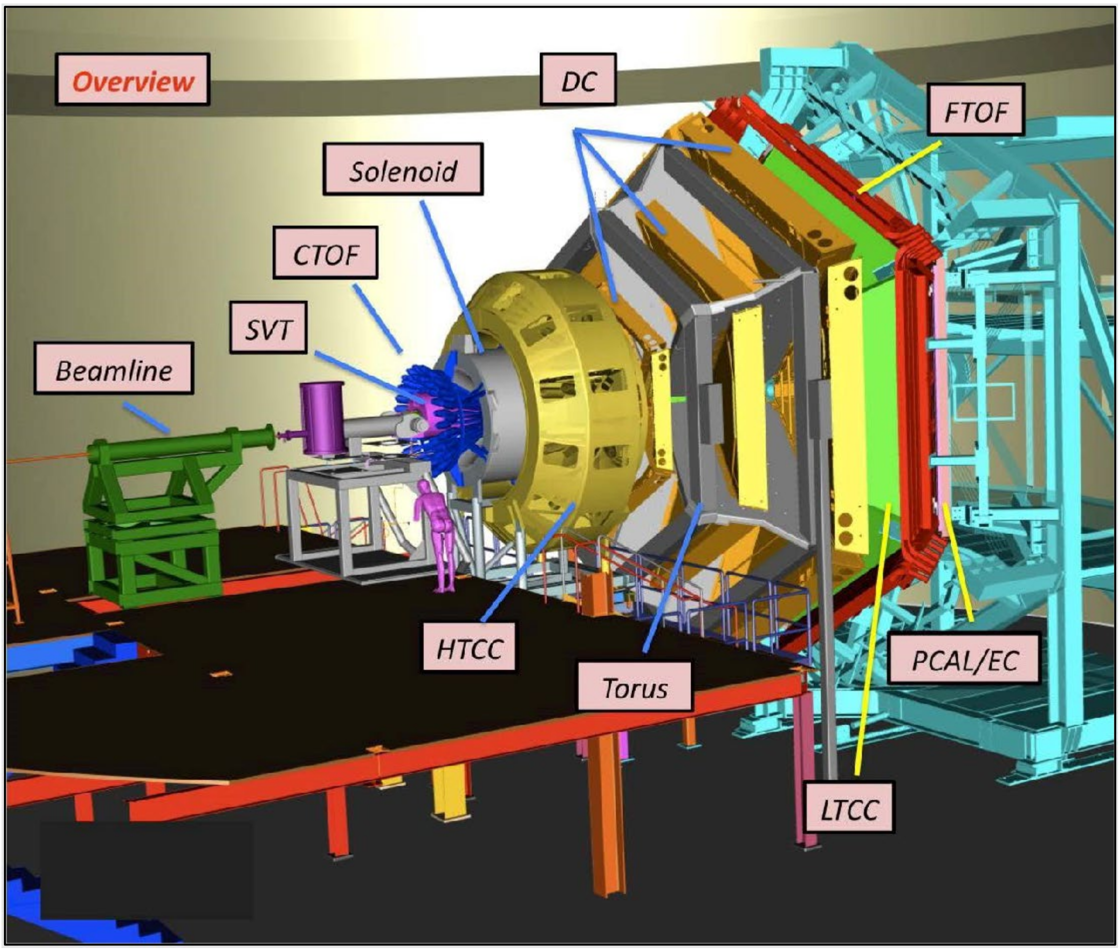

Figure 6. Experimental Hall B

4.3.1.2.3. Experimental End Station – Hall C

Hall C (see Figure 7, Experimental Hall C) contains instrumentation designed to perform medium-resolution, high-accuracy experiments. Instruments include the High Momentum Spectrometer (HMS) and the Super-High Momentum Spectrometer (SHMS). The SHMS has a maximum particle momentum of 11 GeV with a momentum resolution of better than 1 part in 1000, an angular range of 5.5 to 40 degrees with respect to the beam, a solid angle of 4 millisteradians, and a target acceptance of 30 centimeters (cm).

The HMS was designed for a maximum momentum of 7.5 GeV with a momentum resolution also better than 1 part in 1000. The HMS has an angular range of 10.5 to about 90 degrees with respect to the incoming beam, a solid angle of about 6 millisteradians, and a target-length acceptance of 10 cm.

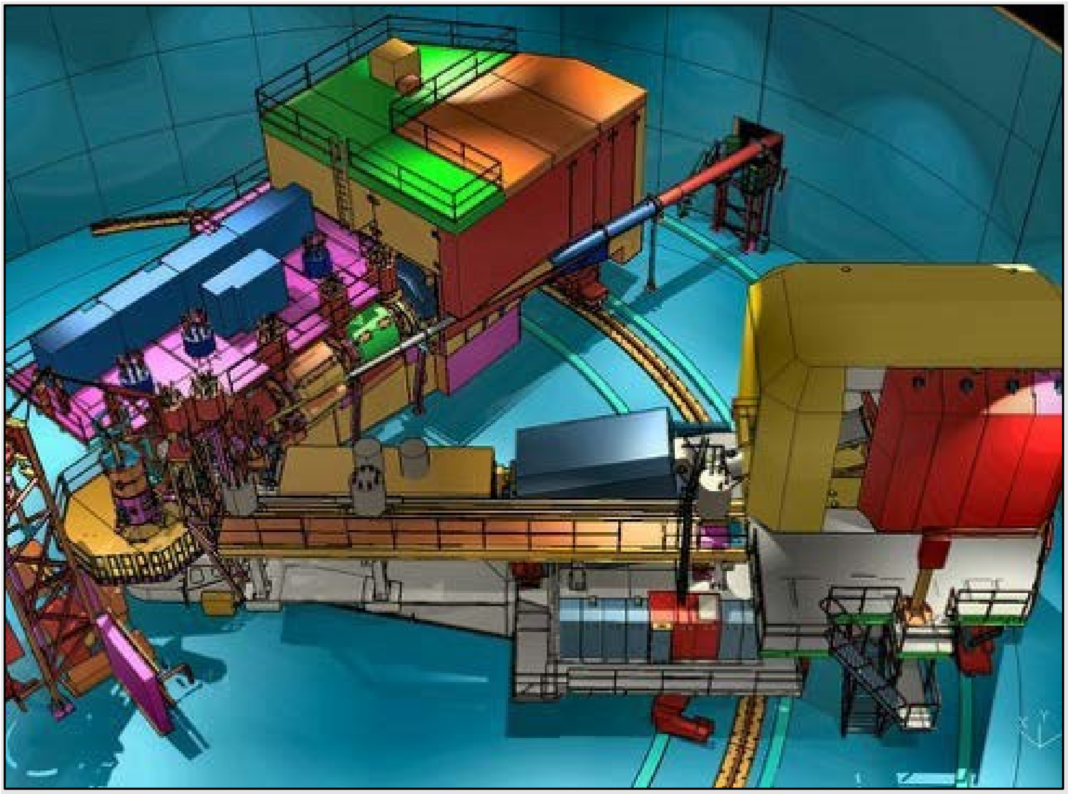

Figure 7. Experimental Hall C

The beam travels from the bottom-left to the top-right. The SHMS is on the top-half section of the figure while the HMS is on the lower-half section of the figure.

4.3.1.2.4. Experimental End Station – Hall D Complex

Hall D (see Figure 9, Experimental Hall D) houses the GlueX Detector, which receives a tagged photon beam from the Tagger Vault via an electromagnetic collimator located at the entrance to the hall. The GlueX Detector consists of a 2.25-Tesla superconducting solenoid, a 3000-element lead-glass forward electromagnetic calorimeter (FCAL), and a scintillator time-of-flight (TOF) wall. GlueX is designed to provide containment of potential exotic states that decay into many particles with a combination of charged and neutral particle final states.

The Hall D complex consists of:

- Tagger;
- Collimator and Experimental hall; and
- Electron and photon beam dumps.

4.3.1.2.5. Hall D Tagger

The concrete tunnel housing the electron beam line extends from the existing North Linac accelerator tunnel to the Tagger area and is large enough for personnel access. Beam extraction and steering components direct the electron beam through a beamline in the accelerator tunnel extension to the Tagger (see Figure 8, Hall D Tagger) where a thin radiator, roughly 20 microns thick, produces a beam of bremsstrahlung photons at an average energy of approximately 9 GeV. Since Hall D shielding is designed for several watts of photon beam, the proper function of the diamond radiator and the Tagger magnet is essential. The electron beam is steered by the Tagger magnet to the Hall D electron beam dump, which extends to the southeast of the Tagger area.

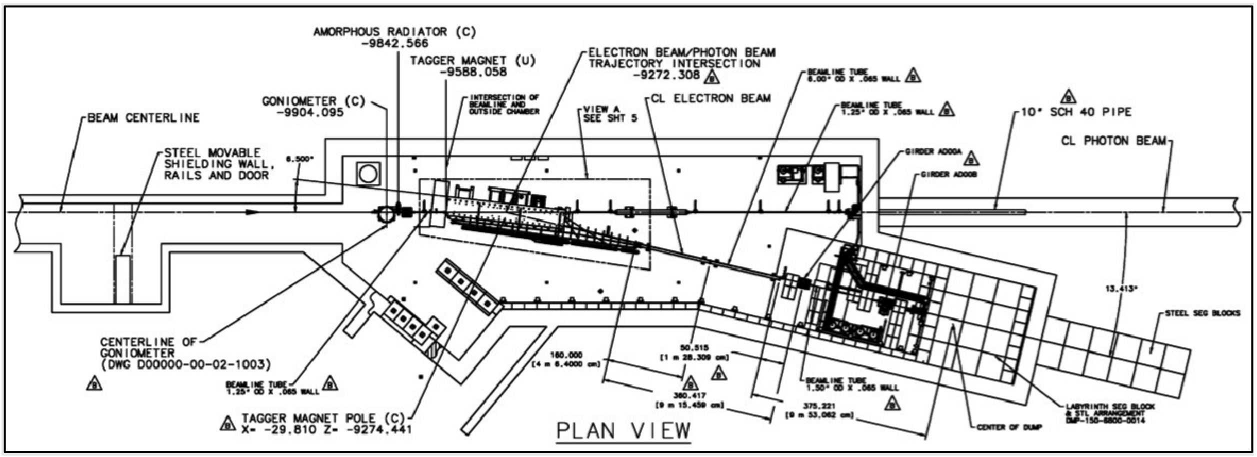

Figure 8. Hall D Tagger

In Figure 8, the electron beam arrives from the left. It goes through a radiator to produce a photon beam directed to Hall D proper (horizontal beam line at top-right) and it is then bent by the Tagger magnet (center) and sent to the electron beam dump (lower-right). Electrons that have lost energy producing a photon bend more in the Tagger magnet and hit various detectors located on the tagger magnet side close to the bottom of the figure. The hit location indicates the energy of the produced photon – it has been "tagged." The photon beam is directed to Hall D via a photon beam pipe and collimator.

4.3.1.2.6. Hall D Collimator

The photon beam produced in the Tagger enters Hall D from the left side of the hall (see Figure 9). The photon beam passes through the collimator at the entrance to Hall D. The collimator is in a concrete-shielded, below-grade enclosure, which is accessible to personnel via a staircase from Hall D interior.

The horizontal cylinder represents the GlueX superconducting solenoid; the structure on top of it supports the vacuum and cryogenic infrastructure needed by the magnet. The rectangular box located at the right of the solenoid is the TOF and FCAL. The unused photon beam leaves the hall toward the right side of the figure on its way to the photon dump.

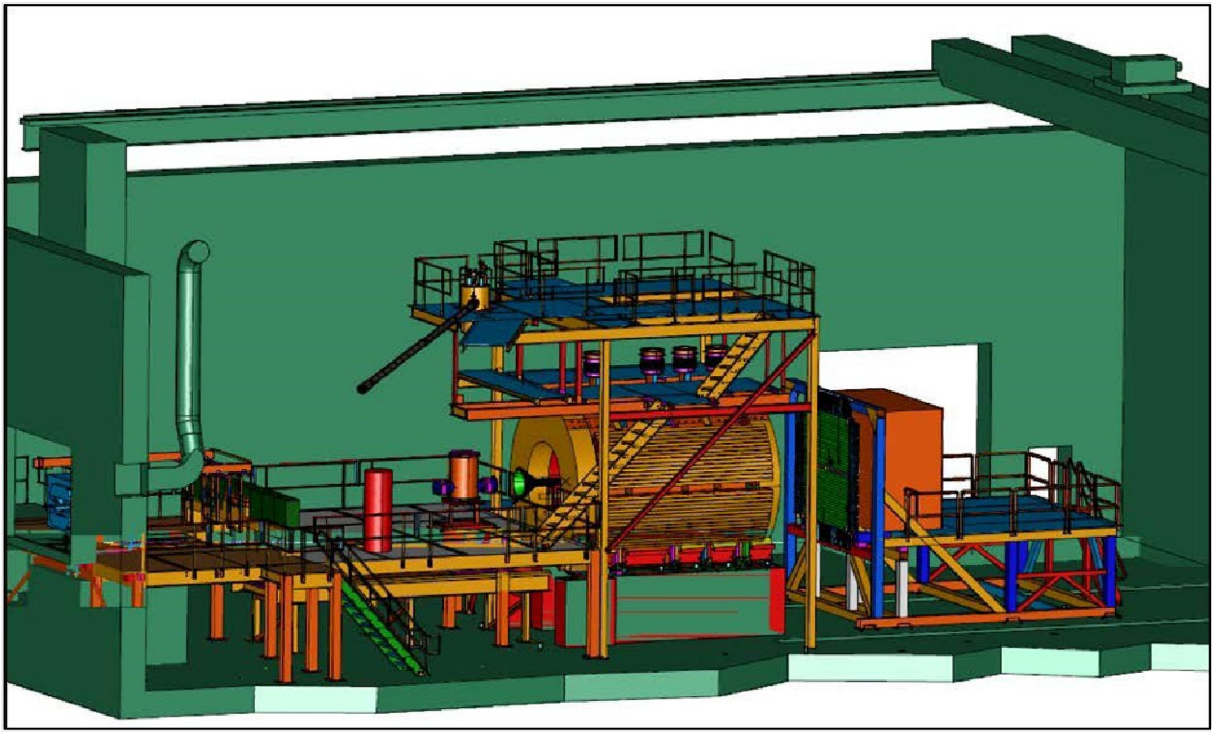

Figure 9. Experimental Hall D

4.3.1.3. Beam Termination

4.3.1.3.1. Halls A and C Beam Dumps

The Halls A and C beam dumps are designed to absorb the total power of the beam and, consequently, can become some of the most radioactive components in the accelerator. The high-power beam dumps for Halls A and C consist of aluminum housing and aluminum plates that have relatively low radio-activation potential and are cooled by circulating water. At the highest beam energy, approximately two-thirds of the beam power is deposited in the aluminum plates and about one-third of the power is absorbed in the cooling water. These dumps have dedicated primary cooling systems, and each contains about 1,500 gallons of water.

These primary loops have heat exchangers housed in beam-dump cooling buildings located above ground and adjacent to the halls. The cooling water is conditioned by water treatment components located in the beam- dump cooling buildings (filters and ion-exchange media) that remove some of the radioactivity and recombine radiolytically produced hydrogen and oxygen.

The primary heat exchanger transfers heat to a secondary, intermediate loop. The secondary loop transports water from the shielded beam-dump cooling buildings to a third building where heat is transferred to a common forced-air evaporative cooling system that serves both Hall A and Hall C.

This configuration ensures that activated water is confined to the cooling loop in the halls and the beam-dump cooling buildings. Even in the case of leakage from a primary heat exchanger, activated water that might transfer to the secondary loop would not enter the external common evaporative cooling loop.

The combined heat removal design capacity of this evaporative cooling system is about 1.1 MW, although excursions up to about 10% above that level can be handled without compromising the system.

4.3.1.3.2. Hall D Tagger Dump

The electron beam dump in the Hall D Tagger has two sections, one aluminum and one copper, that are electrically isolated and independently cooled.

Each section has an independent, closed-loop, low-conductivity water cooling system with a total volume of less than 100 gallons, and each is cooled by a separate heat exchanger that rejects heat to the LCW water supply for the Hall D complex. The overall power rating of this dump is 60 kW; the cooling system for the copper section is rated at 40 kW and the aluminum section is rated at 20 kW. Due to the much lower power and consequently lower radioactivity content, it is not necessary to implement a multi-stage cooling system similar to the beam dumps in Hall A and C. A nitrogen blanket is maintained on both cooling systems, and radiolytic gases generated in this dump are vented to the atmosphere outside the Hall D Tagger building.

4.3.1.3.3. Hall B Photon and Electron Dumps

The beam power delivered to Hall B for electron experiments has been historically limited to 5 kW or less. The electron beam is terminated in either an actively cooled copper core beam dump (originally designed to handle 17 kW) or a Faraday cup, located directly downstream of the copper dump, which can handle up to 1 kW of continuous beam power.

Prior to 2023, the dump and Faraday cup were located just beyond the alcove in the beam dump tunnel, well forward of the optimally shielded location at the end of the beam dump tunnel. The expectation of experiments requiring higher beam power prompted an evaluation of the impact of beam delivery to the dump and Faraday cup in this location; this evaluation is presented in RCD-RPN-22 #001.[34] As a result of the evaluation, both the dump and Faraday cup were relocated to the optimally shielded downstream area. Hall B also tentatively envisions the future installation of a 60-kW beam-dump design (similar to the Hall D Tagger electron beam dump). The need for and timing of this upgrade is driven by the experimental physics program in Hall B. The current beam power limit imposed by the EA for Hall B is 27.5 kW. The planned upgrade would allow for higher power if the environmental assessment (EA) limit is raised.

For tagged photon beam experiments, the primary electron beam of up to 6.2 GeV is deflected downward into a low-power beam dump at the end of the tunnel inserted into the floor of Hall B. Very-low-power (< 5 W) photon beam is terminated in the same beam dump designed for the electron experiments.

The tagger yoke dump is established to allow tuning of a high-energy electron beam (< 200 W) before sending it to the CLAS12 targets. The beam is dumped about 10 inches inside the shielded yoke hole.

4.3.1.3.4. Hall D Photon Dumps

Approximately 5 W of photons are delivered to Hall D from the Hall D Tagger. Hall D has a low-power beam dump consisting of a long section of metal blocks that begin at the exterior of the Hall D east wall and extend to a length sufficient to absorb that photon beam and the muons generated by photons absorbed in the dump.

4.3.1.4. Hazard Summary

The CEBAF Accelerator has the following on-site hazards associated with its operation:

- Cryogenic liquids and gasses;
- Oxygen displacing gas;
- Pressure and vacuum systems;
- Prompt ionizing radiation exposure;
- Radiation exposure from radioactive materials that are:
  - high-power beam-dump primary cooling systems; and
  - targets and accelerator beamline components;
- Nonionizing radiation: lasers, static magnetic fields, RF;
- Noxious and radioactive gases; and
- Groundwater and soil activation.
- Thermal stress
- Link to Table 21, Controls Summary
- Link to Table 22, Basis for CEBAF/LERF ASE

The CEBAF Accelerator has the following potential off-site hazards associated with its operation:

- Off-site dose from prompt ionizing radiation (skyshine) and radioactive gas released to the atmosphere; and
- groundwater activation.

4.3.2. LERF Accelerator

The LERF (Building 18) is in a self-contained, non-segmented superconducting linear accelerator located within the CEBAF footprint and east of the CHL. The LERF uses the same multi-cell superconducting niobium cavity structures as the CEBAF accelerator. User laboratories and power and controls for the accelerator are housed on an upper floor, while the accelerator is located in a lower, partially below-ground vault about 10 feet below grade. The LERF vault is a concrete enclosure that provides radiological isolation for the control room, support equipment areas, and user laboratories above. The LERF accelerator consists of a 10 MeV injector and a superconducting linac with a maximum accelerating gradient of 180 MeV. The LERF has a nominal configuration of two beamlines, one capable of supporting infrared (IR) lasing and terahertz (THz) beams, and one supporting ultraviolet (UV) lasing, each with a permanent magnet wiggler. The beamlines may be modified to include other experiments. The LERF accelerator was designed with an energy-recovery linac.

4.3.2.1. Beam Generation and Transport (Original Design)

The LERF injector uses a laser-driven photocathode and one, 2-cavity 'quarter' cryomodule capable of delivering a maximum electron beam current of 10 milliamps (mA) at 10 MeV. The high-voltage section of the LERF injector provides 350-kV bias voltage and requires SF_6 insulating gas. The LERF accelerates beam with up to three full cryomodules to a maximum energy of 180 MeV.

The original configuration of the LERF was beam transport from the injector through the linac to the first recirculation arc and to either the IR or UV wiggler depending on the operational mode selected. After passing through a wiggler, the beam was transported around the second recirculating arc and returns the beam to the linac for the energy-recovery pass. An energy-recovery linac allowed for the recirculated beam to “donate” energy to injected electrons and interact with a beam stop at the injection energy. Beam losses in an energy-recovery linac are self-limiting; significant loss results in a failure to recirculate beam, limiting energy to the installed linac energy.

The LERF accelerator enclosure can be used for fixed target irradiation where the beam may be directed to an experimental physics target installed along the beamline. Fixed target irradiation is governed by an experiment review process which analyzes potential hazards in proposed experiments that could result in accelerator-specific accidents and determines effective mitigations, which are then included in the design of the experiment. This process is identified in Section 4.2.2.1, Physics Governing Processes and Procedures which identifies *ES&H Manual Chapter 3120, The CEBAF Experiment Review Process* and in 4.2.1.1, *Accelerator Governing Processes and Procedures*, which identifies *ES&H Manual Chapter 3130 Accelerator Experiment Safety Review Process*, as necessary review processes.

The LERF enclosure is also used to operate accelerator components by providing a shielded enclosure and a source of RF energy for the purposes of performance testing.

4.3.2.2. Experimental Areas

LERF power and controls for the accelerator and several laboratories are housed on the upper floor above the vault. The laboratories are independent and have a number of uses. Users conduct experiments using equipment staged in the second-floor user labs using IR and UV laser light and THz radiation generated by the accelerator. The electron beam remains in the lower-level enclosure. The LERF has no dedicated experimental halls to which beam can be delivered.

The LERF accelerator is also used as a testbed for an advanced accelerator physics research & development program.

The techniques and models developed are used to advance the state-of-the-art electron source and superconducting accelerator technology and for training on the operation of energy-recovery linacs.

The LERF can conduct materials tests inside the accelerator vault using direct electron-beam irradiation. This will occasionally require the affected beamline(s) to be temporarily modified with test fixtures and special beamline configurations.

The LERF is capable of conducting nuclear physics research. All experiments are fixed-target experiments where the electron or a generated photon beam interacts with a solid, liquid, or gaseous target in the LERF accelerator vault and continues on to a shielded beam dump.

4.3.2.3. Beam Termination

The LERF electron beam dump is located in the LERF vault. During energy recovery, the beam dump is only required to dissipate approximately 120 kW of beam power and at much lower energy than in the CEBAF accelerator. The dump is used most frequently at 10 MeV for energy-recovered beam. The LERF dump is composed of copper and stainless steel. Most of the electron beam power goes into a copper plate at an angle to the beam. Some of the electron beam reflects off the plate and is absorbed in a stainless-steel sleeve upstream of the copper plate.

Both the copper and the stainless sleeve are water-cooled by a closed loop, low-conductivity water cooling system that has a total volume of less than 100 gallons. Water in the cooling system for this dump does not experience any significant activation at 10 MeV. This has been confirmed by periodic sampling, and no special radiological control features are included in the design of this system. However, the cooling system is an isolated, closed-loop design. The impact of a leak from this system is minimized by the limited volume.

4.3.2.4. Hazard Summary

The LERF accelerator has the following on-site hazards associated with beam operation.

- Cryogenic liquids and gases
- Oxygen displacing gas
- Pressure and vacuum systems
- Prompt ionizing radiation exposure
- Radiation exposure from radioactive materials that are:
  - beam-dump cooling system; and,
  - targets and accelerator beamline components
- Nonionizing radiation: lasers, static magnetic fields, RF
- Noxious and radioactive gases
- Groundwater and soil activation
- Link to Table 21, Controls Summary
- Link to Table 22, Basis for CEBAF/LERF ASE

The LERF accelerator has the following on-site hazards associated with beam operation:

- Off-site dose from radioactive gas released to the atmosphere; and
- Groundwater activation.

The LERF accelerator enclosure may be used to test accelerator components and accelerator systems. The hazard profile associated with testing accelerator components and systems is adequately addressed by onsite hazards associated with beam operations.

4.3.3. LERF Gun Test Stand (GTS)

The GTS is located in the southwest corner of the LERF Bldg. 18. The GTS beam enclosure shares a wall with the LERF vault, and is fitted with a PSS/LPSS maintained by the SSG. The beam enclosure houses a laser-driven DC electron gun (photogun) coupled to a 15 ft. long beamline terminating in a 2.5 kW water-cooled beam dump. The beamline has a RF cavity for beam diagnostics. The GTS is routinely utilized to test photogun high-voltage processing techniques, and to conduct beam characterization and photocathode R&D.

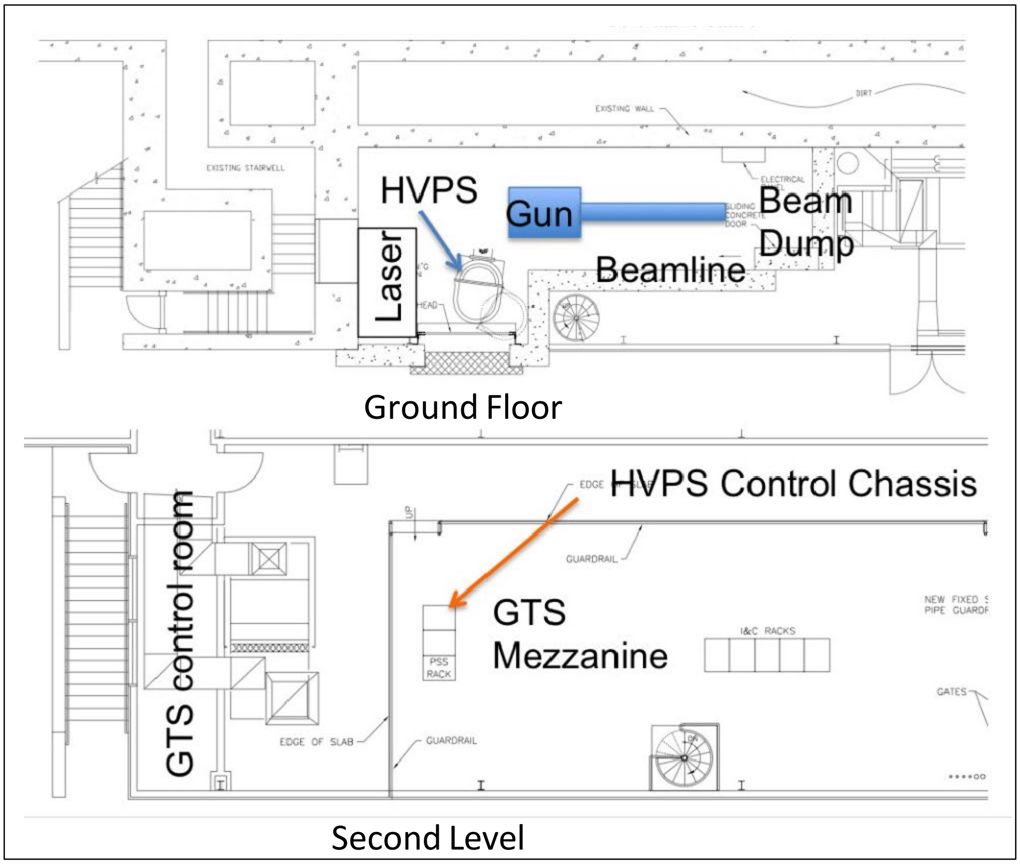

Figure 10. GTS Floorplan

4.3.3.1. Beam Generation and Transport

The photogun is connected to a 550 kV, 5 mA DC power supply inside a tank filled to 10 PSIG of SF_6. The tank has a 14 PSIG relief valve. The electron beam energy and CW beam current are operator-controlled by the high voltage power supply setpoint and by the drive laser power attenuator setpoint, respectively. The photogun high voltage setpoint is typically 200-300 kV. A variety of drive lasers can be used to generate electron beam, but only one laser can be used at a time.

All drive lasers are in a laser hutch and are interlocked to the PSS. Beam is transported from the photocathode to the beam dump by adjusting steering and focusing magnets to center the beam on three beam viewers (YAG screens).

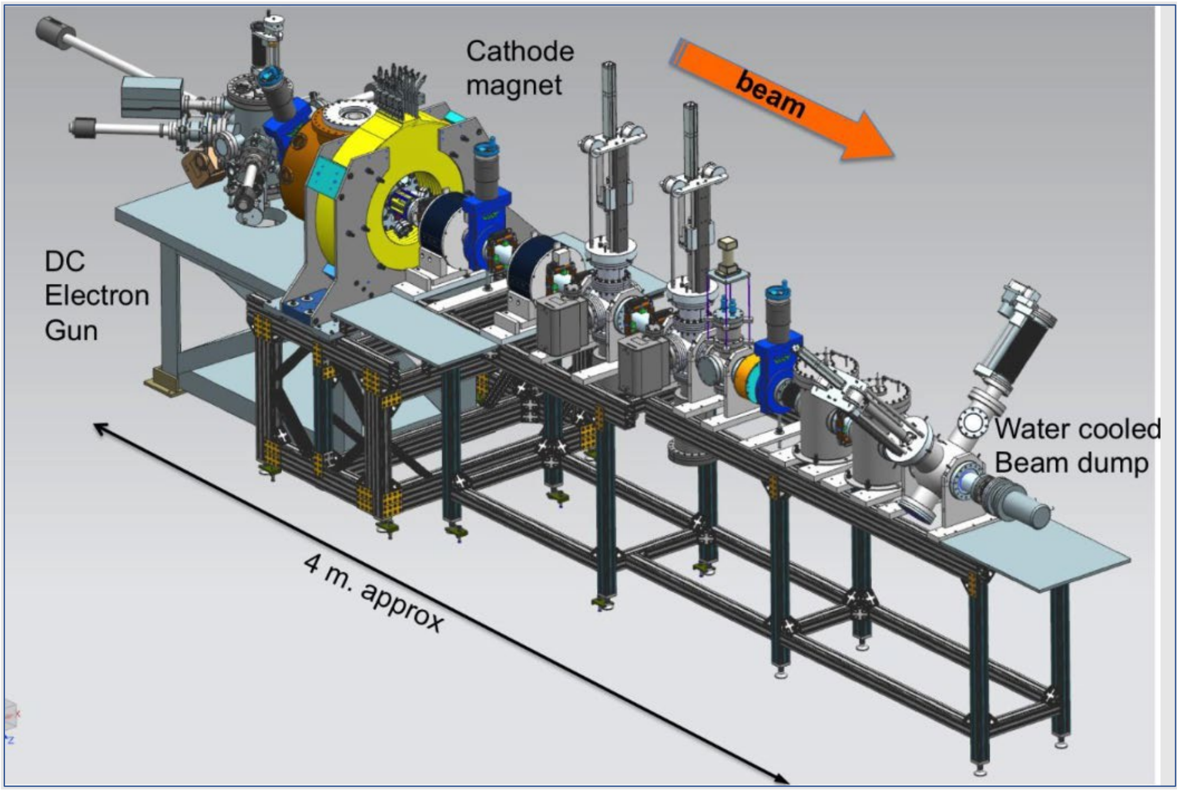

Figure 11. GTS Beamline

4.3.3.2. Experimental Area

The GTS principal use is to test photocathode material performance and photo-gun configuration. It is not used to conduct nuclear physics experiments.

4.3.3.3. Beam Termination

As mentioned in the Description and Operational Summary, electrons produced by the GTS photogun terminate in a 2.5 kW water-cooled beam dump.

4.3.3.4. Hazard Summary

The GTS has the following on-site hazards associated with its operation:

- oxygen-displacing gas;
- pressure and vacuum systems;
- prompt ionizing radiation exposure;
- nonionizing radiation: lasers, static magnetic fields, RF.
- Link to Appendix B: Hazard Analysis for Accelerators Operating at or below 10MeV

4.4. Accelerator Areas Outside the Site Safety Fence

There are three installations operated within the Test Lab that are managed under the ASO: the Upgraded Injector Test Facility (UITF), Cryomodule Test Facility (CMTF) and Vertical Test Area (VTA).

