Revision 8a

Thomas Jefferson National Accelerator Facility

Final Safety Assessment Document

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APPROVAL

for the
Thomas Jefferson National Accelerator Facility
Final Safety Assessment Document

	Signature	Date
Thomas Jefferson National Accelerator Facility Director	Stuart Henderson	11/29/18
Associate Director, Accelerator Operations, Research and Development Division	Andrei Seryi	11/21/18
Associate Director, Experimental Nuclear Physics Division	Rolf Ent	11/26/18
Associate Director, Environment, Safety, Health and Quality	Mary Logue	11/14/18

DOCUMENT REVISION HISTORY

APPROVALS

Major revisions require full Jefferson Science Associates, LLC, (JSA) approval on a new signature page and are identified as Revision 7, 8, etc.

Interim revisions incorporating minor changes, such as clarifications, minor corrections that do not change the intent of the document, and typographical corrections require JSA approval by the Associate Director of the affected division(s): the Accelerator Operations, Research and Development Division or the Experimental Nuclear Physics Division. Approval of these minor changes is indicated in the following revision history table. Interim revisions are identified with a letter suffix e.g. Revision 7a, 7b, 7c, etc.

REVISION HISTORY

Rev.	Reason for Revision	Approval	Date
Periodic Review	No changes as no positive USI that requires an update to the FSAD. Robert May, Deputy Director ES&H	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.	ESH&Q AD (minor update)Andre signoff	9/30/2019
8	Revised layout of FSAD, 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 FSAD and ASE revised to comply with DOE-O-420.2C	see signature page	08/27/2012

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1.0 EXECUTIVE SUMMARY

In compliance with the requirements of the Department of Energy (DOE) Accelerator Safety Order (ASO), DOE O 420.2C, this Final Safety Assessment Document (FSAD) provides a qualified safety assessment of the hazards specific to the operation of the Continuous Electron Beam Accelerator Facility (CEBAF), the Low Energy Recirculator Facility (LERF), and the Upgraded Injector Test Facility (UITF). In keeping with the memo issuing the revised ASO, this FSAD is focused on specific accelerator hazards not addressed in other regulations. As such, it does not address standard industrial hazards that are managed under the Thomas Jefferson National Accelerator Facility (Jefferson Lab) Worker Safety and Health Program, which applies federal and local statutes and consensus standards to the mitigation of common industrial hazards present at Jefferson Lab. However, the analyses in this FSAD evaluate industrial hazards that have the potential to initiate or contribute to postulated accelerator-specific accidents.

This FSAD includes an overview of the Jefferson Lab accelerator facilities, analysis of hazards associated with accelerator operations, and a description of the employed hazard mitigations. All of the hazards associated with operations at Jefferson Lab's 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 for the CEBAF, LERF and UITF accelerators, were developed. 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 of the safety of the workers, the public, and the environment.

2.0 INTRODUCTION

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

A secondary purpose is to utilize the technology in the primary program to develop technology for the next generation of accelerators, including high-brightness electron guns, high-gradient superconducting cavities, and energy-recovery linear accelerators.

Jefferson Lab's mission also 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 Jefferson Lab's 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.

Three accelerators support Jefferson Lab's mission:

- The CEBAF accelerator;
- The LERF accelerator; and
- The UITF accelerator.

The CEBAF and LERF accelerators are located within a fence boundary with a single point for routine access that is staffed by security guards around the clock. The fenced boundary designates a controlled area, where training or escort is required for entry. The CEBAF and LERF accelerators share certain utilities and operational interfaces.

The UITF accelerator is located outside the fence boundary but inside the Test Lab. The Test Lab is a Radiologically Controlled Area and General Radiological Training or escort is required for entry.

The Jefferson Lab FSAD presents the information and analyses that demonstrate that the 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 Jefferson Lab personnel, visiting scientists, the public, and the environment. This FSAD was prepared in accordance with the requirements of the ASO, DOE O 420.2C, and the guidance in its associated 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 and FSAD Sections

The objective of this FSAD is to describe the accelerator facility, identify the hazards that are unique to Jefferson Lab accelerator operations and operations support activities, to provide an analysis of postulated operational events that can lead to adverse consequences, and to identify the complete collection of specific controls necessary to minimize the risks associated with these hazards to acceptable levels.

The remainder of this FSAD is divided into the following sections:

- Section 3.0 *SITE LOCATION AND UTILITIES* – discusses the local area and utilities that support Jefferson Lab.

- Section 4.0 *DESCRIPTION OF ACCELERATOR ORGANIZATION AND FACILITY* – describes the Jefferson Lab organization and the features that support safe and effective accelerator operations, the accelerator facility, and component test areas referred to as Technical Areas.
- Section 5.0 *HAZARD ASSESSMENT AND MITIGATION* – discusses the safety analysis methodology, hazards, and related hazard mitigations.
- Section 6.0 *POST-OPERATIONS PLANNING* – discusses post-operations planning (decommissioning and decontamination) as the final phase in the Accelerator Facility lifecycle.
- *Appendix A* Appendix A – Acronyms – provides a glossary of terms and list of acronyms.
- *Appendix B* *Appendix B* – HAZARD ANALYSIS FOR TECHNICAL AREAS – discusses Technical Areas found within the Accelerator Facility, which meet one or more of the definitions of an accelerator but cannot serve as an initiator or contributor to an accelerator specific postulated accident sequence.
- A list of references concludes this FSAD.

2.2 Scope and Assessment Methodology

The scope of the hazard assessment in the FSAD includes hazards unique to the operation of Jefferson Lab's accelerators; therefore, it focuses on hazards in and around the accelerator enclosures and associated support buildings, including above-ground control systems and activities that can impact 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 Regulation (CFR), Part 835 (10 CFR 835) and Part 851 (10 CFR851), 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; therefore, they require an augmented approach. This augmented 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 whole 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 are referred to as Credited Controls. 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 to 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 sometimes used in addition to credited controls 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 accelerator operations at Jefferson Lab. As a result, changes to the Accelerator Facility or its operations that are inconsistent with the underlying basis of the ASE will require additional analysis. This analysis is referred to as the un-reviewed safety issue (USI) process. The USI process is also applied to any discovered conditions. Depending on the outcome of the USI process, changes to this document and to the ASE may result and may require DOE approval.

2.4 Summary

The FSAD 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* *HAZARD ASSESSMENT AND MITIGATION*, below). As such, the FSAD is the safety basis document for the operation of the CEBAF, the LERF, and the UITF. The necessary controls, identified in the FSAD as Credited Controls, and any key requirements associated with these Credited Controls, 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.

3.0 SITE LOCATION AND UTILITIES

3.1 Site Description

The 214-acre Jefferson Lab site 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. Jefferson Lab is located just east of Jefferson Avenue, a main thoroughfare, and is less than one mile to the west of Interstate 64. The Jefferson Lab site is part of the Jefferson Center for Research and Technology and is situated just north of the Oyster Point Industrial Park and southwest of the Marketplace at Tech Center. The general vicinity layout of Jefferson Lab is included as Figure 1 Jefferson Lab Vicinity Plan. Two schools and railroad tracks serving the local rail system are located within one mile of the site. The Newport News/Williamsburg International Airport (airport code PHF) is located two 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 Jefferson Lab operations and is managed by the Army Corps of Engineers.

The federal government owns 169 acres, the Southeastern Universities Research Association, Inc. (SURA) owns 37 acres, and the Commonwealth of Virginia owns 8 acres that are leased through JSA to the DOE. The Jefferson Lab site is an accelerator facility that is home to three accelerators, as well as office, engineering, laboratory, and materials storage buildings and various other structures.

Portions of Jefferson Lab are built on the former Space Radiation Effects Laboratory (SREL) site operated by the College of William & Mary for the National Aeronautics and Space Administration in the 1960s. The Commonwealth of Virginia, in support of the administration's decision to build SREL, developed the Virginia Associated Research Campus, which is now referred to as the Support Service Center. SREL included a synchrocyclotron with a primary beam of 600 Million electron Volts (MeV) protons and secondary beams of 400 MeV pions and muons produced for the purpose of studying the effects of radiation on materials planned for use in space. The synchrocyclotron was removed in 1980 when SREL shut down. The repurposing of the remaining infrastructure was a key consideration in the site selection for the construction of Jefferson Lab. As mentioned above in *Section 2.0* *INTRODUCTION*, the campus is home to three accelerators. The CEBAF and LERF accelerators are located on the 169 acre tract of land in a fenced area known historically as the Accelerator Site. The third accelerator is located in the former SREL main building, now called the Test Lab. Consequently, only portions of the campus are directly involved in or affected by accelerator operations. However, for the purposes of this document, the campus is treated as the accelerator facility.

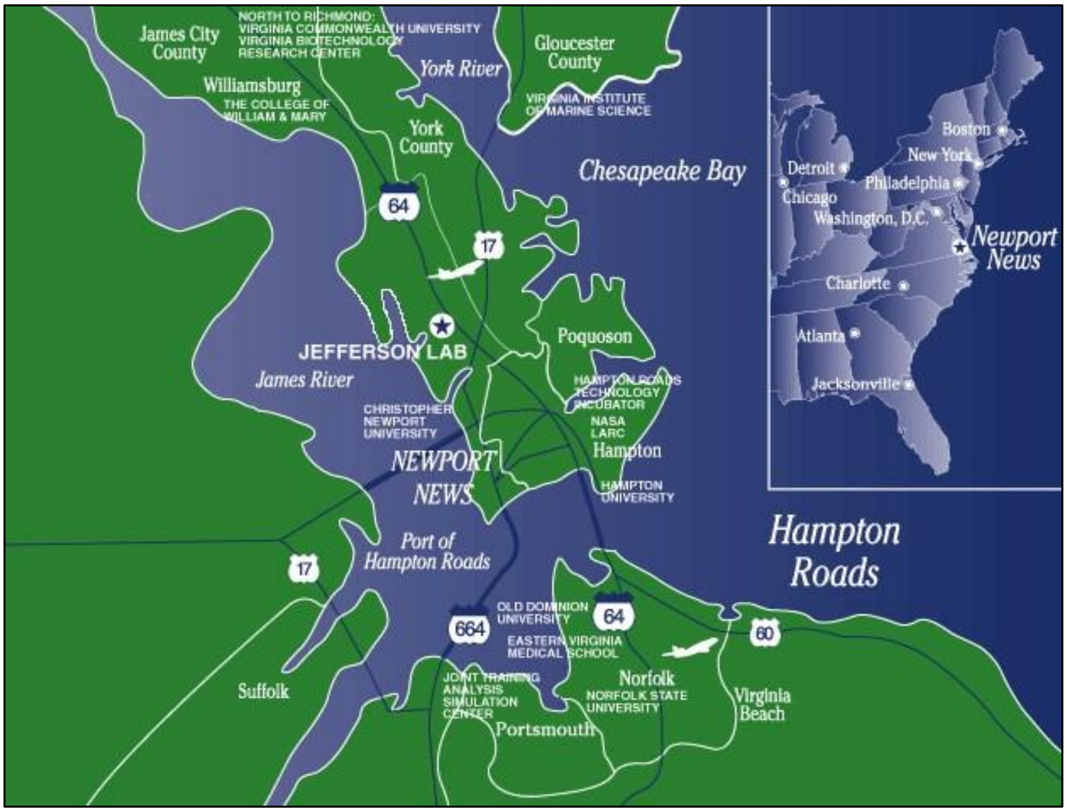

Figure 1 - Jefferson Lab Vicinity Plan

3.2 Area Description and Demography

3.2.1 Population

The population of Newport News has steadily grown over the last 20 years. The U.S. Census Bureau estimated the 2010 population of Newport News at 180,719, an increase of 25% 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 1,585,416 in 2010, up 32% from the 1,201,400 documented in the 1987 Environmental Assessment (EA).

3.2.2 Climate

The meteorology of the Jefferson Lab 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 ºF (January 1940) to 94 ºF (March 1907) with a mean of 37.9 ºF and, in summer, ranged from 46 ºF (August 1934) to 107 ºF (August 1918) with a mean of 78.2 ºF.

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. Heavy fog, reducing visibility to less than 0.25 miles, occurs on an average of 23 days/year. Thunderstorms and other similar severe weather occurs an average of 37 days/year. 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

The Jefferson Lab site 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 is located on the Huntington Flat, which is underlain by the Norfolk Formation and the Yorktown Formation. The site is located in an area of low seismic risk. The most recent large earthquake 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. It 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* *HAZARD ASSESSMENT AND MITIGATION*. The Jefferson Lab site has an average elevation of 34 feet above mean sea level, with an elevation range from approximately 29 to 35 feet, which is above the 100-year floodplain level of 13 feet. The Jefferson Lab site is located in the coastal plain of the lower York-James Peninsula and is a part of the Brick Kiln Creek watershed, which discharges into the Big Bethel Recreational Area (operated by the United States Army).

Three major aquifers are present in the site area: 1) an unconfined water table aquifer, 2) an upper artesian aquifer, and 3) a principal artesian aquifer. The unconfined aquifer present in the Norfolk and Yorktown Formations has a low yield, with thicknesses ranging from 50 to 100 feet below the ground surface. The upper artesian aquifer underlies the water-table aquifer and lies in the Miocene-Eocene age sediments. The principal artesian aquifer is present in sediments of the Cretaceous period.

3.2.5 Air Quality

The Jefferson Lab site 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 standards for water quality.

The Jefferson Lab 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 Publically Owned Treatment Works

The site is served by the Hampton Roads Sanitation District (HRSD). All Jefferson Lab sewer discharges are routed through the western side of the site through four existing lines designated A, BC, D, and EF lines. Most of the industrial wastewater discharges authorized by Jefferson Lab'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 the floor drain sump pit located on the Accelerator Site that also contains low conductivity water (LCW) with low levels of radionuclides. The permit requires pH monitoring of two existing industrial effluent lines (lines D and EF), along with flow meter volumes submitted monthly to HRSD. The permit also requires pH monitoring, flow meter volumes (reported monthly), and periodic radionuclide analysis of the floor drain sump pit.

3.3.3 Storm Water Management

The City of Newport News has developed a comprehensive storm water 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-

yearfrequency storm without surcharging the pipes or overtopping the off-site channels. Site drainage consists of existing channels and two storm water retention ponds that flow to the Brick Kiln Creek Watershed in accordance with an 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 the DOE from the State of Virginia, the City of Newport News, and SURA.

Jefferson Lab is authorized to discharge storm water through the Municipal Separate Storm Sewer Systems (MS4) permit with the Virginia Department of Environmental Quality (DEQ). Several Best Management Practices are utilized as part of the MS4 permit to prevent unauthorized nonstorm water discharges into Jefferson Lab's storm water management system of ditches, drains, and ponds. These Best Management Practices include:

- Annual MS4 Report/Program Plan submittal to DEQ;
- Monthly on-site self-inspections of MS4 under the 'Illicit Discharge Detection and Elimination program';
- Routine preparation/submittal of a 'Chesapeake Bay Total Maximum Daily Load Action Plan' to account for proper management of nutrient loads in storm water runoff; and
- Yearly DEQ approval of an 'Annual Standards and Specifications for Stormwater Management/Erosion & Sediment Control.'

3.3.4 Power: Electrical and Natural Gas

Dominion/Virginia Power provides three independent medium voltage services to the Jefferson Lab site to meet power requirements.

Two substations located on the Accelerator Site, a 40 and 33 megavolt-Amperes (MVA) substation, 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 the Jefferson Lab site, is powered by a separate feed coming from the Rock Landing substation. In addition, Dominion provides electric service, also from the Rock Landing substation, to buildings 13, 19 and 28 that are located away from the main campus.

Natural gas is supplied to the site by Virginia Natural Gas Company through a pipeline from Jefferson Avenue. Natural gas service supplies boilers for heat and hot water and also fuels several standby emergency power generators. See *Section 3.4.1*, Site Power, Emergency Power, and Uninterruptable Power 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 different locations to provide redundant connections. A second company provides most of the long distance phone service via connection with the Federal Telephone Service.

The main Internet service is provided by one telecom through a fiber-optic ring that Jefferson Lab shares with the College of William & Mary and Old Dominion University in a partnership arrangement. This fiber-optic ring allows connections through Atlanta and Washington D.C. with the DOE Energy Science Network (ESNet) that connects all DOE-related laboratories. This same telecom brings connection to two different locations at Jefferson Lab. There is a second, lowerspeed backup circuit provided by a second telecom company. Telecom and Internet services are redundant, have automatic fail-over features, and are geographically diverse to provide reliability.