The UITF is a traditional particle accelerator, consisting of typical beam generation, transport and termination hardware and systems. The CMTF and VTA are accelerator component test facilities. They are not intended to produce or transport particle beams as part of the testing, and they are not used for conducting nuclear physics experiments. However, as a byproduct of operations, they can produce high-energy electrons that are accelerated and transported as “dark current” by the high-gradient RF field applied to the devices under test. These accelerated electrons may exceed 10 MeV, and the resulting prompt radiation field can be significant. ASO requirements for accelerators operating above 10 MeV are applied to all three of these test facilities.

4.4.1. Upgraded Injector Test Facility (UITF)

The UITF is an upgrade to the former Injector Test Stand (ITS) located in the Test Lab High Bay. The UITF occupies both the former ITS cave (Cave 1) and includes a second contiguous enclosure (Cave 2) that extends the former ITS further into the High Bay area. The upgrade extends the capability of the former ITS 100-kV electron source to 10 MeV by adding a quarter cryomodule based on the same superconducting RF acceleration used in CEBAF and the LERF. The shielded overhead view of the UITF can be seen in Figure 12, UITF Exterior View.

The UITF has two principal purposes: conduct small-scale physics research experiments at low energy and serve as a research accelerator to test accelerator capability and accelerator components. For these purposes, beam can be delivered to inline dumps and experimental apparatus in Cave 1 or 2. The first small-scale physics research experiment in the UITF was the operation of the HD-Ice Target for the CEBAF Experimental Hall B. The convention for the following discussion of the UITF is that the electron beam travels the beamline from right to left.

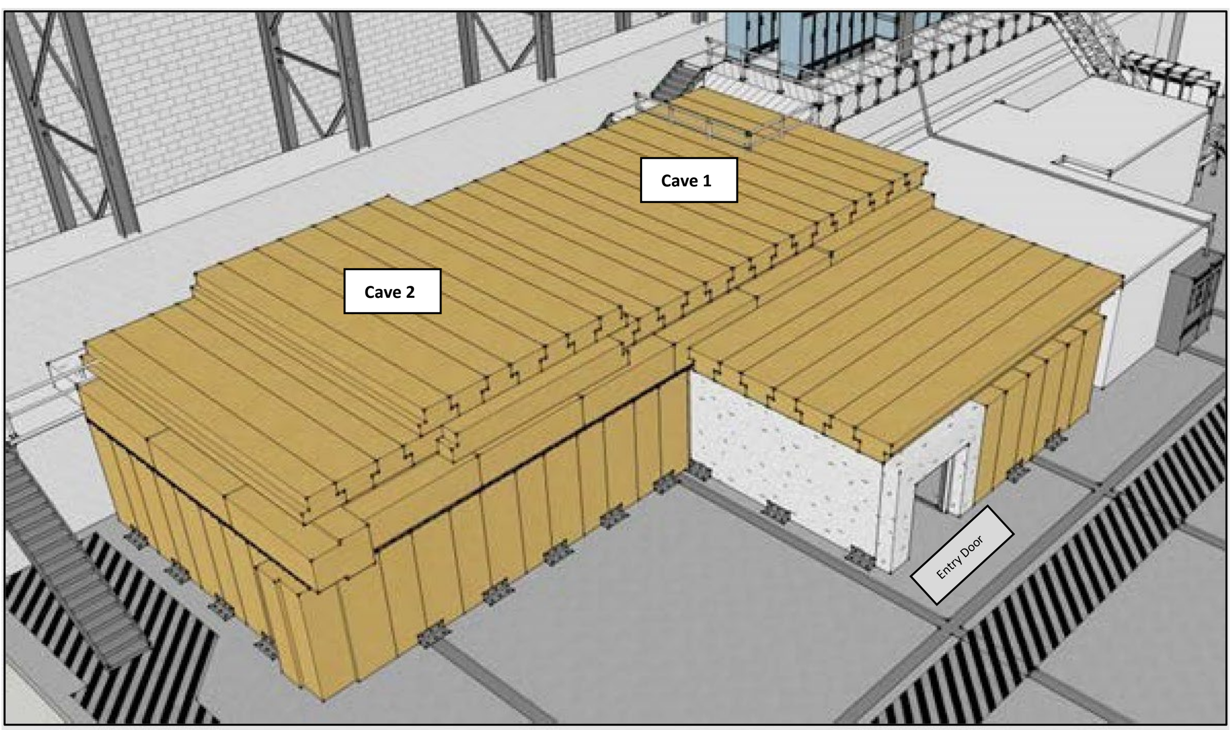

Figure 12. UITF Exterior View

4.4.1.1. Beam Generation and Transport

The UITF uses a laser-driven photo-electron injector operating at either 200 kV or 350 kV, depending on the configuration of the quarter-cryomodule. The photo-electron injector (see Figure 13, UITF interior view) employs a Class 3B seed laser and several Class 4 drive lasers to generate electrons from the photocathode. These lasers are installed in a special clean enclosure outside the UITF with separate interlocked access controls that are part of a Laser PSS. As mentioned above, the photo-electron gun generates electrons at either 200 or 350 keV for accelerator operations at MeV energy, with MeV beam current limited by available shielding (see below). However, the UITF can also serve as a gun test stand, with no RF acceleration and with beam terminated in water-cooled Faraday cups located upstream of the quarter-cryomodule. The UITF gun high-voltage power supply requires the use of sulfur hexafluoride as an insulating gas to suppress corona discharge. (When functioning independently as a gun test stand, the gun may be operated with a 225-kV power supply with a maximum current of 32 mA, and with a 450-kV power supply with a maximum current of 3 mA.) Acceleration in the UITF is accomplished with a quarter-cryomodule, also located in Cave 1 (See Figure 14), where the electron beam can gain energy up to 10 MeV.

There are three operating conditions for the UITF: beam OFF, RF operations, and beam ON. Beam OFF is defined as the UITF PSS being in the OPEN or SWEEP state (a safe condition where the UITF is incapable of delivering beam of any type). Beam ON is defined as the UITF PSS being in the RUN State. RF-only operations is defined as the application of RF power >100 W to superconducting cavities without injection of a bunched electron beam from an external source. There are principally two modes for beam ON: Gun Test Stand Mode and Accelerator Mode. Accelerator Mode can generate Tune Mode and CW beam. The maximum beam power that can be produced in CW Mode is 2 kW. Tune mode represents a low-duty factor machine-safe condition used for tuning the accelerator to obtain optimum running conditions. In tune mode, the beam structure consists of a macro-pulse with a 200-microsecond duration, a peak electron beam current of 8 µA, and an average current of 100 nA.

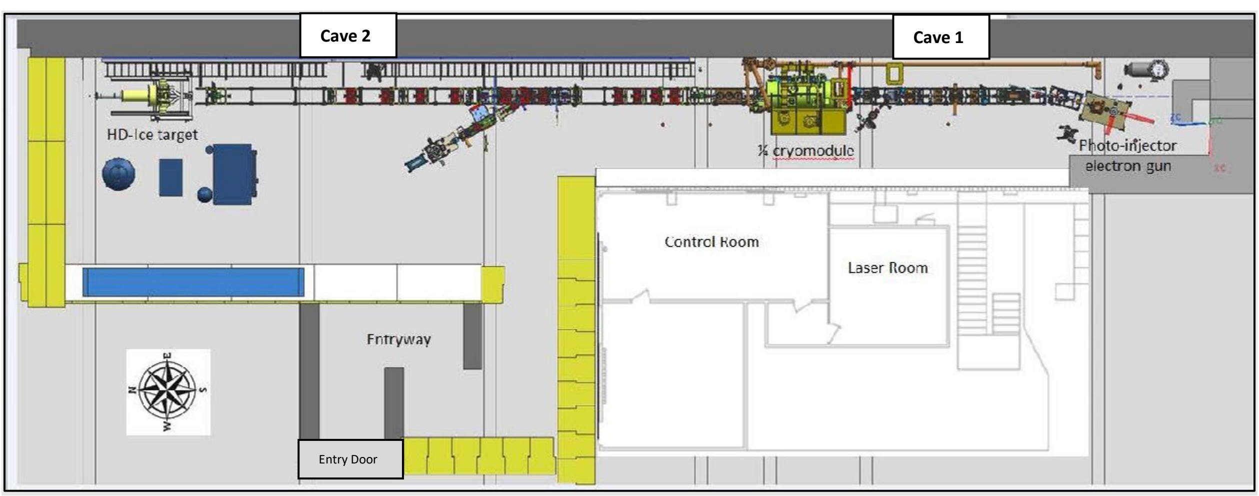

Figure 13. UITF Interior View

The required staffing for the UITF is based on the operational state and is discussed in the *UITF Operations Directives* for each operational state. The requirements are summarized below:

Operating Condition	PSS State	Minimum Required Staffing
Beam OFF	*OPEN ACCESS*	None
Beam OFF	*SWEEP*	UITF Operator
RF Only Operations	*RUN*	UITF Operator
Beam ON		
Gun Test Stand Mode	*RUN*	UITF Operator (within the UITF)
Accelerator Mode	*RUN*	UITF Operator (within the UITF)

4.4.1.2. Experimental Area

The principal use for the UITF Cave 2 is to conduct small-scale physics research experiments. Figure 13 shows the UITF roof removed. Experiments requiring electron energy of 10 MeV or less, such as Polarized Electrons for Polarized Positrons, and certain bubble chamber experiments previously conducted in the CEBAF accelerator injector, may use UITF. Experiments conducted in the UITF will be reviewed using the ERR process as defined in the UITF ASE to assess experiment safety and to safely conduct research.

4.4.1.3. Beam Termination

There are diagnostic insertable Faraday cups to measure (low-power) current at key locations in the injector and the accelerator and water-cooled electron beam dumps for higher-current (higher-power) operation for the injector. Computer simulations indicate that a 10 MeV beam delivered to an experiment can be substantially scattered in the experimental equipment. Therefore, the electron “beam dump” is dependent on a particular experiment design. Operational experience at the LERF can be translated to UITF operations and indicates that activation of the LERF dump and related cooling system does not pose any significant radiological hazard at 10 MeV, even at high current. Since UITF operation at 10 MeV is at a relatively low current, activation is expected to be minimal, and the beam dump is not expected to require active cooling. However, the beam dumps are actively cooled using low-conductivity water in anticipation of higher-current operations in the future. The principal consideration will be the application of local shielding to reduce prompt ionizing radiation dose.

4.4.1.4. Hazard Summary

The UITF accelerator has the following on-site hazards associated with its operation:

- cryogenic liquids and gases;
- oxygen-displacing gas;
- pressure and vacuum systems;
- nonionizing radiation: lasers, static magnetic fields, RF; and
- prompt ionizing radiation.
- Link to Table 21, Controls Summary
- Link to Table 23, Basis for UITF ASE

The hazards are addressed principally by laboratory programs that implement 10 CFR 851 and 835, and the processes for hazard control are discussed in the SAD in general and in the UOD specifically.

An analysis of the prompt ionizing radiation produced from beam loss under normal conditions is consistent with the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001)*. The shielding for Cave 2 is designed such that an average current loss of 100 nanoamperes (nA) at 10 MeV will not result in a radiologically controlled area at floor level. An analysis of radiation produced by credible accident scenarios at much higher current shows that when all shielding is in place, the resulting hazard does not produce an unacceptable condition; therefore, a Credited Control to limit beam current is not required for beam containment purposes. The UITF uses administrative controls on the gun power-supply current to limit current to less than 100 µA.

4.4.2. Cryomodule Test Facility (CMTF)

The CMTF is located in the center of the High Bay area of the Test Lab (Building 58). The facility includes a test area (cave), a control room along its north wall, and a labyrinth between the Cave and the control room. The cave is a legacy feature of the NASA Space Radiation Effects Laboratory (SREL) facility that has been retained to take advantage of existing thick shielding. The cave provides a shielded area 18 feet wide, 20 feet high, by 56 feet long. The North, East and West walls are 21’ thick concrete. The East wall contains a large penetration for cryogenic transfer lines to the Cryogenic Test Facility (CTF), which employs a shielded labyrinth consisting of lead brick and concrete blocks. The South wall of the CMTF (shared with the VTA) is 4.5’ thick concrete. The roof is 3’ thick concrete with a 16 sq.ft. penetration housing a fan which actively ventilates the CMTF in the event of ODH conditions. The fan stack is shielded by 15” of concrete and 2” of lead in order to sufficiently protect the CMTF mezzanine and retain its RCA designation.

The cave has two access points: one for equipment access at the west end, consisting of two interlocked concrete doors with a total thickness of about 13.5’, that rise from and lower through the floor (a third door is inactive); and a personnel door and labyrinth at the northeast end.

The CMTF is used for testing of RF and SRF structures, including fundamental power couplers, waveguide assemblies, ceramic RF windows, and cryogenic assemblies such as SRF cavity strings assembled in a cryomodule.

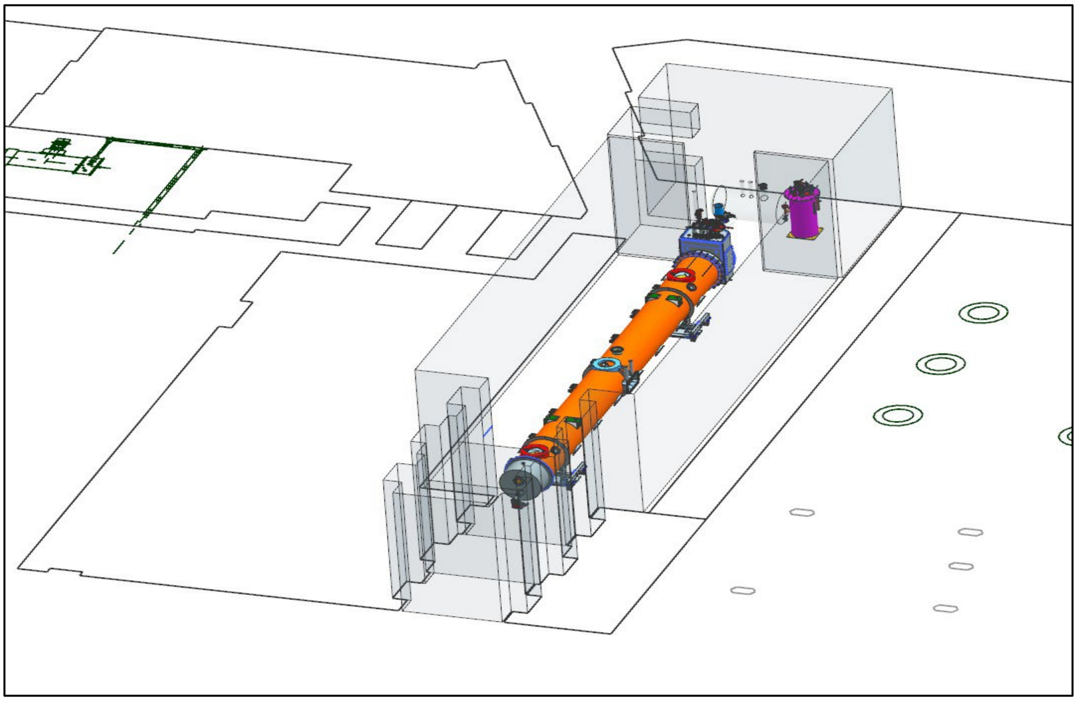

Figure 14: CMTF Test Cave

4.4.2.1. Beam Generation and Transport

The CMTF has no electron gun. The only source of electrons is field emission from superconducting cavity surfaces while those cavities are undergoing RF testing. RF power is supplied to test cavities by two sets of paired 8-kW, 1497-MHz klystrons, each set with its own waveguide delivering approximately 12 kW to the cave based on the CPS High Voltage– only one set of klystrons operates at a time to power a single SRF cavity in a cryomodule.

It is not currently possible to apply high-power RF to all superconducting cavities in an accelerator cryomodule; however, full CM testing has been conducted in the past, supported by source term modeling for operation at 120 MeV[40, 41]. Additional analysis was performed in 2024 to evaluate shielding performance for accelerating gradients up to 208 MeV[45]. Cryomodule tests up to 208 MeV are permitted under this SAD should future testing warrant it.

4.4.2.2. Experimental Area

The CMTF is not used to conduct nuclear physics experiments. The CMTF is used for high-power testing of RF and SRF structures to verify that these components meet design criteria. The CMTF enclosure has been evaluated for the safe operation of all of the cavities in a cryomodule at energies up to 208 MeV, though at present RF sources are capable only of single cavity testing.

No beam operations occur; no beam is delivered to experiments. During SRF testing, electrons can be randomly generated through field emission and accelerated by the RF-field gradient. Consequently, limited and low- quality coherent electron beam can be transported through SRF components under test. This can produce prompt X-rays that can be very intense but, by the nature of the operation, of short duration, erratic and intermittent.

Some activation in SRF components during testing (niobium and structural materials) indicates that electrons can gain sufficient energy to produce high-energy X-rays (and the resultant neutrons). However, the loss of field-emission electrons is at relatively low power and tends to be self-limiting. A few tens of watts of local heating inside an SRF cavity can cause the cavity to quench – lose superconductivity – and effectively disrupt SRF cavity performance and cryomodule testing. For purposes of estimating radiation levels in the CMTF, it is assumed that a total, effective loss of about 15 watts (~127 nA current at 120 MeV) can be sustained in a cryomodule indefinitely[40]. Transient conditions during cavity quenching up to 1 μA are considered possible for brief periods lasting on order of microseconds. [37] PSS-interlocked CARMs monitor the area both inside of and in the vicinity of these CMTF as a matter of defense-in-depth. While CMTF Operations are not expected to generate new radioactive material, activated cryomodules previously operated at other laboratory facilities (CEBAF, LERF, etc.) are periodically tested here.

Cryogenic liquid helium is supplied to the CMTF by a dedicated helium refrigerator located in the CTF Building 57, adjacent to the Test Lab. The CTF supplies gaseous helium to purge and cool cryogenic assemblies to temperatures between 2 and 4 Kelvin. Cryogenic distribution connections are located at the east end of the cave through a number of well-shielded penetrations.

The roof of the CMTF also contains a Warm Window Test Stand. There is a special opportunistic RF configuration for the Warm Window Test Stand which is made when the CMTF is not in use: RF from one set of the paired 8-kW, 1497 MHz klystrons using a single waveguide is routed to the Warm Window Test Stand. The single waveguide assembly can be terminated by either an RF load or a shorting plate. The operation of the RF source for the Warm Window Test Stand is described in detail in a separate work control document.

4.4.2.3. Beam Dump

There is no electron gun and no source of coherent electron beam. No dump is required. Field-emitted electrons can gain energy sufficient to produce neutrons and cause low-level activation of the cryomodule under test.

4.4.2.4. Hazard Summary

The CMTF has the following on-site hazards associated with its operation:

- Cryogenic liquids and gases;
- Oxygen-displacing gas;
- Pressure and vacuum systems;
- Prompt ionizing radiation (neutron and photon) exposure from field emission;
- Radiation exposure from radioactive materials; and
- Nonionizing radiation.
- Link to Table 21, Controls Summary
- Link to Table 24, Basis for CMTF ASE

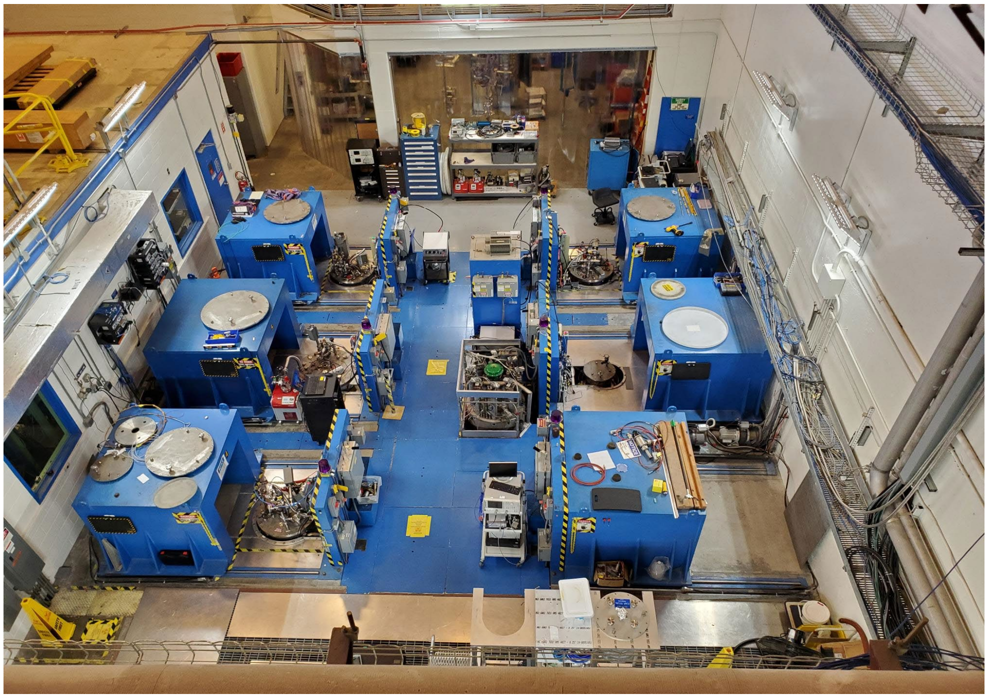

Figure 15. Test Lab VTA

4.4.3. Vertical Test Area (VTA)

The VTA is located in the center of the first floor, High Bay, against the east wall of the Test Lab (Building 58). The VTA provides a safe and secure facility for testing SRF cavities and allows cryogenic testing of other related components. The facility includes the test area (Room 1116) and the Control Rooms (Rooms 1114 and 1115), along its south side. SRF cavity tests evaluate the RF field-gradient performance of cavities.

4.4.3.1. Beam Generation and Transport

There is no electron gun and no coherent electron beam generated by components in the VTA. The only source of electrons is field emission from superconducting cavity surfaces while those cavities are undergoing RF testing. During SRF testing, electrons can be randomly generated through field emission and accelerated by the RF field gradient. Consequently, limited and low-quality coherent electron beam can be transported through the cavities under test. This can produce prompt X-rays that can be very intense but, by the nature of the operation, of short duration, erratic and intermittent.

SRF cavity accelerating gradients can readily exceed 20 MV/m, leading to neutron production (and activation of material). However, heating that leads to cavity quenching limits the total power available for radiation production. Cavity testing often involves higher levels of field emission than full cryomodule tests for several reasons. Testing in the VTA usually represents the first application of RF power to a cavity following production (or refurbishment). During testing, the cavities are pushed to their full operating limits. In some cases, minute quantities of surface contamination exist post-processing and can be “burned off” by the RF testing regime.

Often, the field-emission levels will drop significantly after initial testing, as these emission sources are removed by the act of testing. For single-cavity testing, the hazard assessment assumes continuous emission of electrons exceeding 40 MeV, with radiation levels normalized to the highest historically measured values. Brief transients during cavity quench events are assumed to couple all available RF power (several hundred Watts) briefly to the cavity, but such events are only sustainable for timescales of microseconds.

High-power (> 1 watt) RF amplifiers operating in the frequency range 0.3-4 GHz at power levels up to 500 watts, are used during testing in the VTA, depending on the test parameters. The RF power source is normally a solid- state amplifier, with the output coupled to cavities by coaxial lines that pass through blind ducts into each test enclosure.

4.4.3.2. Experimental Area

No large-scale experiments are conducted in the VTA. The VTA plays a vital role in the development, fabrication, and testing of SRF cavities on a cavity-by-cavity basis.

There are eight test dewars (vertical cryostats) in the VTA. Two dewars (1 and 2) are used only for low-power tests (< 1 W) and require no radiation shielding. Radiation production under these conditions is highly unlikely, and worst-postulated conditions for such testing do not exceed the threshold to require Credited Controls or coverage by an ASE. Interlocked CARMs monitor the area in the vicinity of these dewars. The remaining six dewars (3 through 8) are used for testing that employs high-power RF energy. Each of these six dewars is contained in test enclosures provided with separate radiation shielding, which enables test preparations in one dewar while another is in active use. Dewars 3 through 8 have interlocked radiation detectors that monitor radiation emitted from cavities under test while the shielding is closed and can terminate RF if radiation is detected when the shielding is open. In addition, an interlocked CARM with neutron detectors is deployed to monitor the VTA during testing.

Cryogenic helium is supplied by a helium refrigerator located in an attached building adjacent to the CTF (Building 57). The CTF supplies gaseous and liquid helium to purge and cool the dewars, and it allows the VTA operators to test components and assemblies at cryogenic temperatures between 4.2 and 1.5 Kelvin.

4.4.3.3. Beam Dump

There is no electron gun and no source of coherent electron beam. No dump is required. The loss of field-emission electrons in niobium and structural materials is typically at low power and is self-limiting. Field-emitted electrons can be coupled to RF and gain energy sufficient to produce neutrons and cause low-level activation of the cavities under test.

4.4.3.4. Hazard Summary

The VTA has the following on-site hazards associated with its operation:

- cryogenic liquids and gases;
- oxygen-displacing gas;
- pressure and vacuum systems;
- prompt ionizing radiation (neutron and photon) exposure from field emission;
- radiation exposure from radioactive materials; and,
- nonionizing radiation.
- Link to Table 21, Controls Summary
- Link to Table 25, Basis for VTA ASE

4.5. Accelerator Organization and Facility Summary

Section 4.0, *DESCRIPTION OF ACCELERATOR ORGANIZATION AND FACILITY,* provides an overview of the geographical area, the local environs, and the Jefferson Lab Accelerator Facility. The Accelerator Facility description consists of a summary of laboratory organizations and their safety support activities for accelerator operations, and the basic features of the six accelerators identified in Section 2.0, *INTRODUCTION*. The hazards associated with accelerators that can operate above 10 MeV are further analyzed in Section 5.0, *HAZARD ASSESSMENT AND MITIGATION,* and hazard mitigations necessary for safe operation are identified.

5. HAZARD ASSESSMENT AND MITIGATION

5.1. Hazards Other Than Accelerator-Specific Hazards

On-site hazards that are safely managed as part of a facility's overall ISM program and addressed by meeting the requirements of 10 CFR 835, 10 CFR 851, and DOE ES&H directives are not addressed in the SAD and are considered standard industrial hazards unless they can reasonably serve as initiators to or contribute to other accelerator-specific hazards. As mentioned in Section 4.2.5.1**,** *ES&H Governing Processes and Procedures***,** Jefferson Lab's principal administrative programs are: Worker Safety and Health, Radiation Protection, Environmental Protection, and Quality Assurance.

Hazards at Jefferson Lab that are generally considered standard industrial hazards include vacuum/pressure systems, RF generated by klystrons, static magnetic fields, X-rays generated by radiation-generating devices, lasers, handling and use of toxic materials and gases (including SF_6, which is an oxygen-displacement hazard), unbound nanoparticles, handling of cryogens, use of pressurized gases, oxygen-deficient atmospheres, stored mechanical and electrical energy, electricity, and working with activated materials or radioactive sealed sources. The nature and magnitude of these hazards fall well within the regulatory framework of 10 CFR 835, 10 CFR 851, and the DOE ES&H directives under which the laboratory operates. In addition, accelerators operating at or below 10 MeV may be managed under Jefferson Lab's ISM program, in accordance with the ASO.

Fire hazards are addressed in the *ES&H Manual Chapter 6900, Fire Protection Program Summary*, which lists the responsibilities and qualifications of personnel associated with Jefferson Lab's Fire Protection Program and provides a summary of documents and elements that collectively comprise the Fire Protection Program. The *Fire Protection Manual* details specific processes and procedures performed by trained individuals.

5.2. Accelerator-Specific Hazards

For the purposes of this SAD, an accelerator is defined as an assembly of components configured such that it can produce, accelerate, and transport charged particles, *and* is capable of producing a radiological area (as defined in 10 CFR 835) during operation. These components may include but are not limited to, electron guns, RF or SRF cavities and cavity assemblies, X-ray tubes, klystrons, and other devices that operate at sufficient energy to produce energetic particle beams capable of producing significant external radiation fields. As mentioned in Section 2.0, *INTRODUCTION*, the devices that are considered accelerators in this SAD are:

- CEBAF
- LERF
- UITF
- CMTF
- VTA
- GTS

From the hazards listed in Section 4.0, *DESCRIPTION OF ACCELERATOR ORGANIZATION AND FACILITY*, the following are considered accelerator-specific hazards due to the nature and magnitude of the hazards or by the simple fact that they are a direct result of accelerator operation, or both:

1. Prompt ionizing radiation
   - Unintentional beam loss such as beam loss during transport due to unintended beam interactions in the accelerator;
   - Intentional beam loss such as beam loss in diagnostic devices inserted into the beam, physics targets, and beam dumps;
   - Field emission from high-voltage sources and SRF cavities, and
2. Activation of materials in certain systems and components
   - Beamline and beam transport components
   - Experimental targets and equipment
   - Beam-dump cooling systems including beam dump cooling water
   - Beam-related air and groundwater activation
3. Radiogenic hazardous gases (e.g., oxides of nitrogen, hydrogen)
4. RF generated by the electron beam transitioning through a tuned cavity
5. Oxygen-deficient atmosphere due to loss of helium in superconducting RF cavities and superconducting magnets inside an accelerator enclosure
6. Hazardous material for use in or as physics targets
7. Class 3 electrical energy (> 800 V and/or 600 amps alternating or direct) at exposed magnet leads, power supplies, transformers, or energy stored in capacitors.

These hazards occur principally within the accelerator site safety fence – the CEBAF and LERF accelerators, including the accelerator enclosures and contiguous associated support buildings. These hazards can or may also occur in the Test Lab, in association with the three accelerators operating there.

A summary of hazard conditions, locations, and controls can be found in Table 21. Controls Summary.

As described earlier, accelerators operating at or below 10 MeV are not subject to certain provisions of the ASO, such as requirements for an accelerator safety envelope (ASE), safety assessment document (SAD) or accelerator readiness review (ARR). Hazards from such accelerators may be assessed and managed in accordance with the lab's ISM program and are not addressed in this section. One such accelerator is the GTS. Due to common features (e.g., shield enclosure, certified PSS system, etc.) and shared infrastructure of the GTS with the other accelerators within the accelerator site footprint, the hazard assessment for the GTS is included in this document and presented in Appendix B, *HAZARD ANALYSIS FOR ACCELERATORS OPERATING AT OR BELOW 10 MeV,* using the methodology in this section. Hazard assessments and operational procedures for other devices that may meet the definition of an accelerator are documented using the protocols established in the ISM program (as implemented under the *Radiation Protection Program* and *Worker Safety and Health Program*). These devices may include test stands that can produce X-rays and commercially available portable diagnostic test devices. Hazard assessment and mitigation follow the general process for radiation-generating devices (RGDs).

The general approach to mitigating accelerator-specific hazards is the same approach for mitigating all hazards at Jefferson Lab, employing the following hierarchy of controls:

1. Process design or substitution for hazardous materials or conditions
2. Applied engineered safeguards
3. Use of administrative controls
4. Use of personnel protective equipment to reduce hazards

Wherever possible, process design or substitution is used to reduce hazards. Radiation shielding and the PSS are the two principal passive and active engineered safeguards for prompt ionizing radiation hazards. Access control to the accelerator enclosure relies on active engineered safeguards and supporting administrative controls.

The safety analysis in this document for each accelerator was prepared using the methodology outlined in Figure 16, Safety Analysis Methodology in Section 5.3. Hazard Assessment Method.

5.2.1. Prompt Ionizing Radiation

One of the principal accelerator-specific hazards at Jefferson Lab is prompt ionizing radiation: high-energy electromagnetic and particulate radiation that results from the physical processes associated with electron energy loss principally in substances with intermediate to high atomic numbers. The prompt ionizing radiation levels associated with beam loss during production and transport can be very high. Protection against prompt ionizing radiation is accomplished by applying engineered safeguards that keep people away from the electron beam and the electron beam away from people. In practice, this is accomplished by contiguous radiation shielding (concrete and soil) sufficient to protect personnel and that forms an accelerator enclosure with means of limiting access.

Beam loss during accelerator operation can be conveniently divided into two types: unintentional and intentional beam loss. Unintentional beam loss occurs for a number of reasons; for example, electrons scatter off gas molecules due to imperfect vacuum within the beam pipe or when misadjusted magnets result in electron beam interaction with accelerator components. Intentional beam loss occurs when a low-power beam is intentionally steered into beamline components including inline dumps, foils, and magnet yokes, during testing or tune-up, or when a high-power beam is directed to a physics target and to a high-power beam dump.