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 Power, Emergency Power, and Uninterruptable Power

As mentioned in *Section 3.3.4* *Power: Electrical and Natural Gas* above, there are three sources of power to the laboratory. 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" that is 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 as the 37 MVA Substation. 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 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 3.4.4* *Low Conductivity Cooling Water (LCW)*, above experience power outages. The generators use natural gas, diesel fuel, or liquid propane, depending on location. 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 FM&L:

- CEBAF Center (Building 12) – Computer Center;
- Service Support Center (Building 28) – Finance and main fire control system;
- Applied Research Center Building – Life safety systems and fire pumps;

- Experimental Halls A (Building 101), B (Building 94), and C (Building 96), – Ground water pumps, Oxygen Deficiency Hazard (ODH) alarms, and Hall equipment support;
- Counting House (Building 97) – Ground water pumps, ODH alarms and Hall equipment support;
- Accelerator Emergency Loop (Building 67) – Pumps and equipment and ODH Alarms
- Test Lab (Buildings 58) – Life safety, ODH alarms, Scrubber Vent System and other equipment;
- Technology and Engineering Development (Building 55) – Life safety;
- Accelerator Maintenance Support (Building 87) – Phone switch system;
- Low Energy Recirculator Facility (Building 18) – Sump pumps and ODH alarms;
- Machine Control Center (MCC) (Building 85);
- Security Post 2 (Building 51 – Accelerator Gatehouse); and
- Central Utility Plant (Building 60).

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

Jefferson Lab utilizes several types of telecommunications service. Telephone services include telephone landlines, mobile phone and Voice over Internet Protocol services. A paging service is also used for rapid notification and text messaging.

Jefferson Lab is served by a wide area network connection provided by ESNet, 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 on-site are based on gigabit and fast Ethernet technology and provide connectivity for computer systems, printers, VOIP telecommunications, and other network devices in all buildings.

Jefferson Lab's computer networks, including the networks used for facility infrastructure controls and accelerator controls, are protected against unauthorized use and malicious intrusion by a layered defense model that 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.

With very few exceptions, systems associated with the CEBAF accelerator are controlled and monitored by an Experimental Physics and Industrial Control System (EPICS). Software control is managed by the Accelerator Control Group. The group provides a structured and controlled software development and maintenance environment. Consequently, software for EPICS accelerator control is developed using standard development methods that include planning, testing, documentation, and configuration management.

Conventional Facilities control systems for buildings (access, Heating, Ventilation and Air Conditioning, etc.) cooling towers and water supplies, cryogenic plant, 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 (CHL)

There are two helium refrigerators at CHL (CHL1 and CHL2) that support 2 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 Linear Accelerators (LINACs). CHL1 is normally configured to support the South LINAC and LERF. CHL2 is normally configured to support the North LINAC 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 because of the high noise levels. There are two, 20,000-gallon LN2 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 Refrigerator (ESR) for the physics experimental halls. 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 support the recovery system at the CHL.

3.4.3.2 End Station Refrigerator (ESR)

The ESR is located near Halls A, B, and C within the west side of the fenced boundary. The ESR provides 4 and 15 Kelvin gas to Halls A, B, and C via a transfer line system. The CHL is also capable of sending up to 20 g/s of 4 Kelvin helium through a transfer line from the CHL to the ESR 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. There is a 6,000-gallon LN2 dewar and a 1,000-gallon liquid helium dewar east of the Hall D Refrigerator building. Cooling water is supplied from cooling towers west of building, and there is one, 30,000-gallon warm helium gas tank also on the west side of Building 201.

3.4.3.4 Cryogenic Test Facility (CTF)

The CTF (Building 57) is located on the east side of the Test Lab outside the fence boundary. There are two helium refrigerators at the CTF that support 2, 4, and 35 Kelvin operations in the Vertical Test Area (VTA), Cryomodule Test Facility (CMTF), and the UITF via transfer line systems. There is a 13,000-gallon liquid nitrogen dewar and a 7,000-gallon liquid helium dewar north of the building. Cooling water is supplied from cooling towers on the north side of the CTF. There are four, 30,000-gallon warm helium gas tanks located on the south side of the Building 57.

3.4.4 Low Conductivity Cooling Water (LCW)

LCW is water that has been processed to remove impurities to lower or eliminate conductive and corrosive properties of water used to cool electrically energized systems. There are four LCW systems; one located in the North Linac Service Building, one located in the South Linac Service Building, one located at Experimental End Stations A, B and C, and one located near Experimental End Station 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.

LCW 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, which are located inside accelerator enclosure. LCW is also used to cool several types of accelerator components that directly intercept the beam. This includes direct cooling for low power and tune up dumps, and low power portions of beam 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

Written “Memoranda of Understanding/Agreements” with the City of Newport News Police and Fire Chiefs ensure emergency services through the City’s 911 system. Services include emergency medical response and transport, emergency “technical” rescue, fire-fighting, and hazardous material incident response. These memoranda are kept on file with Jefferson Lab’s Emergency Manager and the City of Newport News Police and Fire Chiefs. Jefferson Lab maintains regular, and mutually beneficial, interactions with local emergency response services in the form of planned exercises, training, and preplanning visits to the site. Jefferson Lab also provides sitespecific 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 resulting from radiological complications and acid exposures that might result from chemicals used in acid-etching processes.

4.0 DESCRIPTION OF ACCELERATOR ORGANIZATION AND FACILITY

4.1 General Description

The Jefferson Lab campus consists of buildings and grounds supporting the operation of two accelerators located inside a fenced boundary, and a third accelerator outside the fenced boundary and located in a multi-purpose building called the Test Lab. There are 57 buildings inside the fenced boundary and 75 buildings in total on the campus. There are three buildings in which space is leased, one building adjacent to the campus and two 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 *Section 3.1 Site Description*. The multi-purpose building that houses the third accelerator contains low level residual radioactivity that remains imbedded in concrete shielding in a few locations. For purposes of DOE O 420.2C, Safety of Accelerator Facilities, 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 Radio-Frequency (SRF) technology, physics detector research and development, data-acquisition, and high-speed computing. Jefferson Lab staff provides management, administrative, logistical, and safety support. Jefferson Lab serves an international user community of approximately 1,500 scientists. On any given day, there are approximately 700 employees and up to 100 visiting scientists.

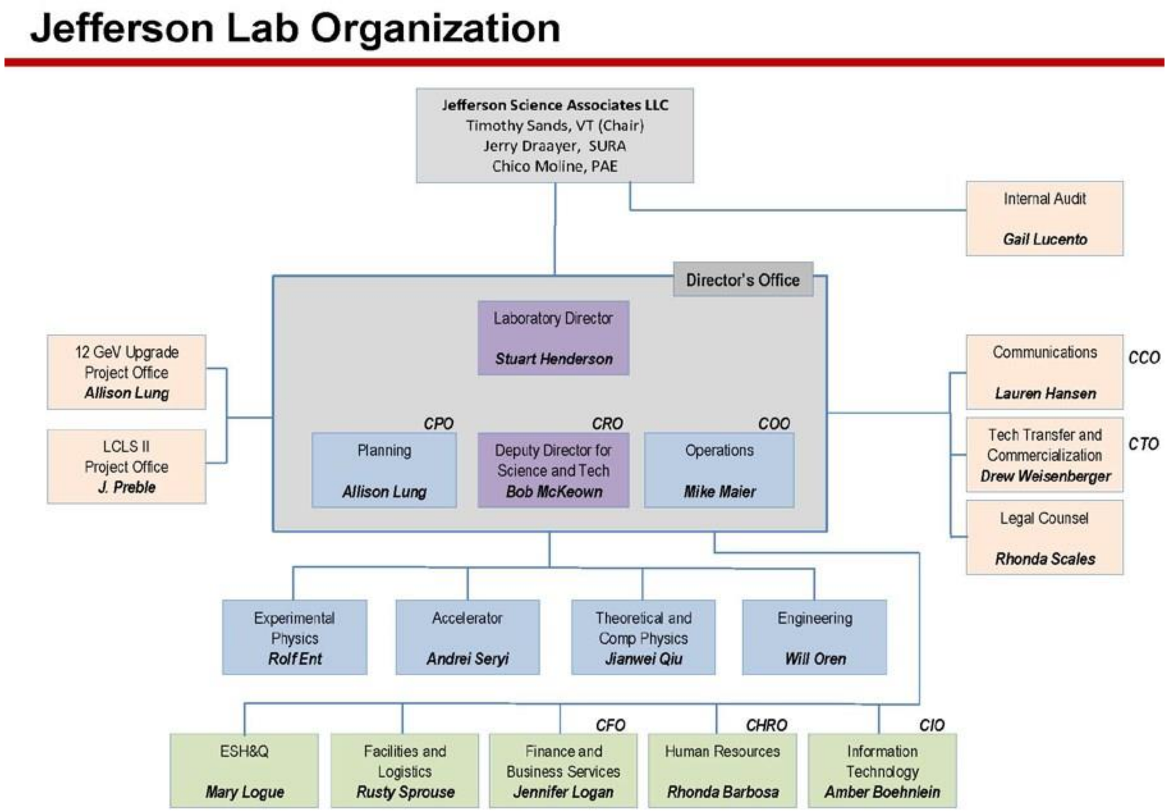

Figure 2 – Jefferson Lab Organization

4.2 Safety Support by Organization

Figure 2 – Jefferson Lab Organization above, shows that safe operation of the accelerators for the conduct of nuclear research is supported by engineered safeguards and processes, and administrative programs, process, and procedures maintained by organizational units throughout Jefferson Lab. 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 simply 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. Accelerator Division manages accelerator repair and maintenance activities performed by division staff and other laboratory organizations. This is discussed in more detail below.

4.2.1.1 Accelerator Governing Processes and Procedures

Accelerator Division develops and maintains the Accelerator Operations Directives (AOD), the LERF Operations Directives (LOD), and the UITF Operations Directives (UOD) which govern accelerator operations for CEBAF and LERF accelerators, the UITF accelerator, and the associated beam-delivery systems. These directives describe how safety is integrated into execution of the CEBAF and LERF accelerator programs and establishes 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 AOD and LOD describe the planning, scheduling, and coordinating of maintenance and repair activities to maintain and improve accelerator availability, integrate projects, and interface with and conduct of physics experiments. The AOD and LOD define the operational interfaces (both processes and hardware) between Accelerator and Physics Division 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 authorization of beam delivery. Note: Gun high voltage processing and/or cathode re-Cesiation and gun operation that produces electrons with energy up to the applied bias voltage on the gun is not considered accelerated beam for the purposes of this FSAD.

The AOD, LOD, and UOD 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 FSAD 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-job planning, hazard analysis, and a standard review/approval process.

Accelerator Division uses a process called System Hot Checkout. This is a period of scheduled, dedicated time, during which all accelerator systems are recovered, exercised, and made ready for beam operation prior to restoring beam. Hot checkout ensures that systems and tools are verified as operational.

At the discretion of the Accelerator Division Associate Director, the Experiment Readiness Review (ERR) process identified in *Section 4.2.2.1 Physics Governing Processes and Procedures* may also be applied to proposed activities outside the experimental end stations. The Accelerator Division Associate Director will determine whether Environment, Safety and Health (ES&H) Manual Chapter 3120 The CEBAF Experiment Review Process, or Chapter 3130 Accelerator Experiment Safety Review Process will be used in a graded approach to assess activities proposed for the CEBAF beam enclosure, or the LERF and UITF accelerators. The Director of Operations shall determine the scope and scale of review methodology selected by the Accelerator Division Associate Director for these cases.

CEBAF-specific OSPs and Temporary OSP are developed when a task involves high-hazard activities, unusual safety hazard activities that are not fully addressed in the ES&H Manual, or unique operational features such as tasks involving multiple work groups (see ES&H Manual Chapter 3310 Operational Safety Procedures (OSP) Program). Copies of specific OSPs and Temporary OSPs that pertain to accelerator operations are maintained in a binder in the Machine Control Center. These documents are reviewed by all operators and Crew Chiefs.

The operational requirements for the UITF are addressed in an approved OSP that governs UITF operation.

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 Personnel Safety Systems (PSS) to the point that they can operate the PSS of each respective accelerator.

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 UOD that governs UITF operation. Training on the operation of the UITF is done by the UITF Facility Manager.

4.2.1.3 Accelerator Engineered Systems

4.2.1.3.1 Accelerator and Beam Dumps

The Accelerator Division is responsible for the proper configuration, maintenance, and operation of the accelerator from the injector to the high-power beam dumps, with the exception of the beamline from the alcove shield wall to the target assembly. The Physics Division is responsible for the beam line from the alcove shield wall to the target assembly. The Accelerator Division is responsible for the electrical distribution, cooling water distribution, vacuum, and pressure related utilities provided by the Facilities Management and Logistics (FM&L) Division pressure and vacuum systems, power supplies, and control systems associated with the accelerator and its components.

4.2.1.3.2 Accelerator Computer Controls System

The systems that constitute the accelerator controls are managed and monitored by EPICS. Computer hardware and software is 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.

4.2.1.3.3 CEBAF Accelerator Max Juice

Max Juice is an active engineered system, required only in the CEBAF accelerator, which turns off the accelerated beam when the beam current reaches a user-specified threshold for a specific destination. The system accommodates multiple, simultaneous beam destinations and is intended to trip the beam before reaching beam current limits.

4.2.2 Experimental Physics Division

The Experimental 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 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 ultra-high-speed data acquisition equipment in four experimental halls.

4.2.2.1 Physics Governing Processes and Procedures

A Memorandum of Understanding is developed and serves as an agreement between a group of experimenters and the Jefferson Lab Director that sets forth the commitments of all parties involved in all phases of an experiment.

Experiment proposals are reviewed for merit and approved experiments are subject to the CEBAF 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 3120 The CEBAF Experiment Review Process.

The ERR process provides a progressive review of an experiment from the proposal stage through to the installation and checkout and their 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, 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 Document, 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, 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 addresses 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.

OSPs and Temporary OSPs are developed when a task involves high-hazard activities, unusual safety hazard activities that are not fully addressed in the ES&H Manual, or unique operational features such as tasks involving multiple work groups (see ES&H Manual Chapter 3310 Operational Safety Procedures (OSP) Program). OSPs 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.

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

4.2.2.2 Physics Training and Personnel

Physics Division provides the personnel and procedures for personnel who operate and maintain the equipment in each of the 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 in OSPs.

To ensure close coordination between Jefferson Lab and external users on operational and ES&H issues, Physics Division assigns a Liaison Physicist/ES&H Coordinator 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.

Physics Division provides Hall Awareness Training; this training familiarizes workers with the hazards and mitigations unique to, and associated with, each experimental hall.

4.2.2.3 Physics Engineered Systems

Physics Division is responsible for beam line hardware from the alcove shield wall to the target assembly and the physics target design, fabrication, assembly and functionality. This includes 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, cryogenic and electrical engineering, design and fabrication support. The division also provides survey and alignment, document control, magnetic measurements, fabrication, and machine shop services. The division maintains and operates the cryogenic production facilities. The division is also home to the Safety Systems Group (SSG). Its expertise extends to risk and reliability analysis, fail-safe design, programming techniques, and development of standards and practices. The SSG manages the PSS, Machine Protection Systems (MPS), and ODH monitoring systems on the accelerator site.

4.2.3.1 Engineering Governing Processes and Procedures

The Engineering Division maintains the Conduct of Engineering Manual (COEM). This manual identifies Configuration Management (CM) requirements on the basis of mission support and safety using a graded approach. CM 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 CM requirements – these systems are critical to mission/operation and have high safety impact. The basis for the application of Level 1 CM systems is discussed in COEM Section 5: Configuration Management. The Level 1 CM 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. Certification involves a multiday procedure-driven process performed by Accelerator Operations and SSG 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. Accelerator Crew Chiefs verify the functionality of the PSS from the MCC while SSG (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.

4.2.3.2 Engineering Training and Personnel

The Engineering Division provides design and operational expertise for vacuum and pressure systems that make up accelerator hardware, and for the design and operation of electron beam dumps.

The SSG trains and certifies Accelerator Operators in PSS function and operation. These trained operators are referred to as SSO. SSOs operate the PSS, perform sweeps in each PSS segment, and facilitate Controlled Access in PSS segments. Accelerator Operators are trained to operate and respond to alarms from the ODH monitoring system.

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

4.2.3.3 Engineered Systems

4.2.3.3.1 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 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 eight logical segments of the PSS are illustrated in Figure 3 – Segments of the PSS below.

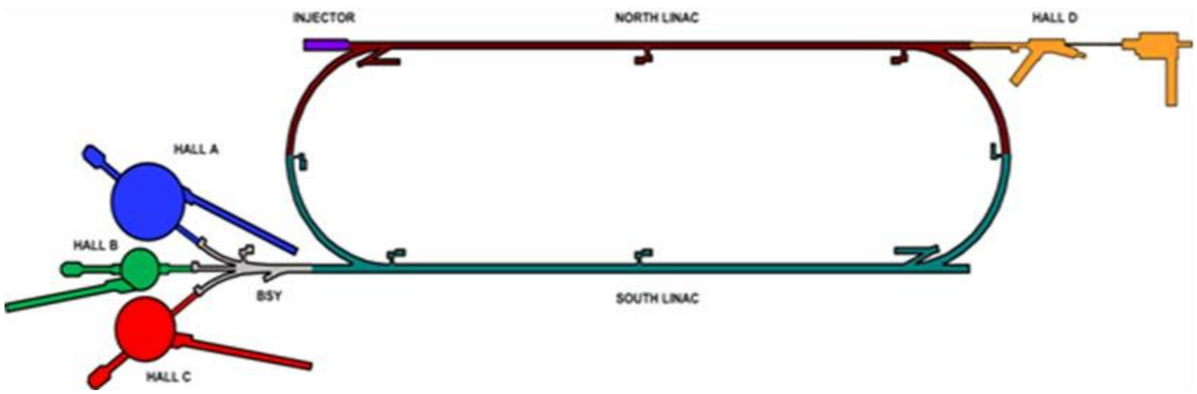

Figure 3 – Segments of the CEBAF PSS

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 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 the SSG 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 also provides for access to already swept areas by a limited number of staff for problem troubleshooting and repair. This entry procedure is referred to as Controlled Access procedure. Under the Controlled Access procedure, each entrant is processed by a 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 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 the SSG within Engineering Division. Other staff may be assigned to work with the SSG on an as-needed basis. However, the SSG 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 FSAD, a PSS failure is characterized by an event where:

- The PSS system fails to function in the manner in which it was designed – (i.e. 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. (i.e. 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 fails to function as designed while providing protection.