All of these modes of beam loss were considered during facility shielding design, and the designs were vetted using peer reviews. In addition, the performance of shielding is assessed as an integral part of accelerator- commissioning activities. The CEBAF and LERF accelerator enclosures and beam dumps are partially or completely below the surface of the ground. The CEBAF accelerator enclosure is built completely underground and is made inaccessible to personnel when it is operational – the principal protection measures are radiation shielding designed into the structure of the accelerator enclosure, supplemental shielding provided by soil overburden, and an access control system capable of shutting off the beam if personnel attempt access while the beam is on. The LERF accelerator vault is built partially below grade and uses soil berms at ground level as shielding. The UITF uses a combination of poured concrete and interlocking concrete block walls and roof materials. Neither the LERF nor the UITF are segmented but have a similar access control system capable of shutting off the beam if personnel attempt access while the beam is on.

For accelerators having only Field-emitted particle beams that are not intentionally transported or directed, beam loss is generally assumed to be continuous and primarily directed along the path of RF acceleration. Assessment of the prompt radiation hazard is conducted by use of conservative assumptions for maximum plausible beam power to assess shielding effectiveness. As is the case with other accelerators, exposure scenarios for these facilities include reasonable assumptions for personnel occupancy and operational duty factors. Access control systems are similar to those in other accelerators. The CMTF has an accessible enclosure with two entrances, while the VTA consists of six separately shielded cryostats capable of high-power operation, with each shield hut being independently interlocked. As a matter of defense in depth, both CMTF and VTA are instrumented with PSS-interlocked CARMs.

5.2.1.1. Shielding for Prompt Ionizing Radiation

Shielding against prompt ionizing radiation has four main functions. It is designed to protect:

- against chronic beam losses during beam transport;
- against full accidental beam loss during transport;
- from intentional beam loss in targets and dumps; and
- from credible field-emission/dark-current production in the absence of a discrete beam source.

The requirements for the application of shielding are found in the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001)*. The *Beam Containment and Access Control Policy* states that personnel protection from prompt ionizing radiation at Jefferson Lab relies on a reasoned combination of active and passive engineered and administrative safeguards.

Together, shielding and access controls represent a reasoned combination of process design and applied active and passive engineered safeguards.

The shielding installed as part of the original design for each facility is listed in Table 2.

Table 2. Nominal *As-Built* Shielding

Component and/or Area	Thickness (ft)*	Notes
CEBAF Tunnels (Includes Beam Switchyard)	15[a]	design goal is met with 9-ft soil construction as-built = 15 ft
Hall A Dome	4.6 – 5.7[b]	thickness thickens to the outer edge
Hall B Dome	4.6 – 5.7[b]	
Hall C Dome	6.1 – 7.2[b]	
Hall A and C Dumps	30[c]	specific ratios of earth or concrete are different for HA & HC vs. HB same equivalent total thickness
Hall B Dump	30[c]	
North Linac Extension Hall D Tagger Area and Dump Photon Beamline to Hall D	13[d]	Berm
Hall D	2.3[d]	non-uniform walls
Hall D Photon Dump	9.8[d]	photon dump is made of iron blocks buried in berm
LERF	8.5[e]	applicable to vertical and lateral approach
UITF Roof (Cave 1/2)	2.5/1.75[f]	
UITF Side Walls (Cave 1/2)	4.6/4.0[f]	Cave 1 is 4.6 ft thick up to a height of 7 ft and 2.25 ft thick above that
CMTF	3 – 21[g]	roof is 3 ft thick, south side wall is 4.5 ft thick, north and east walls are 21 ft thick
VTA	varies[h]	monolithic sand-filled vault below floor level, at least 6 ft thick, shield lid is 10” lead plus 2” steel

*Thickness nominally applies to the vertical dimension, and includes the concrete structure (unless noted). The specified values are in terms of earth- equivalent thickness, which is the ratio 145/125 times the concrete thickness (the ratio of nominal concrete and earth densities in pounds per cubic foot). Requirements generally applicable to all shielding are found in the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001)*. Shielding configuration is tracked via the RCD shielding package database (https://misportal.jlab.org/radcon/shielding) Specifications taken from the following documents.

[a] TN-97-017; also see TN-0061, CEBAF 1989 PSAR, and as-built drawings
[b] TN-97-017; also see TN-89-156, and as-built drawings
[c] TN-97-017; also see TN-89-174, and as-built drawings
[d] TN-08-033; also see as-built drawings and RCD-DEP-16 #003.
[e] TN-95-044 (2.3 meters concrete); also see as-built drawings for berm shape and extent
[f] TN-18-020[10]; thickness values for UITF are actual concrete thickness
[g] See CEBAF TN-89-0161, JLAB TN-16-009 and JLAB TN-16-010, RCD-DEP-24-003
[h] See CEBAF TN-91-035, JLAB TN-12-045 and RCD-DEP-24 #001

The radiation levels at the locations of beam loss are dependent on beam energy, current, angle, and the composition and dimensions of that material. One kilowatt (kW) of electron beam at nominal CEBAF or LERF energy is capable of producing a lethal ionizing radiation dose in a fraction of a second within 1 meter directly downstream of the point of beam interaction. The bremsstrahlung (electromagnetic radiation) component of a 1-kW, 1-GeV beam loss in a large accelerator component is the largest component of ionizing radiation dose and is, at 1 meter, approximately 3 x 10^7 rad/hour at zero degrees and 5 x 10^3 rad/hour[5] perpendicular to the direction of beam travel. Operational experience has shown that localized beam loss above about 1 kW can damage accelerator components. Such damage typically results in immediate loss of beamline vacuum, resulting in an inability to transport beam (historically, beam “burn-through” and other damage has occurred at power levels of a few hundred watts). Distributed loss over a number of accelerator components can result in component degradation due to accumulated radiation dose. Beam loss at a level that causes damage or vacuum degradation is typically incompatible with beam-quality requirements for nuclear physics experiments. Accelerator operators are responsible for “tuning” the accelerator to minimize such losses. With the exception of targets and beam dumps designed to handle the full accelerator power, high-power beam loss (in excess of approximately 100 kW) is unsustainable in accelerator components due to the immediate physical damage it causes. The MPS systems, described in *Engineering MPS*, is designed to detect such losses and shut off the beam before damage occurs. Accelerators that lack a particle source (i.e., gun) are limited in beam power by the HV or RF power source producing the field emission. The maximum sustained power of a beam produced by field emission in an SRF cavity or cryomodule may exceed tens of watts. [13,36,37,43] Shielding is conservatively evaluated under the assumption that such conditions are maintained continuously. Short-duration transients during a cavity quench may be several orders of magnitude higher, but are extremely short-lived and conservatively estimated to persist for about one second.

The shielding design for the CEBAF accelerator incorporated assumptions of distributed beam loss during transport at a fraction of a percent of full power.[8] A loss of 0.1% of 1 MW beam power is 1 kW. Experience has been consistent with this assumption in CEBAF. The shielding design basis for Table 2 – Nominal “As-Built” shielding for Experimental End Stations A and C is a beam loss of less than about 0.1 kW in an experimental nuclear physics target.

The expected equivalent dose to a person outside a shielded accelerator enclosure can, in many locations, actually be higher from lower-power sustained beam losses during normal operations than from a high-power ~ 1-MW beam loss, which would be limited in duration by damage to the accelerator hardware. Shielding effectiveness for these conditions was reevaluated during the 12 GeV Upgrade and reviewed during the 12 GeV ARR for accelerator commissioning and operations. For purposes of evaluating potential doses under such beam loss conditions, 1 kW of beam loss at a point is considered a conservative reference for sustained, chronic beam loss in most of CEBAF. In locations such as the linacs, this is a highly conservative value. In some locations, such as beam extraction and switchyard regions, a higher value of 3 kW is considered plausible and is used to determine bounding conditions only in those areas.

LERF shielding is based on similar assumptions: a chronic point loss of 1 kW, a distributed loss of approximately 0.1% of full operational beam power at the high energy, and a short-duration accidental beam loss of approximately 1 MW.

For the purposes of this SAD, the description of beam loss for CEBAF in Tables 3 through 5 can be considered conservative bounding conditions for the purposes of evaluating beam loss hazards in CEBAF and LERF (cited as FEL in the reference).[9] Values normalized to a kW can be scaled according to power up to several kW for estimating the dose rates from chronic losses. Dose rates normalized to 1 MW can also be scaled, for the purposes of estimating short-duration accidental beam loss, up to the NEPA power limit of 2 MW.

UITF shielding is designed for a continuous loss of 100 nA at 10-MeV beam. The electron gun is capable of and may be operated at a substantially higher current for lower beam energy (i.e., gun voltage). Accidental transport of high-current beam at higher energy has been evaluated as part of the shielding design.[10]

The CMTF is located in the center of the High Bay area of the Test Lab. The area is specially designed to test cryomodules, cryogenic assemblies, and other RF structures to verify that they meet design criteria. The CMTF vault takes advantage of preexisting thick shield walls on three sides from the former SREL facility. Original shielding parameters were based on conservative assumptions for field-emission radiation from first- generation CEBAF cryomodules.[39] This includes the assumption of 10-MV/m gradient, and the ability to produce 200 W of Field-emitted electrons, all at 5 MeV. This produces a lateral source term of 1500 rad m^2 h^{-1} and an exposure rate outside the south wall of about 0.3 mR/h. No radiation approaching these levels has ever been measured in the CMTF. In 2016, source-term calculations were updated to include contributions from neutrons and consideration of testing cryomodules for the LCLS-II accelerator at SLAC.[40,41] These calculations relied on more realistic estimates of power loss in a cryomodule of about 15 W and retained an extremely conservative assumption that the entire dark-current beam (127 nA) was produced at 120 MeV (the skyshine assessment assumed 130 MeV). These calculations provided the basis for enhanced shielding above the shield doors on the west side of the cave and confirmed the need to control the areas beyond the south wall and the roof of the CMTF vault as Radiologically Controlled Areas (RCAs). These calculations were revisited in 2024 to consider the testing of LCLS-II HE modules in the CMTF, and the source term for those modules was found to lie within the initial conservative assumptions from 2016 – thus permitting possible testing.

The VTA is located next to the CMTF, sharing the 4.5-foot thick wall that makes up the south shield wall of the CMTF. Superconducting radio frequency (SRF) cavity tests evaluate the radio frequency (RF) field gradient performance of cavities. Testing occurs in six shielded dewars and two unshielded dewars, buried in the floor of the VTA in the central high bay which was converted from the NASA Space Radiation Effects Laboratory (SREL) cyclotron bay pit (15 ft deep, concrete lined, and filled with sand). Six dewars supporting high power (1-500 Watt) testing are encased in wells of cast concrete and are equipped with both stationary lead shielding and retractable lids – thus forming a shield hut around each dewar under test and still allowing for the easy insertion and removal of cavities when necessary.

Review of Radiation Production and Shielding Effectiveness at the Vertical Test Area[43] revisited the shielding configuration with modern Monte Carlo techniques and cavity energy assumptions (40+ MeV dark current possible, superseding earlier works) and normalized results against comparable VTA cavity tests for which RCD monitoring was employed. Analysis confirmed the adequacy of the existing shielding for personnel protection from radiation produced during testing.

To summarize the safety assessment with respect to the application of DOE O 420.2D to the VTA, the key aspects of the safety controls are as follows.

- The movable shielded huts and shielding enclosure and associated PSS interlocks provide the necessary credited controls.
- Conditions outside the shielded huts meet the requirements of the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001)* for expected conditions, including normal and accident conditions, up to the limits of the existing RF power capabilities.

- The radiation monitoring system, and existing administrative controls provide defense in depth to minimize worker exposures.

Radiation shielding has certain design features that affect its performance:

- Penetrations for the purposes of ventilation or delivering power, cryogens or other utilities to equipment in the shielded accelerator enclosure,
    - Penetrations are aligned off-center to the beamline where possible and generally oriented away from the beamlines and points of loss,
    - Penetrations may contain removable shielding materials to facilitate maintenance.
- Personnel and equipment accessways
    - Contain labyrinths with multiple bends to scatter radiation, and
    - Are generally oriented away from the beamlines and points of loss.

Important design features that have an impact on personnel radiation exposure are the shielding and access control around penetrations. A chronic-point beam loss in the vicinity of unshielded penetrations is, in practice, the principal concern in CEBAF above the linacs and arcs. The service buildings above the CEBAF linacs are more frequently occupied and the penetrations contain removable "pea gravel" shielding. In addition, the penetrations are typically covered by equipment racks, making them functionally inaccessible. The service buildings above the CEBAF arcs are less frequently occupied. The penetrations to these service buildings are not shielded with removable pea gravel. Not all penetrations are covered by equipment racks. As a result, the area above open Arc Service Building penetrations is made inaccessible by an exclusion barrier and has additional administrative controls in the form of radiological postings. This information is summarized in Table 5, where the equivalent dose for various beam loss scenarios, absent the exclusion barrier over open CEBAF Arc Service Building penetrations, is presented.

In the LERF, the principal concern is above the linac. The RF waveguide and instrumentation penetrations are designed with two right-angle bends, and no permanent exclusion barrier is required at any waveguide penetration. Straight penetrations through the accelerator enclosure have shielding installed from inside the enclosure and/or removable shielding at the penetration opening. Some penetrations are angled and require no additional shielding. At several locations, the area above penetrations is augmented with CARMs that monitor radiation levels, provide local alarms, and are interlocked to the accelerator's personnel safety system (PSS). As an additional administrative control, the klystron gallery is a posted RCA.

Most penetrations in the UITF roof shielding have shielding installed from inside the UITF accelerator enclosure. The area in which these penetrations are installed is augmented with CARMs that monitor radiation levels, provide local alarms, and are interlocked to the PSS. CARMs are also used at certain unshielded penetrations that serve as helium vents are designed to mitigate a cryogen loss. As an additional administrative control, the area around penetrations in the UITF roof shielding is a posted RCA.

There are relatively few penetrations in the CMTF shield. The primary concern is an opening in the roof about 16 ft^2 designed for the removal of helium in the event of a spill of liquid helium in the test cave. This penetration was specifically evaluated in 2016 to address the issue of neutron radiation produced by C100 and LCLS-II cryomodules.[41] A vertical shield wall encloses the area and acts as a barrier to prevent bodily entry above the opening. Another penetration in the east wall is semi-permanently closed by a thick shield wall consisting of almost 3 feet of concrete and 1 foot of lead shielding. A second shield wall prevents any line of sight from the cryomodule to the primary wall in the penetration. The effectiveness of this shielding has been validated by many years of measurements showing no significant radiation levels.

The VTA testing stations consist of small huts that have no penetrations above floor level. Some penetrations exist below the "false floor" for cryogen and power supplies to the dewars and cavities. The false floor area in the VTA high bay is posted as a High Radiation Area, with no access during operations without a job-specific radiation work permit (RWP) and radiological control oversight.

5.2.1.1.1. Unintentional Beam Loss

CEBAF Accelerator

As mentioned above, radiation shielding to protect against ionizing radiation is based on a series of conservative assumptions (see Table 3) regarding beam power and duration of beam losses in the CEBAF accelerator.

Table 3. CEBAF Beam Loss Duration as a Function of Beam Power

Beam Loss Condition Designation	Beam Power Loss Condition in kW	Max Duration of Exposure to Person Outside Shielding	Notes
1	1*	240 min	results in the highest potential dose during a normal operational mode
2	1.7 (tune beam)	60 min	maximum loss condition during normal operation
3	10	10 min	results in the highest potential dose for "accidental" losses
4	100	1 min	
5	1100	2 sec	operations envelope

* 3 kW in extraction/BSY, see text

A value of 1-kW beam loss, with an exposure period of 240 minutes (four hours, or half of an eight-hour shift), is conservatively used to bound chronic beam-loss exposure scenarios in the CEBAF accelerator during normal operations. While such beam loss at a point would likely result in rapid vacuum loss, a somewhat distributed loss could potentially persist for a longer period (such distributed loss consequently reduces the potential dose rate in an affected area).

In limited regions of the CEBAF accelerator (extraction regions, switchyard), the chronic beam loss condition is bounded at a slightly higher value of 3 kW based on design-basis estimates and historical data indicating somewhat higher general losses in these regions.

Another normal operating condition is delivery of tune-mode beam. Tune-mode beam is operationally restricted to a maximum of 2 kW, which is the operational limit for locally shielded low-power tune-up dumps located in the linac and beam switchyard (BSY) sections of the CEBAF accelerator. These tune-up dumps were installed because operational experience has shown that a loss of tune-beam at a single location in the accelerator, even for relatively brief periods of time, consistently results in beamline vacuum problems and eventually causes component failure. In practice, tune-up beam power is maintained at levels below 2 kW (typically no more than 1.7 kW) for ALARA and machine protection purposes. During tune-mode operation, it is not unusual for the entire beam to be lost in various regions of the accelerator. However, as described above, these losses must be restricted to short durations or distributed over a wide area, else they will result in loss of vacuum or accelerator damage that prevents operation. For purposes of this assessment, this condition is conservatively bounded by a 1.7 kW beam loss lasting one hour.

Exposure duration bounding conditions presented in Table 3 are conservative estimates that consider the likelihood and potential duration of a sustained point-like loss at the power indicated as well as the likelihood and duration of occupancy at the location of concern. The following tables present equivalent dose rates outside the accelerator shielding based on the defined parameters:

- Table 4. Dose for Beam-Loss Conditions Outside CEBAF Shielding
- Table 5. Dose for Beam-Loss Conditions Outside CEBAF Shielding at Unshielded Penetrations
- Table 6. Dose for Beam-Loss Conditions Outside CEBAF Shielding at Shielded Penetrations
- Table 7. Minimum Shielding Requirements for CEBAF Penetrations
- Table 8. Movable Shield Wall Performance Summary
- Table 9. Dose for Beam-Loss Conditions Outside LERF Shielding
- Table 10. Dose for Beam-Loss Conditions Outside LERF Shielding at Penetrations
- Table 11. Dose for Beam-Loss Conditions Outside UITF Shielding
- Table 12. Dose for Beam-Loss Conditions Outside UITF Shielding at UITF Penetrations
- Table 13. Dose for Beam-Loss Conditions at CMTF
- Table 14. Dose for Beam-Loss Conditions at VTA

Table 4. Dose for Beam-Loss Conditions Outside CEBAF Shielding

Power Lost (kW)	**Maximum Dose Rate Outside Shielding** (mrem/hr)	**Maximum Dose Outside Shielding*** (mrem)	**Notes**
1	0.6	2.4	- reasonable estimates for the equivalent dose rate outside shielding vary by a factor of 3 - the value chosen is a maximum - in practice, the equivalent dose rate outside shielding is dominated by the contribution from nearby penetrations
1.7	1	1	
3	1.8	7.2	
10	6	1	
100	60	1	
1100	660	0.4	

* based on exposure duration in Table 3

Table 5. Dose for Beam-Loss Conditions Outside CEBAF Shielding at Unshielded Penetrations

Penetration Location	Power Lost (kW)	Dose Rate (rem/hr) (above / beside penetration)	Dose (rem) (above / beside penetration) *	Notes
Injector	1	78[δ]	312[δ]	
Linacs	1	0.80	3.18	assumes personnel directly over or adjacent to open unshielded linac penetration even though area above almost all linac penetrations is functionally inaccessible
	1.7	1.35	1.35	
	10	7.95	1.33	
	100	79.53	1.33	
	1100	874.82	0.49	
ARCs	1	1.64 / 0.01	6.54 / 0.05	exclusion barriers with configuration control are used in these locations
	1.7	2.78 / 0.02	2.78 / 0.02	
	10	16.35 / 0.13	2.73 / 0.02	
	100	165.53 / 1.31	2.73 / 0.02	
	1100	1798.82 / 14.41	1.00 / 0.01	
BSY & Extraction	3	4.92 / 0.04	19.68 / 0.16	cable penetrations**
	3	5.41 / 1.07	21.64 / 4.3	extraction alignment penetration
Helium Vents***	1	0.007	0.028	midpoint of north and south linacs
	1	6.73	26.92	NE spreader – line of sight penetration

[δ] highest value for injector – line-of-sight penetration
* based on exposure durations in Table 3
** values for these locations based on ARC penetration model
*** dose rate at 30 cm; duct prevents access directly above

Table 6. Dose for Beam-Loss Conditions Outside CEBAF Shielding at Shielded Penetrations

Penetration Location	Power Lost (kW)	Dose Rate (mrem/hr) (above/beside penetration) *	Dose (mrem) (above/beside penetration) **	Notes
Injector	1	0.2	0.8	applicable accessible areas posted for sustainable conditions
Linacs	1	43 / 3.8	172 / 15.2	
	1.7	73.1 / 6.46	73.1 / 6.46	
	10	430 / 38	71.7 / 6.3	accident scenarios
	100	4300 / 380	71.7 / 6.3	
	1100	47,300 / 4180	26.3 / 2.3	
Spreader / Recombiner	1	2.2	8.8	gravel shielding in cable penetrations
Extraction / BSY	3	6.6	26.4	buildings posted accordingly as radiologically controlled areas
Alignment Penetrations	1	16	64	shielded with iron blocks all values reflect most conservative case in South extraction region areas posted accordingly as radiation areas
	3	48	192	

* levels adjacent to penetrations in non-Linac areas are similar to levels above penetrations due to shielding configuration
** based on exposure durations in Table 3

Shielding thickness requirements for the CEBAF linac, spreader/recombiner, and extraction/BSY penetrations were established in CEBAF-TN-95-026.[35] Table 7 gives the thickness requirements. Since unshielded conditions could hypothetically lead to a condition that exceeds the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001)* limits, the shielding for the southwest alignment penetration meets the definition of a Credited Control (as does other penetration shielding in the injector, spreader/extraction, and BSY regions). In addition, conditions at the NE spreader helium vent penetration require Credited Controls. This is implemented through a locked, bolted, or barred access point.

Table 7. Minimum Shielding Requirements for CEBAF Penetrations

Penetration Type and Region	Minimum Thickness of Pea Gravel
North Linac Cable	15 inches
North Linac Waveguide	23 inches
North Linac Spreader	84 inches
South Linac Cable	16 inches
South Linac Waveguide	24 inches
South Linac Spreader	85 inches
Recombiner (all)	78 inches
Alignment	(S2) SEG steel block
Injector	per RCD-DEP-19 #001

In practice, the most limiting value (thickest shield) for common types of penetrations has been used around the CEBAF accelerator (e.g., 24 inches in waveguide penetrations). Specific calculations were not performed for the Beam Switchyard, but the BSY has been conservatively assumed to have similar potential beam loss conditions as a spreader region. Given the beamline and penetration geometry in the BSY, applying the same shielding thickness as in spreader/extraction regions provides at least as much protection for the BSY.

Radiation transport through penetrations, both with and without the previously specified shielding, was re- evaluated using Monte Carlo simulations during the 12 GeV upgrade. The results of these studies are in JLAB- TN-14-033 and RCD-DEP-19 #009. The dose-rate values shown in the tables above are based on that reevaluation. Simulations for the four survey/alignment penetrations (one in each spreader/recombiner region) to validate the iron block shielding on these penetrations also included verification of effectiveness of the most heavily shielded penetrations in the extraction/BSY regions. Results are in RCD-DEP-19 #009 and also shown in the tables. Thick-target Monte Carlo source-term modeling was benchmarked experimentally in 2016 (see RCD-DEP-17 #010) with good agreement between measured and calculated results. The varied configurations of shielding, and alignment of certain penetrations with the beamline in the injector segment, prompted a review and update of RCD-DEP-19 #001 in 2021, with the addition of the results of that analysis to the tables above.

The results affirmed confidence in the overall approach used for the simulations of the conditions at penetrations. The results of the modeling for penetration shielding indicated that potential dose rate above shielded penetrations was of order two times the originally calculated values. In all cases, the installed shielding is effective in meeting current shielding policy requirements. Because the postulated doses for the unshielded case for penetrations in the spreader/extraction (and by extension, BSY) regions exceed the shielding policy limits, installed penetration shielding in these regions is designated a Credited Control.[34]

Additional unshielded penetrations extend between the beam-transport tunnels for Halls A, B, and C, and cable chase shafts that are accessible during beam operations. Potential doses in the cable shafts were evaluated in RCD-DEP-19 #002. The evaluation found that doses requiring the application of Credited Controls were not plausible, but that radiation levels could exceed 100 mrem/h, and therefore these areas are posted as high- radiation areas in accordance with 10 CFR 835.

Beam-loss scenarios that result in conditions that do not require a Credited Control are controlled in accordance with 10 CFR 835, implemented through the Jefferson Lab Radiation Protection Program. This results in controlling all service buildings as radiologically controlled areas (RCA), posting for radiation and high-radiation areas in some service buildings, and in the application of exclusion barriers in locations where plausible operational scenarios could result in equivalent whole-body doses above 1 rem in an hour.

Movable iron walls located at all four CEBAF end station segmentation points act as both access barriers and shielding. The postulated doses for at least one of the conditions given in Table 2 at the locations of each of these walls exceed the threshold for requiring a Credited Control. In addition, the walls and associated access points act as exclusion barriers that prevent access to beam enclosures with potential for lethal prompt radiation hazards. Calculations of potential dose and required wall thicknesses were documented for the Hall A, B and C walls in RCG Notes #93-15 and #94-01. JLAB-TN-08-033 contains the shielding requirements for the Hall D complex, including the transport tunnel shield wall, which is based on the Hall B design. Although the nominal point of accidental loss (beam stoppers) for Hall D is significantly further away from the shield wall than Hall B (over 60 meters compared to about 20 meters), there is some uncertainty in beam loss locations for accident scenarios involving miss-steered beam from Hall A or C. For this reason, we adopt the same assumptions used for Hall B. Hall D has an additional movable shield wall at the base of the tagger building truck ramp. This wall consists of a concrete block labyrinth, and was initially described in JLAB-TN-08-033. The wall provides protection for personnel at the outside of the truck ramp. As-built thickness of the wall is 3 feet. The postulated exposure conditions and shielding effectiveness for each wall are summarized in Table 8.

Table 8. Movable Shield Wall Performance Summary

Location	Unshielded Dose Rate at Location of Interest (rem/h/kW)	Limiting Exposure Condition from Table 2 Per Dose in rem	Shield Thickness (inches)	Shielded Dose Rate (mrem/h/kW)
Hall A Transport	5.3	1/21.2	39	5.4
Hall B Transport	25.5	1/102	52	12.4
Hall C Transport	5.2	1/20.8	39	5.0
Hall D Transport	25.5	1/102	52	12.4
Tagger Truck Ramp	4.2	1/16.8	36	8.4

In all cases above, CARMs provide defense-in-depth protection for these locations, and supplemental shielding installations for the transport tunnels enhance the effectiveness of the shield walls. These additional features mitigate the need for radiation area designations in the affected locations.

LERF Accelerator

The design of the LERF as an energy-recovery accelerator limits sustainable loss to approximately 100 kW based on the installed RF power.[9] Applying the same assumptions about sustainable beam loss from Table 3, CEBAF Beam-Loss Duration as a Function of Beam Power, the equivalent dose for a full loss in the LERF is estimated below from the radiation source term given in CEBAF TN-95-044, Shielding, and other radiation safety requirements for the 200 MeV recirculating linac with energy recovery for the UV FEL.[9]

Table 9. Dose for Beam-Loss Conditions Outside LERF Shielding

Power Lost (kW)	Maximum Dose Rate Outside Shielding (mrem/hr)	Maximum Dose Outside Shielding (mrem)	Notes
1	4	16	installed RF power limits sustainable loss to approximately 100 kW
1.7	7	7	
10	40	7	
100	400	7	
1000	4000	2	full instantaneous loss based on 4 rem/h/MW source term in cited reference

In the LERF, the RF waveguide and instrumentation penetrations are designed with two right-angle bends and no permanent exclusion barrier is required at any penetration. Straight penetrations through the accelerator enclosure are angled or have shielding installed from inside the enclosure and/or removable shielding at the penetration opening. The LERF has a truck-access ramp and associated opening in the shield. Concrete blocks provide equivalent shielding to the accelerator vault walls/earth berm in this location. This shielding is considered a Credited Control.

Table 10. Dose for Beam-Loss Conditions Outside LERF Shielding at Penetrations

R	Maximum Dose Rate Outside Shielding (rem/hr)	Maximum Dose Outside Shielding (rem)	Notes
3.6E-02	2.0E-3	8.0E-3	based on a 300 nA tune beam loss on viewer screen
100	5.6	9.3E-2	

UITF Accelerator

The UITF maximum beam energy is below the neutron-production threshold in most materials that comprise the accelerator and anticipated physics targets. The radiation from beam loss is principally high-energy photons. The maximum current (100 microamps) and energy (10 MeV) possible in UITF correspond to 1 kW of beam power.[11] Beam loss under these conditions is capable of producing a dose rate inside the UITF accelerator enclosure perpendicular to the beamline, of approximately 10,000 rad/h at 1 meter.[12] While a full-power beam- loss condition is not judged to be sustainable for a long period, all beam-termination points that can tolerate such conditions must be equipped with shielding designated as a Credited Control. A conservative value of 100 watts is considered the threshold for such control; in the absence of local shielding, such a loss could create a high-radiation area outside the structure.

UITF shielding is designed to maintain dose rates outside the shielding at floor level to less than 0.05 mrem/h (below radiologically controlled area status) with nominal continuous losses of 100 nA at 10 MeV. This criterion is also met for normal operations of the cave when it is configured for keV gun testing. The roof of Cave 1 is posted as an RCA to account for the potential for brief beam-loss excursions and the presence of penetrations. Shielding below these penetrations is a Credited Control. The roof of Cave 2 is posted as a high-radiation area; plausible excursions during normal operating conditions could cause dose rates above 100 mrem/hr, but are below 1000 mrem/h. These areas are also monitored by CARMs that provide defense-in-depth protection from sustained, off-normal conditions, with trip thresholds set conservatively below 100 mrem/hr.

Tables 11 and 12 depict calculated values for the dose rate outside the UITF shielding under worst-plausible accident scenario conditions. Considered conditions include the transport of over-current beam through the cryomodule, with and without the cryomodule operating.[10]

Table 11. Dose for Beam-Loss Conditions Outside UITF Shielding

Beam Loss Location	Beam Power (kW)	Maximum Dose Rate Outside Shielding (rem/hr)	Maximum Dose Outside Shielding (rem)	Notes
Cryomodule exit	3.0	0.09	0.02	at Cave 1 roof
	4.2	2.0	0.5	
Lower beam line, opposite Cave-2 entrance labyrinth	3.0	9.0	2.25	at Cave 2 roof
	4.2	10.0	2.5	

Table 12. Dose for Beam-Loss Conditions Outside UITF Shielding at UITF Penetrations

Power Lost (kW)	Maximum Dose Rate Outside Shielding (rem/hr)	Maximum Dose Outside Shielding (rem)	Notes
4.2	10.0	2.5	Cave 1 roof, 3" steel local shield
1.0	4.0	1.0	Cave 2 roof at helium vent

The UITF gun can also be used as a gun test stand and operated at a high current without SRF acceleration. All safety features such as the PSS and shielding are employed for all operational modes.

CMTF Accelerator

As discussed in previous sections, radiation production from cavity and cryomodule testing is inherently sporadic and unpredictable. There is no intentional beam production and no hardware designed to transport beam. All dark-current production is conservatively assumed to result in "beam loss" and generate radiation. Many studies have been conducted to assess radiation production in SRF cavities and cryomodules. As mentioned above, the most recent specific calculations for the CMTF were performed using measured data to normalize results from Monte Carlo modeling. These calculations focus on the neutron source term, as the assumptions for photon radiation production remain conservative.[40] The results of the updated calculations were used as the source- term assumptions for the basis of testing LCLS-II cryomodules and resulted in installation of additional shielding above the equipment access doors at the west side of the cave. The source term was taken to be 20 rem/h (neutrons) at 1 meter from the end can of the cryomodule, with a continuous Field-emitted loss of 15 watts at 120 MeV.[40] This result compares very well with results obtained by SLAC[37] using simulations linking computer codes for FE production to radiation transport. Instantaneous transients associated with the quench of a cavity are assumed to dump all available power (12 kW), but persist for periods on the order of microseconds. The hazard assessment conservatively assumes a quench duration of 1 msec.

Additional analysis was performed in 2024 to evaluate shielding effectiveness for LCLS-II HE (high energy) cryomodules[45]. These modules have a design energy of 208 MeV. The analysis concluded that the potential exposure from field emission of the HE modules was conservatively bounded by the existing shielding assessments.

Passive and active monitoring over many years of operation of the facility confirms the efficacy of the as-built shielding. Shielding at the north wall of the CMTF is more than 20 feet thick. Shielded doors at the west entrance total more than 12 feet of concrete. The east wall of the cave is also more than 20 feet thick but has a large penetration shielded by a combination of lead and concrete labyrinthine shielding, providing about 8 feet of concrete-equivalent shielding. Only the south wall and the roof are of concern with respect to personnel dose under normal conditions. These areas, as well as the alcove to the entry door at the east end of the cave, are posted as RCAs and have active and passive monitoring installed.