PSS failures are promptly evaluated by the SSG and the Safety Configuration Management Board (SCMB) to determine whether the failure violates the conditions of the ASE or represent 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 SSG 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 to accept beam will also cause the PSS to render safe other potentially hazardous devices within a beam enclosure. The PSS serves to integrate numerous safety functions which are not Credited Controls but serve as defense-in-depth. For example, the PSS receives trip signals from the Controlled Area Radiation Monitors (CARM). 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 may be used to control access temporarily as a means of limiting access to a hazardous condition, e.g. a High Radiation Area with whole body dose rate in excess of 1000 mrem/hr.

4.2.3.3.2 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 from anywhere in the accelerator in less than 100µs. 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 beam loss greater than 2 µA for continuous wave or greater than 25,000 mA µsec for a pulsed beam will interrupt beam delivery.

In addition, the Beam Envelope Limit System (BELS) ensures that the CEBAF accelerator does not exceed its design beam power envelope of 1 Megawatt (MW). 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 a 900 Kilowatt (kW) operational limit. If necessary, however, the Beam Envelope Limit System has the ability to turn off the beam before the operations limit is exceeded.

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 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 inhibits.

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

4.2.3.3.3 Engineering ODH

ES&H Manual Chapters 6540 Oxygen Deficiency Hazard (ODH) Control Program and ES&H Manual Chapter 6550 Cryogenic Safety Program serve as the basis for the Jefferson Lab ODH management program. These requirements apply to each accelerator and technical area where the uncontrolled release of compressed and/or liquefied gasses can result in cryogenic burns and lead to a reduction in the concentration of available oxygen in the work area, creating an ODH. There is potentially serious health effects 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 such as lintels and helium removal vents situated in key locations. Administrative controls include training and specialized Personal Protective Equipment (PPE) and monitoring equipment. Active controls include engineered safeguards such as floor and ceiling mounted ODH monitors that 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 FSAD, 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 SSG 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.

The ODH System functionality is certified every two years by physical testing of the system. ODH System failures detected during calibration are not ASE violations but shall be evaluated by the SSG 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, and UITF accelerators are considered Credited Active Engineered Controls.

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 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 Training and Performance 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, Health, and Quality (ESH&Q)

ESH&Q 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 and DOE requirements (including DOE rules and orders as imposed on Jefferson Lab by the maintenance 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 ESH&Q Division, which serves as a resource for the lab as a whole by providing industrial safety, industrial hygiene, health physics, radiation control, environmental management, occupational medicine, and quality assurance. The ES&H program extends to visiting researchers, subcontractors, and the public through all divisions and offices.

4.2.5.1 ESH&Q 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 ESH&Q 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, Environmental Protection, and Quality Assurance.

4.2.5.1.1 ESH&Q Worker Safety and Health

The Jefferson Lab Worker Safety and Health Program defines a program that satisfies the requirements of 10CFR851 Worker Safety and Health Program and assures industrial worker safety and health. ES&H policies for industrial hazards are contained in the ES&H Manual. OSPs and Temporary OSPs are work control documents that are required by Jefferson Lab policy, as specified in the Jefferson Lab ES&H Manual 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 developed and specific controls 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 FSAD which focuses on industrial hazards that are specific to accelerators or have the potential to initiate or contribute to postulated acceleratorspecific accidents.

4.2.5.1.2 ESH&Q Radiation Protection

The Jefferson Lab Radiation Protection Program (RPP) defines the program that satisfies the requirements of 10CFR835 and addresses radiological worker safety and health. The RPP defines requirements for the management of dose 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. The Beam Containment Policy and Access Control Policy provide 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 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 ESH&Q Radiation Protection*) that are typically located outside shielding.

Shielding is identified as a Credited Passive Engineered Control in an ASE. The RCD is responsible to verify, 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. Operational radiological controls and monitoring systems and outside shielding serve as defense-in-depth Administrative Controls.

4.2.5.1.3 ESH&Q Environmental Protection

The Jefferson Lab Environmental Protection Program governs the environmental management practices of the lab, provides oversight and monitoring of operations that could have environmental impacts, and assures compliance with the various federal, state and local regulations that apply to the facility and all operations. The RPP is coordinated with the Environmental Protection Program to assure protection of the environment and the public. ESH&Q publishes an Annual Site Environmental Report, available to the public, which presents the results of monitoring processes conducted by Jefferson Lab.

4.2.5.1.4 ESH&Q Quality Assurance Program (QAP)

It is Jefferson Lab's policy to integrate "quality and self-assessment into all activities for continuous improvement." As part of the Jefferson Lab Contractor Assurance System, quality management activities are based on a graded approach that assures appropriate controls and feedback commensurate with the scope and associated risk for each activity. The Quality Assurance Department 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 describes how the applicable criteria are implemented at Jefferson Lab. The QAP also facilitates implementation of DOE O 420.2C – Safety of Accelerator Facilities, incorporating requirements into Integrated Safety Management where possible and providing functional oversight for other key activities including the Accelerator Readiness Review and USI process.

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

- Ensuring the integrity of PSS software changes, system maintenance, and testing, which are maintained according to the PSS Configuration Management Procedure;
- 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,

- Assessment of accelerator operations in reference to DOE 420.2C, Safety of Accelerator Facilities.

4.2.5.2 ESH&Q Subcommittees

A number of ES&H Subcommittees function under the Associate Director, EHS&Q. 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, EHS&Q, to address accelerator-specific safety issues. As such, the SCMB is charged with:

- Screening safety concerns pertaining to accelerator operations;
- Determining whether the safety concerns are USIs, ASE violations, or deficiencies in Jefferson Lab policies or the implementation thereof; o Determine whether discovered conditions are in violation of requirements in the ASE or represent conditions not (properly) assessed in the FSAD; and, o Evaluate planned changes to ensure they occur in a manner consistent with the FSAD and requirements in the ASO and in compliance with the ASE;
- Reviewing and approval of changes to the credited controls defined in the ASE and to other systems or processes that can impact the effectiveness of the credited controls;
- Determining whether changes that potentially impact accelerator safety have been implemented and documented properly; and
- Recommending training to assure 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 FSAD document and the ASE.

4.2.5.3 ESH&Q Training and Personnel

The Associate Director for ESH&Q 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 ESH&Q Division has been delegated by TJSO to serves as the electrical “Authority Having Jurisdiction.”

Training, to obtain the industrial safety skills in a Skill Requirements List, is provided by SMEs in ESH&Q Division and in the line organizations that have responsibility for certain accelerator specific hazard controls. ESH&Q 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 ESH&Q includes ODH Training, and Radiation Worker training including the process for making a Controlled Access.

Radiation Worker Training provided by the RCD is considered a defense-in-depth control.

4.2.5.4 ESH&Q Engineered Systems

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

CARMs are high-reliability devices with sensitive detectors that measure prompt ionizing radiation from accelerator operation and from radiation generating devices such as accelerator component test stands. CARMS have internal data logging features and 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 the CEBAF, LERF, and UITF accelerator enclosures. The data and alarms that CARMs provide are monitored centrally by CEBAF and LERF Accelerator Operators in the MCC, and in the UITF control room. CARMs deployed at radiation generating devices are operated according to requirements specific Radiation Control Operating Procedures or Operational Safety Procedures.

RBMs are located at the Jefferson Lab site boundary outside 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 centralized display for Accelerator Operators and data logging for RCD staff.

Hydrogen gas monitoring systems maintained, calibrated, and operated by ESH&Q 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 air.

The CARMs are considered defense-in-depth controls for CEBAF, LERF, and UITF. The hydrogen gas monitors are considered as defense-in-depth controls for the buildings that house high-power beam dump cooling system components.

4.2.6 Information Technology (IT)

The IT Department 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 IT, 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.

4.2.6.1 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.

4.2.6.2 IT Training and Personnel

CNI provides cyber security infrastructure for the lab and supports cyber security for accelerator operations computers and network. 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.

4.2.6.3 IT Engineered Systems

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

4.2.7 Facilities Management and Logistics (FM&L)

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

4.2.7.1 FM&L Governing Processes and Procedures

FM&L is responsible for the buildings and utilities on the accelerator site that serve the CEBAF accelerator, experiment halls, LERF, and UITF. FM&L implements security on the Jefferson Lab campus by executing the Site Security Plan. This includes 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 and LERF accelerators.

Facility conditions including the integrity of shielding and the high-power Beam Dump Cooling Buildings (Buildings 91 and 95) structural integrity is verified at least every five years. Facility integrity, including shielding material (depth, thickness, etc.) is verified by FM&L and is tracked in the Facilities Information and Management System 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.

4.2.7.2 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 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 Subcontracting Officer's Technical Representative, who is responsible for evaluating subcontractor training, determines training requirements for subcontracted activities.

4.2.7.3 FM&L Engineered Systems

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

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

4.3 Accelerators and Technical Areas within the Fence

There exists a security fence around the two main accelerators at the Accelerator Facility. 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.

Both the CEBAF and LERF accelerators are also used as test beds for an advanced accelerator physics research and 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.

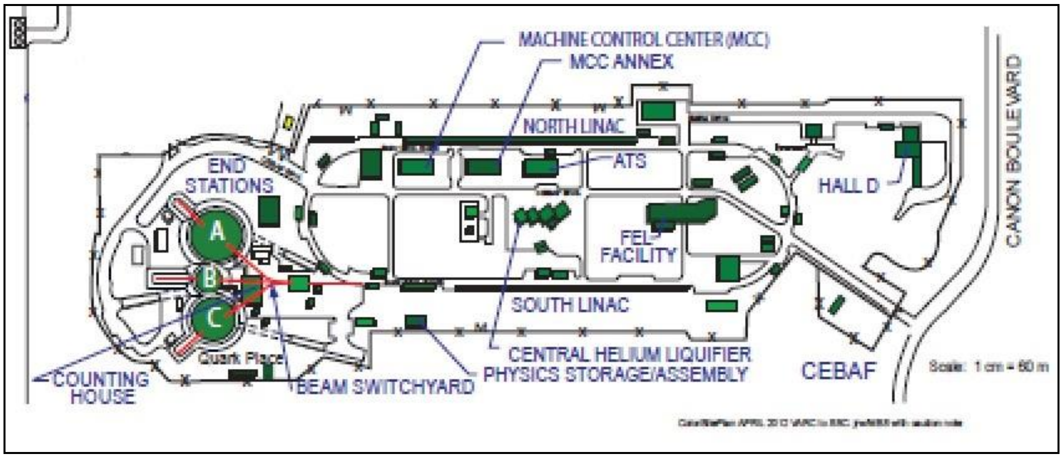

Figure 4 – Accelerator Site Plan within the Fence

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, ten 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 Gigaelectron-Volt (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 MW however BELS alerts the control room staff when beam power reaches a 900 kW operational limit. 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. The Accelerator Operations application Max Juice is used to govern beam current delivery to beam destinations (experimental halls / beam dumps).

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 provides the beam containment and access controls necessary for segmented operations.

4.3.1.1 Beam Generation and Transport

The CEBAF injector is located within the accelerator enclosure and contiguous to the CEBAF accelerator tunnel. This injector uses a laser-driven photocathode designed to provide four spin polarized electron beams which can be accelerated and directed to different experimental end stations simultaneously. In the injector, the electron beam is shaped and accelerated by one ¼ cryomodule and two full cryomodules before it is injected into the north LINAC.

The laser-driven photoelectron gun can be biased at negative high voltage using two different Glassman high voltage power supplies with the following voltage and current specifications: 150kV/10mA and 350kV/4.5mA. The lower voltage power supply is used to provide 130keV beam. The higher voltage power supply uses sulfur hexafluoride (SF6) as an insulating gas and will be used to generate 200keV beam consistent with requirements of an anticipated injector upgrade. The excess voltage available from both high voltage power supplies is used during high voltage commissioning of a new photoelectron gun to process-out field emitters that degrade vacuum and limit operational lifetime.

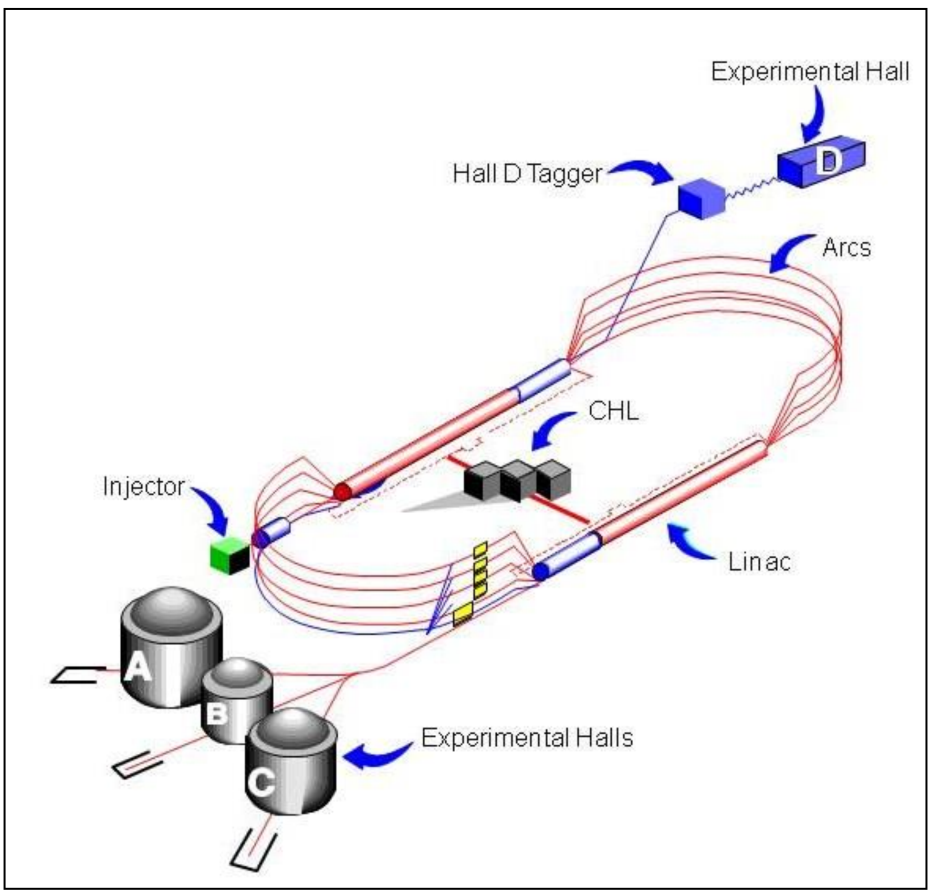

Figure 5 – CEBAF Accelerator Layout

The injected beam is accelerated by two parallel LINACs consisting of multi-cell superconducting niobium cavity structures housed in 25 cryomodules cooled to two Kelvin by liquid helium supplied by the CHL. Each niobium cavity in a cryomodule is powered by a klystron that provides 1497 megahertz (MHz) RF radiation and produces a CW acceleration gradient from 5 to 30 MV/meter. Because of the geographical orientation of the accelerator, these LINACs are referred to as the North and South LINACs. 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.

Once the beam is injected into the North LINAC it is accelerated to an energy of approximately 1.1 GeV. At the end of the North LINAC, the beam reaches a magnetic spreader region. The spreader bends the beam into an arc with the ability to transport the beam to a recombiner where it enters the South LINAC. Once in the South LINAC, the beam is accelerated by up to 25 more cryomodules to approximately 2.2 GeV. At the end of this first pass through the accelerator, beam may be transported to the next arc for another pass or extracted to the beam switch yard and sent to an experimental facility. Each pass through the accelerator adds 2.2 GeV to the beam energy and presents the opportunity to extract beam to an experimental facility or continue to the next pass.

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 on 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 6 – Jefferson Lab 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 large solid angle and target acceptance (6 millisteradian and +/- 5 centimeter).

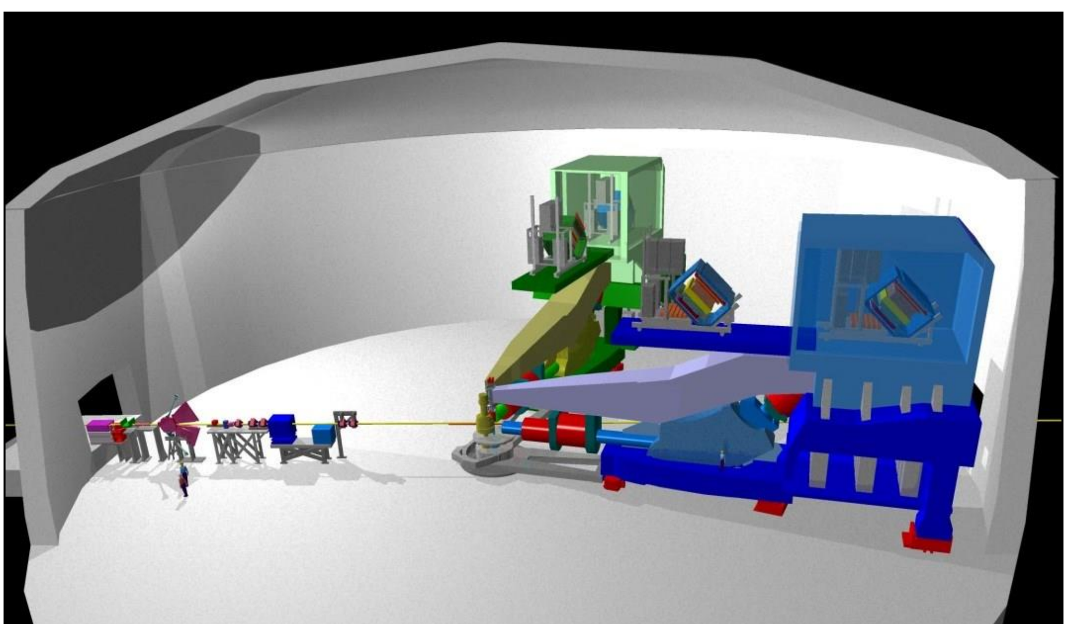

Figure 6 – Jefferson Lab Experimental Hall A

Figure 6 – Jefferson Lab Experimental Hall A 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).

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 (left of Figure 7 – Jefferson Lab Experimental Hall B) 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 GeV can be used with the tagger.

Experimental data are collected by the CEBAF Large Acceptance Spectrometer (CLAS12) shown schematically in Figure 7 – Jefferson Lab 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).

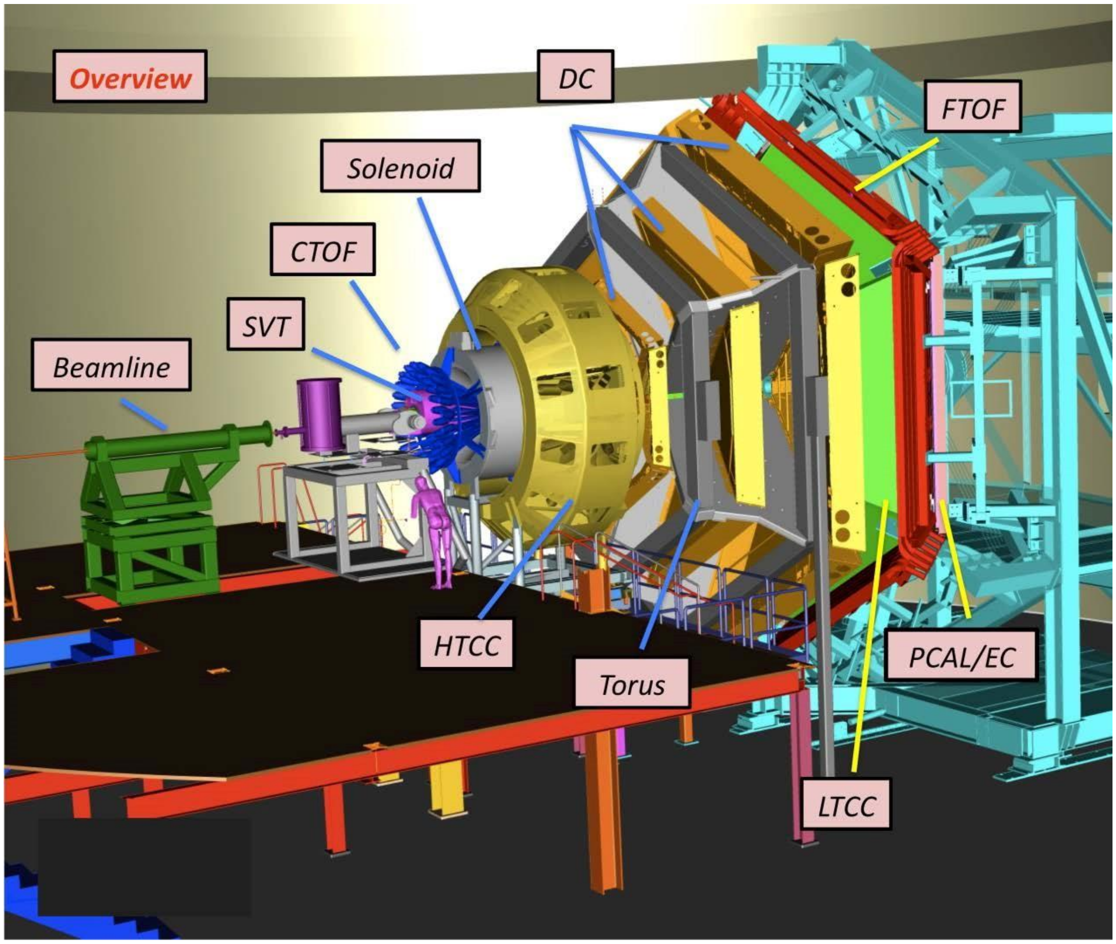

Figure 7 – Jefferson Lab Experimental Hall B

4.3.1.2.3 Experimental End Station (Hall) C

Hall C (see Figure 8 – Jefferson Lab 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 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.

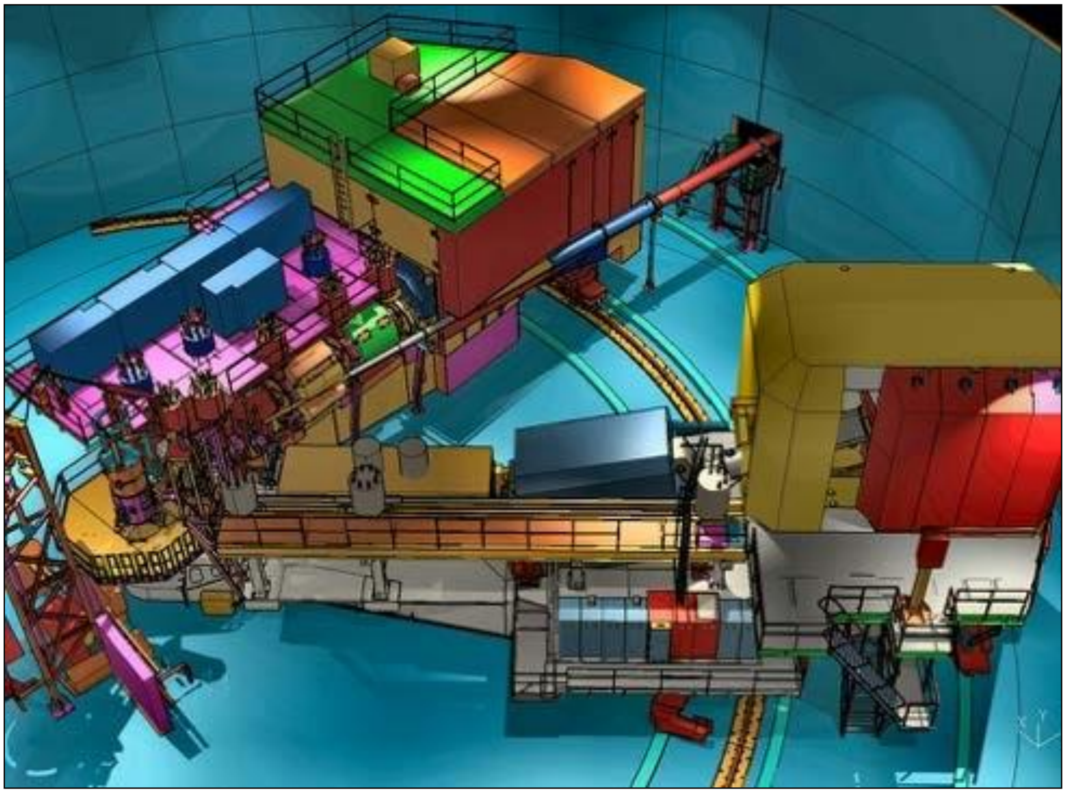

Figure 8 – Jefferson Lab Experimental Hall C

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 experimental hall (see Figure 10 – Jefferson Lab 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.

4.3.1.2.4.1 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 beam line in the accelerator tunnel extension to the Tagger (see Figure 9 – 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, 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.

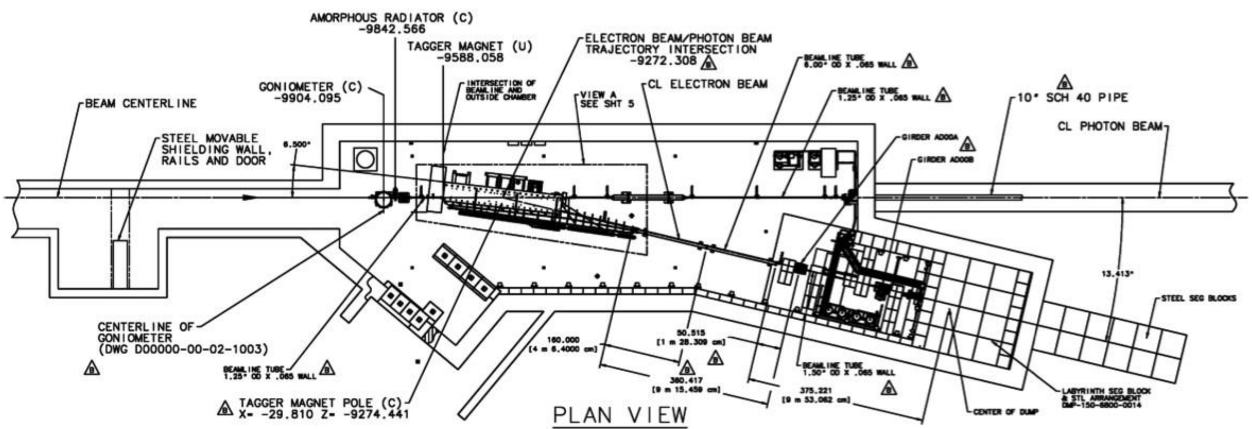

Figure 9 – Hall D Tagger

In Figure 9 – Hall D Tagger above, 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.

4.3.1.2.4.2 Hall D Collimator

The photon beam produced in the Tagger enters Hall D from the left side of the hall, see Figure 10 – Jefferson Lab Experimental Hall D, below. 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.

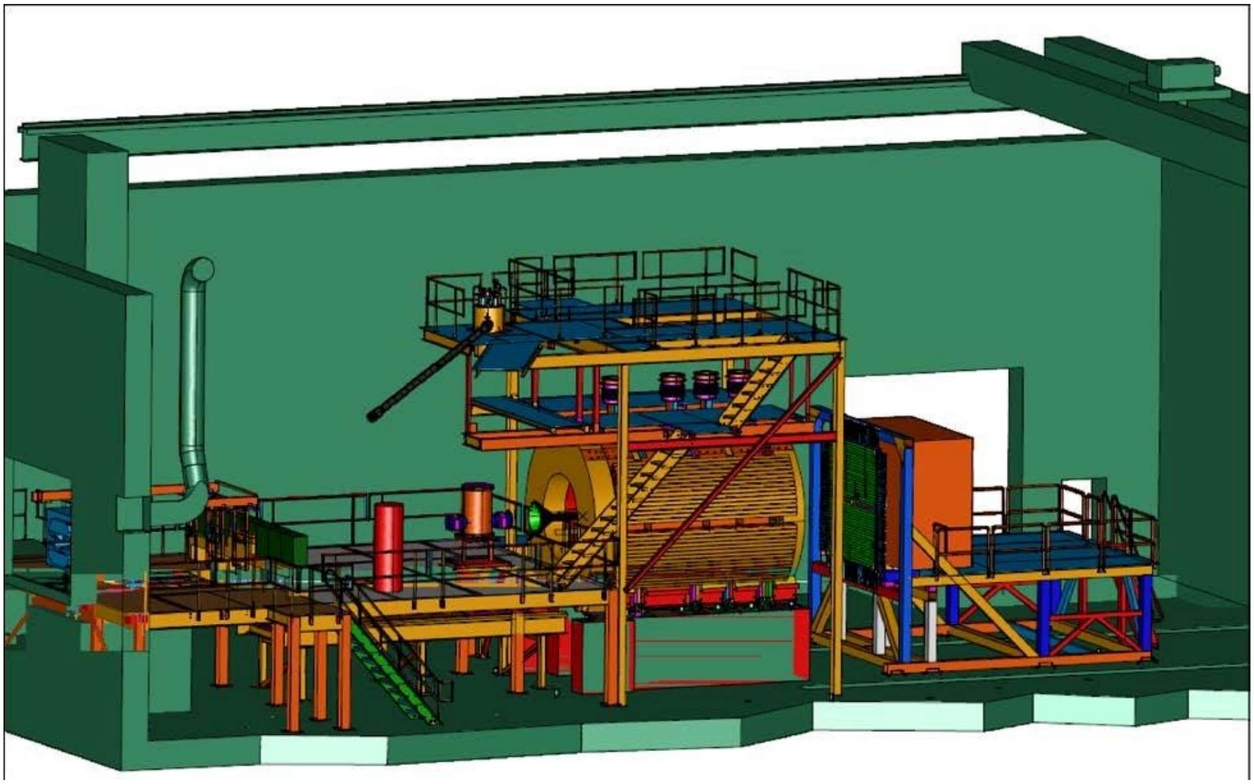

Figure 10 – Jefferson Lab Experimental Hall D

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 towards the right side of the figure on its way to the photon dump.

4.3.1.3 Beam Termination

4.3.1.3.1 Hall A and C Beam Dumps

Hall 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 which have relatively low radio-activation potential, and are cooled by circulating water. At the highest beam energy approximately 2/3 of the beam power is deposited in the aluminum plates and about 1/3 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 aboveground 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 Beam Switchyard and Hall D Tagger Dumps

The beam switchyard dump and the electron beam dump in the Hall D Tagger share a common design. These dumps have two sections; one aluminum, one copper, that are electrically isolated and independently cooled.

The Beam Switchyard dump, is rated at 120 kW of beam power: the aluminum section is rated at 100 kW and is cooled by a closed loop low-conductivity water system, with a total volume of less than 100 gallons, cooled by a heat exchanger that rejects heat to the LCW water supply for the Halls A, B, and C. Radiolytic gasses generated in the 100 kW section are vented to the atmosphere outside the Beam Switchyard. The 20 kW primary cooling water system is cooled directly by the same LCW water supply.

For the Hall D Tagger Dump, 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 purge is maintained on both cooling systems and radiolytic gasses generated in this dump are vented to the atmosphere outside Hall D Tagger.

4.3.1.3.3 Hall B Photon and Electron Dumps

Beam power delivered to Hall B is typically less than 1 kW. For tagged photon experiments, the primary electron beam is deflected downward into a low-power beam dump at the end of a tunnel inserted into the floor of Hall B. Untagged electron beam is terminated in a Faraday cup in a shielded, downstream alcove designed for that purpose. Due to the much lower power and consequently low radioactivity content, no active cooling systems are required for the low power dumps in Hall B.

4.3.1.3.4 Hall D Photon Dumps

Approximately 5 Watts of photons are delivered to Hall D from the Hall D Tagger. Hall D has a low power beam dump that consists of a long section of metal blocks that begin at the exterior of Hall D 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 hazards on-site associated with its operation:

- Electricity: high current, high voltage;
- 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 beam-line components;
- Nonionizing radiation: lasers, static magnetic fields, RF;
- Noxious and radioactive gasses; and
- Groundwater and soil activation.

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

- Offsite dose from prompt ionizing radiation (sky shine) 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. 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, a superconducting LINAC with a maximum accelerating gradient of 180 MeV. The LERF has a nominal configuration of two beam lines, one capable of supporting infrared (IR) lasing and Terahertz (THz) beams and one supporting ultraviolet (UV) lasing each with a permanent magnet wiggler. The beam lines 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 350kV bias voltage and requires SF6 insulating gas. The LERF accelerates beam with three full cryomodules to a maximum energy of 180 MeV. The nominal configuration of the LERF is 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 is transported around the second recirculating arc and returns the beam to the LINAC for the energy recovery pass. The energy-recovery LINAC allows 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.

Instead of operating as a recirculating energy recovery LINAC, the beam may also be directed to an experimental physics target installed along the beamline.

The IR or UV light and THz radiation is directed out of the accelerator enclosure to the laboratories above through enclosed beam pipes that penetrate the vault shielding. The general layout of the accelerator in the vault is shown in Figure 11 – Jefferson Lab LERF Accelerator. The convention for the following discussion of the LERF as represented in Figure 11 – Jefferson Lab LERF Accelerator is that the electron beam travels the acceleration beamline from right to left.