CMTF workload can vary significantly with the cryomodule production and refurbishment schedule but has been estimated at 400 hr/y[45] on average. Occupancy on the roof and in the VTA test bay to the south of the CMTF is conservatively assumed to be 50%, therefore, exposure to radiation workers in these areas is taken to total about 200 hours/year.

Doses outside the shielding are calculated using the source term described above, applicable distances to the occupied areas, and transmission-reduction values from the shielding basis documents noted above. Table 13 provides the calculated doses for these locations.

Table 13. Dose for Beam-Loss Conditions at CMTF

Loss Condition	Location	Maximum Dose Rate Outside Shielding (mrem/hr)	Maximum Dose Outside Shielding (mrem/y)	Notes
15 Watt continuous	South wall	0.3	60	Areas are RCAs Occupancy 50%
	Roof	0.51	102	
12000 Watt instantaneous	South wall	240	~0.003	1-msec duration 50 events/y
	Roof	408	~0.006	

The dose estimates for occupied spaces around the CMTF are well within the 250 mrem/y design goal for radiation workers. The presence of CARMs with conservatively chosen alarm thresholds also limits such doses. Historically, passive area-monitoring results (which represent 100% occupancy) show no doses above 100 mrem/y, and no workers who occupy this space have ever received doses approaching this value.

VTA Accelerator

As in the case of the CMTF, testing of cavities in the VTA involves conditions amounting to continuous, unintentional beam loss. The same approach to assessing the prompt radiation hazard is used as with the CMTF. To support the transition of the VTA to accelerator status, a review of the source term and shielding effectiveness was conducted in 2024.[43] This review applied updated assumptions about FE power losses and extended the energy range of the assessment to address foreseeable increases in cavity gradients. New assumptions were applied to the potential FE beam power that might be produced during cavity testing by normalizing simulation results to measured data and applying exponential scaling with energy. The updated assessment confirms the adequacy of the installed shielding and PSS configuration.

For testing high-gradient cavities, neutron radiation becomes the primary source term outside the VTA dewar shielding assembly. Above floor level, shielding consists of thick lead shield huts that are relatively ineffective against neutrons. Updated assumptions, using historical cavity performance data, suggest that sustainable FE power levels could approach 140 watts, though this condition could not persist for a long period (< 30 min) due to cryogenic load. Simulations indicate that maximum plausible neutron dose rates outside a shield hut under such conditions could approach 600 mrem/h. Normally, interlocked CARMs prevent radiation levels from approaching a small fraction of this amount. During special tests in which CARM trip points were temporarily adjusted, radiation levels were measured at about 1/10th of this value. Given the administrative protocols in place during testing, as well as the CARM trip function, no credible scenario exists for operations involving routine exposure to radiation levels of this magnitude. Credible exposure conditions involve dose to operators in the VTA control room or making short-duration entries to the test high bay during periods of high field emission. For this assessment, we apply the prevailing conditions measured during the special tests (60 mrem/h outside the shield hut and ~ 0.12 mrem/h in the control room), corresponding to a measured FE power of about 40 watts. Again, such conditions are normally prevented by the interlocked CARMs. Due to the relatively localized nature of the radiation fields, and the conservatism of the estimates just described, the values presented in Table 14 are considered valid for conditions involving concurrent high-power operations of multiple cavities, up to the maximum capacity of the cryogenic system.

In addition to these conditions, excursions from cavity quench events may occur. As in the case with the CMTF, these events are conservatively assumed to persist for one millisecond (in reality, the timeframe is measured in microseconds). Using this conservative assumption, and assuming a cavity operating in excess of 50 MeV, the dose from such an event is estimated at 0.06 mrem. This scenario is a relatively rare event, as the VTA test bay is usually unoccupied during high power testing.

Given the distance and shielding afforded by the control room walls, doses to operators in the VTA control room during such events is negligible. An operator who is present in the control room during 500 such quench events in a year is estimated to receive ~ 0.05 mrem. Table 14 summarizes the above discussion.

Table 14. Dose for Beam-Loss Conditions at VTA

Loss Condition	Location	Maximum Dose Rate Outside Shielding (mrem/hr)	Maximum Dose Outside Shielding (mrem)	Notes
40 watt continuous	Control room	0.12	60	Total dose assumes 500 hr/y in control room and total of 1 hr in high bay
	Adjacent to shield hut	60	60	
275 watt instantaneous	Control room	324	0.05	Total doses for control room occupancy for 500 quenches and one event adjacent to hut
	Adjacent to shield hut	200 (rem/h)	0.06	

Under the conservative conditions assumed above, a combination of all the exposure scenarios combined gives a total dose of about 120 mrem/y, which is below the shielding policy design goal for radiation workers. Historically, VTA operators typically receive annual doses in the range of background.

The monolithic shielding below the floor level of the VTA is considered credited structural shielding. This shielding consists of concrete and sand and extends laterally for at least 6 feet in every direction around the dewars. Access points to areas adjacent to this shielding are precautionarily posted as high radiation areas (estimated maximum steady state dose rate in this area is of order 1 mrem/h, with a maximum instantaneous dose rate of about 3 rem/h). Plausible exposure scenarios result in total doses of < 1 mrem.

The movable shield-hut lids on each test dewar perform a similar function to the movable shield walls in the CEBAF accelerator. Postulated sustained dose rates inside the huts are of order 5000 rem/h. The lid closure is interlocked to the PSS and the shielding provides essential protection from the high radiation fields inside the hut.

Summary of Unintentional Beam Loss Shielding

The structural shielding associated with the accelerator enclosures described above is considered a Credited Passive Engineered Control. Certain movable shielding installations as noted above also meet the criteria for Credited Controls. The configuration (design, installation, modification, and maintenance) of radiation shielding for accelerators, including shielding of penetrations, is subject to the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001)*. Structural shielding – shielding that is part of the physical structure of the accelerator enclosure – is inspected as specified by FM&L procedures and recorded in the CAIS at least every five years. Design changes are reviewed in accordance with the *ASE Violation/USI Review Process*. Earth berms/overburden are inspected by FM&L and reviewed by the RCD according to procedure and documented at least every five years. In addition, Jefferson Lab uses a Dig/Blind Penetration Permit specified in *ES&H Manual Chapter 3320, Temporary Work Permits*, to manage configuration during excavation activities in earth overburden used as accelerator enclosure shielding or drilling into any structural shielding.

Personnel also are excluded from sources of prompt ionizing radiation by locked doors, gates, fences, and other barriers – these are considered Credited Administrative Controls – as well as shielded enclosures and shielding for penetrations in these enclosures, which are considered Credited Passive Engineered Controls. Actively engineered safeguards such as interlocked radiation monitors are considered Defense-in-Depth Controls.

It should be noted that passive area-monitoring data collected to date in locations adjacent to accelerator enclosures indicate the combined active and passive measures (architectural shielding, administrative controls, interlocked radiation monitors) are effective. Radiation dose measurements in these locations have historically met and continue to meet the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001)*.

5.2.1.1.2. Intentional Beam Loss

There are a variety of diagnostic devices around the CEBAF accelerator that are inserted into the beam at low power to measure beam properties. These include thin foils to generate optical transition radiation, thin wires to scan across the beam (HARPS, beam profile monitors), Faraday cups, and small LCW-cooled insertable dumps to terminate the beam at specific locations around the accelerator. The hazard is bounded by the 1.7-kW value specified in Table 4, Dose for Beam-Loss Conditions Outside CEBAF Shielding, and Table 5, Dose for Beam-Loss Conditions Outside CEBAF Shielding at Unshielded Penetrations. Similar devices are used in the LERF and UITF. The installed shielding in the accelerator in Table 2, Nominal *As-Built* Shielding, is designed to mitigate the associated prompt ionizing radiation hazard.

The primary purpose of the accelerators at Jefferson Lab is to conduct nuclear physics experiments. This is accomplished by directing high-power beam on nuclear physics targets. These targets consist of a range of materials from low atomic number gases, liquids, and solids to high atomic number metals in different states and configurations. The targets may be situated in an RF field or magnetic field to enhance or maintain a polarization state and may be cooled, including cryogenic cooling, to change the material phase. By design, these targets are very "thin" (compared to the thickness necessary for a high-energy electron to lose 1/e of its energy) to promote single interactions by the beam in the target. In the LERF and the UITF, physics targets are installed inside the enclosure with shielding if needed to maintain radiation levels consistent with the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001)*. Nuclear Physics targets used in CEBAF are typically situated in the experimental end stations, which have the equipment necessary to support these targets and house the large detectors designed to acquire data of value to nuclear physicists. Occasionally, physics targets are installed in specific locations in the CEBAF accelerator depending on the beam energy needs for that particular experiment. The installed shielding in the accelerator in Table 2, Nominal "As-Built" Shielding, is designed to mitigate the associated prompt ionizing radiation hazard inside the accelerator. The experimental end stations also use soil as shielding, and the thickness of the soil is limited by the roof's load-bearing capacity. Prompt ionizing radiation produced in the targets installed in the experimental end stations contributes to air activation and materials activation in the end station and skyshine contributes to the site-boundary dose. Since the average power deposited in a thin physics target is very low – of order 200 W maximum - the equivalent dose rate is very low.

A second concern with CEBAF experimental end station overhead shielding is the potential exposure to personnel who might access the roof of the Experimental End Stations A and C during beam delivery.

During high-power beam operations, workers could be exposed to radiation equivalent dose rates of some tens of mrem/hr during normal operations at maximum beam power, and several hundred rem/hr worst-case in the event of accidental beam loss into an optimally thick target below (some component that is much thicker than an experimental target).[33] However, the worst-case condition cannot be sustained by the accelerator and would, therefore, be a peak value of very short duration resulting in an equivalent dose that is conservatively estimated to be 240 mrem. The areas on top of the halls are designated as radiation areas and bounded by locked fences located at the top of the earth berms. Outside the fence, and associated boundaries, the potential radiation level is within accepted limits for general employees.

5.2.1.1.3. Dark Current

As described above, high-gradient cavities and cryomodules (CMs) can generate electrons by field emission (dark current), which can couple to RF and achieve energy up to the full gradient supplied by the available RF power. Dark-current production and the ionizing radiation that results have been shown to be independent of beam conditions. Ionizing radiation levels from dark current can represent the principle radiation source term inside the accelerator enclosure in the vicinity of CMs when nominal losses from beam transport are low.

Calculations and measurements show that dose rates in excess of 1000 rem/h gamma and 50 rem/h neutron are possible at a position reasonably representative of whole body exposure (30 cm from a C100 CM end flange) and contact dose rates on the surface of a C100 CM have been estimated to be in the range of 3 to 14 krad/h at the end flange and 0.3 to 0.4 krad/h at a lateral position on the side of the CM.[12] The contact dose rates were estimated using passive integrating dosimeters and operating hours at high-gradient. Monte Carlo simulations by SLAC result in estimates of several tens of rem per hour equivalent dose rate whole body exposure at a lateral position with respect to LCLS-II (high gradient) CMs normalized to a dark-current value of 1 nA.[13]

Radiation levels increase exponentially with gradient (based on the number of powered cavities in a CM as well as overall applied power) and the exposure position. This seems to be independent of beam current and energy. The same simulations by SLAC suggest that measurements on-axis within a meter from the beamline exit for a single high-gradient cavity can reach 10 kilorad/h. While more effort is needed to completely characterize the source term for dark current in high-gradient CMs, there is sufficient data to demonstrate the need to apply the same controls for prompt ionizing radiation associated with beam delivery any time high-power SRF components are operated within CEBAF, LERF or the UITF. Accordingly, these activities are considered part of accelerator operations.

5.2.1.1.4. Shielding for Skyshine

Skyshine is the name given to radiation passing through the relatively thin radiation shielding above a radiation source that is scattered in the air downward to areas accessible by staff or the general public. Skyshine is dominated by neutron radiation, but there is a photon radiation component. The main concern with skyshine radiation is its contribution to the radiation levels outside the Jefferson Lab property boundary. The contribution to workers on-site is considered along with other sources of radiation and reflected in the shielding design policy. The source of radiation exposure from the CEBAF Experimental End Stations A, C, and D is almost exclusively due to skyshine.[15] Due to the shielding design and accelerator position (with respect to the site boundary), the LERF and UITF accelerators do not constitute a skyshine source at the site boundary.

Radiation measurements during commissioning confirm the as-built shield design adequacy for reducing radiation levels, both on-site (outside the hall roof fences) and off-site. Effective shielding and sound experiment design together limit losses such that the total boundary dose due to skyshine does not exceed 10 mrem/y (one- tenth of the 100 mrem/y regulatory limit identified in 10 CFR 835 and DOE O 458.1)[41] and that in a credible exposure scenario, dose to a member of the public does not exceed 1 mrem/y.

5.2.1.1.5. Summary, Shielding for Intentional Beam Loss, Dark Current, Skyshine

The Credited Controls specified in Section 5.2.1.1.1, *Unintentional Beam Loss*, are the same controls for hazards associated with intentional beam loss and dark current in CMs and SRF cavities. As a hazard, skyshine requires no additional Credited Controls and is tracked using radiation monitors, similar to CARMs used for Defense-in-Depth Controls, but carefully designed and calibrated to operate at very low equivalent dose rates by the RCD.

5.2.1.1.6. Access Control for Prompt Ionizing Radiation

The PSS provides Access Controls for the VTA, CMTF, GTS, UITF, LERF, and CEBAF accelerator enclosures. PSS Access Controls are described in Section 4.2.1.3.1, *Accelerator Engineering PSS,* and are considered Credited Active Engineered Controls for accelerators operating >10 MeV. PSS Access Controls prevent people from entering areas where accelerator beam is delivered and prevent beam delivery (and the prompt ionizing radiation generated by the beam) to areas where people may be located.

PSS Access Controls also serve as a principal protection for prompt ionizing radiation by preventing the delivery of RF to CMs and accelerator components in any PSS segment where people may be located. The PSS is interlocked to the RF systems power supplies. RF power can only be supplied to the accelerator enclosure when it is properly configured. The requirements for the application of access controls are found in the *Beam Containment and Access Control Policy*. The PSS access controls system is operated by trained staff. The training requirements are found in the AOD, LOD, UOD, and the respective operating directives for VTA and CMTF. The trained staff who operate the PSS are also discussed in Section 4.2.1.2, *Accelerator Training and Personnel*. The presence of trained staff (i.e. SSO) who can operate the PSS Access Controls is considered a Credited Administrative Control**.**

5.2.2. RF Generated by Beam Through Tuned Cavity

In addition to high-power RF supplied by a klystron, another source of RF is possible. Under certain circumstances, an SRF cavity can couple RF energy from an electron beam moving through the cavity and transmit the RF through a waveguide toward the klystron – beam induced RF radiation. This RF can be very intense; when traversed by an electron beam, a seven-cell cavity tuned for maximum performance can radiate significant RF power. Depending on design and performance, a 1-mA beam of electrons can generate 6755 W of power.[16] It is also evident that even minor detuning of an SRF cavity can significantly reduce out-coupled power. For example, an SRF cavity can have a drop in out-coupled power of 99.7% for a 1 ppb frequency change (0.75 kHz from the resonant operating frequency). The detuning angle bandwidth is a small percentage of the base frequency but can have a dramatic effect on electron beam coupling and beam-related induced RF. If the waveguide is properly connected, a circulator in the RF supply system will absorb the beam-induced RF power.

When the waveguide is disconnected for any reason, open and accessible to personnel, then RF exposure is possible. For this reason, beam delivery is not allowed in the affected machine segment during klystron replacement, circulator work, or “open waveguide” activities.

For the purposes of evaluating this hazard, it was assumed that a person, in contact with and looking at the waveguide at arm’s length, was exposed to 1-kW RF at 1497 MHz. This exposure could result in moderate to severe consequences such as muscle and tissue injury in the extremities and, within the reaction time for such an event, result in RF exposure sufficient to induce cataracts in the lens of the eye.[17] The probability of such an event is low. Therefore, if a waveguide is open for repair, due consideration must be given to the hazard. In addition to standard work controls, the waveguide is pressurized, and a waveguide pressure sensor is interlocked to the PSS. Waveguide leakage resulting in sufficient pressure drop will prevent RF power from being applied to the affected PSS segment. This waveguide pressure interlock is applied to all CEBAF, LERF, and UITF RF systems as a means of continuously checking waveguide integrity and serves as a Defense-in-Depth Control for mitigating the hazard associated with RF generated by beam through a tuned cavity.

5.2.2.1 Special Considerations for RF Generated by Dark Current in High-Gradient Cryomodules

As mentioned above in Section 5.2.1.1.3, *Dark Current,* high-gradient CMs can generate electrons by field emission (dark current), which can couple to RF and achieve energy up to the full gradient supplied by the CM. This dark current can occur in either direction along the beamline and can transition to an adjacent CM. Estimates of dark current vary. Data suggest that Field-emitted electrons are largely confined to impact sites in the same or an adjacent cavity lobe. There are large uncertainties in the evaluation of peak current from an emitter due to the range of possible emitter geometries and electric field strength. An extremely conservative way to place an upper bound on a dark current in a high-gradient CM is to divide the measured heat load in Watts by the accelerating gradient in Volts assuming that all heat in a CM is due to Field-emitted electrons. This results in a dark-current estimate of approximately 2 microamps in a high- gradient CM. Actual observed levels of dark current in high-gradient CMs are typically lower by orders of magnitude.

Using the value of 7833 W[52] of power reduced by the ratio of beam current and estimated maximum dark current results in approximately 16 W at an open waveguide. This could result in RF exposure to a worker up to approximately a factor of 10 times the eight-hour, time-weighted average threshold limit value for RF exposure at 1500 MHz This does not present a hazard that can result in immediate physical harm but points to the need for the use of monitoring or work controls as mitigation.

As mentioned in Section 4.0, *DESCRIPTION OF ACCELERATOR ORGANIZATION AND FACILITY*, work control documents (WCDs) are developed when a task involves assembly and fabrication, maintenance, repair, and R&D (research and development). See *ES&H Manual 3240 Work Planning, Control, and Authorization Using ePAS*.

5.2.3. Activation of Materials

Hazards associated with low-level radiation exposure from working on radioactive components or radioactive material generated by accelerator operation is not addressed in this section. These hazards are managed by the Radiation Protection Program identified in Section 4.2.5.1.2, *ES&H Radiation Protection*, which implements the requirements in Title 10 CFR 835. Two hazards that are treated as accelerator-specific hazards in this section are short-lived radioactive materials in the high-power beam-dump cooling system water during beam delivery and beam-related air and groundwater activation.

5.2.3.1. High-Power Beam-Dump Cooling Systems (BDCS)

The High-Power BDCS, identified in Section 4.3.1.3.1, *Hall A and C Beam Dumps*, are located in Hall A and Hall C Beam Dump Cooling Buildings (Buildings 91 and 95). Each system consists of a primary cooling loop that contains about 1,500 gallons of low-conductivity water and a heat exchanger. Short-lived isotopes are produced in the beam-dump cooling water and reach an equilibrium activity fairly quickly – within a few minutes to hours depending on the isotope. The short-lived isotopes present in this water are shown in Table 15. These isotopes also decay rather quickly after beam is terminated. These short-lived isotopes create the high-radiation areas inside the beam-dump cooling buildings during beam operation.

Longer-lived isotopes are also produced in the cooling system. The principal isotopes of concern are tritium and beryllium-7 because they decay relatively slowly compared to the other isotopes (53 days for beryllium-7 and 12 years for tritium). The maximum concentration of tritium and beryllium-7 in the beam-dump cooling water varies between about 0.1 and 1 microcuries per milliliter after high-power beam operations.

Table 15. Short Half-Life Isotope Content in a BDCS

Isotope	Half Life	Saturation Activity in Curies
Oxygen-15	2 minutes	784
Nitrogen-13	10 minutes	8.25
Carbon-11	20 minutes	34.1

The beam can also activate impurities in the primary cooling-loop water and the materials of the cooling system (e.g., piping), which can become entrained in the cooling water through corrosion of these materials. Each high- power BDCS uses low-conductivity water. The conductivity of each BDCS is maintained by ion exchange resin tanks housed in the BDCS buildings. This resin is in the form of small-diameter beads (~1 millimeter diameter), and because its effectiveness diminishes with time, it is replaced with new (non-radioactive) resin at approximately 10-year intervals. The worst case for isotopic content of the resin (at the end of its approximately 10-year life) is approximated by the quantity of longer-lived isotopes produced in the coolant over that same period. This is shown in Table 16 below.

Table 16. Long Half-Life Isotope Content in a BDCS

Isotope	Half Life	Cumulative Activity in Curies
Beryllium-7	53 days	0.445
Manganese-54	312 days	0.00445
Sodium-22	2.6 years	1.334
Cobalt-60	5.27 years	0.0028
Hydrogen-3 (Tritium)	12 years	0.237

The RCD routinely samples the radioactivity content of the water in the primary loop for longer-lived radionuclides.

Provided that the beam dump is undamaged and properly operating, the principal hazard is associated with a large quantity of short-lived radionuclides in the cooling water (identified in Table 15, Short Half-Life Isotope Content in a BDCS). This high-power beam-dump cooling water circulates through equipment located aboveground in the high-power BDCS. During high-power operations, the BDCS buildings are high-radiation areas (> 10 rem/h to the whole body) due to the presence of activated cooling water. These buildings are shielded and locked to only allow access under controlled conditions. Each high-power BDCS building has 24- inch-thick reinforced concrete roof and walls designed to provide the required radiation shielding for radionuclides in the primary cooling loop and the water-treatment components. Each building has a sump capable of containing a worst-case spill of the aboveground volume of cooling water and also has leak detection capability.

Additionally, movable shielding is used at the equipment doors of the BDCS buildings. This shielding is not a Credited Control. Analysis indicates[29] that the unshielded dose rate outside the doors may be on the order of 2 rem/h when the activity shown in Tables 15 and 16 are present. It should be noted that the same configuration control requirements are used to manage all movable shielding whether it is a Credited Control or not. Plausible exposure conditions yield total doses below that requiring the shielding to be a Credited Control. But like all accelerator-related shielding, the configuration control on these shields is the same as for credited shielding.

Technical Note 16-016, *Analysis of key accident scenarios for high-power beam dump cooling systems* (see Endnote 21), evaluates several potential sources of release for radioactivity contained in the high-power beam- dump cooling systems. The principal concern for the mitigation of the loss of radioactive materials from the high-power beam-dump cooling systems are the long half-life radionuclides listed in Table 14. The accident scenarios addressed in JLAB-TN-16-016 are:

- leakage due to component failure
- earthquake
- hydrogen detonation
- kinetic impact with corresponding release of aqueous resin

The leakage-detection system on the floor and in the sump and the hydrogen gas monitoring system in the ceiling of the high-power beam-dump cooling buildings are considered Defense-in-Depth Controls. The building structural design and containment sump is considered a Credited Passive Engineered Control.

Damage to the high-power beam dumps identified in Section 4.3.1.3.1, *Hall A and C Beam Dumps*, can occur if a focused high-power electron beam damages the beam-dump "window," a thin section of water-cooled metal that allows beam to enter the dump. This damage can release a portion of the high-power electron beam-dump cooling water. Each high-power electron beam dump is housed in a tunnel and each tunnel has two weirs installed in the tunnel floor, to contain the spill, and a pipe that can be used to drain the water in the event of a spill. A spill reaching the floor of an experimental end station will be collected in the end station floor drain sump, which is sampled before discharge. Significant groundwater contamination is not considered a credible scenario; any spill would be highly diluted by the many thousands of gallons of groundwater that are pumped daily by permit from under each high-power end station floor. There are several engineered safeguards used to diffuse a high-power electron beam so that it can pass through the window without damage. A spill of beam dump cooling water (starting shortly after beam shutdown) does not present an accelerator-specific hazard to personnel or pose a significant hazard to the environment, the engineered safeguards are considered as one of a series of machine protection systems and are not further discussed.

It is conceivable that localized flooding identified in Section 3.2.4, *Surface Hydrogeology,* could result in water intrusion into the accelerator tunnel and end stations. The question arises as to whether floodwater could become contaminated as a result of contact with the accelerator tunnel, end stations, or equipment contained therein. Exposure to radioactive material that results from accelerator operation is managed as described earlier in this section – by the Radiation Protection Program identified in Section

4.2.5.1.2, *ES&H Radiation Protection*. Most of the radioactive material that results from accelerator operation is contained in the structural materials that make up the tunnel and accelerator components; bulk activation. Sumps around the accelerator collect groundwater and process water leakage and air conditioning condensate. These sumps, which may contain low levels of tritium and beryllium-7, are collected and routed to the combined end station sump, which is sampled before discharge. Significant removable surface contamination is rare, and contaminated areas do not cover significant portions of enclosure spaces that are subject to flooding. Consequently, it is very unlikely that floodwater capable of overwhelming collection sumps and discharge systems would become contaminated by radioactive material to any significant level.

Water removed from the tunnel or end stations to recover from flooding is expected to meet existing permitted discharge levels with respect to accelerator-produced radioactivity content.

5.2.3.2. Beam-Related Air and Groundwater Activation

Activated materials can exist along most of the beam's path but are expected at beam destinations such as physics targets, beam dumps (where the majority of the beam's energy is captured), and at high-gradient CMs. The highest radiation levels are found at beam dumps that are not normally accessible to personnel. Radiation from activated materials in the beam dumps can exceed tens of rem/hr. Radiation from dark-current-induced activation in CMs can approach levels of a few tens to a few hundred millirem/h in high-gradient cryomodules[18] located in the accelerator enclosure. Most of the radioactive materials produced at Jefferson Lab are "volume- activated" or self-contained; the radioactivity remains embedded in the substance in which it is created. Exceptions include the high-power beam dump cooling systems and activated air and groundwater, which have radioactive materials that are dispersible.

The production of radioactivity in air has been evaluated for CEBAF [18,21,33] and LERF.[9] The operational energy for UITF is below the threshold for radionuclide production in air. The frequency and duration of operations above thresholds for air activation at CMTF and VTA are low, and total power deposition in the air during these operations is less than 1 watt. The design of the LERF tends to minimize beam loss when operated as an energy- recovery linac. Measurements taken from the LERF accelerator enclosure during energy-recovery operations confirm negligible airborne radioactivity production. Measurements during fixed-target experiments show low levels of airborne activity production, consistent with estimated values. Experiment reviews are required for fixed-target operations, and include assessment of air activation. Airborne radioactivity-monitoring systems are in use by the RCD at key locations in the CEBAF and LERF accelerator enclosures to measure radionuclide concentration. Air exchange rates for these locations are used to calculate radionuclide-release rates. TJNAF uses an Environmental Protection Agency (EPA)-approved computer code (CAP88 PC) to calculate the maximum exposure to airborne radioactivity by a member of the public. These calculations show that Jefferson Lab's operational emissions remain several orders of magnitude lower than the EPA's 10 mrem/year dose limit for a member of the general public. The results are reported to EPA annually and summarized in the TJNAF Annual Site Environmental Report.[19] The impact on air emissions from operating at total power above 1 MW in CEBAF was evaluated in RCD-DEP-21 #004.[33] The analysis indicates that air emissions would remain well below the EPA limits for total beam power up to 2 MW. Specific reviews of individual emission points should be made if CEBAF upgrades that allow more than 1.5 MW total power occur.

The CEBAF and LERF shielding is designed such that the maximum radioactivity that can be produced in groundwater or in soil will remain at or below permitted limits.[9,26,33] This is a principal consideration for the shielding listed in Table 2, Nominal "As-Built" Shielding (above). By permit with the Commonwealth of Virginia, TJNAF monitors groundwater pumped from around the experimental halls that are discharged to the surface and at monitoring wells strategically placed around the site. Results are reported in accordance with the applicable permits and summarized annually in the Annual Site Environmental Report.[19] No accelerator- produced radionuclides have been detected to date at groundwater monitoring locations. RCD-DEP-21 #004 evaluated the impact of increased total beam power in CEBAF and concluded that operations up to 2 MW would be unlikely to significantly impact groundwater quality. However, as with air emissions, further modeling and analysis should be conducted in the event the CEBAF accelerator is upgraded to support routine operations above 1.5 MW. The operational energy for the UITF is below the threshold for radionuclide production in soil or in groundwater. Air and groundwater activation do not present an unacceptable risk at Jefferson Lab, and do not require the application of Credited Controls.

5.2.4. Radiogenic Hazardous Gases

The production of non-radioactive hazardous gases (hydrogen, oxides of nitrogen, ozone) from electron-beam interaction occurs principally at locations where beam interaction in surrounding material is most intense. Since physics targets are most often contained in vacuum space, most radiogenic hazardous gases occur in the atmosphere surrounding the high-power beam dumps[23] and beam-dump cooling water. The high-power beam- dump cooling systems are closed systems designed with hydrogen recombiners that remove hydrogen as it is created.[24] The possibility of hydrogen leakage and the associated mitigation measure is discussed in Section 5.2.3.1, *High Power Beam-Dump Cooling Systems (BDCS),* above.

The tunnel surrounding the high-power beam dump is enclosed, and the atmosphere within is purged with dry nitrogen gas. The absence of both oxygen and moisture limit the production of oxides of nitrogen and the development of nitric acid. The nitrogen atmosphere is maintained by a very slow purge, and radioactive materials entrained in the nitrogen are treated as beam-related air activation in Section 5.2.3.2, *Beam Related Air and Groundwater Activation*, above.

Radiogenic hazardous gases are sometimes present in the air inside the accelerator enclosure. This occurs when physics experiments require low energy, high current, and use relatively thick physics targets, or accelerator transport losses or tune-up losses result in a relatively large amount of scattered radiation entering the air. This is reasonably predictable when it occurs; accelerator diagnostics can be used to identify beam losses during transport. Typically, there are elevated levels of airborne radiation simultaneously produced; this is detected by the installed airborne radioactivity monitoring systems. This situation is relatively rare, and the radiogenic hazardous gas exposure to personnel is low, carefully monitored, and managed by the Worker Health and Safety Program in accordance with 10 CFR 851. Radiogenic hazardous gases do not present an unacceptable risk at Jefferson Lab and do not require the application of Credited Controls.

5.2.5. Oxygen-Deficient Atmosphere Inside Accelerator Enclosures

While management of oxygen deficiency hazards in general industry may be applied to the use of cryogens at Jefferson Lab, industrial practices typically address various types of above-ground enclosures or small confined spaces. A relatively large volume of cryogens combined with a limited choice of egress routes and the presence of other accelerator-specific safety hazards present a condition in which standard industrial practices and guidance do not fully address the ODH risks.

The primary cryogen used at Jefferson Lab is helium, a lighter-than-air element that expands in volume over 700 times from a liquid to room temperature gas. A large volume (over 153,000 liquid liters) of helium is contained in the cryomodules in accelerator enclosures. Extremely cold helium gas is delivered to the cryomodules of the CEBAF, LERF, UITF, and CMTF accelerators, as well as cryogenic dewars in the VTA, where it transitions to a liquid and cools the cavities. As heat enters the cryostats, some of the helium vaporizes and becomes a gas. This vaporized helium (gas), under normal operating conditions, is collected in a return line and returned to the refrigeration plant, where it is cooled and ultimately returned to the cryostats. However, if the discharge to the return line is blocked, or if gas pressure in the cryostat increases above the primary cryostat relief valve set point, the helium gas is released through the relief valve.

The primary cryomodule relief valves for the CEBAF and LERF accelerators discharge the gas, via a guard vacuum system, to a vent line that terminates above ground outside of the enclosure, thus eliminating a helium gas accumulation hazard. If the primary cryomodule relief valve does not lift as designed, a secondary relief valve is provided, but it discharges into the space surrounding the cryomodule. If this should occur, the rapid release of helium would inherently provide audible and visual indications (a white condensation cloud would form from the cold gas rapidly escaping into room air) alerting personnel to the rapid leak and enabling a quick exit from the respective enclosure. The CEBAF accelerator tunnel is designed with lintels that help confine helium gas to the linac areas in the accelerator tunnel, prevent helium gas collection in associated stairwells, and allow helium gas to exit the tunnel through strategically placed penetrations that act as passive vents.

The LERF accelerator enclosure and the UITF are also designed with strategically placed penetrations that act as passive vents. It is also assumed, for the purposes of evaluating the ODH hazard, that a slow leak of helium gas into the area around a cryomodule, such as might occur at a flanged piping joint, may not be observable to personnel in the vicinity.

The primary cryostat relief valves for the UITF & VTA vent directly to the Test Lab High Bay, whereas the relief for the CMTF Cryomodule under test vents directly into the CMTF enclosure, which is then exhausted into the Test Lab High Bay. Secondary relief valves for both the UITF and CMTF vent into the accelerator enclosure in the event of primary relief valve's failure to open.