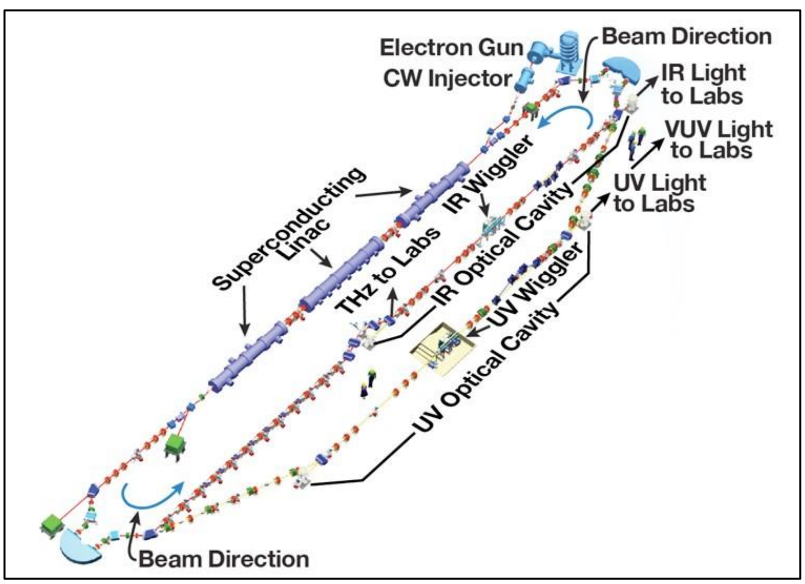

Figure 11 – Jefferson Lab LERF Accelerator

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 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 test bed for an advanced accelerator physics research and 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.

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

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 hazards on-site associated with its operation:

- Electricity: high current, high voltage;
- Cryogenic liquids and gasses;
- 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 beam-line components;
- Nonionizing radiation: lasers, static magnetic fields, RF;
- Noxious and radioactive gasses; and
- Groundwater and soil activation.

The LERF accelerator has the following potential hazard off-site associated with its operation:

- Groundwater activation.

4.3.3 LERF Gun Test Stand (GTS)

The LERF GTS is located adjacent to the vault on the lower level of the LERF Facility. The GTS is used to test electron-gun high-voltage processing techniques and has a modest diagnostic beam line, about 10 feet long, terminating in a water-cooled Faraday Cup. The LERF GTS is not considered an accelerator; electrons from the gun are limited to the high voltage applied to the gun.

4.3.3.1 Beam Generation and Transport

DC high voltage electron guns - thermionic and photoemission - are developed and studied at the GTS. Electron guns can be biased at negative high voltage using three different high voltage power supplies with the following voltage and current specifications: 580kV/5mA, 250kV/32mA and 150kV/65mA. The 580kV higher voltage power supply uses SF6 as an insulating gas. For photoemission electron guns, a variety of drive lasers can be used to generate electrons beams, but only one laser can be used at a time. All drive lasers are interlocked to the PSS.

4.3.3.2 Experimental Area

The GTS principal use is to test photocathode material performance and electron 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 terminate in a water-cooled Faraday Cup. There is no requirement for a beam dump.

4.3.3.4 Hazard Summary

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

- High voltage electricity
- Oxygen displacing gas
- Pressure and vacuum systems
- Prompt ionizing radiation exposure
- Nonionizing radiation

4.4 Accelerator and Technical Areas Outside the Site Safety Fence

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 ¼ cryomodule based on the same superconducting RF acceleration used in CEBAF and LERF. The shielded overhead view of the UITF can be seen in Figure 12 – UITF Exterior View.

The UITF has two principle 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 in-line dumps and experimental apparatus in Cave 1 or 2. The first small-scale physics research experiment in the UITF is operations of the HD-Ice Target for the CEBAF Hall B experimental.

The UITF also serves as an electron gun test stand. Electron gun test stand operation is not accelerator operation and is governed by Operational Safety Procedure.

The convention for the following discussion of the UITF is that the electron beam travels the beamline from right to left.

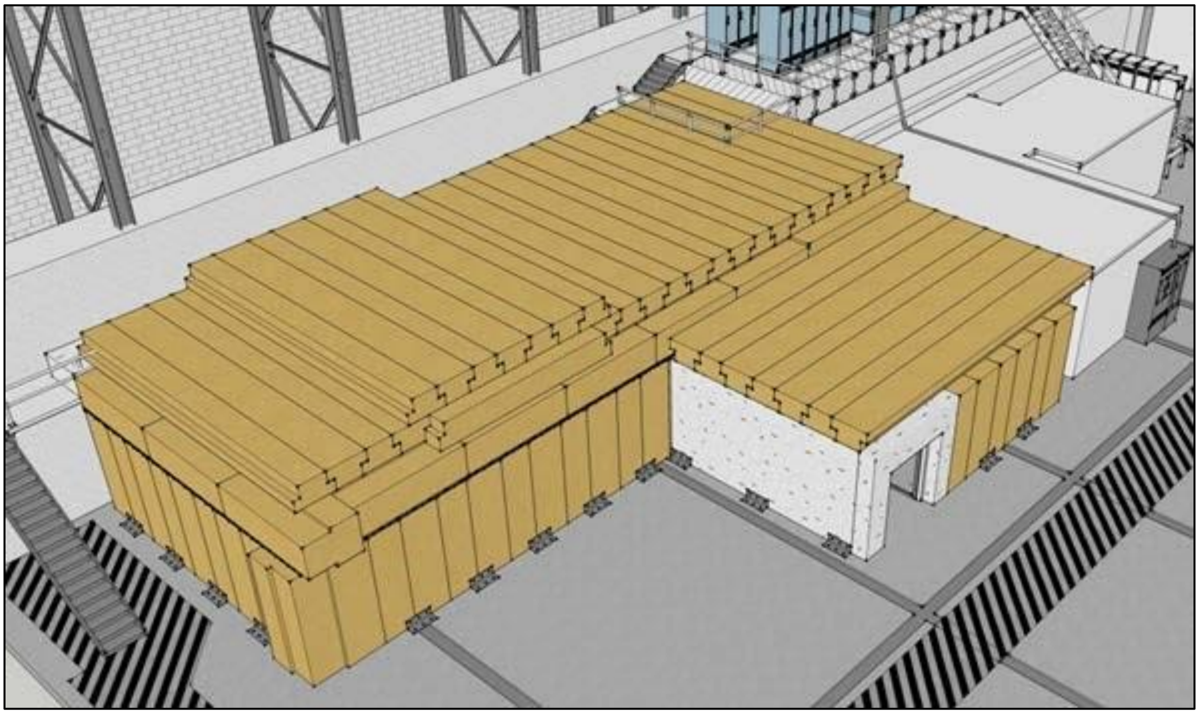

Figure 12 – UITF Exterior View

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 ¼ cryomodule. The photo-electron injector (see Figure 13 UITF Interior View) employs a Class 3B alignment laser and several Class 4A 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 up-stream of the ¼ 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 under an OSP, the gun may be operated with a 225 kV power supply with a maximum current of 32 mA, and at 450 kV power supply with a maximum current of 3 mA.) Acceleration in the UITF is accomplished with a ¼ cryomodule, also located in Cave 1 (see Figure 13), where the electron beam can gain energy up to 10 MeV.

There are principally two beam modes: tune mode and CW. 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 200 microsecond duration, with peak electron beam current of 8 uA, and average current of 100 nA.

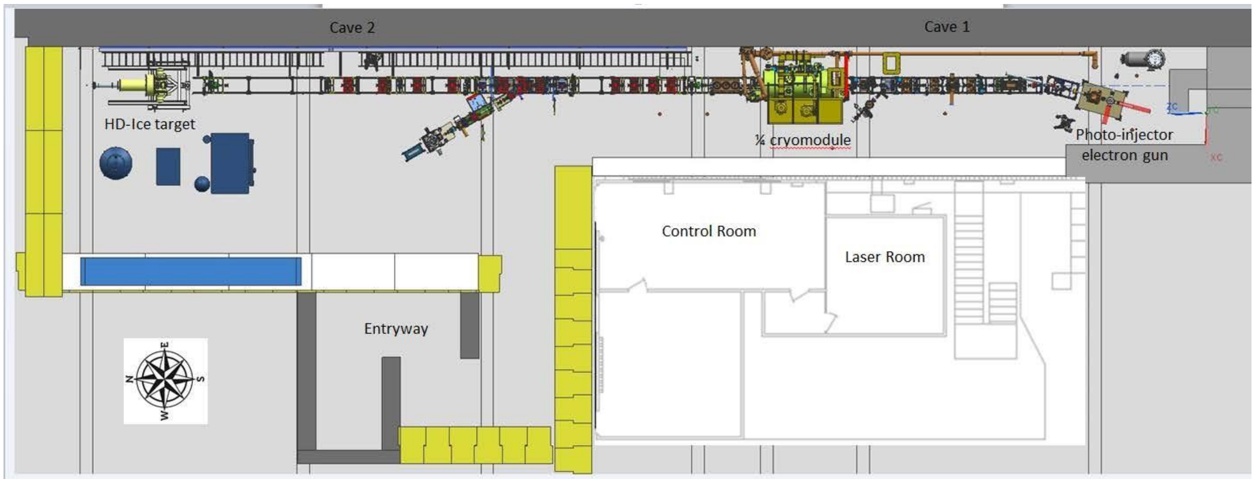

Figure 13 – UITF Interior View

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. (Beam delivery to Cave 2 for HD-Ice is limited to approximately 1 nA average current at 10 MeV because the HD-Ice target can handle no more than 1 nA without being de-polarized. The testing period with the target will allow a better understanding of the de-polarization phenomena and will lead to targets that can handle higher currents.) 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, will use UITF. Experiments conducted in the UITF will be reviewed using the CEBAF ERR process as defined in the 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 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 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 hazards on-site associated with its operation:

- High voltage electricity;
- Cryogenic liquids and gasses;
- Oxygen displacing gas;
- Pressure and vacuum systems;
- Nonionizing radiation, and
- Prompt ionizing radiation.

The hazards are addressed principally by laboratory programs that implement 10 CFR 851 and 835 and the process for hazard control is discussed in the FSAD 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. The shielding for Cave 2 is designed such that an average current loss of 100 nanoAmps (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; does not require a Credited Control for beam containment purposes. The UITF uses administrative controls on the gun power supply current to limit current to less than 100 µA. An active engineered control - a beam current monitoring system is under development and will eventually be deployed in lieu of the administrative control on the gun power supply for the purposes of operational flexibility and ALARA.

4.4.2 Cryomodule Test Facility (CMTF)

The CMTF is located in the center of the high bay area of the Test Laboratory (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 that has been retained since its earlier use as a National Aeronautics and Space Administration synchrocyclotron facility. The Cave provides a shielded area 18-foot wide, by 20-foot high, by 56-foot long. There are four access doors to the cave: two interlocked concrete lift doors for equipment access at the west end, which rise from and lower through the floor (a third lift 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.

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 radiation is supplied to test cavities by several RF power sources ranging from a few Watts to many kW. There are several RF sources located on mezzanine above the cave:

1. Two sets of paired 8 kW, 1497 MHz klystrons, each set with its own waveguide delivering approximately 12 kW to the cave – only one set of klystrons operates at a time to power a single SRF cavity in a cryomodule; and
2. A series of eight 6 kW, 1.3 Gigahertz (GHz) solid state amplifiers. Each solid state amplifiers is connected by 1.3 GHz hardline coaxial cable to each SRF cavity in a cryomodule allowing all SRF cavities to be powered simultaneously – RF sources can be and are typically operated from the CMTF control room.

It is possible to apply high-power RF to all superconducting cavities assembled in a complete accelerator cryomodule.

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 structures such as fundamental power couplers, waveguide assemblies, ceramic RF windows, and cryogenic assemblies (such as SRF cavity strings assembled in a cryomodule) to verify that these components meet design criteria. High-power RF delivery to all SRF cavities in a cryomodule occurs relatively infrequently.

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 which can be very intense but, by the nature of the operation, of short duration, erratic and intermittent.

Activation in SRF components (niobium and structural materials) indicates that electrons can gain sufficient energy to produce high energy x-rays. However, the loss of field emission electrons is at relatively low power and tends to be self-limiting. About 10 Watts of local heating inside a SRF cavity can cause the cavity to quench – lose superconductivity – and effectively disrupt SRF cavity performance and cryomodule testing. Nevertheless, personnel are excluded from the test area.

Cryogenic liquid helium is supplied 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. Cryogen distribution connections are located at the east end of the cave.

The CMTF also contains the Warm Window Test Stand. There is a special RF configuration for the Warm Window Test Stand: RF from one set of the paired 8K, 1497 MHz klystrons using a single wave guide, is routed to the Warm Window Test Stand. The single waveguide assembly can be terminated by either an RF load or shorting plate. 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.

4.4.2.4 Hazard Summary

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

- High voltage electricity;
- Cryogenic liquids and gasses;
- Oxygen displacing gas;
- Pressure and vacuum systems;
- Prompt ionizing radiation exposure; and
- Nonionizing radiation.

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 Laboratory (Building 58). The VTA provides a safe and secure facility for testing single 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. 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 for cryogenic tests only and are incapable of generating prompt ionizing radiation; they require no radiation shielding. The remaining six dewars (3 through 8) are used for testing that employs highpower 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 allows the VTA operators to test components and assemblies at cryogenic temperatures between 4.2 and 1.5 Kelvin. Liquid nitrogen may occasionally be used in the test area for coldshocking components, cryogenic leak testing, or in vacuum-system cold traps.

4.4.3.3 Beam Dump

There is no electron gun and no source of coherent electron beam. The loss of field emission electrons in niobium and structural materials is typically at low power and is self-limiting. More than a few Watts of local heating inside an SRF cavity will cause the cavity to quench – lose superconductivity – and effectively shut off. Field emitted electrons are sometimes 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 hazards on-site associated with its operation:

- High-voltage electricity;
- Cryogenic liquids and gasses;
- 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.

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 three accelerators and the three technical areas identified in *Section 2.0* *INTRODUCTION*. The hazards associated with each are further analyzed in *Section 5.0* *HAZARD ASSESSMENT AND MITIGATION* and hazard mitigations necessary for safe operation are identified.

5.0 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 FSAD 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* *ESH&Q 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 accelerator component operation (when not installed in an accelerator), 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 radioactive materials. The nature and magnitude of these hazards falls well within the regulatory framework of 10 CFR 835, 10 CFR 851 and the DOE ES&H directives under which the laboratory operates.

Fire hazards are addressed in the ES&H Manual Chapter 6900 Fire Protection Program Summary, which lists 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 Supplement details specific procedures performed by trained individuals.

5.2 Accelerator Specific Hazards

For the purposes of this FSAD, an accelerator is defined as an assembly of components configured to intentionally produce, accelerate, and transport a beam of charged particles (electrons or ions) for a specific purpose. These components include, but are not limited to, a charged particle source, a method of intentionally imparting kinetic energy to the charged particles (above the energy imparted by the source), magnets and other devices necessary to modify and steer the accelerated charged particles, and a stop for the accelerated charged particles. As mentioned in *Section 2.0* *INTRODUCTION*, the three devices that are considered accelerators in this FSAD are the CEBAF accelerator, the LERF accelerator; and the UITF accelerator.

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, beam dumps
   - Sky-shine, and
   - Dark current from high-gradient SRF CMs
2. Activation of materials in certain systems and components
   - 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. 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 UITF accelerator in the Test Lab.

Certain activities at Jefferson Lab are related to research, development, and testing accelerator components. Consequently, accelerator components and their test stand(s) may meet one or more definitions of an accelerator even though they are not an operational accelerator. These test stands are designated Technical Areas to avoid confusion in this document. There are two Technical Areas outside the accelerator site safety fence in the Test Lab – the Cryomodule Test Cave and the Vertical Test Area, and one technical area adjacent to the LERF accelerator enclosure called the Gun Test Stand. These are analyzed in *Appendix B – HAZARD ANALYSIS FOR TECHNICAL AREAS* of this document using the methodology in this section.

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 14 – Safety Analysis Methodology.

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 number. 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 low-power beam is intentionally steered into beam line components including in-line dumps, foils, and magnet yokes, during testing or tune-up, or when 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 concreted 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.

5.2.1.1 Shielding for Prompt Ionizing Radiation

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

- Protect against chronic beam losses during beam transport,
- Protect against full accidental beam loss during transport,
- Protect for intentional beam loss in targets and dumps.

The requirements for the application of shielding are found in the Shielding Policy for Ionizing Radiation (See Radiation Control Supplement - Appendix 2C). 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 the Table 1 - Nominal "As Built" Shielding below.