The LERF, UITF, and CMTF also have penetrations to act as passive vents. In the LERF the passive vents release helium gas outdoors whereas the UITF and CMTF vent to the Test Lab High Bay. Some passive vents are also equipped with fans to assist with the removal of helium gas.

In the VTA, the cavity test dewars are supplied with liquid helium at the rate of about 250-300 liters per hour. Dewars are pumped to sub-atmospheric pressures to achieve temperatures as low as 1.9K, using a vacuum pump with a capacity of about 7 grams per second. Multiple dewars can be pumped down simultaneously, in accordance with system capabilities (defined by vacuum pump mass flow limits). All helium used in the VTA is returned to the refrigeration plant where it is purified of any contaminants (most notably nitrogen) and is re-liquefied. In the case of VTA dewars, helium gas is vented to the Test Lab High Bay.

Nitrogen gas is used for low flow-rate purging and backfilling of vacuum components in the accelerator enclosures. It is supplied as warm gas from two, 20,000-gallon liquid dewars located above ground near the CHL or by liquid dewars located above ground near the Test Lab. It is assumed that helium or nitrogen gas from a large liquid source is always present in the cryomodules and gas distribution systems in the CEBAF accelerator tunnel, LERF accelerator enclosure, and UITF enclosure. ODH conditions at the CMTF change relative to the presence of a cryogenically connected module and position of the concrete shielding doors, and is posted accordingly. In addition, nitrogen generators are used in the fire protection sprinkler piping to reduce corrosion in the CEBAF enclosure. Regardless of the operational state of these accelerators, the potential for an oxygen deficiency hazard exists whenever cryogens are present in the respective enclosure or nitrogen gas is available from the purge line or nitrogen generators.

Nitrogen generators also provide nitrogen gas for low-flow purging to inert the atmosphere in the high-power beam dump tunnels for Halls A and C. These high-power beam-dump tunnels are Permit Required Confined Spaces, and personnel are excluded from these spaces while under purge. Entry is managed by the *ES&H Manual Chapter 6160, Confined Space Program*.

Physics detector systems, located in the CEBAF experimental end stations, use superconducting magnets. These magnets are constructed with thermal shielding that uses cryogenic nitrogen, and the magnet coils are cooled with cryogenic helium. These superconducting magnet systems are designed to vent to the respective experimental end stations in the event of a magnet quench. The experimental end stations have a relatively large volume compared with accelerator tunnels and have helium vents located in the top of the structure that allow helium to vent outside. As a maximum credible bound case for the ODH hazard, it is assumed that the cryogenic supply system releases its full capacity of cryogenic helium, limited by the piping design, into an end station.

TJNAF developed *ES&H Manual Chapter 6540, Oxygen Deficiency Hazard (ODH) Control Program*, and *ES&H Manual Chapter 6550, Cryogenic Safety Program*, to address these hazards. Chapter 6540 and its appendices refer to the lab's ODH program, which uses a standard method to classify the hazard from systems and processes that can create an oxygen deficiency hazard and identifies certain mitigation requirements in the form of engineered safeguards, administrative controls, and personnel protective equipment. An ODH hazard assessment has been conducted for each accelerator enclosure where an ODH hazard exits.

According to the requirements in Chapter 6540, these ODH assessments are reevaluated periodically to ensure that they correctly reflect the actual conditions in the affected area: every three years or whenever there is a change that can affect the technical basis of the assessment.

Passive and active engineered controls, along with administrative controls, are all used as Credited Controls for all accelerator enclosures. For example, the nitrogen-distribution lines associated with the gaseous nitrogen supply to the CEBAF accelerator enclosure (tunnel portion) are fitted with 1/8" flow-limiting orifice plates that limit the maximum flow rate to 5 SCFM. The flow and total quantity of nitrogen used to provide corrosion protection for fire protection sprinkler piping is limited by the pipe size in the sprinkler system.

The ODH analysis for the CEBAF accelerator enclosure (tunnel portion) shows that, assuming no ventilation air exchanges in the accelerator enclosure (tunnel portion), it would take 12 days for the oxygen level to reach the limit of the Jefferson Lab administrative control threshold of 19.5% identified in *ES&H Manual Chapter 6540, Oxygen Deficiency Hazard (ODH) Control Program*. Nitrogen gas is distributed to the accelerator enclosures via fail-closed solenoid-operated valves located upstream of the flow-limiting orifices. Where specified in the relevant ODH analysis, the flow-limiting orifice plates in nitrogen gas distribution lines are considered Credited Passive Engineered Controls.

The fail-closed solenoid-operated valves, which provide additional ODH mitigation for the accelerator enclosures in the event of an electrical power outage, are considered Defense-in-Depth Controls.

The principal Credited Active Engineered Control for ODH at Jefferson Lab is an ODH monitoring system that uses sensors positioned at the ground and/or ceiling level for both gaseous helium and nitrogen depending on the hazard. The ODH monitoring system provides local alarms to warn personnel in the area of low-oxygen levels and may initiate other actions depending on the system design. ODH monitoring systems[22] are based on commercial off-the-shelf equipment designed specifically for sensing reduced oxygen levels in occupied spaces. ODH systems are installed on the basis of area-specific oxygen deficiency analyses. Functional test procedures, alarm response procedures, and ODH head change-out procedures are used to maintain the operability and reliability of these systems. Warning alarms on the ODH monitoring system include flashing beacons and audible devices, both of which are distinct from other systems (e.g., fire and radiation) to enable personnel to distinguish the hazard. ODH flashing beacons are located outside entry points to the beam enclosures to warn personnel of potential ODH conditions within. These systems are designed, installed, and maintained by the Safety Systems Group and are used throughout the Jefferson Lab accelerator enclosures. They are labeled as Credited Controls. ODH monitoring systems are used for non-accelerator applications at Jefferson Lab. Consequently, not all ODH monitoring systems are identified or addressed in this SAD.

Where specified in the relevant ODH analysis, lintels are installed in the overhead space of the accelerator tunnels to delay the flow of helium from the tunnels from moving into the stairwells (which personnel climb to exit the tunnels) or into the arc sections (where there are no helium sources). In addition, the LERF vault has a similar feature inherent in the design of the building and the configuration of the doorways. The bounding case for a cryogenic helium release event is a rapid release of helium in the CEBAF accelerator tunnel. In this event, the volume above the level of the lintels is sufficient to contain a buoyant helium gas/air mixture (~16% oxygen (O_2)) for a period of five minutes before the gas spills under the lintels into the arcs or stairways. This is considered to be ample time for personnel to exit the tunnel enclosure without adverse health effects. The lintels in CEBAF and exit design featured in LERF are considered Credited Passive Engineered Controls.

The primary helium gas pressure relief valves on each cryomodule in both CEBAF and LERF are routed to the guard vacuum lines of their respective helium-distribution systems. The guard vacuum space is connected to low-pressure differential relief valves that allow any released helium to exit into the atmosphere aboveground. The primary helium gas pressure relief valve on the cryomodule in the UITF is vented out of the UITF enclosure to the Test Lab High Bay. VTA Dewar reliefs are vented directly into the Test Lab high bay. The CMTF cryomodule primary and secondary reliefs exhaust directly into the accelerator enclosure, and when ODH conditions are detected a 42” 10,000 CFM fan fitted to a 16 ft^2 shielded ceiling vent activates and exhausts the enclosure directly into the Test Lab high bay. These piping and vent configurations are designated as Passive Credited Engineered Controls[46].

Training is provided to workers on general safety awareness and oxygen deficiency hazards associated with the accelerators. This training assures understanding of visual and audible indicators and signage, recognition of hazardous conditions, and appropriate responses to unplanned events. A graded approach, in which the workers are trained to an appropriate level for their assigned work locations and activities, is used. This training is considered a Defense-in-Depth Control.

5.2.6. Hazardous or Exotic Material for Use in or as Physics Targets

Experimental nuclear physics targets at Jefferson Lab can be solid (typically thin metal), liquid (often cryogenic), or gaseous (often cryogenically cooled). The targets can be non-hazardous or hazardous material; sometimes several targets that fall into several categories, depending on the needs of the experimenters, are used. All hazards associated with experimental nuclear physics targets are carefully reviewed during the ERR process. As a function of the ERR process, the ESAD addresses the hazards specific to a particular experiment and the associated experimental apparatus. The involvement of the RCD Manager (who is also a member of the SCMB), or designee, in ESAD reviews incorporates the USI process managed by the SCMB as described in Section 4.2.5.2, *ES&H Subcommittees*. The ERR also requires the development of an RSAD as mentioned in Section 4.2.2.1, *Physics Governing Processes and Procedures*. The RSAD identifies the controls associated with physics targets, including handling and storage based on physical and radioactive characteristics of the target. The USI process is used to ensure that any target materials that may present unique hazards, and that may not be sufficiently analyzed in the SAD, are given a thorough hazard evaluation and mitigations are identified, documented, and in place before the experiment begins.

The ERR process is considered a Credited Administrative Control.

5.3. Hazard Assessment Method

The hazard assessment used by Jefferson Lab follows the method outlined in Figure 16 below. It is based on a preliminary analysis in 1986 and a subsequent review of the project in the Preliminary Safety Analysis Report[25] in 1989. The hazard analysis method has evolved through the Accelerator Readiness Review process and with successive versions of the ASO. This progress resulted in the preoperational CEBAF Hazards Analysis[27] in 1993 and the development of the *CEBAF Beam Containment Policy*[25] in 1994, which established the initial requirements for the PSS. Revision 6 of this SAD brought the hazard assessment process into compliance with DOE O 420.2C, and Revision 9 updates brought it into compliance with O 420.2D.

The SAD hazard assessment method uses a bounding event approach where the most severe case of each particular category of credible hazard event was analyzed to obtain worst-case results. Each hazard event analysis included a determination of the initiating occurrence, possible detection methods, the safety features that might have prevented or mitigated the event, the possible consequences, and the probability of that hazard event occurring. The complete process used to assess and mitigate hazards is described in Figure 16, Safety Analysis Methodology, below.

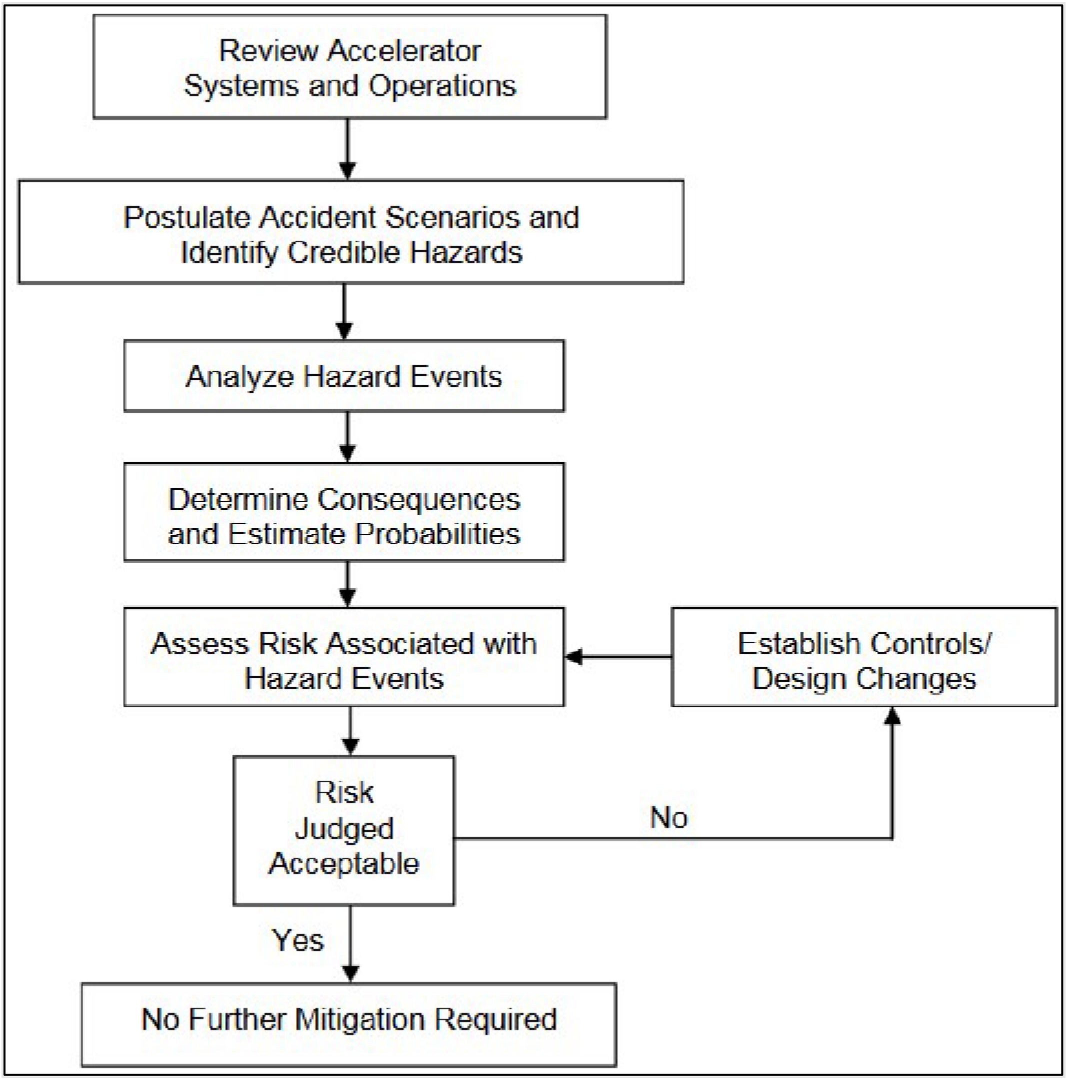

Figure 16. Safety Analysis Methodology

There is no standard methodology or industry guidance for a quantitative comparison of risk from fundamentally different hazards. Typically, a qualitative assignment of risk supported by professional experience is used to bridge such a gap. The lab has chosen to avoid a completely subjective approach, however well- informed it is by professional opinion. Jefferson Lab believes a reasonable approach is to compare the prompt somatic effects of each hazard. Professional experience and opinion are, in this case, applied to this comparison of health effects and the resulting binning of exposure categories for the hazards. This is backed up by independent peer review by professionals at other laboratories. Parity is required between these two hazards to proceed with a meaningful hazard analysis. Table 17, Classification of Radiation and ODH Health Effects for Workers, provides a means of comparing the health effects of exposure to ionizing radiation and an oxygen- deficient environment.

Table 17. Classification of Radiation and ODH Health Effects for Workers

Exposure		Health Effect*
Ionizing Radiation Dose	Oxygen Concentration***	
< 15 rem	> 16% O_2	Extremely Low
15 to 100 rem	12.5% to 16% O_2	Low
100 to 450 rad**	8% to 12.5% O_2	Medium
> 450 rad****	< 8%	High

* Table 15 considers health effects for exposure to a worker in the immediate vicinity of an exposure to prompt ionizing radiation or an oxygen deficient atmosphere. There are no credible events where off-site members of the general public are affected by prompt ionizing radiation exposure or an oxygen- deficient atmosphere due to accelerator operations. Therefore, the Health Effect "High" does not have an off-site component.

** The rem is not a measure of exposure; it is a measure of increased stochastic risk – a measure of increased risk of death from cancer after some latency period measured in years. Non-stochastic (prompt somatic) effects from radiation exposure as a function of absorbed radiation dose measured in rad.

*** Exposure to an oxygen-deficient atmosphere results in prompt (non-stochastic) health effects: heart arrhythmia, nausea, vomiting, unconsciousness, etc.

**** The dose of radiation expected to cause death to an exposed population within 30 days to 50 percent (LD 50/30) of those exposed. Typically, the LD 50/30 is understood to be in the range from about 400 to 450 rem (4 to 4.5 Sieverts) received over a very short period of time (acute dose). (Citation: Glossary of Environmental Restoration Terms, DOE Oak Ridge Operations Office Environmental Restoration/Waste Management Risk Assessment Program.)

The first value in column 1 of Table 17, the Ionizing Radiation Dose, is < 15 rem. This value coincides with the maximum integrated equivalent dose for a credible accident scenario (mis-steering or loss of control of the electron beam under conditions corresponding to the upper limit of the beam power possible in a specific area) in the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001)*.

The consequences of various events are grouped in Table 18 (below) and binned into consequence levels. The binning is based on the methodology used in SAD, Revision 7a, which was revised to better align with a recent consensus standard[23] that addresses occupational hazards and risks in process design.

Table 18. Consequence Rating Levels

Consequence Level	Description Words	Maximum Consequence
H	high	- serious impact on and off-site - may cause on-site deaths or loss of facility &/or operation - major impact on the environment
M	medium	- major impact on site and/or minor impact off-site - may cause severe injury, severe occupational illness to personnel - minor impact on the environment - capable of returning to operation
L	low	- minor impact onsite with no off-site impact - may cause minor injury, minor occupational illness - minor impact on the environment
EL	extremely low	- will not result in a significant injury or occupational illness - no significant impact on the environment

The probability rating levels are shown in Table 19 below. The five categories, their estimated range of occurrence probability (per year), and their description provide the basis for qualitative assessment of the likelihood of a hazard event.

Table 19. Probability Rating Levels

Category	Symbol	Description	Estimated Range of Probability of Accident Descriptive Work Occurrence per Year
High	H	event is likely to occur several times during the facility's operational lifetime	$> 10^{-1}$
Medium	M	event may occur during the facility's operational lifetime	10^{-2} to 10^{-1}
Low	L	probability of occurrence is unlikely or event is not expected to occur during the life of the facility or operation	10^{-4} to 10^{-2}
Extremely Low	EL	- probability of occurrence is extremely unlikely or event is not expected to occur during the life of the facility or operation - events are limiting faults considered in design (Design Basis Accidents)	10^{-6} to 10^{-4}
Incredible	I	- probability of occurrence is so small that a reasonable scenario is not conceivable - these events are not considered in the design or SAD accident analysis	$< 10^{-6}$

The risk matrix shown below in Figure 17 combines the consequence and probability levels to assist in the determination of acceptability of the residual risk. This approach is comparable to that used at other DOE facilities, particularly DOE accelerator facilities, and consistent with standardized approaches.

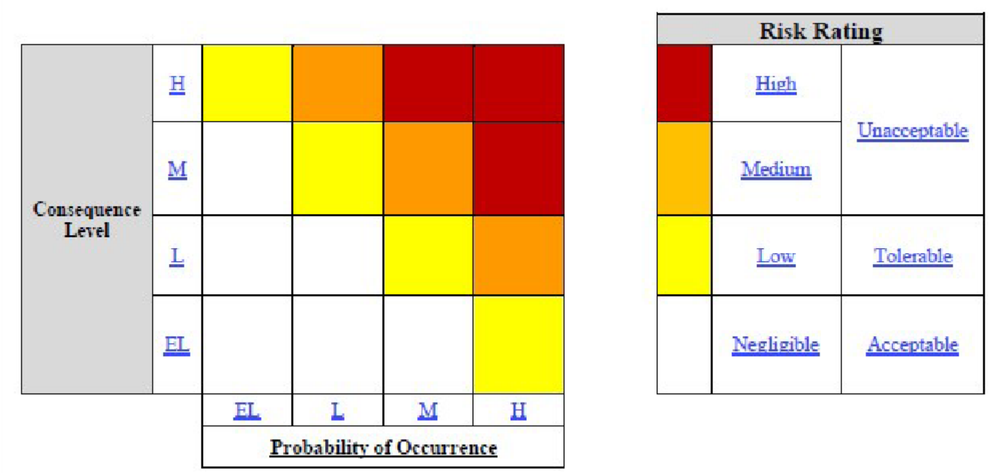

Figure 17. Risk Matrix

Credited Controls are required when a hazard event, absent those controls, can reasonably result in an Unacceptable Risk Rating (High or Medium). The approach is as follows:

- *Unacceptable* risks are mitigated to *Tolerable* by Credited Controls.
- *Tolerable* risks are usually mitigated by defense-in-depth but, although not required, may also benefit from the application of Credited Controls using an ALARA approach.
- *Acceptable* risks may be further mitigated where additional Defense-in-Depth Controls can reasonably be implemented using an ALARA approach.

Best industry practice uses an exposure minimization philosophy known as the ALARA Principle.

5.4. Hazard Assessment Results

Table 20, *Hazards, Postulated Initiating Events and Worst-case Accident Scenarios*, provides an analysis of the hazards, postulated initiating events, and worst-case accident scenarios for Jefferson Lab's accelerators. Table 20 also identifies and categorizes accelerator-specific hazards by assigning each an Event ID number and evaluates these hazards by assigning them an unmitigated risk rating.

In Table 20, the events that are considered to be bounding scenarios are emphasized in bold font. The table lists controls that address unmitigated risks that are rated *unacceptable* for the purposes of mitigating (reducing) risk (and the risk-ranking) for each of these risks to a rating of *tolerable* or *acceptable*. Credited controls that are identified in the table are included in the ASE. Appendix B contains a similar table for Technical Areas. The same rigor is applied to the hazard assessment for Technical Areas.

The Basis/Assumptions for many events in the *Hazards, Postulated Initiating Events and Worst-case Accident Scenarios* table state that there is either "no warning" or the hazard is "avoidable." These assumptions are important in determining the unmitigated probability of the hazard because they are strong factors in predicting human response to the event. No warning means that personnel affected by the event would have no indication prior to the event and could not take evasive action such as evacuation, whereas avoidable means that there is time to recognize and react to an off-normal condition.

When assessing a hazard event, it can be assumed that certain controls, inherent in the construction of an accelerator facility, are in place.

Controls assumed to be in place in the *unmitigated* case include:

- fixed shielding provided by the concrete structures of the beam enclosures and the beam-dump cooling buildings;
- earth cover over and around the beam enclosures including end stations;
- architectural features such as labyrinths, bends in the accelerator tunnels, non-line-of-sight penetrations into accelerator enclosures; and
- structural strength and containment features of beam-dump cooling buildings.

Certain limiting assumptions are made – these include:

- The LERF experimental laboratories are excluded from the analysis because the laser labs are above and separate from the accelerator enclosure, also known as the vault. The laser beam is transported to the experimental laboratories; the electron beam is confined to the accelerator enclosure.
- The CMTF Window Test Stand – located on the CMTF mezzanine – is excluded from analysis as the stand is above and separate from the CMTF accelerator enclosure. Up to 13 kW of RF power may be redirected from one of the pairs of klystrons typically supplying the CMTF enclosure when it is not is use via the use of shorting plates and a complex lock-out/tag-out and switching procedure executed by SRF and the Safety Systems Group.
- Explosive force, flying debris, and any related hazards that are associated with overpressure of the cryogenic helium vessels are considered to be industrial hazards. These hazards are not evaluated in this safety analysis but are mitigated by design requirements that require the incorporation of pressure relief valves. However, ODHs associated with the release of gas through these relief valves are considered to be accelerator-specific and are evaluated in this analysis.

Table 20 analyzes each of the accelerator-specific hazards identified in Section 5.2, *Accelerator Specific Hazards,* in the following numbered sequence:

1. Prompt ionizing radiation
   - unintentional beam loss such as beam loss during transport due to unintended beam interactions in the accelerator
   - intentional beam loss such as beam loss in diagnostic devices inserted into the beam, physics targets, beam dumps
   - skyshine
   - dark current from high-gradient SRF cavities and cryomodules
2. Activation of materials in certain systems and components including
   - Beamline and beam transport components
   - Experimental targets and equipment
   - Beam-dump cooling systems including beam dump cooling water
   - Beam-related air and groundwater activation
   - dark current from high-gradient SRF cavities and cryomodules

3. Radiogenic hazardous gases (e.g., oxides of nitrogen, hydrogen)
4. RF generated by electron-beam transition through a tuned cavity
5. Oxygen-deficient atmosphere from superconducting RF cavities and superconducting magnets inside an accelerator enclosure
6. Hazardous material for use in or as physics targets

The first section on prompt ionizing radiation includes the unintended entry of people to a location where beam is delivered and unintended delivery of beam to locations where people have access, and the failure of controls identified in the previous cases.

Table 20. Hazards, Postulated Initiating Events and Worst-Case Accident Scenarios

Abbreviations: **WBD:** Whole Body Dose **EL:** Extremely Low **L:** Low **M:** Medium **CC:** Credited Control **DD:** Defense-in-depth

								Unmitigated			Mitigated		
ID	Bounding	Hazard Type	Event Description	Potential Initiators	Basis/ Assumptions	Results	Location	Risk rating	Probability	Consequence	Risk rating	Probability	Consequence
1a	Y	Prompt Ionizing Radiation	**High-power beam (900kW) enters occupied area and strikes thick target (X >> X_0) with authorized personnel present downstream in beam enclosure.**	• MCC Operator error • Magnet supply failure • Control system failure	• Sudden event, little to no warning • Beam interacts with accelerator component, worst-case exposure to workers • Condition sustainable for 2 seconds, after that beam burns through vacuum envelope	• Multiple workers exposed to very high radiation fields, worst-case exposure > 450 rad	• CEBAF • LERF	UNACCEPTABLE • Worker deaths • No off-site consequence	M	H	TOLERABLE CC: • PSS Access Controls • PSS Beam Containment (CEBAF) • Minimum staffing levels of qualified operators	EL	H
1b	Y	Prompt Ionizing Radiation	**High-power beam (10kW) enters occupied area and strikes thick target (X >> X_0) with authorized personnel present downstream in beam enclosure.**	• UITF Operator error • Magnet supply failure • Control system failure	• Sudden event, little to no warning • Beam interacts with accelerator component, worst-case exposure to workers • Condition sustainable for 10 minutes, after that beam burns through vacuum envelope	• Multiple workers exposed to very high radiation fields, worst-case exposure > 450 rad	• UITF	UNACCEPTABLE • Worker deaths • No off-site consequence	M	H	TOLERABLE CC: • PSS Access Controls • Minimum staffing levels of qualified operators DD: • Administrative control on gun power supply current	EL	H

NOTES

- **This table applies to accelerators as stated in the table entries.**
- **The ID and Event Description for bounding events are shown in bold font and the letter Y is the "Bounding" column. For "non-bounding" events, the ID number of the bounding event is shown in the Bounding column.**
- **Color-shaded boxes in the table indicate the unmitigated risk rating as determined from the Risk Matrix in Figure 17 to be unacceptable, tolerable or acceptable.**
- **The tables of Credited Controls listed in Section 5.5.1, *Hazard Mitigation Controls Summary*, and the tables of Defense-in-Depth Controls listed Section 5.5.2, *ASE*, include cross references to the corresponding ID numbers for the events in this table.**

Table 20. Hazards, Postulated Initiating Events and Worst-Case Accident Scenarios

Abbreviations: **WBD:** Whole Body Dose **EL:** Extremely Low **L:** Low **M:** Medium **CC:** Credited Control **DD:** Defense-in-depth

								Unmitigated			Mitigated		
ID	**Bounding**	**Hazard Type**	**Event Description**	**Potential Initiators**	**Basis/ Assumptions**	**Results**	**Location**	**Risk rating**	**Probability**	**Consequence**	**Risk rating**	**Probability**	**Consequence**
1c	Y	Prompt Ionizing Radiation	**High-power beam (900kW) enters occupied area and interacts with thin target (X < 0.1X_0) with authorized personnel present in beam enclosure.**	• MCC Operator error • Magnet supply failure • Control system failure	• Sudden event, little to no warning • Beam delivered to experimental target, worst-case exposure to workers • Beam terminated in high-power dump	• Multiple workers exposed to very high radiation fields, worst-case exposure >450 rad	• CEBAF target • LERF target	UNACCEPTABLE • Worker deaths • No off-site consequence	M	H	TOLERABLE CC: • PSS Access Controls • PSS Beam Containment (CEBAF) • Minimum staffing levels of qualified operators	EL	H
1d	Y	Prompt Ionizing Radiation	**High-power beam (10kW) enters occupied area and interacts with thin target (X < 0.1X_0) with authorized personnel present in beam enclosure**	• UITF Operator error • Magnet supply failure • Control system failure	• Sudden event, little to no warning • Beam delivered to experimental target, worst-case exposure to workers	• Few workers exposed to very high radiation fields, worst-case exposure >450 rad	• UITF target	UNACCEPTABLE • Worker deaths • No off-site consequence	M	H	TOLERABLE CC: • PSS Access Controls • Minimum staffing levels of qualified operators DD: • Administrative control on gun power supply current • Interlocked CARMs in some locations • Signs and Posting • Training (general safety and radiation training), RWP	EL	H

NOTES

- **This table applies to accelerators as stated in the table entries.**
- **The ID and Event Description for bounding events are shown in bold font and the letter Y is the "Bounding" column. For "non-bounding" events, the ID number of the bounding event is shown in the Bounding column.**
- **Color-shaded boxes in the table indicate the unmitigated risk rating as determined from the Risk Matrix in Figure 17 to be unacceptable, tolerable or acceptable.**
- **The tables of Credited Controls listed in Section 5.5.1, *Hazard Mitigation Controls Summary,* and the tables of Defense-in-Depth Controls listed Section 5.5.2, *ASE,* include cross references to the corresponding ID numbers for the events in this table.**

Table 20. Hazards, Postulated Initiating Events and Worst-Case Accident Scenarios

Abbreviations: **WBD:** Whole Body Dose **EL:** Extremely Low **L:** Low **M:** Medium **CC:** Credited Control **DD:** Defense-in-depth

								Unmitigated			Mitigated		
ID	**Bounding**	**Hazard Type**	**Event Description**	**Potential Initiators**	**Basis/ Assumptions**	**Results**	**Location**	**Risk rating**	**Probability**	**Consequence**	**Risk rating**	**Probability**	**Consequence**
1e	Y	Prompt Ionizing Radiation	**Personnel gain unauthorized entry to beam enclosure during high-power (900kW) beam operations.**	• MCC Operator error • Unsecured access point (e.g. movable green shield wall not in place, unlocked door, modification to accelerator enclosure, etc.)	• Avoidable	• Few workers exposed to very high radiation fields, worst-case exposure >450 rad	• CEBAF • LERF Vault • Bldg. 200 Manway	UNACCEPTABLE • Worker deaths • No off-site consequence	M	H	TOLERABLE CC: • PSS Access Controls • PSS Beam Containment (CEBAF) • Locked or secured exclusion barrier • Minimum staffing levels of qualified operators DD: • Signs and Posting • Training (general safety and radiation training), RWP	EL	H
1f	Y	Prompt Ionizing Radiation	**Personnel access the North Linac segment while CEBAF Injector segment is operating. Injector beam (10kW) in occupied area and strikes thick target ($X >> X_0$) with authorized personnel present downstream in beam enclosure.**	• Magnet supply failure • Control system failure • MCC Operator error	• Sudden event, little to no warning • Beam interacts with accelerator component, worst-case exposure to workers • Condition sustainable for 10 minutes, after that beam burns through vacuum envelope	• Multiple workers exposed to very high radiation fields, worst-case exposure > 450 rad	• CEBAF Injector, North Linac	UNACCEPTABLE • Worker deaths • No off-site consequence	M	H	TOLERABLE CC: • PSS Access Controls • PSS Beam Containment • Locked or secured exclusion barrier • Minimum staffing levels of qualified operators DD: • Interlocked CARM • Signs and Posting • Training (general safety and radiation training), RWP	EL	H

NOTES

- **This table applies to accelerators as stated in the table entries.**
- **The ID and Event Description for bounding events are shown in bold font and the letter Y is the "Bounding" column. For "non-bounding" events, the ID number of the bounding event is shown in the Bounding column.**
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- **The tables of Credited Controls listed in Section 5.5.1, *Hazard Mitigation Controls Summary*, and the tables of Defense-in-Depth Controls listed Section 5.5.2, *ASE*, include cross references to the corresponding ID numbers for the events in this table.**

Table 20. Hazards, Postulated Initiating Events and Worst-Case Accident Scenarios

Abbreviations: **WBD:** Whole Body Dose **EL:** Extremely Low **L:** Low **M:** Medium **CC:** Credited Control **DD:** Defense-in-depth