Table 1 - Nominal "As Built" Shielding

Component/Area	Thickness (ft)*	Notes
CEBAF Tunnels (incl. Beam Switch Yard)	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/concrete are different for A & C vs. B, 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	8.75[e]	Applicable to vertical and lateral approach.
UITF roof (Cave 1/2)	2.5/1.75[f]	

Component/Area	Thickness (ft)*	Notes
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

* Thickness nominally applies to the vertical dimension, and includes the concrete structure unless noted. The values specified are in terms of "earth equivalent" thickness. The earth-equivalent thickness is the ratio 145/125 times the concrete thickness (the ratio of nominal concrete and earth densities in pounds per cubic foot).
[a] Specifications taken from TN-97-017; also see TN-0061, CEBAF 1989 PSAR and as-built drawings.
[b] Specifications taken from TN-97-017; also see TN-89-156 and as-built drawings.
[c] Specifications taken from TN-97-017; also see TN-89-174 and as-built drawings.
[d] Specifications taken from TN-08-033; also see as-built drawings. See also RCD-DEP-16 #003.
[e] Specifications taken from TN-95-044 (2.3 meters concrete). Also see as-built drawings for berm shape and extent.
[f] Specifications taken from TN-18-020. Thickness values for UITF is actual concrete thickness.

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 one meter directly down-stream 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 one meter, approximately 3 x 10^7 rad/hour at zero degrees and 5 x10^3 rad/hour [1] and perpendicular to the direction of beam travel.

Operational experience has shown that localized beam loss above about 1kW can damage accelerator components. Such damage typically results in immediate loss of beam line vacuum resulting in an inability to transport beam. 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 power of the CEBAF accelerator, full beam loss (up to 900 kW) is unsustainable in accelerator components due to the immediate physical damage it causes. The MPS system, described in *Section 4.2.3.3.2 Engineering MPS*, is designed to detect such losses and shut off the beam before damage occurs.

The shielding design for the CEBAF accelerator incorporated assumptions of distributed beam loss during transport at a fraction of a percent of full power. [2] A loss of 0.1% of full operational beam power is 900 W (~ 1 kW). In practice, beam loss in the accelerator is substantially less. The shielding design basis for Table 1 - 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 some locations, actually be higher from sustained beam losses during normal operations than from a high-power (~ 1 MW) beam loss, which is naturally limited in duration. Shielding effectiveness for such conditions was reevaluated during the 12 GeV Upgrade and reviewed during the 12 GeV

Accelerator Readiness Review 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. [3] 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 FSAD, 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). [4]

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 substantially higher current as a test stand.

Radiation shielding has certain design features that affect its performance:

- Penetrations for the purposes of delivering utilities to equipment in the accelerator enclosure or providing a path for helium venting to mitigate a loss of cryogenic liquids in the accelerator enclosure,
    - Penetrations are aligned off center to the beam line where possible and generally oriented away from the beam lines and points of loss,
    - Penetrations may contain removable shielding materials to facilitate maintenance
- Personnel and equipment access ways
    - Contain labyrinths with multiple bends to scatter radiation, and
    - Are generally oriented away from the beam lines 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 un-shielded 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 shadow 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 Radiologically Controlled Area.

Most penetrations in the UITF roof shielding have shadow 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 un-shielded penetrations that serve as helium vents that are designed to mitigate a cryogen loss. As an additional administrative control the area around penetrations in the UITF roof shielding is a posted Radiologically Controlled Area.

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 about beam power and duration of beam losses in the CEBAF accelerator. Those assumptions are in Table 2 – CEBAF Beam Loss Duration as a Function of Beam Power, below.

Table 1 – 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 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 highest potential dose for "accidental" losses.
4	100	1 min	
5	900	2 sec	Full power beam loss.

* 3 kW in extraction/BSY, see text

A value of 1 kW beam loss, with an exposure period of 240 minutes (4 hours, or ½ of an 8 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. Another normal operating condition is delivery of tune-mode beam. At 1.7 kW, tune-mode beam is the highest power beam loss that can be considered "normal". Tune-mode beam is usually delivered to locally shielded, low-power tune-up dumps 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 1.7 kW tune-beam at a single location in the accelerator, even for relatively brief periods of time, consistently results in beam-line vacuum problems and eventually causes component failure.

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. Exposure duration bounding conditions in Table 2 – CEBAF Beam Loss Duration as a Function of Beam Power are conservative estimates that take into account 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 tables below present equivalent dose rates outside the accelerator shielding based on the defined parameters:

- Table 3 – Dose for Beam Loss Conditions: outside CEBAF Shielding
- Table 4 – Dose for Beam Loss Conditions: outside CEBAF Shielding at Unshielded Penetrations
- Table 5 – Dose for Beam Loss Conditions: outside CEBAF Shielding at Shielded Penetrations
- Table 6 – Minimum Shielding Requirements for CEBAF Penetrations
- Table 7 Moveable Shield Wall Performance Summary
- Table 8 – Dose for Beam Loss Conditions: Outside LERF Shielding
- Table 9 – Dose for Beam Loss Conditions: outside LERF Shielding at Penetrations
- Table 10 – Dose for Beam Loss Conditions: outside UITF Shielding
- Table 11 - Dose for Beam Loss Conditions: outside UITF Shielding at UITF Penetrations

Table 2 – Dose for Beam Loss Conditions: outside CEBAF Shielding

Power Lost kW	Maximum Dose rate (mrem/hr) outside shielding	Maximum Dose (mrem) outside shielding*	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 contribution from nearby penetrations.
1.7	1	1	
3	1.8	7.2	
10	6	1	
100	60	1	
900	540	0.3	

*Based on exposure duration in Table 2

Table 3 – 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
LINACs	1	0.80	3.18	Assumes personnel directly over or adjacent to open unshielded penetration even though area above linac penetration is functionally inaccessible
	1.7	1.35	1.35	
	10	7.95	1.33	
	100	79.53	1.33	
	900	715.76	0.40	
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	
	900	1471.76/11.79	0.82/0.01	
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

* Based on exposure durations in Table 2

** Values for these locations based on Arc penetration model

Table 4 – 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
LINACs	1	43 / 3.8	172 / 15.2	Applicable accessible areas posted for sustainable conditions
	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	
	900	38,700 / 3420	21.5 / 1.9	
Spreader/ recombiner	1	2.2	8.8	Gravel shielding in cable penetrations. Buildings posted accordingly as radiologically controlled areas.
Extraction/ BSY	3	6.6	26.4	
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 2

Shielding thickness requirements for the CEBAF LINAC, Spreader / recombiner, and Extraction / BSY penetrations were established in CEBAF-TN-95-026. Table 6 gives the thickness requirements. Since unshielded conditions could hypothetically lead to a condition that exceeds the Jefferson Lab Shielding Policy limits, the shielding for the southwest alignment penetration meets the definition of a Credited Control (as does other penetration shielding in the spreader/extraction and BSY regions).

Table 5– Minimum Shielding Requirements for CEBAF Penetrations

Penetration Type/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

In practice, the most limiting value (thickest shield) for common types of penetrations has been used around the 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 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. 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 re-evaluation. 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 extraction/BSY region. 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 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 2 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. [30]

Additional unshielded penetrations extend between the beam transport tunnels for halls A, B and C and cable chase shafts which are accessible during beam operations. Potential doses in the cable shafts were evaluated in RCD Note RCD-DEP-19 #002 [31]. 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.

Moveable 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 #9315 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 moveable 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 7.

Table 6 – Moveable Shield Wall Performance Summary

Location	Unshielded Dose Rate at Location of Interest (rem/h/kW)	Limiting exposure condition from Table 2 /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

Location	Unshielded Dose Rate at Location of Interest (rem/h/kW)	Limiting exposure condition from Table 2 /Dose in rem	Shield Thickness (inches)	Shielded Dose Rate (mrem/h/kW)
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 there are supplemental shielding installations for the transport tunnels that 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[5]. Applying the same assumptions about sustainable beam loss from Table 2 – 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, G. Neil, G. Stapleton, May 1995.

Table 7– Dose for Beam Loss Conditions: Outside LERF Shielding

Power Lost kW	Maximum Dose rate (mrem/hr) outside shielding	Maximum Dose (mrem) outside shielding	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 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 shadow 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 8– Dose for Beam Loss Conditions: outside LERF Shielding at Penetrations

R	Maximum Dose rate (rem/hr) outside shielding	Maximum Dose (rem) outside shielding	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.[6] Beam loss under these conditions is capable of producing a dose rate inside the UITF accelerator enclosure perpendicular to the beam line, of approximately 10,000 rad/h at one meter[7]. 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 a 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/h, but are below 1000 mrem/h. These areas are also monitored by CARMs which provide defense in depth protection from sustained, off-normal conditions, with trip thresholds set conservatively below 100 mrem/h.

Tables 10 and 11 depict calculated values for the dose rate outside the UITF shielding under worst plausible accident scenario conditions. Conditions considered include transport of over-current beam through the cryomodule, with and without the cryomodule operating.[6]

Table 9– Dose for Beam Loss Conditions: outside UITF Shielding

Beam Loss Location	Beam Power (kW)	Maximum Dose rate (rem/hr) outside shielding	Maximum Dose (rem) outside shielding	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 10 - Dose for Beam Loss Conditions: outside UITF Shielding at UITF Penetrations

Power Lost kW	Maximum Dose rate (rem/hr) outside shielding	Maximum Dose (rem) outside shielding	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 high current without acceleration. When configured as a test stand, safety features such as the PSS and shielding are employed, but operations is conducted under standard hazard mitigation protocols such as OSPs.

5.2.1.1.2 Summary for Unintentional Beam Loss Shielding

The structural shielding associated with the CEBAF, LERF, and UITF accelerator enclosures is considered a Credited Passive Engineered Control. Certain moveable 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. Structural shielding, shielding that is part of the physical structure of the accelerator enclosure, is inspected as specified by Facilities Management and Logistics procedures and recorded in Facilities Information and Management System (FIMS) at least every five years. Design changes are reviewed in accordance with the ASE Violation/USI Review Process. Earth berms/overburden are inspected by Facilities Management and Logistics 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 are also 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 – these are considered

Credited Passive Engineered Controls. Active 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 CEBAF and LERF 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.

5.2.1.1.3 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 3 – Dose for Beam Loss Conditions: outside CEBAF Shielding and Table 4 – 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 1 - 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. 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 1 - 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 sky-shine contributes to the site boundary dose. Since the average power deposited in a thin physics target is very low, the equivalent dose rate is very low; on the order 200 W maximum.

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 up to 100 mrem/hr during normal operations at maximum beam power, and up to 30 rem/hr worst-case in the event of accidental beam loss into a thick target below. 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 less than 3 rem. 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, the potential radiation level is within accepted limits for radiation workers.

5.2.1.1.4 Dark Current

Advances in SRF technology have allowed the production of CMs that can achieve accelerating gradients a factor of five (5) or higher than the original 20 MeV CEBAF design (C20 CMs). Highgradient C100 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. Dark current production and the ionizing radiation that results has 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 C100 CMs when nominal losses from beam transport are low.

Actual measurements of dark current have not been made for high-gradient CEBAF cryomodules. However, the RCD has studied C100 CMs by measuring the prompt radiation using real-time monitoring and induced radioactivity using gamma ray spectroscopic measurements.[8] The RCD also made reasonable estimates of the dose rate from C100 CMs operated at near maximum gradient using real-time monitoring (calibrated radiation detectors) and passive integrating dosimeters. Equivalent dose rates of 100 rem/h gamma and 10 rem/h neutron have been observed at a position reasonably representative of whole body exposure (30 cm from a C100 CM end flange) and estimates of the 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.[9] 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[10].

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 beam line 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 CEBAF high-gradient CMs, there is sufficient data to compel a conservative approach and apply the same credited controls for prompt ionizing radiation associated with beam delivery.

5.2.1.1.5 Shielding for Sky-shine

Sky-shine is the name given to radiation passing through the relatively thin radiation shielding above a radiation source that is scattered in air downward to areas accessible by staff or the general public. Sky-shine is dominated by neutron radiation but there is a photon radiation component. The main concern with sky-shine 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 Shielding Design Policy. The source of radiation exposure from the CEBAF experimental end stations A, C, and D is almost exclusively due to skyshine[11]. Due to the shielding design and accelerator position (with respect to site boundary), the LERF and UITF accelerators do not constitute a sky-shine 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[40]) and that in a credible exposure scenario, dose to a member of the public does not exceed 1 mrem/y.

5.2.1.1.6 Summary, Shielding for Intentional Beam Loss, Dark Current, Sky-shine

The Credited Controls specified in *Section 5.2.1.1.2 Summary for Unintentional Beam Loss Shielding*, are the same controls for hazards associated with intentional beam loss and dark current in CMs. As a hazard, Sky-shine requires no 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.

5.2.1.2 Access Control for Prompt Ionizing Radiation

The PSS provides access controls access controls for the UITF, LERF, and CEBAF accelerator enclosures. PSS Access Controls are described in *Section 4.2.3.3.1 Engineering PSS* and are considered Credited Active Engineered Controls. 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 radiation caused by dark current by preventing the delivery of RF to CMs 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 accelerator enclosure during Beam or Power Permit. The requirements for the application of access controls are found in the Beam Containment and Access Control Policy. The PSS access controls system operated by trained staff. The training requirements are found in the AOD, LOD, and the UOD. 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 who can operate the PSS Access Controls is considered a Credited Administrative Control.

5.2.2 RF Generated by Beam through Tuned Cavity

5.2.2.1 LERF and CEBAF Operations

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 radiation from an electron beam moving through the cavity and transmit the RF through a waveguide toward the klystron - beam induced RF. This RF can be very intense: when traversed by an electron beam, a 7-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.[12] It is also evident that even minor detuning of an SRF cavity can significantly reduce out-coupled power. For example, an SRF cavity in can have a drop in out-coupled power of 99.7% for a 1 ppb frequency change (0.75 kHz from the operating frequency of 1497 MHz). 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 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 wave guide 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.[13] 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, 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 wave-guide pressure interlock is applied to all CEBAF, LERF, and UITF RF systems as a means of continuously checking wave-guide integrity and also serves as a **Defense-in Depth** control for mitigating the hazard associated with RF generated by beam through a tuned cavity.

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

As mentioned in *Section 5.2.2.1 LERF and CEBAF Operations* above, high-gradient C100 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 beam line 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. 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. Estimates for dark current in high-gradient CMs are typically lower by orders of magnitude.

Using the value of 6755 W 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 8 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*, when a task involves high-hazard activities or unusual safety hazard activities that are not fully addressed in the ES&H Manual, an OSP or Temporary OSP are developed in accordance with ES&H Manual Chapter 3310 Operational Safety Procedures (OSP) Program. The Defensein Depth Control applied to this hazard is an OSP that addresses hazards encountered during RF repairs.

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 ESH&Q Radiation Protection*, which implements the requirements in Title 10 CFR Part 835. Two hazards that are treated as accelerator-specific hazards in this section are radioactive materials in the highpower beam dump cooling system water 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 (Building 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 12 – Short Half Life Isotope Content in a BDCS. 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 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 is approximately 0.1 microCuries per milliliter after high-power beam operations.

Table 11 – 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 13 – Long Half Life Isotope Content in a BDCS.

Table 12 – 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	0.445

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 12 – Short Half Life Isotope Content in a BDCS. This high-power beam dump cooling water circulates through equipment located above-ground in 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 inches 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 above-ground volume of cooling water and also has leak detection capability.

Additional, moveable shielding is used at the equipment doors of the BDCS buildings. Analysis indicates [29] the unshielded dose rate outside the doors may be on the order of 2 rem/h when activity shown in Tables 12 and 13 are present. 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.

TN 16-016 *Analysis of key accident scenarios for high-power beam dump cooling systems* (see End Note 20), evaluates several potential sources of release for radioactivity contained in the highpower 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 13 **–** Long Half Life Isotope Content in a BDCS. These accident scenarios addressed in 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 combined end station sump which is sampled before discharge. A spill with the potential of reaching the end station floor can be contained and managed by staff using absorbent material for spill control. 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. Since a spill, as described, does not present an accelerator specific hazard to personnel or pose 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 flood water 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* *ESH&Q Radiation Protection*. Most of the radioactive material that results from accelerator operation in 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, contaminated areas do exist from time to time but the radionuclide contaminants are short lived. 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, at 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 which 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/hr in high-gradient cryomodules [14] located in the accelerator enclosure. Most of the radioactive materials produced at Jefferson Lab are "volume-activated" or self-contained; the radioactivity remains imbedded 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. Associated radiation hazards are managed by the Jefferson Lab Radiation Protection Program and personnel doses remain at a fraction of the limits in 10 CFR835. The former is discussed in *Section 5.2.3.1* *High-Power Beam Dump Cooling Systems (BDCS)* above.

The production of radioactivity in air has been evaluated for CEBAF[15] and LERF[16]. The operational energy for UITF is below the threshold for radionuclide production in air. The design of the LERF as an energy recovery linac tends to minimize beam loss and measurements taken from the LERF accelerator enclosure by the RCD have shown no detectable airborne radioactivity. Airborne radioactivity monitoring systems are in use by the RCD at key locations in the CEBAF accelerator enclosure to measure radionuclide concentration. Air exchange rates for these locations are used to calculate radionuclide-release rates. Jefferson Lab 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 calculated 2016 dose to the Maximum Exposed Individual among members of the public was 0.0037 millirem/y due to airborne releases. The results are reported annually in Jefferson Lab Annual Site Environmental Report [17].