								Unmitigated			Mitigated		
ID	Bounding	Hazard Type	Event Description	Potential Initiators	Basis/ Assumptions	Results	Location	Risk rating	Probability	Consequence	Risk rating	Probability	Consequence
1g	Y	Prompt Ionizing Radiation	**Personnel gain unauthorized entry to beam enclosure during high-power (10kW) beam operations.**	• Human error • UITF Operator error • Unsecured access point (e.g. movable shielding wall not in place, unlocked door, modification to accelerator enclosure, etc.)	• Avoidable	• Few workers exposed to very high radiation fields, worst-case exposure >450 rad	• UITF	UNACCEPTABLE • Worker deaths • No off-site consequence	M	H	TOLERABLE CC: • PSS Access Controls • Locked or secured exclusion barrier • Minimum staffing levels of qualified operators DD: • Signs and Posting • Training (general safety and radiation training), RWP • Administrative control on gun power supply current	EL	H
1h	Y	Prompt Ionizing Radiation	**Personnel gain unauthorized entry to beam enclosure during RF operations, Beam OFF.**	• Human error • Unauthorized Operator • Unsecured access point (e.g. movable green shield wall not in place, unlocked door, modification to accelerator enclosure, etc.)	• Avoidable • RF operating at max. gradient • Few workers exposed to high radiation fields	• Few workers exposed to >15 rem dose	• CEBAF • LERF • UITF	UNACCEPTABLE • Serious injury • Potential long-term health effects from ionizing radiation • No off-site consequence	M	M	ACCEPTABLE CC: • PSS Access Controls • PSS Beam Containment (CEBAF) • Locked or secured exclusion barrier • Minimum staffing levels of qualified operators DD: • Signs and Posting • Training (general safety and radiation training), RWP	EL	M

NOTES

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- **The tables of Credited Controls listed in Section 5.5.1, *Hazard Mitigation Controls Summary,* and the tables of Defense-in-Depth Controls listed Section 5.5.2, *ASE,* include cross references to the corresponding ID numbers for the events in this table.**

Table 20. Hazards, Postulated Initiating Events and Worst-Case Accident Scenarios

Abbreviations: **WBD:** Whole Body Dose **EL:** Extremely Low **L:** Low **M:** Medium **CC:** Credited Control **DD:** Defense-in-depth

								Unmitigated			Mitigated		
ID	**Bounding**	**Hazard Type**	**Event Description**	**Potential Initiators**	**Basis/ Assumptions**	**Results**	**Location**	**Risk rating**	**Probability**	**Consequence**	**Risk rating**	**Probability**	**Consequence**
1h.1	Y	**Prompt Ionizing Radiation**	**Personnel gain unauthorized entry to CMTF enclosure during RF operations.**	• Human error • Unauthorized Operator • Unsecured access point (e.g. unlocked door, modification to accelerator enclosure, etc.) • Loss of configuration control	• Avoidable • RF operating at max. gradient • Few workers exposed to high radiation fields	• Few workers exposed to >15 rem dose	• CMTF	**TOLERABLE** • Serious injury • Potential long-term health effects from ionizing radiation • No off-site consequence	L	M	**ACCEPTABLE** CC: • PSS Access Controls • Locked or secured exclusion barrier • Minimum staffing levels of qualified operators • Movable Shielding DD: • Interlocked CARMs • Signs and Posting • Training (general safety and radiation training), RWP • RCD shielding/barrier surveillance requirements	EL	M
1h.2	Y	**Prompt Ionizing Radiation**	**Personnel gain unauthorized entry to VTA shield hut during RF operations.**	• Human error • Unauthorized Operator • Unsecured access point (e.g. unlocked door, modification to accelerator enclosure, etc.) • Loss of configuration control	• Avoidable • RF operating at max. gradient • Few workers exposed to high radiation fields	• Few workers exposed to >200 rem dose	• VTA	**UNACCEPTABLE** • Worker deaths • Potential long-term health effects from ionizing radiation • No off-site consequence	L	H	**TOLERABLE** CC: • PSS Access Controls • Locked and secured exclusion barrier • Minimum staffing levels of qualified operators DD: • Interlocked CARMs • Signs and Posting • Training (general safety and radiation training), RWP • RCD shielding/barrier surveillance requirements	EL	H
1i	Y	**Prompt Ionizing Radiation**	**Personnel gain access to exclusion zone in Arc service building during high-power beam operations.**	• Loss of configuration control	• Sudden event, little to no warning • Service building penetration unshielded	• Few workers exposed to <15 rem dose at CEBAF Arc building penetrations	• CEBAF Arc service building zones	**TOLERABLE** • Potential long-term health effects from ionizing radiation • No off-site consequence	H	EL	**ACCEPTABLE** CC: • Locked or secured exclusion barrier DD: • Signs and Posting • Training (general safety and radiation training), RWP • RCD exclusion barrier surveillance requirements	M	EL

NOTES

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Table 20. Hazards, Postulated Initiating Events and Worst-Case Accident Scenarios

Abbreviations: **WBD:** Whole Body Dose **EL:** Extremely Low **L:** Low **M:** Medium **CC:** Credited Control **DD:** Defense-in-depth

								Unmitigated			Mitigated		
ID	**Bounding**	**Hazard Type**	**Event Description**	**Potential Initiators**	**Basis/ Assumptions**	**Results**	**Location**	**Risk rating**	**Probability**	**Consequence**	**Risk rating**	**Probability**	**Consequence**
1j	Y	Ionizing radiation	**Unauthorized entry in to the beam dump cooling building during high-power beam operations.**	• Human error	• Avoidable • Beam power 0.8 MW • Table 15 quantities of short-lived radionuclides: 80 rem/hr whole body • Worker stays in building for 4 hrs.	• Few workers exposed to 320 rem dose	• CEBAF dump cooling buildings (bldg. 91 or 95)	**UNACCEPTABLE** • Recoverable radiological injury to worker • No off-site consequence	M	M	**ACCEPTABLE** CC: • Locked exclusion barrier (gate to bldgs. 91 & 95) DD: • Signs and Posting • Training (general safety and radiation training), RWP • RCD exclusion barrier surveillance requirements	L	L
1k	Y	Prompt Ionizing Radiation	**Passive (earth) shielding removed and up to 3 kW beam loss in enclosure.**	• Erosion • Human error	• Avoidable • Only concrete shielding remains • Worst-case dose rate is at tunnel ceiling with beam loss in thick target and personnel adjacent to location • Exposures to personnel adjacent to location for 4 hours • Exposure to personnel above ground but within site fence	• Few workers exposed to <15 rem dose	• CEBAF Arcs and BSY • LERF Berm	**ACCEPTABLE** • Elevated worker exposure rates • No health consequences • No off-site consequence	L	EL	**ACCEPTABLE** DD: • RCD concurrence on Dig/Blind Penetration Permit • Shielding Policy for Ionizing Radiation – shielding design and surveillance requirements	EL	EL
1l	Y	Prompt Ionizing Radiation	**PSS functional failure or unauthorized by-pass.**	• PSS maintenance error • PSS Specification error • PSS Documentation error • PSS Installation error • Unauthorized change to PSS equipment • Mechanical failure	• Avoidable • Common cause failure of redundant chains of PSS • Redundant permits to radiation generating device enabled in access mode	• PSS logic failure • Protective function appears functional when it is not • Worker exposure	• CEBAF • LERF • UITF • CMTF • VTA	**UNACCEPTABLE** • Radiation exposure (see 1a, 1c, 1h, 1h.1, 1h.2) • No off-site consequence	M	H	**TOLERABLE** CC: • PSS Access Controls: Annual certification results • PSS Beam Containment (CEBAF) DD: • Configuration Management Procedure	EL	H

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- **The tables of Credited Controls listed in Section 5.5.1, *Hazard Mitigation Controls Summary,* and the tables of Defense-in-Depth Controls listed Section 5.5.2, *ASE,* include cross references to the corresponding ID numbers for the events in this table.**

Table 20. Hazards, Postulated Initiating Events and Worst-Case Accident Scenarios

<u>Abbreviations</u>: **WBD:** Whole Body Dose **EL:** Extremely Low **L:** Low **M:** Medium **CC:** Credited Control **DD:** Defense-in-depth

								Unmitigated			Mitigated		
ID	**Bounding**	**Hazard Type**	**Event Description**	**Potential Initiators**	**Basis/ Assumptions**	**Results**	**Location**	**Risk rating**	**Probability**	**Consequence**	**Risk rating**	**Probability**	**Consequence**
1m	Y	**Prompt Ionizing Radiation**	**Radiation transmitted into occupied area during high-power beam operations.**	• Loss of configuration control	• Sudden event, little to no warning • Penetration unshielded (RF, Controls, Alignment, etc.) • Open shielding penetration (Helium vent, etc.) • Insufficient shielding around UITF beam dump	• Few workers exposed to >15 rem dose CEBAF SW Alignment penetrations, BSY penetrations, Helium vent penetrations • Few workers exposed to <15 rem dose CEBAF Linac service buildings, LERF top floor, UITF exterior	• CEBAF • LERF • UITF • CMTF	**UNACCEPTABLE** • Potential long-term health effects from ionizing radiation • No off-site consequence	H	L	**TOLERABLE** CC: • Movable Shielding including penetrations • Exclusion barriers DD: • Interlocked CARMs in some locations • Signs and Posting • Training (general safety and radiation training), RWP • Shielding Policy for Ionizing Radiation – shielding design and surveillance requirements	M	L

<u>**NOTES**</u>

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- **The ID and Event Description for bounding events are shown in bold font and the letter Y is the "Bounding" column. For "non-bounding" events, the ID number of the bounding event is shown in the Bounding column.**
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Table 20. Hazards, Postulated Initiating Events and Worst-Case Accident Scenarios

Abbreviations: **WBD:** Whole Body Dose **EL:** Extremely Low **L:** Low **M:** Medium **CC:** Credited Control **DD:** Defense-in-depth

								Unmitigated			Mitigated		
ID	**Bounding**	**Hazard Type**	**Event Description**	**Potential Initiators**	**Basis/ Assumptions**	**Results**	**Location**	**Risk rating**	**Probability**	**Consequence**	**Risk rating**	**Probability**	**Consequence**
1n	Y	Prompt Ionizing Radiation	**Radiation transmitted into occupied area during high-power beam operations.**	• Loss of configuration control	• Sudden event, little to no warning • Service building penetration unshielded	• Few workers exposed to >15 rem dose CEBAF Extraction/BSY service buildings	• CEBAF Extraction/ BSY service building zones	**UNACCEPTABLE** • Potential long-term health effects from ionizing radiation • No off-site consequence	H	L	**TOLERABLE** CC: • Movable Shielding: penetrations DD: • Signs and Posting • Training (general safety and radiation training), RWP • Shielding Policy for Ionizing Radiation – shielding design and surveillance requirements	M	L
1o	Y	Prompt Ionizing Radiation	**Radiation transmitted into occupied area during high-power beam operations that strikes thick target ($X >> X_0$) in enclosure.**	• Magnet supply failure • Control system failure • MCC Operator error • Loss of shielding (SL)	• Sudden event, little to no warning • Worst case 1kW loss for 4 hrs.	• Few workers exposed to high radiation fields, worst-case exposure >15 rem	• CEBAF North/East (E-1) and South/ West (W-2) Service Building Helium vent penetration	**UNACCEPTABLE** • Potential long-term health effects from ionizing radiation • No off-site consequence	H	L	**TOLERABLE** CC: • Exclusion barriers: Fences, barriers, and locked gates • Permanent shielding • Movable Shielding: penetrations DD: • Interlocked CARM (NL) • Signs and Posting • Training (general safety and radiation training), RWP • Shielding Policy for Ionizing Radiation – shielding design and surveillance requirements	M	L
1p	Y	Prompt Ionizing Radiation	**Radiation transmitted into occupied area during high-power beam operations.**	• Loss of configuration control	• Sudden event, little to no warning • UITF movable shielding removed or modified	• Few workers exposed to high radiation fields, worst-case exposure of 160 rem	• UITF penetrations • UITF cave 2 roof	**UNACCEPTABLE** • Potential long-term health effects from ionizing radiation • No off-site consequence	M	M	**TOLERABLE** CC: • Movable Shielding: penetrations • Exclusion barriers: Fences, barriers, and locked gates DD: • Signs and Posting • Training (general safety and radiation training), RWP • Shielding Policy for Ionizing Radiation – shielding design and surveillance requirements	L	M

NOTES

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Table 20. Hazards, Postulated Initiating Events and Worst-Case Accident Scenarios

Abbreviations: **WBD:** Whole Body Dose **EL:** Extremely Low **L:** Low **M:** Medium **CC:** Credited Control **DD:** Defense-in-depth

								Unmitigated			Mitigated		
ID	**Bounding**	**Hazard Type**	**Event Description**	**Potential Initiators**	**Basis/ Assumptions**	**Results**	**Location**	**Risk rating**	**Probability**	**Consequence**	**Risk rating**	**Probability**	**Consequence**
1p.1	**Y**	**Prompt Ionizing Radiation**	**Radiation transmitted into occupied area during high-power RF operation.**	• Loss of configuration control	• Sudden event, little to no warning • Helium vent stack unshielded • East wall penetration shielding removed	• Few workers exposed to high radiation fields, worst case exposure >15 rem	• CMTF roof and east wall penetrations	**UNACCEPTABLE** • Serious injury • Potential long-term health effects from ionizing radiation • No off-site consequence	M	M	**TOLERABLE** CC: • Movable Shielding: penetrations DD: • Signs and Posting • Training (general safety and radiation training), RWP • Shielding Policy for Ionizing Radiation – shielding design and surveillance requirements	L	M
1p.2	**Y**	**Prompt Ionizing Radiation**	**Radiation transmitted into occupied area during high-power RF operation.**	• Loss of configuration control	• Sudden event, little to no warning • Movable dewar shielding removed or modified	• Few workers exposed to high radiation fields, worst case exposure >100 rem	• VTA	**UNACCEPTABLE** • Serious injury • Potential long-term health effects from ionizing radiation • No off-site consequence	M	M	**TOLERABLE** CC: • Movable Shielding DD: • Interlocked CARMs • Signs and Posting • Training (general safety and radiation training), RWP • Shielding Policy for Ionizing Radiation – shielding design and surveillance requirements	L	M
1q	**Y**	**Prompt Ionizing Radiation**	**Personnel outside permanent shielding are exposed to ionizing radiation from normal and off-normal accelerator operation.**	• Accelerator operations including off-normal events	• Accelerator operations including off-normal events	• Multiple workers outside the accelerator enclosure exposed to very high radiation fields, worst-case exposure > 450 rad	• Anywhere outside the accelerator enclosure for: CEBAF, LERF, UITF, CMTF, VTA	**UNACCEPTABLE** • Worker deaths • No off-site consequence	H	H	**TOLERABLE** CC: • Permanent shielding as part of the accelerator enclosure DD: • Signs and Posting • Training (general safety and radiation training), RWP • Shielding Policy for Ionizing Radiation – shielding design and surveillance requirements	H	EL
2a	**Y**	**Radioactive Materials**	**Cross contamination between primary and intermediate dump cooling loops.**	• Beam loss in cooling water, produces radioactive materials in system • Heat exchanger develops leak and radioactive materials circulate in intermediate cooling loop	• Avoidable • Leak occurs during beam power 0.8 MW • Table 15 quantities of short-lived radionuclides • Leak not detected for several hours • Radioactive materials circulate in intermediate cooling loop	• Radioactive contamination in intermediate cooling loop • Radiation exposure to personnel in vicinity of bldg. 92	• CEBAF Halls A and C beam dump cooling water systems (bldg. 91 or 95) • Vicinity of bldg. 92	**ACCEPTABLE** • Worker exposure within limits	L	L	**ACCEPTABLE** DD: • Facility design (Intermediate dump loop pressure higher than primary loop so that water only leaks from ILCW to primary beam dump cooling water loop)	EL	EL

2b	**Y**	**Radioactive Materials**	**Activation of materials Beam dump cooling water. Detonation of hydrogen from beam dump cooling water.**	• Beam loss in cooling water, radiolysis produces hydrogen in system	• Hydrogen leaks from system and collects in service building • Hydrogen ignites and causes over-pressure in service building • No workers present – building locked during beam operation	• Release of ion exchange radioactive material • Spill contained within dump cooling building • Nearby personnel sustain recoverable injury • Building damaged but in-tact	• CEBAF Halls A and C beam dump cooling water systems (bldg. 91 or 95)	**UNACCEPTABLE** • Recoverable injury to worker • No off-site consequence	M	M	**ACCEPTABLE** CC: • Bldg. 91/95 design and structural integrity DD: • Hydrogen recombiner in affected system • Hydrogen detector system in ceiling of affected building with alarms at MCC at a fraction of LEL for H_2 in air	EL	M

<u>NOTES</u>

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Table 20. Hazards, Postulated Initiating Events and Worst-Case Accident Scenarios

Abbreviations: **WBD:** Whole Body Dose **EL:** Extremely Low **L:** Low **M:** Medium **CC:** Credited Control **DD:** Defense-in-depth

								Unmitigated			Mitigated		
ID	**Bounding**	**Hazard Type**	**Event Description**	**Potential Initiators**	**Basis/ Assumptions**	**Results**	**Location**	**Risk rating**	**Probability**	**Consequence**	**Risk rating**	**Probability**	**Consequence**
2c	Y	Radioactive Materials	**Dispersal of activated dump cooling water or ion exchange resin.**	• Kinetic impact to building sufficient to destroy building (aircraft impact, earthquake, extreme tornado damage, etc.)	• Sudden event, little to no warning • Event occurs during extended 0.9 MW beam power run • Building 91/95 internal piping disrupted and building destroyed	• Building destroyed • Activated water is vaporized and ion exchange material is 100% vaporized into respirable form	• CEBAF Halls A and C beam dump cooling water systems (bldg. 91 or 95)	**ACCEPTABLE** • Worst-case exposure offsite 60 mrem (annual limit 100 mrem)	EL	EL	**ACCEPTABLE** DD: • Bldg. 91/95 design and structural integrity • Leak check alarms • Hydrogen gas alarms	EL	EL
2d	2c	Ionizing Radiation (Radioactive material)	**Over temperature/ over pressure of dump primary cooling water. Pressure relief valve opens in beam dump cooling building.**	• Cooling system failure • Primary or secondary loop pump mechanical failure or loss of power • Evaporative cooling loop failure • Control system leak • Valve failure	• Avoidable • Normal full power operation into Hall A or C • Beam power 0.8 MW	• Spill of all activated dump cooling water contained in primary cooling loop.	• CEBAF Halls A and C beam dump cooling water systems (bldg. 91 or 95)	**TOLERABLE** • Contained within building • No unplanned worker exposure • No off-site consequence	M	L	**ACCEPTABLE** DD: • Bldg. 91/95 design and structural integrity • Leak check alarms	M	EL
3a	Y	Hazardous Material	**Radiogenic hazardous gases (e.g. oxides of nitrogen, hydrogen).**	• Beam loss in air generates noxious gases in beam enclosure	• Avoidable • Workers exit area where exposure occurs • Worst-case exposure to a worker	• Workers exposed slightly in excess of 8 hr Time Weighted Average (TWA) for applicable air contaminant	• CEBAF • LERF • UITF	**ACCEPTABLE** • Worker suffers temporary eye and respiratory irritation	L	L	**ACCEPTABLE** DD: • Worker Health and Safety Program Plan • Industrial Hygiene Sampling	L	EL
3b	Y	Hazardous Material	**Radiogenic hazardous gases (e.g. oxides of nitrogen, hydrogen). Detonation of hydrogen from beam dump cooling water**	• Beam loss in cooling water, radiolysis produces hydrogen in system	• Hydrogen leaks from system and collects in service building • Hydrogen ignites and causes over-pressure in service building • No workers present – building locked during beam operation	• Nearby personnel sustain recoverable injury • Building structure not damaged • Release of materials contained in building sump	• CEBAF Halls A and C beam dump cooling water systems (bldg. 91 or 95)	**ACCEPTABLE** • Building damaged but intact	EL	M	**ACCEPTABLE** DD: • Hydrogen recombiner in affected system • Hydrogen detector system in ceiling of affected building with alarms at MCC at a fraction of LEL for H_2 in air	EL	EL

NOTES

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Table 20. Hazards, Postulated Initiating Events and Worst-Case Accident Scenarios

__Abbreviations__: **WBD:** Whole Body Dose **EL:** Extremely Low **L:** Low **M:** Medium **CC:** Credited Control **DD:** Defense-in-depth

								Unmitigated			Mitigated		
ID	**Bounding**	**Hazard Type**	**Event Description**	**Potential Initiators**	**Basis/ Assumptions**	**Results**	**Location**	**Risk rating**	**Probability**	**Consequence**	**Risk rating**	**Probability**	**Consequence**
4a	**Y**	**Non-ionizing Radiation**	**RF waveguide open and electron beam is on. Beam is allowed to transition through a tuned cavity generating RF at an open waveguide.**	• RF maintenance work started before beam is shut down, or Beam is started during RF maintenance work.	• Avoidable • Worst-case exposure to a worker • Cryomodule (CM) undergoing maintenance	• Immediate muscle and tissue injury in the extremities • Exposure sufficient to induce cataracts in the lens of the eye	• CEBAF Service Building • LERF Klystron Gallery • UITF Mezzanine	**TOLERABLE** • Recoverable occupational injury	L	M	**ACCEPTABLE** DD: • RF waveguide pressure interlocks connected to PSS beam inhibit • WCDs requiring an up-stream dump, Faraday cup, vacuum valve, or gun to be locked out when waveguide is opened	EL	M
4b	**4a**	**Non-ionizing Radiation**	**RF waveguide open while dark current transitions from adjacent cavities or adjacent CM through a tuned cavity generating RF at an open waveguide.**	• RF maintenance work	• Avoidable • Worst-case exposure to a worker • CM undergoing maintenance	• Workers exposed to RF radiation slightly in excess of 8 hr. Time-weighted average (TWA)	• CEBAF Service Building • LERF Klystron Gallery • UITF Mezzanine • CMTF	**ACCEPTABLE** • Worker suffers eye injury and 2nd degree burns to extremities	EL	M	**ACCEPTABLE** DD: • WCD that requires adjacent CM zone(s) to be depowered	EL	M
4c		**Non-ionizing Radiation**	**RF cable or waveguide open while klystron is on.**	• RF maintenance work • RF component testing	• Avoidable • RF power not shut down prior to starting work • RF power applied while waveguide is open	• Workers exposed to RF radiation of • 0.5 W/cm2 at 30 cm (head, upper torso) and 10 W/cm2 at 5 to 6 cm (fingers, hands) per 1000 W RF power	• CEBAF • LERF • UITF • CMTF • VTA	**TOLERABLE** • Worker suffers eye injury and second degree burns to extremities	M	M	**ACCEPTABLE** DD: • RF leakage test • LOTO Waveguide • Bolt-up/tagging procedure	EL	M
5a	**Y**	**ODH**	**CM outlet valves closed with cryogen present in CM.**	• Outlet valves closed • Pressure excursion • Temperature excursion • Control system failure • Operator error	• Avoidable • Release rate at capacity of respective helium refrigerator	• Helium gas return system bypassed • Helium vented through primary CM relief valve, preventing failure due to pressurization	• CEBAF Linacs • LERF • UITF • CMTF	**TOLERABLE** • Workers exit tunnels, and climb stairs to ground level within 5 minutes	M	L	**ACCEPTABLE** DD: • Pressure relief systems in place and functional • Passive ceiling vents • Primary CM relief vents to above ground • ODH training	M	EL

__NOTES__

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Table 20. Hazards, Postulated Initiating Events and Worst-Case Accident Scenarios

Abbreviations: **WBD:** Whole Body Dose **EL:** Extremely Low **L:** Low **M:** Medium **CC:** Credited Control **DD:** Defense-in-depth

								Unmitigated			Mitigated		
ID	**Bounding**	**Hazard Type**	**Event Description**	**Potential Initiators**	**Basis/ Assumptions**	**Results**	**Location**	**Risk rating**	**Probability**	**Consequence**	**Risk rating**	**Probability**	**Consequence**
5b	**5a**	**ODH**	**CM outlet valves closed with cryogen present in CM.**	• Outlet valves closed • Pressure excursion • Temperature excursion • Control system failure • Operator error	• Avoidable • Pressure relief systems in place and functional • Release rate at capacity of respective helium refrigerator	• Helium gas return system bypassed • Helium vented through primary CM relief valve, preventing failure due to pressurization	• UITF • CMTF	**ACCEPTABLE** • Workers exit UITF or CMTF vault within 5 minutes	L	L	**ACCEPTABLE** DD: • Pressure relief systems in place and functional • Passive ceiling vents • Primary CM relief vents to above ground • ODH training	L	EL
5c	**Y**	**ODH**	**Outlet valves closed during routine operation Primary relief valve fails to open.**	• Outlet valves closed • Pressure excursion • Temperature excursion • Control system failure • Operator error	• Avoidable • Visible plume • Secondary cryomodule or superconducting magnet relief valve in place and functional • Release rate at capacity of respective helium refrigerator	• Helium gas return system bypassed • Helium vented to enclosures via secondary relief valve, preventing failure due to pressurization	• CEBAF Linacs • LERF • UITF • CMTF	**ACCEPTABLE** • Workers exit enclosure and climb stairs to ground level within 5 minutes • Workers exit UITF vault or CMTF within 5 minutes	L	L	**ACCEPTABLE** DD: • CEBAF lintels, LERF door, UITF enclosure configuration slows helium gas entry into stairwells • Active CMTF enclosure venting into Test Lab High Bay under ODH conditions • ODH training	L	EL
5d	**Y**	**ODH**	**Slow leak of helium or warm nitrogen service line inside enclosure.**	• Secondary CM relief valve failure • Secondary superconducting magnet valve failure • Piping flange leak • Valve failure • Human error	• Sudden event, little to no warning • Workers inside beam enclosure or entering beam enclosure • Gas mixes throughout tunnel area • No visible plume • Hazard to personnel entering accelerator enclosure	• Helium and/or nitrogen vented to tunnels • O_2 level in general area < 12.5% • Workers experience hypoxia	• CEBAF Linacs • LERF • UITF • CMTF	**UNACCEPTABLE** • Worker hypoxia/ disorientation • No off-site consequence	M	M	**ACCEPTABLE** CC: • Nitrogen lines outfitted with flow restricting orifice (CEBAF, LERF) • ODH System Alarm (sensors positioned for N_2 and He) • Passive ceiling vents • CEBAF lintels and LERF door configuration slows helium gas entry into stairwells DD: • ODH training • Active CMTF enclosure venting into Test Lab High Bay under ODH conditions • Nitrogen supply line solenoid valves (CEBAF, LERF, UITF)	L	L

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Table 20. Hazards, Postulated Initiating Events and Worst-Case Accident Scenarios

Abbreviations: **WBD:** Whole Body Dose **EL:** Extremely Low **L:** Low **M:** Medium **CC:** Credited Control **DD:** Defense-in-depth

								Unmitigated			Mitigated		
ID	**Bounding**	**Hazard Type**	**Event Description**	**Potential Initiators**	**Basis/ Assumptions**	**Results**	**Location**	**Risk rating**	**Probability**	**Consequence**	**Risk rating**	**Probability**	**Consequence**
5e	**Y**	**ODH**	**Valve/piping failure during Cryo procedure.**	• Human error during U-Tube operation	• Avoidable • Visible plume • Work conducted under ODH 4 work restrictions	• Available helium inventory spills in tunnel • O_2 level in immediate area of leak < 16%	• CEBAF Linacs • LERF • UITF • CMTF	**ACCEPTABLE** • Workers exit tunnels and climb stairs to ground level within 5 minutes	L	L	**ACCEPTABLE** CC: • ODH System Alarms • CEBAF lintels and LERF door configuration slow helium gas entry in to stairwells • Passive ceiling vents DD: • Cryogenic Work Control Process • Active CMTF enclosure venting into Test Lab High Bay under ODH conditions • ODH training	L	EL
5f	**Y**	**ODH**	**Personnel gain unauthorized entry to enclosure during power outage.**	• Weather related or other external electrical power distribution system failure	• Sudden event, little to no warning • ODH conditions inside enclosure • Loss of ODH monitoring	• Potential worker exposure to ODH conditions	• CEBAF • LERF • UITF • CMTF	**TOLERABLE**	L	M	**ACCEPTABLE** DD: • Emergency power supply for safety systems • Nitrogen supply line solenoid valves (CEBAF, LERF, UITF) • CMTF shield door fails open in the event of power loss	EL	L
5g	**Y**	**ODH**	**Uncontrolled nitrogen or helium gas leak.**	• System overpressure relief valve opens • Mechanical component failure • Operator error • Control system failure • Kinetic impact to transfer lines from powered industrial equipment	• Sudden event, little to no warning • Nitrogen source from CHL • Helium source from CHL, ESR, or CMTF • May not have visible plume	• Available nitrogen or helium inventory released in to accelerator enclosure • O_2 level drops below 12.5%	• CEBAF • LERF • UITF • CMTF	**UNACCEPTABLE** • Worker hypoxia/ disorientation • No off-site consequence	M	M	**TOLERABLE** CC: • ODH System Controls • Door configuration and CEBAF lintels slow helium gas entry in to stairwells • Passive ceiling vents DD: • Nitrogen supply line solenoid valves (CEBAF, LERF, UITF) • ODH training	EL	M

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Table 20. Hazards, Postulated Initiating Events and Worst-Case Accident Scenarios

Abbreviations: **WBD:** Whole Body Dose **EL:** Extremely Low **L:** Low **M:** Medium **CC:** Credited Control **DD:** Defense-in-depth

ID	Bounding	Hazard Type	Event Description	Potential Initiators	Basis/ Assumptions	Results	Location	Unmitigated Risk rating	Unmitigated Probability	Unmitigated Consequence	Mitigated Risk rating	Mitigated Probability	Mitigated Consequence
5h		ODH	**Gaseous nitrogen supply fails.**	• Component failure	• ODH conditions inside enclosure: combination of highest leakage volume, and highest Pi	• Worker exposure to <19.5% O2 • ODH conditions	• Inside CMTF cave	UNACCEPTABLE Worker health effects up to and including death	M	M	**ACCEPTABLE** CC: • ODH System Controls • Passive ceiling vent DD: • ODH training • Ceiling vent fan activates upon ODH alarm • PPE	EL	L
5i		ODH	**Gaseous helium supply fails.**	• Component failure	• ODH conditions inside cave: combination of largest helium spill volume and highest probability	• Worker exposure to <19.5% O2 • ODH conditions	• Inside CMTF cave	UNACCEPTABLE Worker health effects up to and including death	EL	H	TOLERABLE CC: • ODH System Controls • Passive ceiling vent DD: • ODH training • Ceiling vent fan activates upon ODH alarm • PPE	EL	L

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Abbreviations: **WBD:** Whole Body Dose **EL:** Extremely Low **L:** Low **M:** Medium **CC:** Credited Control **DD:** Defense-in-depth

								Unmitigated			Mitigated		
ID	**Bounding**	**Hazard Type**	**Event Description**	**Potential Initiators**	**Basis/ Assumptions**	**Results**	**Location**	**Risk rating**	**Probability**	**Consequence**	**Risk rating**	**Probability**	**Consequence**
5j		ODH	**Gaseous nitrogen supply fails.**	• Component failure	• ODH conditions inside cave: combination of largest spill volume and highest probability	• Worker exposure to <19.5% O2 • ODH conditions	• Inside CMTF control room	**ACCEPTABLE** • Worker health effects up to and including temporary impairment	EL	EL	**ACCEPTABLE** CC: • ODH System Controls DD: • Penetrations to control room sealed • ODH training • PPE	EL	EL
5j.1		ODH	**Gaseous Helium supply fails.**	• Component failure	• ODH conditions inside cave: combination of largest spill volume and highest probability	• Worker exposure to <19.5% O2 • ODH conditions	• Inside CMTF control room	**ACCEPTABLE** • Worker health effects up to and including temporary impairment	EL	EL	**ACCEPTABLE** CC: • ODH System Controls DD: • Penetrations to control room sealed • ODH training • PPE	EL	EL
5k			**Oxygen deficiency.**	• Confined space entry into floor level dewar for repairs	• Worker crosses plain of confined space	• Worker exposure to <19.5% O2	• VTA	**TOLERABLE** • Worker hypoxia/ disorientation • No off-site consequence	EL	M	**ACCEPTABLE** DD: • Confined Space Entry Procedure for dewar access	L	L
6a	Y	Multiple	**Hazardous material or stored energy for physics experiment presents exposure hazard or potential injury to personnel.**	• Failure of material confinement or controls • Human error – mishandling • Damage due to beam operations	• Avoidable • Physics experiment involves unspecified hazards • Other controls effective and operational • Physics target contains sufficient material to present exposure to personnel in excess of TLV/BEI or Ionizing Radiation Shielding Policy	• Exposure to personnel in excess of TLV/BEI or Ionizing Radiation Shielding Policy • Severe occupational illness or injury	• CEBAF • LERF • UITF	**UNACCEPTABLE** • Severe injury, severe occupational illness • No off-site consequence	M	M	**TOLERABLE** CC: • ERR Process assesses risk from hazards, specifies controls DD: • Pressure relief systems in place and functional • Signs and Posting • Pressure Systems Training	L	M

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ID	Bounding	Hazard Type	Event Description	Potential Initiators	Basis/ Assumptions	Results	Location	Unmitigated Risk rating	Unmitigated Probability	Unmitigated Consequence	Mitigated Risk rating	Mitigated Probability	Mitigated Consequence
6b	6a	Radioactive Material	**Tritium target approximately 1.1 kiloCuries is damaged, causes dose to individuals on-site and off-site.**	• Failure of target material due to mishandling, kinetic damage • Damage due to beam operations	• Avoidable • Physics target contents dispersed • Release of material to air on-site causes dose to personnel • Airborne material released off-site caused dose to general public	• Target handler receives dose < 15 rem occupational exposure • Personnel present in hall truck ramp receive dose < 15 rem occupational exposure • Exposure to personnel within CEBAF occupational exposure limits • Offsite exposure within limits	• CEBAF • Offsite at fence boundary	**TOLERABLE** • Some on-site radiological impact • Worker exposure within limits • Off-site exposure within limits	EL	H	**ACCEPTABLE** DD: • ERR Process assesses risk from hazardous material used as physics target, specifies controls • Facility design: optimized ventilation and exhaust • Hazard specific training • Administrative access controls	EL	L
6c	6a	Hazardous Material	**Explosion/Fire of hydrogen or another potentially flammable target or detector gas inside experimental hall or accelerator enclosure.**	• Kinetic damage to target, gas storage containers, detectors • Leak of potentially flammable target or detector gas • Source of ignition	• Avoidable • Explosion/fire damages equipment and produces radioactive contamination	• Damage to equipment • Dispersal of radioactive contaminants within hall/enclosure below limits • Limited dispersal of radioactive contaminants on-site, contamination below limits	• CEBAF • LERF • UITF	**ACCEPTABLE** • Some on-site radiological impact • Worker exposure within limits • Off-site exposure within limits	L	L	**ACCEPTABLE** DD: • ERR Process assesses risk from hazardous material used in experiments • Fire Protection Program • Pressure Systems Program	L	EL

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5.5. Hazard Mitigation Controls Summary and ASE

Table 20, above, identifies the accelerator-specific hazard events that require Credited Controls and Defense- in-Depth Controls to mitigate risk. Those hazard events, locations, and controls specific to each are identified in Table 21 (Controls Summary) and Tables 22-25 (Basis for ASE of CEBAF/LERF, UITF, CMTF, and VTA) in the following two sections.