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. This is a principal consideration for the shielding listed in Table 1 - Nominal "As Built" Shielding above. By permit with the Commonwealth of Virginia, Jefferson Lab monitors groundwater pumped from around the experimental halls that is discharged to the surface and at monitoring wells strategically placed around the site and the results are published annually in the Annual Site Environmental Report.[18] No accelerator-produced radionuclides have been detected to date at groundwater monitoring locations. The operational energy for 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 [19] 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 [20]. 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 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 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 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 the CEBAF accelerator tunnel. Extremely cold helium gas is delivered to the cryomodules of the CEBAF, LERF, and UITF accelerators where it transitions to a liquid and cools the cavities in the cryomodules. As heat enters the cryomodules, 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 CMs. However, if the discharge to the return line is blocked, or if gas pressure in the cryomodule increases above the primary cryomodule relief valve set point, the helium gas is released through the relief valve. The primary CM 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 the enclosure, eliminating a helium gas accumulation hazard. The primary CM relief valve for the UITF vents to the Test Lab High Bay. If the primary CM relief valve does not lift as designed, a secondary relief valve is provided, but it discharges to the space surrounding the CM. 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 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. Some of the passive vents are also equipped with fans that can be turned on manually to assist with the removal of helium gas. 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 CM, such as might occur at a flanged piping joint, may not be noticeable - may not be observable to personnel in the vicinity. Over time, the accumulation of helium gas could displace sufficient oxygen from the tunnel to create a significant oxygen deficiency hazard.

The Moller Polarimeter superconducting magnet, which is located on the Hall C beam line, is in a location that has limited air flow and egress and, therefore, presents an ODH risk. The Moller Polarimeter superconducting magnet vent is directed into Hall C. Physics detectors located in the CEBAF experimental end stations use cryogenic helium to cool superconducting magnet systems and use cryogenic nitrogen in thermal shielding vessels within those systems. 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. It is assumed, for the purposes of evaluating the ODH hazard to a particular end station, that the cryogenic supply system releases its full capacity of cryogenic helium to that end station as a maximum credible bound for the hazard.

Nitrogen gas is also used for low flow rate purging and backfilling of vacuum components in the CEBAF, LERF, and UITF 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 near the 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. 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.

Jefferson Lab developed ES&H Manual Chapters 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 any location in the CEBAF, LERF, or UITF accelerator enclosures where an ODH hazard exits.
According to the requirements in Chapter 6540, these ODH assessments are re-evaluated evaluated periodically to ensure that they correctly reflect the actual conditions in the affected area: three years or whenever there is a change that can affect the technical basis of the assessment.

Passive and active engineered controls, and administrative controls are all used as Credited Controls for the CEBAF, LERF, and UITF 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 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 Chapters 6540 Oxygen Deficiency Hazard (ODH) Control Program. Nitrogen gas is distributed to the CEBAF, LERF, and UITF 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 for CEBAF, LERF, and UITF 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 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[21] are based on commercial off-the-shelf equipment designed specifically for sensing reduced oxygen levels in occupied spaces. 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 CEBAF, LERF, and UITF beam enclosures. ODH monitoring systems are used for non-accelerator applications at Jefferson Lab. Consequently, not all ODH monitoring systems are identified or addressed in this FSAD.

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 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 feature 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 above ground. Helium and nitrogen gas pressure relief valves on the Moller Polarimeter in the beam line entrance tunnel leading to Hall C are directed to the large volume of the experiment hall to similarly mitigate ODH risks in the beam line entrance tunnel. The primary helium gas pressure relief valve on the quarter-CM in the UITF is vented out of the UITF enclosure to the Test Lab High Bay. These piping and vent configurations are designated as Passive Credited Engineered Controls.

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 is used in which the workers are trained to an appropriate level for their assigned work locations and activities. This training is considered a Defense-inDepth control.

5.2.6 Hazardous or Exotic Material for use in or as Physics Targets

Experimental nuclear physics targets at JLab can be solid (typically thin metal), liquid (often cryogenic), or gaseous (often cryogenically cooled). The targets can non-hazardous or hazardous material; sometimes several targets are used that fall into several categories depending on the needs of the experimenters. A recent suite of experiments used, and will continue to use a cryogenically cooled gaseous tritium target with an activity of approximately 10^3 Curies. 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 in ESAD review – RCD Manager is a member of the SCMB – incorporates the USI process managed by the SCMB as described in *Section 4.2.5.2* *ESH&Q 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 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 FSAD, 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 15 below. It is based on a preliminary analysis in 1986 and a subsequent review of the project in the Preliminary Safety Analysis Report [22] 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[23] in 1993 and development of the CEBAF Beam

Containment Policy [24] in 1994, which established the initial requirements for the PSS. Revision 6 of this FSAD brought the hazard assessment process into compliance with DOE Order 420.2C and subsequent versions of the FSAD maintain that alignment.

The FSAD 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 14 – Safety Analysis Methodology below.

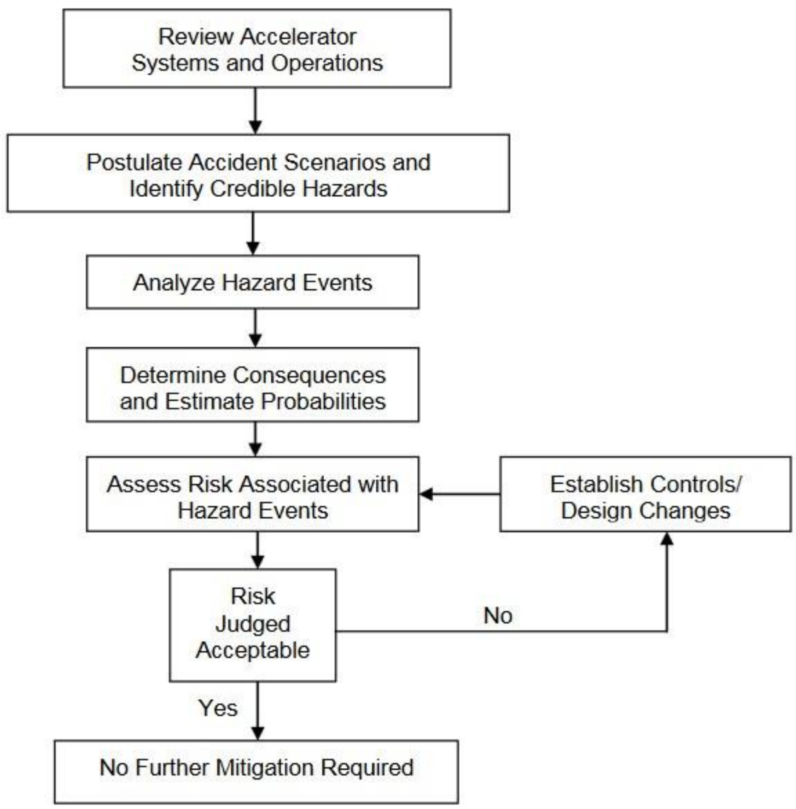

Figure 14 – Safety Analysis Methodology

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. Parity is required between these two hazards to proceed with a meaningful hazard analysis. Table 13 – 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 13– 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 5-11 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 13 – Classification of Radiation and ODH Health Effects for Workers 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.

The consequences of various events are grouped in Table 15 – Consequence Rating Levels and binned into consequence levels. The binning is based on the methodology used in FSAD, Rev. 7a which was revised to better align with a recent consensus standard [22] that addresses occupational hazards and risks in process design.

Table 14– Consequence Rating Levels

Consequence Level	Description Words	Maximum Consequence
H	High	Serious impact on-site and off-site. May cause on-site deaths or loss of facility/operation. Major impact on the environment

Consequence Level	Description Words	Maximum Consequence
M	Medium	Major impact on-site and/or /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 on-site 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, occupational illness. No significant impact on the environment

The probability rating levels are shown in Table 15 – Probability Rating Levels. 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 15– 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		Probability of occurrence is so small that a reasonable scenario is not conceivable. These events are not considered in the design or FSAD accident analysis.	$<10^{-6}$

The risk matrix shown in Figure 15 – Risk Matrix below 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.

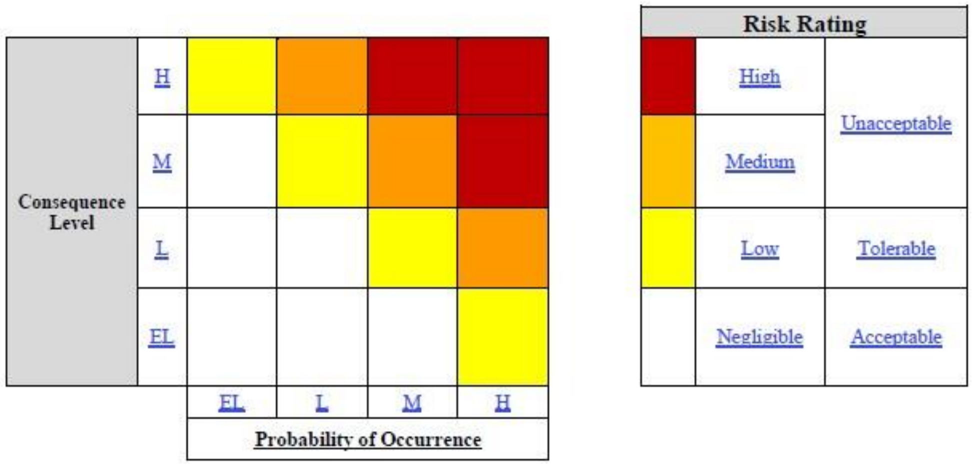

Figure 15 – Risk Matrix

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 16, *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 16 also identifies and categorizes accelerator specific hazards by assigning each an event ID number and evaluates these hazards assigning them an un-mitigated risk rating.

In Table 16, 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 – Hazards, Postulated Initiating Events and Worst-Case Accident Scenarios 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
- 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.
- 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 which require the incorporation of pressure relief valves. However, ODH associated with the release of gas through these relief valves is considered to be accelerator-specific and are evaluated in this analysis.

Table 16 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,

- Sky-shine
- Dark current from high-gradient SRF Cavities

2. Activation of materials in certain systems and components 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 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 16 – 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
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 • MCC Operator error	• 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 • 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 • 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	• UITF	UNACCEPTABLE • Worker deaths No off-site consequence	M	H	TOLERABLE CC: • PSS Access Controls • PSS Beam Containment • Minimum staffing levels of qualified operators • DD: • Administrative control on gun power supply current	EL	H
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 • MCC Operator error	• 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 • Minimum staffing levels of qualified operators	EL	H

NOTES

- **This table applies to the CEBAF, LERF, and UITF 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 15 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 16 – 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**
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 • Operator error	• 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 • PSS Beam Containment • 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
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. moveable 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 • UITF • Bldg. 200 Manway	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: • 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 • Minimum staffing levels of qualified operators DD: • Interlocked CARM • Signs and Posting • Training (general safety and radiation training), RWP	EL	H

NOTES

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Table 16 – 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
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. moveable 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	• UITF	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: • 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. moveable 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 • Locked or secured exclusion barrier • Minimum staffing levels of qualified operators DD: • Signs and Posting. • Training (general safety and radiation training), RWP	EL	M
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 DD: • Locked or secured exclusion barrier. • RCD exclusion barrier surveillance requirements • Radiation Training , RWP • Signs and Posting	M	EL

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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**
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 5-9 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: • RCD exclusion barrier surveillance requirements • Radiation Training, RWP • Signs and Posting • Bldgs. 91 & 95 door locked	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 – shield 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	**UNACCEPTABLE** • Radiation exposure (see 1a, 1c) No off-site consequence	L	H	**TOLERABLE** CC: • PSS annual certification DD: • PSS Safety interlock and Access Control Configuration Management Procedure	EL	H

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Table 16 – 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, BBY penetrations, Helium vent penetrations, • Few workers exposed to <15 rem dose CEBA linac service buildings, LERF top floor, UITF exterior	• CEBAF • LERF • UITF	**UNACCEPTABLE** • Potential long term health effects from ionizing radiation • No off-site consequence	H	L	**TOLERABLE** CC: • Shielding in some penetrations, local shielding on UITF beam dumps, barriers DD: • Interlocked CARMs in some locations • Shielding in some penetrations, barriers • Shielding Policy for Ionizing Radiation – shield design and surveillance requirements • Radiation Training , RWP • Signs and Posting	M	L
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: • Penetration shielding DD: • Shielding Policy for Ionizing Radiation – shield design and surveillance requirements • Radiation Training , RWP • Signs and Posting	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 hours	• 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: • Fenced barrier and locked gate (NL) • Shielding (SL) DD: • Interlocked CARM (NL) • Radiation Training, RWP • Signs and Posting	M	L

<u>NOTES</u>

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Table 16 – 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	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 penetration unshielded	• Few workers exposed to high radiation fields, worst-case exposure of 160 rem	• UITF penetrations	**UNACCEPTABLE** • Potential long term health effects from ionizing radiation • No off-site consequence	M	M	**TOLERABLE** CC: • Penetration shielding • Fenced barrier and/or locked gate • PSS Beam Containment DD: • Shielding Policy for Ionizing Radiation – shield design and surveillance requirements • Radiation Training , RWP Signs and Posting	M	L
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	**UNACCEPTABLE** • Worker deaths • No off-site consequence	H	H	**TOLERABLE** CC: • Permanent shielding as part of the accelerator enclosure DD: • Shielding Policy for Ionizing Radiation – shield design and surveillance requirements • Radiation Training , RWP • Signs and Posting	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 5-9 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 (Buildings 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) Water only leaks from ILCW to primary beam dump cooling water loop	EL	EL

NOTES

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Table 16 – 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
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 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 (Buildings 91 or 95)	**UNACCEPTABLE** • Recoverable injury to worker • No off-site consequence	M	M	**ACCEPTABLE** CC: • Bldg. 91/95 building 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
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 (Buildings 91 or 95)	**ACCEPTABLE** • Worst-case exposure offsite 60 mrem (annual limit 100 mrem)	EL	EL	**ACCEPTABLE**	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 (Buildings 91 or 95)	**TOLERABLE** • Contained within building • No unplanned worker exposure • No off-site consequence	M	L	**ACCEPTABLE** DD: • Bldg. 91/95 building design and structural integrity	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 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

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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
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 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 (Buildings 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
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 • 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	**TOLERABLE** • Recoverable occupational injury	L	M	**ACCEPTABLE** DD: • RF waveguide pressure interlocks connected to PSS beam inhibit	EL	M
4b	4a	Non-ionizing Radiation	RF waveguide open while dark current transitions from adjacent cryomodule(s) 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 TWA	• CEBAF Service Building • LERF Klystron Gallery • UITF Mezzanine	**ACCEPTABLE** • Worker suffers eye injury and 2nd degree burns to extremities	EL	M	**ACCEPTABLE** DD: • OSP that requires adjacent CM zone(s) to be depowered	EL	M
5a	**Y**	**ODH**	**Cryomodule outlet valves closed with cryogen present in cryomodule**	• 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 cryomodule relief valve, preventing failure due to pressurization	• CEBAF linacs • LERF • UITF	**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 cryomodule relief vents to above ground • ODH training	M	EL
5b	5a	ODH	Cryomodule outlet valves closed with cryogen present in cryomodule	• 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 cryomodule relief valve, preventing failure due to pressurization	• UITF	**ACCEPTABLE** • Workers exit UITF vault within 5 minutes	L	L	**ACCEPTABLE** DD: • Pressure relief systems in place and functional • Passive ceiling vents • Primary quarter cryomodule relief vents to Test Lab High Bay • ODH training	L	EL

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								Unmitigated			Mitigated		
ID	**Bounding**	**Hazard Type**	**Event Description**	**Potential Initiators**	**Basis/ Assumptions**	**Results**	**Location**	**Risk rating**	**Probability**	**Consequence**	**Risk rating**	**Probability**	**Consequence**
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 tunnels via secondary relief valve, preventing failure due to pressurization	• CEBAF linacs • LERF • UITF	**ACCEPTABLE** • Workers exit tunnels or and climb stairs to ground level within 5 minutes • Workers exit UITF vault within 5 minutes	L	L	**ACCEPTABLE** DD: • CEBAF lintels, LERF door, UITF enclosure configuration slows helium gas entry into stairwells • ODH training	L	EL
5d	**Y**	**ODH**	**Slow leak of helium or warm nitrogen service line inside enclosure**	• Secondary cryomodule 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	**UNACCEPTABLE** • Worker hypoxia/disorientation • No off-site consequence	M	M	**ACCEPTABLE** CC: • Nitrogen lines outfitted with flow restricting orifice • ODH System Alarm (sensors positioned for N_2 and He) • Passive ceiling vents in CEBAF, LERF, UITF • CEBAF lintels and LERF door configuration slows helium gas entry into stairwells DD: • ODH Training	L	L
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	**ACCEPTABLE** • Workers exit tunnels, and climb stairs to ground level within 5 minutes	L	L	**ACCEPTABLE** DD: • Cryogenic Work Control Process • ODH System Alarms • CEBAF lintels and LERF door configuration slow helium gas entry in to stairwells • Passive ceiling vents in CEBAF, LERF, UITF • ODH training	L	EL

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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	**TOLERABLE**	L	M	**ACCEPTABLE** DD: • Emergency power system for safety systems • Nitrogen supply line solenoid valves	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 CTF • May not have visible plume	• Available nitrogen or helium inventory released in to accelerator enclosure • O_2 level drops below 12.5%	• CEBAF • Moeller polarimiter • LERF • UITF	**UNACCEPTABLE** • Worker hypoxia/disorientation • No off-site consequence	M	M	**TOLERABLE** CC: • ODH System Alarm (sensors positioned for N2 and He) • CEBAF lintels and LERF door configuration slow helium gas entry in to stairwells • Passive ceiling vents in CEBAF, LERF, UITF • Nitrogen lines outfitted with flow restricting orifice • Moeller polarimeter vent line DD: • Nitrogen supply line solenoid valves • ODH training	EL	H
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 • Training	L	M

NOTES

- **This table applies to the CEBAF, LERF, and UITF 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 15 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 16 – 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
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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NOTES

- **This table applies to the CEBAF, LERF, and UITF 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 15 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.**

5.5 Hazard Mitigation Controls Summary and ASE

Table 16 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 in Table 17 – Controls Summary and Table 18 – Basis for CEBAF/LERF ASE in the following two sections.