5.5.1 Hazard Mitigation Controls Summary

Table 21, Controls Summary, summarizes the hazard events where controls are applied and the locations are specific to each. Those hazard events that are considered "Unacceptable" without mitigation require Credited Controls. *Tolerable* risks are usually mitigated by defense-in-depth as indicated in the table below, although not required, may also benefit from the application of Credited Controls using an ALARA approach. "Acceptable" risks may be further mitigated where additional Defense-in-Depth Controls can reasonably be implemented using an ALARA approach.

At times, a Credited Control for a hazard that is *Unacceptable* when unmitigated, is applied as a Defense-in-Depth Control for another hazard that is already *Tolerable* or *Acceptable* when unmitigated. It is assumed that any management and surveillance or acceptable compensatory measures defined for the Credited Control are valid for the Defense-in-Depth Control.

The configuration of engineered Credited Controls is managed according to the requirements for Level 1 Configuration Management systems in the COEM as identified in Section 4.2.3.1, *Engineering Governing Processes and Procedures*. The configuration of each engineered Defense-in-Depth Control is managed according to the requirements for Level 2 Configuration Management systems in the COEM. Administrative Credited Controls are given an equivalent level of configuration management. For example, the ERR process is found in *ES&H Manual Chapter 3120, The CEBAF Experiment Review Process*. The Technical Point of Contact is responsible for the integrity and applicability of the chapter content as specified in *ES&H Manual Chapter 1300, Content Review Process*.

Table 21. Controls Summary

Hazard Event ID	Location	Credited Control(s)	Defense-in-Depth Control(s)
1a	CEBAF, LERF	• PSS Access Controls • PSS Beam Containment (CEBAF) • Minimum staffing levels of qualified operators	• None
1b	UITF	• PSS Access Controls • Minimum staffing levels of qualified operators	• Administrative control on gun power supply current
1c	CEBAF target, LERF target	• PSS Access Controls • PSS Beam Containment (CEBAF) • Minimum staffing levels of qualified operators	• None
1d	UITF target	• PSS Access Controls • Minimum staffing levels of qualified operators	• Administrative control on gun power supply current • Interlocked CARMs in some locations • Signs and Posting • Training (general safety and radiation training), RWP
1e	CEBAF, LERF Vault, Bldg. 200 Manway	• PSS Access Controls • PSS Beam Containment (CEBAF) • Locked or secured exclusion barrier • Minimum staffing levels of qualified operators	• Signs and Posting • Training (general safety and radiation training), RWP
1f	CEBAF Injector, North Linac	• PSS Access Controls • PSS Beam Containment • Locked or secured exclusion barrier • Minimum staffing levels of qualified operators	• Interlocked CARM • Signs and Posting • Training (general safety and radiation training), RWP
1g	UITF	• PSS Access Controls • Locked or secured exclusion barrier • Minimum staffing levels of qualified operators	• Signs and Posting • Training (general safety and radiation training), RWP • Administrative control on gun power supply current
1h	CEBAF, LERF, UITF	• PSS Access Controls • PSS Beam Containment (CEBAF) • Locked or secured exclusion barrier • Minimum staffing levels of qualified operators	• Signs and Posting • Training (general safety and radiation training), RWP
1h.1	CMTF	• PSS Access Controls • Locked or secured exclusion barrier • Minimum staffing levels of qualified operators • Movable Shielding	• Interlocked CARMs • Signs and Posting • Training (general safety and radiation training), RWP • RCD shielding/barrier surveillance requirements

Hazard Event ID	Location	Credited Control(s)	Defense-in-Depth Control(s)
1h.2	VTA	• PSS Access Controls • Locked or secured exclusion barrier • Minimum staffing levels of qualified operators	• Interlocked CARMs • Signs and Posting • Training (general safety and radiation training), RWP • RCD shielding/barrier surveillance requirements
1i	CEBAF Arc service building zones	• Locked or secured exclusion barrier.	• Signs and Posting • Training (general safety and radiation training), RWP • RCD shielding/barrier surveillance requirements
1j	CEBAF dump cooling buildings (bldg. 91 or 95)	• Locked exclusion barrier (gates to bldgs. 91 & 95)	• Signs and Posting • Training (general safety and radiation training), RWP • RCD shielding/barrier surveillance requirements
1k	CEBAF Arcs and BSY, LERF Berm	• None	• RCD concurrence on Dig/Blind Penetration Permit • Shielding Policy for Ionizing Radiation – shielding design and surveillance requirements
1l	CEBAF, LERF, UITF, CMTF, VTA	• PSS Access Controls: Annual certification results • PSS Beam Containment (CEBAF)	• Configuration Management Procedure
1m	CEBAF, LERF, UITF, CMTF	• Movable Shielding including penetrations • Exclusion barriers	• Interlocked CARMs in some locations • Signs and Posting • Training (general safety and radiation training), RWP • Shielding Policy for Ionizing Radiation – shielding design and surveillance requirements
1n	CEBAF Extraction/BSY service building zones	• Movable Shielding: penetrations	• Signs and Posting • Training (general safety and radiation training), RWP • Shielding Policy for Ionizing Radiation – shielding design and surveillance requirements
1o	CEBAF North/East (E-1) and South/West (W-2) Service Building Helium vent penetration	• Exclusion barriers: Fences barriers and locked gates • Permanent shielding • Movable Shielding: penetrations	• Interlocked CARM (NL) • Signs and Posting • Training (general safety and radiation training), RWP • Shielding Policy for Ionizing Radiation – shielding design and surveillance requirements

Hazard Event ID	Location	Credited Control(s)	Defense-in-Depth Control(s)
1p	UITF penetrations, UITF cave 2 roof	• Movable Shielding: penetrations • Exclusion barriers: Fences barriers and locked gates	• Signs and Posting • Training (general safety and radiation training), RWP • Shielding Policy for Ionizing Radiation – shielding design and surveillance requirements
1p.1	CMTF roof and east wall penetrations	• Movable Shielding: penetrations	• Signs and Posting • Training (general safety and radiation training), RWP • Shielding Policy for Ionizing Radiation – shielding design and surveillance requirements
1p.2	VTA	• Movable Shielding	• Interlocked CARMs • Signs and Posting • Training (general safety and radiation training), RWP • Shielding Policy for Ionizing Radiation – shielding design and surveillance requirements
1q	Anywhere outside the accelerator enclosure for: CEBAF, LERF, UITF, CMTF, VTA	• Permanent shielding as part of the accelerator enclosure	• Signs and Posting • Training (general safety and radiation training), RWP • Shielding Policy for Ionizing Radiation – shielding design and surveillance requirements
2a	CEBAF Hall A and C beam dump cooling water systems (bldg. 91 or 95), Vicinity of bldg. 92	• None	• Facility design (Intermediate dump loop pressure higher than primary loop so that water only leaks from ILCW to primary beam dump cooling water loop)
2b	CEBAF Hall A and C beam dump cooling water systems (bldg. 91 or 95)	• Bldg. 91/95 design and structural integrity	• Hydrogen recombiner in affected system • Hydrogen detector system in ceiling of affected building with alarms at MCC at a fraction of LEL for H_2 in air
2c	CEBAF Hall A and C beam dump cooling water systems (bldg. 91 or 95)	• None	• Bldg. 91/95 design and structural integrity • Leak check alarms • Hydrogen gas alarms
2d	CEBAF Hall A and C beam dump cooling water systems (bldg. 91 or 95)	• None	• Bldg. 91/95 design and structural integrity • Leak check alarms
3a	CEBAF, LERF, UITF	• None	• Worker Health and Safety Program Plan • Industrial Hygiene Sampling

Hazard Event ID	Location	Credited Control(s)	Defense-in-Depth Control(s)
3b	CEBAF Hall A and C beam dump cooling water systems (bldg. 91 or 95)	• None	• Hydrogen recombiner in affected system • Hydrogen detector system in ceiling of affected building with alarms at MCC at a fraction of LEL for H_2 in air
4a	CEBAF Service Building, LERF Klystron Gallery, UITF Mezzanine	• None	• RF waveguide pressure interlocks connected to PSS beam inhibit • WCDs requiring an up-stream dump, Faraday cup, vacuum valve, or gun to be locked out when waveguide is opened
4b	CEBAF Service Building, LERF Klystron Gallery, UITF Mezzanine, CMTF	• None	• WCD that requires adjacent CM zone(s) to be depowered
4c	CEBAF, LERF, UITF CMTF, VTA	• None	• RF leakage test • LOTO Waveguide • Bolt-up/tagging procedure
5a	CEBAF Linacs, LERF, UITF, CMTF	• None	• Pressure relief systems in place and functional • Passive ceiling vents • Primary CM relief vents to above ground • ODH Training
5b	UITF, CMTF	• None	• Pressure relief systems in place and functional • Passive ceiling vents • Primary CM relief vents to above ground • ODH training
5c	CEBAF Linacs, LERF, UITF, CMTF	• None	• CEBAF lintels, LERF door, UITF enclosure configuration slows helium gas entry into stairwells • Active CMTF enclosure venting into Test Lab High Bay under ODH conditions • ODH Training
5d	CEBAF Linacs, LERF, UITF, CMTF	• Nitrogen lines outfitted with flow restricting orifice (CEBAF, LERF) • ODH System Alarms (sensors positioned for N_2 and He) • Passive ceiling vents • CEBAF lintels and LERF door configuration slows helium gas entry into stairwells	• ODH Training • Active CMTF enclosure venting into Test Lab High Bay under ODH conditions • Nitrogen supply line to solenoid valve (CEBAF, LERF, UITF)
5e	CEBAF Linacs, LERF, UITF, CMTF	• ODH System Alarms • CEBAF lintels and LERF door configuration slows helium gas entry into stairwells • Passive ceiling vents	• Cryogenic Work Control Process • Active CMTF enclosure venting into Test Lab High Bay under ODH conditions • ODH training

Hazard Event ID	Location	Credited Control(s)	Defense-in-Depth Control(s)
5f	CEBAF, LERF, UITF, CMTF	• None	• Emergency power supply for safety systems • Nitrogen supply line solenoid valves (CEBAF, LERF, UITF) • CMTF shield door fails open in the event of power loss
5g	CEBAF, LERF, UITF, CMTF	• ODH System Controls • Door configuration and CEBAF lintels slow helium gas entry in to stairwells • Passive ceiling vents	• Nitrogen supply line solenoid valves (CEBAF, LERF, UITF) • ODH training
5h	Inside CMTF cave	• ODH System Controls • Passive ceiling vent	• ODH training • Ceiling vent fan activated upon ODH alarm • PPE
5i	Inside CMTF cave	• ODH System Controls • Passive ceiling vent	• ODH training • Ceiling vent fan activated upon ODH alarm • PPE
5j	Inside CMTF control room	• ODH System Controls	• Penetrations to control room sealed • ODH training • PPE
5j.1	Inside CMTF control room	• ODH System Controls	• Penetrations to control room sealed • ODH training • PPE
5k	VTA	• None	• Confined Space Entry Procedure for dewar access
6a	CEBAF, LERF, UITF	• ERR Process assesses risk from hazards, specifies controls	• Pressure relief systems in place and functional • Signs and Posting • Pressure Systems Training
6b	CEBAF, Offsite at fence boundary	• None	• ERR Process assesses risk from hazardous material used as physics target, specifies controls • Facility design: optimized ventilation and exhaust • Hazard specific training • Administrative access controls
6c	CEBAF, LERF, UITF	• None	• ERR Process assesses risk from hazardous material used in experiments • Fire Protection Program • Pressure Systems Program

5.5.2 ASE

The ASE for CEBAF and LERF is composed of engineered and administrative Credited Controls applicable to both accelerators and provides for the safe operation of these accelerators and experimental areas. The ASE for UITF is very similar to CEBAF and LERF, but the content is adjusted for the scope and configuration of the accelerator. Further adjustments apply to the ASE for the CMTF and VTA. The following tables are the basis for the CEBAF/LERF ASE (Table 22), the UITF ASE (Table 23), the CMTF ASE (Table 24) and the VTA ASE (Table 25).

Table 22. Basis for CEBAF/LERF ASE

1. Credited Passive Engineered Controls	Event ID No.	Highest Unmitigated Risk Rating
1.1 Permanent Shielding	1o, 1q	**UNACCEPTABLE**

Applicability:

- When beam delivery into the affected CEBAF segment is possible.
- When beam delivery is possible in the LERF and LERF is in Beam Permit.
- When SRF operations are possible in the affected CEBAF segment or the LERF.

Specific Controls:

Permanent shielding:

- Structural shielding, typically reinforced concrete that defines the accelerator enclosure,
- Built-in shielding design features such as labyrinths and penetration routing,
- Earthen berms and overburden.

Management and Surveillance:

- In accordance with *HPP-OPS-002 Performance of Periodic Routines* and *HPP-OPS-015, Shielding Package Determination and Tracking*, earthen berms and overburden for an accelerator (or a segment of an accelerator) shall be visually inspected prior to operation and the results of the visual inspection shall be recorded in the JAM before facility operation.
- Structural shielding shall be inspected as specified by FM&L Procedures and recorded in the Condition Assessment Information System (CAIS) at least every five years. Inspection results shall be communicated to the RCM or designee. The RCM or designee shall evaluate the data and document the evaluation in an RCD Note.
- Permanent shielding shall be subject to the Shielding Policy for Ionizing Radiation (RCD-POL-14-001). Shielding design and changes shall be reviewed in accordance with the *ASE Violation/USI Review Procedure* and approved by the RCM or designee.
- The Dig/Blind Penetration Permit specified in *ES&H Manual Chapter 3320 Temporary Work Permits* shall be used to manage configuration during excavation activities in overburden used as shielding.

Acceptable compensatory measures:

If RCD evaluation determines the condition of permanent shielding associated with an accelerator enclosure does not meet requirements specified in the SAD or is otherwise unacceptable, the Radiation Control Manager will recommend compensatory measures (such as additional access control, installation of temporary shielding, etc.), if necessary, to maintain performance specified in the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001)* until the shielding is restored to the values specified in the SAD or the SAD is amended. The SCMB shall review and evaluate RCM recommendations using the *ASE Violation/USI Review Process*. The design, approval, and use of compensatory measures for permanent shielding shall be subject to the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001)*.

1.2 Movable Shielding	1m, 1n, 1o	**UNACCEPTABLE**

Applicability:

- When beam delivery into the affected CEBAF segment is possible.
- When beam delivery is possible in the LERF and LERF is in Beam Permit.
- When SRF operations are possible in the affected CEBAF segment or the LERF.

Specific Controls: Movable Shielding.

Management and Surveillance:

- Movable shielding shall be subject to the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001)*.
- Movable shielding design and changes shall be reviewed in accordance with the *ASE Violation/USI Review* Process and approved by the RCM or designee.
- Movable shielding shall be visibly labeled or tagged consistent with *ENG-AD-01-001 Conduct of Engineering Manual Section 5.2.6.1 Implementing Item Identification.*

- Correct placement of movable shielding shall be verified in accordance with the Jefferson Lab Radiation Control Department Procedures specified in *HPP-OPS-002, Performance of Periodic Routines* and *HPP-OPS-015, Shielding Package Determination and Tracking.*
- The RCM or designee shall record the movable shielding status, along with the expiration date for the status determination, in the JAM before facility operation.

Acceptable compensatory measures:

Fences or barriers with informational signs or postings consistent with the hazard that prevent inadvertent access to the affected area and that mitigate the radiation hazard consistent with the requirements of the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001).*

1.3 Beam Dump Cooling Building Design	2b	**UNACCEPTABLE**

Applicability:
When beam delivery into the affected CEBAF segment is possible, specifically to Hall A and Hall C.

Specific Controls:
The structural integrity of Buildings 91 and 95 protects the cooling systems from damage and the containment features capture cooling water in the event of leakage.

Management and Surveillance:
- The structural integrity of the Beam Dump Cooling Buildings and their sump pits shall be recorded in the JAM by FM&L before facility operation.
- Buildings shall be visually inspected as specified by FM&L Procedures and recorded in CAIS at least every five years.

1.4 Nitrogen Gas Supply Orifices	5d, 5g	**UNACCEPTABLE**

Applicability:
When affected system is charged with gas and personnel are in the affected area within the accelerator enclosures and flow limited orifice is required by an ODH Analysis.

Specific Controls:
Orifices in the nitrogen service gas distribution supply lines restrict the flow rate to levels that would be dispersed through passive area ventilation without significantly reducing the oxygen concentration.

Management and Surveillance:
- The orifice is in place and labeled in accordance *with ENG-AD-01-001 Conduct of Engineering Manual Section 5.2.6.1 Implementing Item Identification*.
- The orifice shall be function tested no less than every two years to verify requirements of the ODH Analysis are met. The status of the nitrogen gas supply orifice shall be recorded in the JAM.

Acceptable compensatory measures:
Work control procedures for work in affected area shall specify ODH mitigation as required by the *ES&H Manual Chapter 6540 Oxygen Deficiency Hazard (ODH) Control Program*.

1.5 ODH vents, lintels and facility configuration	5d, 5e, 5g	**UNACCEPTABLE**

Applicability:
When cryogens are supplied to the accelerator enclosure for CEBAF or LERF.

Specific Controls:
- CEBAF and LERF passive ceiling vents.
- CEBAF door configuration slows helium gas entry into stairwells and lintels slow helium migration from linacs.
- LERF door configuration slows helium gas entry into stairwells.

Management and Surveillance:
Structural features shall be inspected as specified by FM&L Procedures and recorded in the CAIS at least every five years.

Inspection results shall be recorded in the JAM by FM&L before facility operation. Design changes shall be reviewed in accordance with the *ASE Violation/USI Review Procedure.*

Acceptable compensatory measures:
Work control procedures for work in affected area shall specify ODH mitigation as required by the *ES&H Manual Chapter 6540 Oxygen Deficiency Hazard (ODH) Control Program*.

2. Credited Active Engineered Controls	Event ID No.	Highest Unmitigated Risk Rating
2.1 PSS Access Controls	1a, 1c, 1e, 1f, 1h, 1l	**UNACCEPTABLE**

Applicability:

- When beam delivery into the affected CEBAF segment is possible.
- When beam delivery is possible in the LERF and LERF is in Beam Permit.
- When SRF operations are possible in the affected CEBAF segment or the LERF.

Specific Controls:
The CEBAF PSS and the LERF PSS shall have no loss of safety function in any segment during facility operation in that segment.

Management and Surveillance:

- PSS components shall be visibly labeled or tagged consistent with *ENG-AD-01-001 Conduct of Engineering Manual Section 5.2.6.1 Implementing Item Identification*.
- Changes to the PSS are reviewed and approved in accordance with the *PSS Configuration Management Procedure* and *the ASE Violation/USI Review Process*. PSS functional requirements are established in the *Beam Containment and Access Control Policy.*
- The CEBAF PSS and the LERF PSS shall be certified annually.
- The Safety Systems Group shall verify the status of the CEBAF PSS and the LERF PSS, along with the expiration date for the status determination, in the JAM.

Acceptable Compensatory Measures:
Use of locked doors, gates, or fences consistent with 3.3.1 Doors, Gates, Fences, and other Barriers, below.

2.2 CEBAF PSS Beam Containment Controls	1a, 1c, 1e, 1f, 1h, 1l	**UNACCEPTABLE**

Applicability:

- When beam delivery is possible into CEBAF segments adjacent to the affected segment.
- When SRF operations are possible in the CEBAF segment adjacent to the affected segment.

Specific Controls:
The CEBAF PSS shall have no loss of safety function in any segment during facility operation in that segment.

Management and Surveillance:

- PSS components shall be visibly labeled or tagged consistent with *ENG-AD-01-001 Conduct of Engineering Manual Section 5.2.6.1 Implementing Item Identification*.
- Changes to the PSS are reviewed and approved in accordance with the *PSS Configuration Management Procedure* and the *ASE Violation/USI Review Process*. PSS functional requirements are established in the *Beam Containment and Access Control Policy.*
- The CEBAF PSS shall be certified annually.

Acceptable Compensatory Measures:
Use of locked doors, gates, or fences consistent with 3.3.1 Doors, Gates, Fences, and other Barriers, below.

2.3 ODH System Controls	5d, 5e, 5g	**UNACCEPTABLE**

Applicability:
When required by the *ES&H Manual Chapter 6540 Oxygen Deficiency Hazard (ODH) Control Program* and an ODH Analysis document, a fixed ODH monitoring system shall be installed and maintained functional in CEBAF and LERF areas.

Specific Controls:
An ODH system shall be installed according to the requirements in an ODH Analysis.

Management and Surveillance:

- ODH system components shall be visibly labeled or tagged consistent with *ENG-AD-01-001 Conduct of Engineering Manual Section 5.2.6.1 Implementing Item Identification*.
- The system shall be maintained such that it is operational when required by the ODH assessment for the location.
- ODH-sensing devices shall be tested every two years and the status shall be recorded in the JAM.

Acceptable compensatory measures:

- Entry only by authorized personnel in accordance with *ES&H Manual Chapter 6540 Oxygen Deficiency Hazard (ODH) Control Program*.
- Procedures for entry into a reduced oxygen atmosphere.
- Exclusion of personnel from the areas in which the ODH system performance is inadequate.

3. Credited Administrative Controls	Event ID No.	Highest Unmitigated Risk Rating
3.1 Doors, Gates, Fences, and other Barriers	1e, 1f, 1h, 1i, 1j, 1m, 1o, 5g	**UNACCEPTABLE**

Applicability:

- When beam delivery into the affected CEBAF segment is possible.
- The associated Beam Dump Cooling Building is included if beam delivery segments include Hall A or C. Applies to the Injector, North and/or South Linac PSS segments in Beam or Power Permit independent of other segments.
- When the LERF is in Beam or Power Permit.

Specific Controls:
Entrances to the accelerator enclosure and other designated spaces shall be interlocked via the PSS Interlocks or shall be locked in accordance with *ES&H Manual Chapter 6111, Administrative Control Using Locks and Tags*, barred, or bolted into place to prevent unauthorized access.

Management and Surveillance:

- Doors, gates, fences, and other barriers serving as Credited Controls shall be clearly identified by visible labels or tags consistent with *ENG-AD-01-001 Conduct of Engineering Manual Section 5.2.6.1 Implementing Item Identification.*
- The RCM or designee shall verify the locked, barred, or bolted entrances in accordance with the Radiation Protection Department Procedures specified in *HPP-OPS-002, Performance of Periodic Routines* and *HPP-OPS-015, Shielding Package Determination and Tracking.* The status, along with the expiration date for the status determination, shall be recorded in the JAM.

3.2 Lab Experimental Review Process	6a	**UNACCEPTABLE**

Applicability:

- When beam delivery is possible into the affected CEBAF segment containing an approved nuclear physics experiment.
- When beam delivery is possible in the LERF and LERF is in Beam Permit.

Specific Controls:

- Any experiment that has completed the Proposal Phase described in the *ES&H Manual Chapter 3120 The CEBAF Experiment Review Process*, that is, the experiment has a decision by the Lab Director to grant beam-time formally communicated by a letter from the Lab Director accompanying the Program Advisory Committee (PAC) report, will undergo the remaining steps in the experimental review process before the experiment is run at the CEBAF or LERF accelerator.
- A proposal that has not completed the Proposal Phase described in the *ES&H Manual Chapter 3120 The CEBAF Experiment Review Process,* i.e. has not been granted beam time but has been evaluated by laboratory

leadership and found to have sufficient merit to pursue that proposal using laboratory resources, shall follow the requirements in the *ES&H Manual Chapter 3130 Accelerator Experiment Safety Review Process,* before the experiment is run at the CEBAF or LERF accelerator.

- If the experiment is not addressed by either Chapters 3120 or 3130, it shall undergo a USI review.

3.3 CEBAF and LERF Operations Staffing - Sweep and Controlled Access	1a, 1c, 1e, 1f, 1h	**UNACCEPTABLE**

Applicability:
When a segment of the CEBAF Accelerator or the LERF is being made ready for Power Permit or Beam Permit.

Specific Controls:
CEBAF or LERF

- One Security Guard on the Jefferson Lab Campus.
- Crew Chief on-call.
- Safety System Operator (SSO).

Management and Surveillance:
The Crew Chief can simultaneously serve as the SSO. The SSO must be in the MCC. Sweeps follow the steps defined in *MCC-PR-17-001 PSS Sweep Procedure*. Controlled Accesses follow the steps defined in *MCC-PR-17-004 PSS Controlled Access Procedures*. These procedures are carried out by a qualified SSO using the Safety Systems Console in the MCC. The Safety Systems Group certifies SSOs and maintains the PSS console and procedures.

3.4 RF Only Operations	1h	**UNACCEPTABLE**

Applicability:
CEBAF

- When the Injector is in Power Permit or lower PSS State.
- When the North Linac is in either Power Permit or Beam Permit.
- When the South Linac is in either Power Permit or Beam Permit.

LERF
When the LERF is in Power Permit or when the LERF is in Beam Permit AND consistent with *ES&H Manual Chapter 6111, Administrative Control Using Locks and Tags*, either vacuum valve VBV0F01 is locked in the beamline downstream of the Injector OR the gun high-voltage power supply is locked out.

Specific Controls:
CEBAF

- One Security Guard on the Jefferson Lab Campus.
- Crew Chief on-call.
- One Operator.

LERF

- One Security Guard on the Jefferson Lab Campus.
- Crew Chief on-call.
- One LERF Operator or LERF Hot-Standby Operator or non-LERF Control Room staff (e.g. RF Operator)

Management and Surveillance:
CEBAF
The Crew Chief can simultaneously serve as the Operator. Either the Operator or the Crew Chief must be on the accelerator site.
LERF
The Crew Chief can simultaneously serve as the LERF Operator, or LERF Hot-Standby Operator, or non-LERF Control Room staff. Either this staff member or the Crew Chief must be on the accelerator site.

3.5 CEBAF Operations Staffing – Beam up to 1D Spectrometer	1a, 1c, 1e, 1f, 1h	UNACCEPTABLE

Applicability:
When beam delivery is possible up to the 1D Spectrometer Dump. Injector PSS Segment is in Beam Permit.

Specific Controls:
- One Security Guard on the Jefferson Lab Campus.
- Crew Chief on-call.
- One Operator.

Management and Surveillance:
The Crew Chief can simultaneously serve as the Operator. Either the Operator or the Crew Chief must be in the MCC.

3.6 CEBAF Operations Staffing – Beam up to Faraday Cup #2	1a, 1c, 1e, 1f, 1h	UNACCEPTABLE

Applicability:
When beam delivery is possible up to Faraday Cup #2. Injector and North Linac PSS Segments are in Beam Permit.

Specific Controls:
- One Security Guard on the Jefferson Lab Campus.
- Crew Chief on-call.
- One Operator.

Management and Surveillance:
The Crew Chief can simultaneously serve as the Operator. Either the Operator or the Crew Chief must be in the MCC.

3.7 CEBAF Operations Staffing – Beam to In-line Dump	1a, 1c, 1e, 1f, 1h	UNACCEPTABLE

Applicability:
When beam delivery up to the Inline Dump possible. Injector and North Linac PSS Segments are in Beam Permit.

Specific Controls:
- One Security Guard on the Jefferson Lab Campus.
- Crew Chief on the accelerator site.
- One Operator.

Management and Surveillance:
The Crew Chief can simultaneously serve as the Operator. Either the Operator or the Crew Chief must be in the MCC.

3.8 CEBAF Operations Staffing – Beam Beyond Inline Dump	1a, 1c, 1e, 1f, 1h, 1i, 1j, 1k, 1l, 1m, 1n, 1o	UNACCEPTABLE

Applicability:
When beam delivery beyond the Inline Dump is possible.

Specific Controls:
- One Security Guard on the Jefferson Lab Campus.
- Crew Chief on the accelerator site.
- One Operator.

Management and Surveillance:
Either the Crew Chief or the Operator must be in the MCC. The other must be on the accelerator site.

3.9 LERF Operations Staffing – Beam Operations	1a, 1c, 1e, 1h, 1k, 1l, 1m, 1n	UNACCEPTABLE

Applicability:
When beam delivery is possible in the LERF. LERF is in Beam Permit.

Specific Controls:
- One Security Guard on the Jefferson Lab Campus.
- Crew Chief on the accelerator site.
- One LERF Operator.

Management and Surveillance:
The LERF Operator must operate from the designated control room, as determined by the Crew Chief.

Table 23. Basis for the UITF ASE

1. Credited Passive Engineered Controls	Event ID No.	Highest Unmitigated Risk Rating
1.1 Permanent Shielding	1q	**UNACCEPTABLE**

Applicability:

- When beam delivery is possible.
- When SRF operations are possible.

Specific Controls:

- Structural shielding, typically reinforced concrete that defines the accelerator enclosure,
- Built in shielding design features such as labyrinths and penetration routing.

Management and Surveillance:

- Permanent shielding shall be subject to the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001).*
- Shielding design and changes shall be reviewed in accordance with the *ASE Violation/USI Review Process* and approved by the RCM or designee.
- The Dig/Blind Penetration Permit specified in *ES&H Manual Chapter 3320 Temporary Work Permits* shall be used to manage penetrating or otherwise disturbing the structure in a way that can impact shielding effectiveness.
- Structural shielding shall be inspected as specified by FM&L and recorded in the CAIS at least every five years. Inspection results shall be communicated to the RCM or designee.
- The RCM or designee shall evaluate all permanent shielding at least every five years against applicable design specifications and SAD requirements, and its general condition with respect to shielding effectiveness. The evaluation shall be recorded in the JAM before facility operation.

Acceptable compensatory measures:

If RCD evaluation determines the condition of permanent shielding associated with an accelerator enclosure does not meet requirements specified in the SAD or is otherwise unacceptable, the Radiation Control Manager will recommend compensatory measures (such as additional access control, installation of temporary shielding, etc.), if necessary, to maintain performance specified in the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001)* until the shielding is restored to the values specified in the SAD or the SAD is amended. The SCMB shall review and evaluate RCM recommendations using the *ASE Violation/USI Review Process*. The design, approval, and use of compensatory measures for permanent shielding shall be subject to the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001)*.

1.2 Movable Shielding	1m, 1p	**UNACCEPTABLE**

Applicability:

- When beam delivery is possible.
- When SRF operations are possible.

Specific Controls: Movable Shielding.

Management and Surveillance:

- Movable shielding shall be subject to the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001)*.
- Movable shielding design and changes shall be reviewed in accordance with the *ASE Violation/USI Review Process* and approved by the RCM or designee.
- Movable shielding shall be visibly labeled or tagged consistent with *ENG-AD-01-001 Conduct of Engineering Manual Section 5.2.6.1 Implementing Item Identification.*
- Correct placement of movable shielding shall be verified in accordance with the Jefferson Lab Radiation Control Department Procedures specified in *HPP-OPS-002, Performance of Periodic Routines* and *HPP-OPS-015, Shielding Package Determination and Tracking.*
- The RCM or desingee shall record the movable shielding status, along with the expiration date for the status determination, in the JAM before facility operation.

Acceptable compensatory measures:
Fences or barriers with informational signs or postings consistent with the hazard that prevent inadvertent access to the affected area and that mitigate the radiation hazard consistent with the requirements of the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001).*

1.3 ODH Vents, Lintels and Facility Configuration	5d, 5e, 5g	**UNACCEPTABLE**

Applicability:
When cryomodule is supplied with cryogens or Target is supplied with cryogens.

Specific Controls:
UITF passive vents in accelerator enclosure and passive vents incorporated into movable shielding.

Management and Surveillance:

- No surveillance is required for these controls if they are part of a concrete structure that defines the UITF accelerator enclosure and, once placed, they are not intended to move to facilitate UITF operation.
- Passive vents, incorporated into movable shielding and identified as Credited Controls, are visibly labeled or tagged consistent with *ENG-AD-01-001 Conduct of Engineering Manual Section 5.2.6.1 Implementing Item Identification* and verified after movement .
- FM&L shall record the status of passive vents incorporated into movable shielding and identified as Credited Controls, along with the expiration date for the status determination, in the JAM before facility operation.

Acceptable Compensatory Measures:
Work control procedures for work in affected area shall specify ODH mitigation as required by the *ES&H Manual Chapter 6540 Oxygen Deficiency Hazard (ODH) Control Program*.

2. Credited Active Engineered Controls	**Event ID No.**	**Highest Unmitigated Risk Rating**
2.1 PSS Access Controls	1b, 1d, 1e, 1g, 1h, 1l	**UNACCEPTABLE**

Applicability:

- When beam delivery is possible.
- When SRF operations are possible.

Specific Controls:
The UITF PSS shall have no loss of safety function during facility operation.

Management and Surveillance:

- UITF PSS components shall be visibly labeled or tagged consistent with *ENG-AD-01-001 Conduct of Engineering Manual Section 5.2.6.1 Implementing Item Identification*.
- Interim changes to the PSS (hardware or software) are reviewed and approved in accordance with the *PSS Configuration Management Procedure* and the *ASE Violation/USI Review Process*. PSS functional requirements are established in the *Beam Containment and Access Control Policy*.
- The UITF PSS shall be certified annually.
- The Safety Systems Group shall verify the status of the UITF PSS, along with the expiration date for the status determination, in the JAM before facility operation.

2.2 ODH System Controls	5d, 5e, 5g	**UNACCEPTABLE**

Applicability:
When required by the *ES&H Manual Chapter 6540 Oxygen Deficiency Hazard (ODH) Control Program* and an ODH Analysis document, a fixed ODH monitoring system shall be installed and maintained functional in UITF areas.

Specific Controls:
An ODH system shall provide adequate monitoring and alarm coverage of the affected areas.

Management and Surveillance:

- UITF ODH system components shall be visibly labeled or tagged consistent with *ENG-AD-01-001 Conduct of Engineering Manual Section 5.2.6.1 Implementing Item Identification.*
- The system shall be maintained such that it is operational when required by the ODH assessment for the location.
- ODH system shall be identified in accordance with *Labeling Procedure for PSS and ODH Equipment* and the status shall be reflected in the JAM.
- ODH sensing devices shall be tested every two years and the status shall be reflected in the JAM.
- The Safety Systems Group shall verify the status of ODH System Controls, along with the expiration date for the status determination, in the JAM before facility operation.

Acceptable compensatory measures:

- Entry only by authorized personnel in accordance with *ES&H Manual Chapter 6540 Oxygen Deficiency Hazard (ODH) Control Program* procedures for entry into a reduced oxygen atmosphere. Exclusion of personnel from the areas in which the ODH system performance is inadequate.

3. Credited Administrative Controls	Event ID No.	Highest Unmitigated Risk Rating
3.1 Doors, Gates, Fences, and other Barriers	1e, 1g, 1h, 1m, 1p, 5g	UNACCEPTABLE

Applicability:

- When beam delivery is possible.
- When SRF operations are possible.

Specific Controls:

Entrances to the accelerator enclosure and other designated spaces shall be interlocked via the PSS Interlocks or shall be locked in accordance with *ES&H Manual Chapter 6111, Administrative Control Using Locks and Tags*, barred, or bolted into place to prevent unauthorized access.

Management and Surveillance:

- Doors, gates, fences, and other barriers serving as Credited Controls shall be visibly labeled or tagged consistent with *ENG-AD-01-001 Conduct of Engineering Manual Section 5.2.6.1 Implementing Item Identification.*
- The RCM or desingee shall verify the locked, barred, or bolted entrances in accordance with the Radiation Protection Department Procedures specified in *HPP-OPS-002, Performance of Periodic Routines* and *HPP-OPS-015, Shielding Package Determination and Tracking*. The status, along with the expiration date for the status determination, shall be recorded in the JAM before facility operation.

3.2 Lab Experimental Review Process	6a	UNACCEPTABLE

Applicability:

When beam delivery to an approved nuclear physics experiment is possible in the UITF.

Specific Controls:

- Any experiment that has completed the Proposal Phase (i.e. the experiment has a decision, formally communicated by the Physics Advisory Committee report and a letter from the Laboratory Director granting beam-time) will undergo the remaining experimental review process steps as described in the *ES&H Manual Chapter 3120 The CEBAF Experiment Review Process* before the experiment is run using the UITF accelerator.
- A proposed experiment that will not undergo the experimental review process steps as described in the ES&H Manual Chapter 3120 described above shall follow the requirements in the *ES&H Manual Chapter 3130 Accelerator Experiment Safety Review Process*.
- If the experiment is not addressed by either Chapters 3120 or 3130, it shall undergo a USI review.

3.3 UITF Staffing – Sweep and Operations	1b, 1d, 1e, 1g, 1h	UNACCEPTABLE

Applicability:
When UITF is being made ready for PSS state above Open Access.

Specific Controls:
One Qualified UITF Operator within UITF.

Management and Surveillance:
- UITF Operators must have current UITF Operator Training, SAF162.
- Trained UITF staff carry out UITF Sweeps follow the steps defined in the specific sweep procedure maintained by the Safety System Group.

3.4 UITF Staffing – Beam On or RF Only Operations	1b, 1d, 1e, 1g, 1h, 1p	UNACCEPTABLE

Applicability:
When UITF PSS is being made ready for PSS state above Open Access.

Specific Controls:
One Qualified UITF Operator within UITF.

Management and Surveillance:
UITF Operators must have current UITF Operator Training, SAF162.

Table 24. Basis for the CMTF ASE

1. Credited Passive Engineered Controls	Event ID No.	Highest Unmitigated Risk Rating
1.1 Permanent Shielding	1q	**UNACCEPTABLE**

Applicability:
Whenever the supply of high voltage to an RF source supplying a cavity in the accelerator enclosure is possible.

Specific Controls:

- Structural shielding, typically reinforced concrete that defines the accelerator enclosure,
- Design feature: access labyrinth and penetration routing to prevent line-of-sight to beamline.

Management and Surveillance:

- Permanent shielding shall be subject to the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001)*.
- Shielding design changes shall be reviewed in accordance with the *ASE Violation/USI Review Process* and approved by the RCM or designee.
- Structural shielding shall be inspected as specified by FM&L at least every five years. The inspection results shall be communicated to the RCM or designee, who shall evaluate the results against applicable design specifications and SAD requirements, and its general condition with respect to shielding effectiveness. The final evaluated status of the shielding shall be recorded in the CMTF portion of the JAM.
- The Dig/Blind Penetration Permit specified in *ES&H Manual Chapter 3320 Temporary Work Permits* shall be used to manage penetrating or otherwise disturbing the structure in a way that can impact shielding effectiveness.

Acceptable compensatory measures:
If RCM evaluation determines the condition of permanent shielding associated with an accelerator enclosure does not meet the requirements specified in the SAD or is otherwise unacceptable, the RCM or designee will recommend compensatory measures (such as additional access control, installation of temporary shielding, etc.), if necessary, to maintain the performance specified in the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001)* until the shielding is restored to the values specified in the SAD or the SAD is amended. The SCMB shall review and evaluate RCM recommendations using the *ASE Violation/USI Review Process.* The design, approval, and use of compensatory measures for permanent shielding shall be subject to the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001)*.

1.2 Movable Shielding	1h.1, 1p.1	UNACCEPTABLE

Applicability:
Whenever the supply of high voltage to an RF source supplying a cavity in the accelerator enclosure is possible.

Specific Controls: Movable Shielding.

Management and Surveillance:

- Movable shielding shall be subject to the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001).*
- Movable shielding design and changes shall be reviewed in accordance with the *ASE Violation/USI Review Process* and approved by the RCM or designee.
- Movable shielding shall be visibly labeled or tagged consistent with *ENG-AD-01-001 Conduct of Engineering Manual Section 5.2.6.1 Implementing Item Identification.*
- Correct placement of movable shielding shall be verified in accordance with the Jefferson Lab Radiation Control Department Procedures specified in *HPP-OPS-002, Performance of Periodic Routines* and *HPP-OPS-015, Shielding Package Determination and Tracking.*
- The RCM or desingee shall record the movable shielding status, along with the expiration date for the status determination, in the JAM before facility operation.

Acceptable compensatory controls:
Fences or barriers with informational signs or postings consistent with the hazard present that prevent inadvertent access to the affected area, and which mitigate the radiation hazard consistent with the requirements of the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001).*

1.3 ODH Vents and Facility Configuration	5d, 5e, 5g, 5h, 5i	**UNACCEPTABLE**

Applicability:
When cryogens are supplied to the CMTF enclosure.

Specific Controls:
CMTF passive ceiling vent.

Management and Surveillance:
FM&L shall record the status of passive vents incorporated into movable shielding and identified as Credited Controls, along with the expiration date for the status determination, in the JAM before facility operation.

Acceptable Compensatory Measures:
Work control procedures for work in affected area shall specify ODH mitigation as required by the *ES&H Manual Chapter 6540 Oxygen Deficiency Hazard (ODH) Control Program*.

2. Credited Active Engineered Controls	**Event ID No.**	**Highest Unmitigated Risk Rating**
2.1 PSS Access Controls	1h.1, 1l	**UNACCEPTABLE**

Applicability:
Whenever the supply of high voltage to an RF source supplying a cavity in the accelerator enclosure is possible.

Specific Controls:
The CMTF PSS shall have no loss of safety function during accelerator operations.

Management and Surveillance:
- CMTF PSS components shall be visibly labeled or tagged consistent with *ENG-AD-01-001 Conduct of Engineering Manual Section 5.2.6.1 Implementing Item Identification.*
- Interim changes to the PSS are reviewed and approved in accordance with the *PSS Configuration Management Procedure* and the *ASE Violation/USI Review Process*. PSS functional requirements are established in the *Beam Containment and Access Control Policy*.
- The CMTF PSS shall be certified annually.
- The Safety Systems Group shall record the status of the CMTF PSS, along with the expiration date for the status determination, in the JAM before facility operation.

Acceptable compensatory controls:
Use of locked doors, gates or fences consistent with 3.1 Doors, Gates, Fences, and other Barriers, below.

2.2 ODH System Controls	5d, 5e, 5h-5j.1	**UNACCEPTABLE**

Applicability:
When required by the *ES&H Manual Chapter 6540 Oxygen Deficiency Hazard (ODH) Control Program* and an ODH analysis document, a fixed ODH monitoring system shall be installed and maintained functional in CMTF areas.

Specific Controls:
An ODH system shall provide adequate monitoring and alarm coverage of the affected areas.

Management and Surveillance:

- CMTF OHD system components shall be visibly labeled or tagged consistent with *Labeling Procedure for PSS and ODH Equipment.*
- The system shall be maintained such that it is operational when required by the ODH assessment for the location.
- Maintenance shall be performed in accordance with *Labeling Procedure for PSS and ODH Equipment.*
- ODH sensing devices shall be tested no less than every two years.
- The Safety System Group shall verify the status of ODH System Controls, along with the expiration date for the status determination, in the JAM before facility operation.

Acceptable compensatory measures:

- Entry only by authorized personnel in accordance with *ES&H Manual Chapter 6540 Oxygen Deficiency Hazard (ODH) Control Program* procedures for entry into a reduced oxygen atmosphere.
- Exclusion of personnel from the areas in which the ODH system performance is inadequate.

3. Credited Administrative Controls	Event ID No.	Highest Unmitigated Risk Rating
3.1 Doors, Gates, Fences, and other Barriers	1h.1	TOLERABLE

Applicability:
Whenever the supply of high voltage to an RF source supplying a cavity in the accelerator enclosure is possible.

Specific Controls:
Entrances to accelerator enclosures shall be interlocked via the PSS Interlocks or shall be locked in accordance *with ES&H Manual Chapter 6111, Administrative Control Using Locks and Tags*, barred, or bolted into place to prevent unauthorized access.

Management and Surveillance:

- Doors, gates, fences, and other barriers serving as Credited Controls shall be clearly identified by visible labels or tags consistent with their function.
- Access shall only be permitted in accordance with approved procedures.
- The RCM or desingee shall verify the locked, barred, or bolted entrances in accordance with the Radiation Protection Department Procedures specified in *HPP-OPS-002, Performance of Periodic Routines* and *HPP-OPS-015, Shielding Package Determination and Tracking*. The status, along with the expiration date for the status determination, shall be recorded in the JAM for the CMTF.

3.2 CMTF Staffing – Sweep	1h.1	TOLERABLE

Applicability:
When CMTF is being made ready for PSS state above Open Access.

Specific Controls:
Trained Sweeper and Guard per the CMTF PSS Sweep Procedure (Note: Control Room can be unstaffed during Sweep).

Management and Surveillance:
Trained CMTF staff carry out CMTF Sweeps and follow the steps defined in the specific sweep procedure maintained by the Safety System Group.

3.3 CMTF Staffing – Operations	1h.1	TOLERABLE

Applicability:
When CMTF PSS is being made ready for RF Operations and PSS State is set to RUN.

Specific Controls
Authorized RF Operator in Control Room.

Management and Surveillance:
One trained RF operator – approved by the Cryomodule Test Facility Manager – must be on-site and in the control room with the CMTF PSS State in RUN mode.

Table 25. Basis for the VTA ASE

1. Credited Passive Engineered Controls	Event ID No.	Highest Unmitigated Risk Rating
1.1 Permanent Shielding	1q	**UNACCEPTABLE**

Applicability:

When high-power RF operations are possible.

Specific Controls:

- Structural shielding, typically reinforced concrete that defines the accelerator enclosure,
- Built in shielding design features such as penetration routing.

Management and Surveillance:

- Permanent shielding shall be subject to the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001).*
- Shielding design and changes shall be reviewed in accordance with the *ASE Violation/USI Review Process* and approved by the RCM or designee.
- The Dig/Blind Penetration Permit specified in *Environment, Safety and Health (ES&H) Manual Chapter 3320 Temporary Work Permits* shall be used to manage penetrating or otherwise disturbing the structure in a way that can impact shielding effectiveness.
- Structural shielding shall be inspected as specified by FM&L and recorded in the CAIS at least every five years. The inspection results shall be communicated to the RCM or designee.
- The RCM or designee shall evaluate all permanent shielding at least every five years against applicable design specifications and SAD requirements, and its general condition with respect to shielding effectiveness. The evaluation shall be recorded in the JAM for the run period identified in the JAM.

Acceptable compensatory measures:

If RCD evaluation determines the condition of permanent shielding associated with an accelerator enclosure does not meet requirements specified in the SAD or is otherwise unacceptable, the RCM or designee will recommend compensatory measures (such as additional access control, installation of temporary shielding, etc.), if necessary, to maintain performance specified in the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001)* until the shielding is restored to the values specified in the SAD or the SAD is amended. The SCMB shall review and evaluate RCM recommendations using the *ASE Violation/USI Review Process*. The design, approval, and use of compensatory measures for permanent shielding shall be subject to the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001)n*.

1.2 Movable Shielding	1p.2	**UNACCEPTABLE**

Applicability:

When high-power RF operations are possible.

Specific Controls: Movable Shielding.

Management and Surveillance:

- Movable shielding shall be subject to the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001).*
- Movable shielding design and changes shall be reviewed in accordance with the *ASE Violation/USI Review Process* and approved by the RCM or desingee.
- Movable shielding shall be visibly labeled or tagged consistent with *ENG-AD-01-001 Conduct of Engineering Manual Section 5.2.6.1 Implementing Item Identification*.
- Correct placement of movable shielding shall be verified in accordance with the Jefferson Lab Radiation Control Department Procedures specified in *HPP-OPS-002, Performance of Periodic Routines* and *HPP-OPS-015, Shielding Package Determination and Tracking.*
- The RCM or designee shall record the movable shielding status, along with the expiration date for the status determination, in the JAM before facility operation.

Acceptable compensatory measures:
Fences or barriers with informational signs or postings consistent with the hazard that prevent inadvertent access to the affected area and that mitigate the radiation hazard consistent with the requirements of the *Shielding Policy for Ionizing Radiation (RCD-POL-14-001)*.

2. Credited Active Engineered Controls	Event ID No.	Highest Unmitigated Risk Rating
2.1 PSS Access Controls	1h.2, 1l	**UNACCEPTABLE**

Applicability:
When high-power RF operations are possible.

Specific Controls:
The VTA PSS shall have no loss of safety function during RF operations.

Management and Surveillance:

- VTA PSS components shall be visibly labeled or tagged consistent with *Labeling Procedure for PSS and ODH Equipment.*
- Interim changes to the PSS are reviewed and approved in accordance with the *PSS Configuration Management Procedure* and the *ASE Violation/USI Review Process*. PSS functional requirements are established in the *Beam Containment and Access Control Policy*.
- The VTA PSS shall be certified annually.
- The Safety Systems Group shall record the status of the VTA PSS, along with the expiration date for the status determination, in the JAM before facility operation.

3. Credited Administrative Controls	Event ID No.	Highest Unmitigated Risk Rating
3.1. VTA Staffing – Operations High Power RF Enabled (No HMI Permit)	1h.2	**UNACCEPTABLE**

Applicability:
When VTA PSS is above disabled state and no HMI Permit.

Specific Controls:
Authorized VTA RF Operator in Test Lab.

Management and Surveillance:
One trained RF operator – approved by the Vertical Test Area Facility Manager – must be on-site and in the Test Lab with the PSS State in High Power RF Enabled (No HMI Permit).

3.2 VTA Staffing – Operations High Power RF Enabled (HMI Permit)	1h.2	**UNACCEPTABLE**

Applicability:
When VTA PSS is in enabled state and has HMI Permit.

Specific Controls:
Authorized VTA RF Operator in Control Room.

Management and Surveillance:
One trained RF operator – approved by the Vertical Test Area Facility Manager – must be on-site and in the control room with the PSS State in High Power RF Enabled (HMI Permit).

5.6. Summary

This hazard analysis addresses accelerator-specific hazards in accordance with DOE O 420.2D, identifies credible maximum bounding accident scenarios and the resulting consequences, and the probability of the event occurring. Appropriate prevention or mitigation controls, or both, are identified to reduce the risks associated with each hazard. The controls reduce the probability, the consequence, or both the probability and consequence of a hazard event. It is the combined effect of these measures that reduces the overall risk rating. The analysis shows that the controls collectively reduce the probability of a postulated worst-case accident to between 10^{-2} to 10^{-6} occurrences per year, which from Table 19 corresponds to a probability rating of Medium to Extremely Low. The controls that reduce the severity of the consequences of such accidents result in consequence levels, as defined in Table 18, of Medium to Extremely Low. With the controls in place, the reduced probability and consequence ratings as applied to the risk matrix, Figure 17, reduce risk rating to tolerable or acceptable for each identified hazard event.

6. POST-OPERATIONS PLANNING

Compared to proton and heavy-ion accelerators, electron accelerators typically produce the least amount of residual radioactivity and have lower occupational equivalent dose from exposure to radioactive materials and radioactive contamination. In a well-designed and well-managed accelerator facility such as Jefferson Lab, little or no environmental radioactive contamination is expected during the operational life of the lab.

The majority of radionuclides are produced in high-power beam dumps and the systems that serve them. The systems that cool the beam dumps and condition the cooling water contain residual radioactivity. These systems can be disposed of by conventional radioactive waste disposal methods. Low levels of activation are expected in shielding associated with beam dumps and in certain beam-transport components. The radioactivity in beam dumps, transport components, and in shielding is in the form of bulk or volume-activated material that will either be stored for decay or disposed of through conventional methods. The result is negligible environmental consequences.

Details as to the expected quantities of specific radionuclides generated by Jefferson Lab operations are found in the Preliminary Safety Analysis (Revision 2) and Tech Notes CEBAF-TN-87-057[18] and CEBAF-TN-87-062,[26] and are reflected in permitting and reporting activities associated with airborne and waterborne environmental radioactivity.

Jefferson Lab has a process to release property for reuse, disposal or recycle (with consideration for restrictions imposed by DOE on release of metals for recycling).[28] This approach considers both surface contamination and volume activated materials. The approach for assessing and dispositioning potentially activated material follows the DOE STD-1241-2023, DOE STD-6004-2016 and complies with DOE O458.1. This release process will be used during the decommissioning process to determine the disposition of affected materials. The process does not apply to real property or to effluent streams managed under permits.

Jefferson Lab will use methodology consistent with the Multi-Agency Radiation Survey and Site Investigation Manual[28] to assess real property during decommissioning, to set limits for residual radioactivity, and to guide remediation efforts. Compliance with applicable permits is assured by measurements conducted by the TJNAF RCD.

Chemicals and other hazardous materials are similar to those of other general laboratory facilities. Consequently, industry standard decommissioning or decontamination procedures will be used for these materials as situations warrant.

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APPENDIX A: Acronyms and Abbreviations

Acronyms & Abbreviations	Definition	Page
ALARA	As Low As Reasonably Achievable	46
AOD	Accelerator Operations Directives	14
ASE	Accelerator Safety Envelope	1
ASO	Accelerator Safety Order	1
BDCS	Beam-Dump Cooling System	73
BELS	Beam Envelope Limit System	18
CAIS	Condition Assessment Information System	29
CARM	Controlled Area Radiation Monitor	18
CEBAF	Continuous Electron Beam Accelerator Facility	1
CHL	Central Helium Liquefier	9
CLAS12	CEBAF Large Acceptance Spectrometer	33
COEM	Conduct of Engineering Manual	22
CM	Cryomodule	70
CMTF	Cryomodule Test Facility	3
CNI	Computing and Networking Infrastructure	27
CTF	Cryogenic Test Facility	12
CTOF	Central Time-of-Flight	33
DEQ	Department of Environmental Quality	8
DC	Drift Chambers	33
DOE	Department of Energy	1
DSO	Division Safety Officer	22
EPA	Environmental Protection Agency	7
EPICS	Experimental Physics and Industrial Control System	11
ERR	Experiment Readiness Review	15
ES&H	Environment, Safety and Health	15
ESH&Q	Environment, Safety, Health, and Quality	130
ESnet	Energy Sciences Network	8
ESR	End Station Refrigerator	11
FCAL	Forward Electromagnetic Calorimeter	35
FM&L	Facilities Management & Logistics	9
SAD	Final Safety Assessment Document	1
FSD	Fast Shutdown	18
FTOF	Forward Time-of-Flight	33
GeV	Gigaelectron-Volt	2
GHz	Gigahertz	47
GTS	Gun Test Stand	2
HMS	High-Momentum Spectrometer	34

HR	Human Resources	23
HRS	High-Resolution Spectrometers	32

Acronyms & Abbreviations	Definition	Page
HRSD	Hampton Roads Sanitation District	7
HTCC	High-Threshold Cherenkov Counter	33
IR	Infrared	39
IT	Information Technology	27
ITS	Injector Test Stand	44
JSA	Jefferson Science Associates, LLC.	5
kV	Kilovolt	9
kW	Kilowatt	55
LCW	Low-Conductivity Water	12
LERF	Low Energy Recirculator Facility	2
Linac	Linear Accelerator	2
LOD	LERF Operations Directive	14
LTCC	Low-Threshold Cherenkov Counter	33
mA	Milliamps	39
MCC	Machine Control Center	10
MHz	Megahertz	31
MeV	Megaelectron Volts	2
MPS	Machine Protection Systems	14
MS4	Municipal Separate Storm Sewer Systems	8
MVA	Megavolt-Amperes	8
MW	Megawatt	2
O2	Oxygen	79
ODH	Oxygen Deficiency Hazard	10
PCAL/EC	Calorimeters	33
PPE	Personal Protective Equipment	19
PSS	Personnel Safety System	14
QAP	Quality Assurance Program	26
RBM	Radiation Boundary Monitors	26
RCD	Radiation Control Department	18
RCM	Radiation Control Manager	22
RPP	Radiation Protection Program	24
RSAD	Radiation Safety Assessment Document	21
SCMB	Safety Configuration Management Board	18
SF6	Sulfur Hexafluoride	30
SHMS	Super-High Momentum Spectrometer	34
SME	Subject Matter Expert	25

SREL	Space Radiation Effects Laboratory	5
SRF	Superconducting Radiofrequency	13
SSG	Safety Systems Group	22
SSO	Safety System Operator	15

Acronyms & Abbreviations	Definition	Page
SURA	Southeastern Universities Research Association	5
SVT	Silicon Vertex Tracker	33
TCC	Threshold Cherenkov Counter	33
THz	Terahertz	39
TJNAF	Thomas Jefferson National Accelerator Facility	1
TOF	Time-of-Flight	35
UITF	Upgraded Injector Test Facility	2
UPS	Uninterruptible Power Supplies	10
USI	Unreviewed Safety Issue	4
UV	Ultraviolet	39
VTA	Vertical Test Area	3

APPENDIX B: Hazard Analysis for Accelerators Operating at or Below 10 MeV

The purpose of this appendix is to provide a hazard analysis framework for accelerators operating below 10 MeV, for which a Safety Assessment Document, ASE, and USI process are not required by the ASO. Accelerators, as defined by the ASO but having less than 10 MeV, are further segregated by their complexity and structural features.

Simple accelerators are generally not considered accelerators within the prevailing safety community or in any other accelerator safety regulatory or guidance publications; these devices are typically not housed in shielded enclosures and may be portable or even handheld. Few or none of the safety features found in conventional accelerators may apply to their operation. Operation of these devices is addressed by the Jefferson Lab Integrated Safety Management program.

Complex accelerators producing energies less than 10 MeV are analogous to conventionally configured accelerators housed in an interlocked, shielded enclosure, employing an access control system, structural shielding, etc. Operation of these accelerators is analogous to that of the accelerators addressed in the body of this document. This appendix provides a hazard analysis framework for these accelerators in accordance with the ASO.

The Gun Test Stand (GTS) is evaluated in this assessment as an example for applying the hazard analysis framework developed herein following the outline in Figure 16 of the SAD; the ODH classification levels (Table 17), consequence rating levels (Table 18), probability rating levels (Table 19) and risk matrix (Figure 17) are utilized for the hazard analysis process.

B.1. Review Accelerator Systems and Operation

The GTS is located in the west side of the LERF building (Bldg. 18) adjacent to the LERF vault. Room 217 is the control room, Room 109A is the shielded enclosure. The GTS consists of a DC electron gun and a beamline, and is designed to test photo emission gun performance after the application of high-voltage processing techniques. The GTS is not a user facility and does not conduct nuclear physics experiments.

GTS operations & maintenance are conducted by the Center for Injectors and Sources (CIS) personnel. Nominal operations are limited to the following modes:

- Tune-up beam (aka viewer-limited) at 350 kV administratively limited to less than 100 microamps average current.
- 350 kV at 5 mA CW max, ultimately limited by the power supply (550 kV, 5 mA; 2.75-kW max beam power)

During operation, the GTS shielded enclosure is interlocked such that personnel access is prohibited; operations staff performs sweeps of the enclosure prior to the accelerator going into operational status. Operation of the GTS is guided by standard operating procedures (SOPs).

The GTS uses engineered and administrative safeguards matched to its intended function to facilitate safe and efficient operation. For internal consistency and ease of use, the methodology found in Chapter 5 of the SAD is represented below.

B.2. Postulated Accident Scenarios and Identify Credible Hazards

The accident scenarios associated with GTS operations are associated with prompt ionizing radiation exposure, ODH, and chemical (toxicological) exposure. Potential exposure to prompt ionizing radiation exists where a person was able to bypass safety systems and/or safety systems and administrative controls failed to eliminate occupancy while gun high voltage was applied. ODH hazards within the GTS stems from the potential release of SF6 gas displacing oxygen in the region and from actions within the LERF involving the release of oxygen displacing gases. The accident scenarios involving the LERF are described in the LERF ODH assessment.

B.3. Analyze Hazard Events, Determine Consequences and Estimate Probabilities, and Asses Risk Associated with Hazard Events

The hazard events associated with operation of the GTS involve exposure to prompt ionizing radiation, toxicological exposures related to SF6, and ODH hazards. The ODH hazard from shared ventilation with the LERF has been addressed within the LERF ODH assessment. The hazards associated with SF6 use within the GTS were specifically addressed within the original safety assessment presentation (Free-Electron Laser & Gun Test Stand SF6 Gas Transfer System, 25 Oct. 2010). The SF6 was found to be below American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit values (TLVs) and not cause an ODH hazard under conservative exposure scenarios.

The results of the analysis methodology used in Section 5, *Hazard Assessment and Mitigation*, as applied to the combination of hazards presented by the GTS, is found below in Table B-1. Since the GTS operates below 10 MeV, the safety controls applied are not represented in an ASE. However, controls required for the GTS are incorporated into Standard Operating Procedures, Work Permits (e.g., RWPs) and other work-control documents that address the hazards specific to the facility. As noted in the SAD, in most cases, the same systems that serve as Credited Engineered Controls for accelerators are used in the GTS. Even though it may not be required as a result of a hazard analysis, this approach promotes the consistent use of proven technology, consistent configuration management, and effective use of resources.

B.4. Summary of Mitigation

The impact of each event is highly localized, limited to directly adjacent spaces, and affects limited (in most cases, one) staff. Each of the analyzed Technical Areas presents hazards that are completely addressed by DOE- approved Jefferson Lab programs designed to address these hazards by meeting the provisions of 10 CFR 835 and 10 CFR 851.

Table B-1. Risk Rating Summary

Unmitigated Hazard Event	Maximum Probability Level	Maximum Consequence Level	Unmitigated Risk Rating	Mitigated Risk Rating
Ionizing Radiation	Medium	Medium	Unacceptable	Acceptable
ODH	Medium	Medium	Unacceptable	Tolerable
Chemical Exposure	Low	Medium	Unacceptable	Acceptable

Table B-2. Hazards, Postulated Initiating Events and Worst-case Accident Scenarios in Technical Areas

							Unmitigated			Mitigated		
ID	**Bounding**	**Hazard Type**	**Event Description**	**Potential Initiators**	**Basis/ Assumptions**	**Results**	**Risk rating**	**Probability**	**Consequence**	**Risk rating**	**Probability**	**Consequence**
1	**Y**	**Prompt Ionizing Radiation**	Personnel present in the GTS while beam on.	• Operator error • Control system failure • Magnet supply failure	• Sudden event, little to no warning • Beam interacts with accelerator component, worst-case exposure to workers • Condition sustainable for 10 minutes (after that, beam burns through vacuum envelope)	• Multiple workers exposed to very high radiation fields, worst-case exposure > 450 rad	UNACCEPTABLE • Worker deaths • No off-site consequence	M	H	TOLERABLE • PSS Access Controls • PSS annual certification • PSS Safety interlock and Access Control Configuration Management Procedure • Minimum staffing levels of qualified operators • CARM probe inside cave	EL	H
2		**ODH**	Personnel exposed to SF6 insulating gas.	• Gun high voltage supply leaks • Leak during transfer	• Sudden event, little to no warning • Personnel present in GTS enclosure	• Oxygen deficiency results in loss of consciousness, injury, or death	UNACCEPTABLE • Worker deaths • No off-site consequence	M	H	TOLERABLE • ODH monitoring system • ODH training	L	M