5.5.1 Hazard Mitigation Controls Summary

Table 17 – Controls Summary, summarizes the hazard events where controls are applied and the locations specific to each. Those hazards events that are considered “Unacceptable” without mitigation require Credited Controls. “Tolerable” risks are usually mitigated by Defense-in-Depth as indicated in the table 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.

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 Control is managed according to the requirements for Level 1 CM 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 CM 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 17 – Controls Summary

Hazard Event ID	Location	Credited Control(s)	Defense-in-Depth Control(s)
1a	CEBAF, LERF	• PSS Access Controls • PSS Beam Containment • Minimum staffing levels of qualified operators	
1b	UITF	• PSS Access Controls • PSS Beam Containment • Minimum staffing levels of qualified operators	

Hazard Event ID	Location	Credited Control(s)	Defense-in-Depth Control(s)
1c	CEBAF target, LERF target	• PSS Access Controls • PSS Beam Containment • Minimum staffing levels of qualified operators	
1d	UITF target	• PSS Access Controls • PSS Beam Containment • 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 • 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 • Minimum staffing levels of qualified operators	• Interlocked CARM • Signs and Posting • Training (general safety and radiation training), RWP
1g	UITF	• PSS Access Controls • PSS Beam Containment • 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 • Locked or secured exclusion barrier • Minimum staffing levels of qualified operators	• Signs and Posting. • Training (general safety and radiation training), RWP
1i	CEBAF Arc service building zones		• Locked or secured exclusion barrier. • RCD exclusion barrier surveillance requirements • Signs and Posting • Radiation Training , RWP
1j	CEBAF dump cooling buildings (Bldg 91 or 95)	Locked exclusion barrier (gate to Bldgs. 91 & 95)	• RCD exclusion barrier surveillance requirements • Radiation Training, RWP • Signs and Posting • Bldgs. 91 & 95 door locked

Hazard Event ID	Location	Credited Control(s)	Defense-in-Depth Control(s)
1k	CEBAF Arcs and BSY LERF Berm		• RCD concurrence on Dig/Blind Penetration Permit • Shielding Policy for Ionizing Radiation – shield design and surveillance requirements
1l	CEBAF, LERF, UITF	PSS annual certification	PSS Safety interlock and Access Control Configuration Management Procedure
1m	CEBAF, LERF, UITF	• Shielding in some penetrations • Barriers at some penetrations • Shielding around UITF beam dumps	• Shielding in some penetrations • Interlocked CARMs in some locations • Shielding Policy for Ionizing Radiation – shield design and surveillance requirements • Radiation Training , RWP • Signs and Posting
1n	CEBAF Extraction/BSY service building zones	Penetration shielding	• Shielding Policy for Ionizing Radiation – shield design and surveillance requirements • Radiation Training , RWP • Signs and Posting
1o	CEBAF North/East (E-1) and South/West (W-2) Service Building Helium vent penetration	• Fenced barrier and locked gate (NL) • Shielding (SL)	• Interlocked CARM (NL) • Radiation Training, RWP • Signs and Posting
1p	UITF penetrations	• Penetration shielding • Fenced barrier and/or locked gate • PSS Beam Containment	• Shielding Policy for Ionizing Radiation – shield design and surveillance requirements • Radiation Training , RWP • Signs and Posting
1q	Anywhere outside the accelerator enclosure for CEBAF, LERF, UITF	Permanent shielding as part of the accelerator enclosure	• Shielding Policy for Ionizing Radiation – shield design and surveillance requirements • Radiation Training , RWP • Signs and Posting

Hazard Event ID	Location	Credited Control(s)	Defense-in-Depth Control(s)
2a	CEBAF Halls A and C beam dump cooling water systems (Buildings 91 or 95), Vicinity of Bldg. 92		• 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 Halls A and C beam dump cooling water systems (Buildings 91 or 95)	Bldg. 91/95 building design and structural integrity	• Hydrogen recombiner in affected system • Hydrogen detector system in ceiling of affected building with alarms at MCC
2c	CEBAF Halls A and C beam dump cooling water systems (Buildings 91 or 95)		
2d	CEBAF Halls A and C beam dump cooling water systems (Buildings 91 or 95)		Bldg. 91/95 building design and structural integrity
3a	CEBAF, LERF, UITF		Worker Health and Safety Program Plan / Industrial Hygiene Sampling
3b	CEBAF Halls A and C beam dump cooling water systems (Buildings 91 or 95)		• Hydrogen recombiner in affected system • Hydrogen detector system in ceiling of affected building with alarms at MCC
4a	CEBAF Service Building LERF Klystron Gallery UITF Mezzanine		RF waveguide pressure interlocks connected to PSS beam inhibit
4b	CEBAF Service Building LERF Klystron Gallery		OSP that requires adjacent CM zone(s) to be depowered
5a	CEBAF Linacs, LERF, UITF		• Pressure relief systems in place and functional • Passive ceiling vents • Primary cryomodule relief vents to above ground • ODH Training

Hazard Event ID	Location	Credited Control(s)	Defense-in-Depth Control(s)
5b	UITF		• Pressure relief systems in place and functional • Passive ceiling vents • Primary quarter cryomodule relief vents to Test Lab High Bay • ODH training
5c	CEBAF Linacs, LERF, UITF		• CEBAF lintels, LERF door, UITF enclosure configuration slows helium gas entry into stairwells • ODH Training
5d	CEBAF Linacs, LERF, UITF	• Nitrogen lines outfitted with flow restricting orifice • 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	ODH Training
5e	CEBAF Linacs, LERF		• Cryogenic Work Control Process • ODH System Alarms • CEBAF lintels and LERF door configuration slows helium gas entry in to stairwells • Passive ceiling vents • ODH training
5f	CEBAF, LERF, UITF		• Emergency power system for safety systems • Nitrogen supply line solenoid valves
5g	CEBAF Linacs, LERF, UITF	• ODH System Alarm (sensors positioned for N2 and He) • CEBAF Lintels • LERF Exit design • Passive Vents • Flow limiting orifices • Moeller vent line	• Nitrogen supply line solenoid valves • ODH training
6a	CEBAF, LERF, UITF	• ERR Process risk from hazards, specifies controls	• Pressure relief systems in place and functional • Signs and Posting • Training

Hazard Event ID	Location	Credited Control(s)	Defense-in-Depth Control(s)
6b	CEBAF and offsite at fence boundary		• 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		• ERR Process assesses risk from hazardous material used in experiments • Fire Protection Program • Pressure Systems Program

5.5.1.1 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. The following two tables are the basis for the CEBAF/LERF ASE and for the UITF ASE.

Table 18– Basis for CEBAF/LERF ASE

1. Credited Passive Engineered Controls	Event ID No.	Highest Unmitigated Risk Rating
1.1. **Permanent Shielding**	1q	UNACCEPTABLE
Applicability: When beam delivery into the affected segment is possible. When beam delivery is possible in the LERF and LERF is in Beam Permit. **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:** The status of structural shielding and earth berms/overburden shall be recorded in the Beam Authorization Tool (BAT) by *Facilities Management and Logistics* for the run period identified in the BAT. Structural shielding shall be inspected as specified by *Facilities Management and Logistics Procedures* and recorded in Facilities Information and Management System at least every five years. Design changes shall be reviewed in accordance with the *ASE Violation/USI Review Process*.		

1. Credited Passive Engineered Controls	Event ID No.	Highest Unmitigated Risk Rating
Earth berms/overburden shall be inspected as specified by the RCD and documented at least every five years. 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, during RCD inspection, the earth berms/overburden shielding over the accelerator enclosure is found to be less than the values specified in the FSAD, the shielding shall be evaluated by the RCD and compensatory measures, (such as additional access control, installation of temporary shielding, etc.) if necessary, shall be used to maintain performance specified in the Jefferson Lab Shielding Policy for Ionizing Radiation until the shielding is restored to the values specified in the FSAD. The SCMB shall review and evaluate RCD recommendations using the *ASE Violation/USI Review Process*. The design, approval, and use of compensatory measures for permanent shielding shall be subject to the *Jefferson Lab Shielding Policy for Ionizing Radiation*.		
1.2. **Movable Shielding**	1m, 1n, 1o	**UNACCEPTABLE**
Applicability: When beam delivery into the affected segment is possible. When beam delivery is possible in the LERF and LERF is in Beam Permit. **Specific Controls:** Movable shielding **Management and Surveillance:** The design, approval, and use of Movable Shielding shall be subject to the *Jefferson Lab Shielding Policy for Ionizing Radiation*. Correct placement of moveable shielding shall be verified in accordance with the Jefferson Lab *Radiation Control Department Procedures* specified in *HPP-OPS-002, Performance of Periodic Routines*. The RCD shall record the status of moveable shielding in the BAT for the run period identified in the BAT. Movable shielding that serves as a Credited Control shall be robustly labeled as such. Movable shielding position may be maintained by PSS interlocks or, locking devices and/or tags shall be used to maintain correct placement of moveable shielding by according to ES&H Manual Chapter 6111, Administrative Control Using Locks and Tags. **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 *Jefferson Lab Shielding Policy for Ionizing Radiation.*		
1.3. **Doors, Gates, Fences, and other Barriers**	1e, 1g, 1h -1j, 1m, 1o	**UNACCEPTABLE**
Applicability: When beam delivery into the affected segment is possible. The associated Beam Dump Cooling Building is included if beam delivery segments include Hall A or C. Includes the North and/or South Linac PSS segments		

1. Credited Passive Engineered Controls	Event ID No.	Highest Unmitigated Risk Rating

in Beam or Power Permit independent of other segments. When beam delivery is possible in the LERF and LERF is in Beam Permit.

Specific Controls:
Entrances to accelerator enclosures and other designated spaces shall be interlocked via the PSS Interlocks or locked, barred, or bolted into place to prevent unauthorized access.

Management and Surveillance:
Access shall only be permitted in accordance with approved procedures. Keys shall be controlled and issued to authorized personnel.

Locked, barred, or bolted entrances shall be verified in accordance with the *Radiation Protection Department Procedures* specified in *HPP-OPS-002, Performance of Periodic Routines*.

1.4. **Beam Dump Cooling Building Design**	2b	**UNACCEPTABLE**

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

Specific Controls:
The structural strength 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 Beam Authorization Tool (BAT) by Facilities Management and Logistics for the run period identified in the BAT.

Buildings shall be visually inspected as specified by Facilities Management and Logistics Procedures and recorded in Facilities Information and Management System at least every five years.

1.5. **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.

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

Management and Surveillance:
Orifice is in place and labeled in accordance with ES&H Manual Chapter 6111 Administrative Control Using Locks and Tags.

1. Credited Passive Engineered Controls	Event ID No.	Highest Unmitigated Risk Rating
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.		
1.6. **Moller Polarimeter Gas Vent to Hall C**	5g	UNACCEPTABLE
Applicability: Polarimeter is supplied with cryogens. **Specific Controls:** The vent line from the helium and nitrogen pressure relief valves for the Moller Polarimeter in the Hall C beamline entrance tunnel is configured to vent to the large volume of Hall C. **Management and Surveillance:** No surveillance is required. This feature is built into permanent piping and is labeled in accordance with ES&H Manual Chapter 6111 Administrative Control Using Locks and Tags. **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.		
1.7. **ODH vents, lintels and facility configuration**	5d, 5g	UNACCEPTABLE
Applicability: 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: No surveillance is required for features that are part of the structure. Other features are labeled in accordance with ES&H Manual Chapter 6111 Administrative Control Using Locks and Tags. 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 – 1h	UNACCEPTABLE
Applicability: When beam delivery into the affected segment is possible. When beam delivery is possible in the LERF and LERF is in Beam Permit.		

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

Management and Surveillance:
Interim changes to the PSS are reviewed and approved in accordance with the *PSS Configuration Control Policy* 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.

2.2.	CEBAF PSS Beam Containment Controls	1a – 1h	UNACCEPTABLE

Applicability:
When beam delivery is possible into the segments adjacent to the affected segment.

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

Management and Surveillance:
Interim changes to the PSS are reviewed and approved in accordance with the *PSS Configuration Control Policy* 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.

2.3.	ODH System Controls	5d, 5g	UNACCEPTABLE

Applicability:
A fixed ODH monitoring system shall be installed in an area when required by the ES&H Manual and an ODH analysis document.

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

Management and Surveillance:
- The system shall be maintained such that it is operational when required by the ODH assessment for the location.
- Maintenance will be done in accordance with Safety Systems Group procedures.
- ODH sensing devices shall be tested every two years.

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.[a]	Highest Unmitigated Risk Rating
3.1. **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 Director of Jefferson Lab to grant beam-time formally communicated by a letter from the Director accompanying the PAC report, will undergo the remaining steps in the experimental review process before the experiment is run using a Jefferson Lab accelerator: CEBAF, LERF, UITF.

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 using a Jefferson Lab accelerator: CEBAF, LERF.

Management and Surveillance:
The CEBAF Experimental Review Process and the Accelerator Experiment Safety Review Process are maintained in accordance with ES&H Manual Chapter 1300 Content Review Process.

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

Applicability:
When beam delivery is possible up to Faraday Cup #2 and Injector and North Linac Segment in Beam Permit. All other segments not specified.

Specific Controls:
The Accelerator or the LERF OD defines minimum requirements for staffing.

Management and Surveillance:
Sweep and Controlled Access operations follow the steps defined in the respective PSS access procedures and are carried out by qualified Safety Systems Operators (SSOs) using the Safety Systems Console in the Machine Control Center (MCC).

3.3. **CEBAF Operations Staffing with Beam to Faraday Cup #2**	1a, 1c, 1e, 1f, 1h	UNACCEPTABLE

Applicability:
When beam delivery is possible up to Faraday Cup #2, and Injector and North Linac Segment in Beam Permit. All other segments not specified.

Specific Controls:
One Accelerator Operator in MCC
One Security Guard on the Jefferson Lab Campus

Management and Surveillance:
The AOD defines requirements for staffing in addition to Controls listed above.

3.4.	CEBAF Operations Staffing with Beam to In-line Dump 0R08	1a, 1c, 1e, 1f, 1h	UNACCEPTABLE

Applicability:
When beam delivery to 0R08 is possible.

Specific Controls:
- One Accelerator Operator in MCC
- Crew Chief within Accelerator Site Security Fence
- One Security Guard on the Jefferson Lab Campus

Management and Surveillance:
The AOD defines requirements for staffing in addition to Controls listed above.

3.5.	CEBAF Operations Staffing with Beam beyond Inline Dump 0R08	1a, 1c, 1e, 1f, 1h	UNACCEPTABLE

Applicability:
When beam delivery beyond 0R08 is possible and all Accelerator Segments in Beam Permit.

Specific Controls:
- One Accelerator Operator in MCC
- Crew Chief within Accelerator Site Security Fence
- One Security Guard on the Jefferson Lab Campus

Management and Surveillance:
The AOD defines requirements for staffing in addition to Controls listed above.

3.6.	LERF Operations Staffing with Beam	1a, 1c, 1e, 1h	UNACCEPTABLE

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

Specific Controls:
One LERF qualified Operator in MCC or LERF
Crew Chief within Accelerator Site Security Fence
One Security Guard on the Jefferson Lab Campus

Management and Surveillance:
The LOD defines the requirements for staffing in addition to controls listed above.

Table 19 - Basis for 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. (Gun high voltage processing and/or cathode re-cessation and gun operation (producing electrons at energy up to the applied bias voltage on the gun) is not considered beam delivery in this ASE.)

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:

- Shielding design changes shall be reviewed in accordance with the ASE Violation/USI Review Process.
- The Dig/Blind Penetration Permit specified in ES&H Manual Chapter 3320 Temporary Work Permits shall be used to manage configuration during any penetration into or disturbance of the shielding.
- Structural shielding shall be inspected as specified by Facilities Management and Logistics Procedures and recorded in the Maximo work order system at least every five years.
- The RCD shall evaluate all permanent shielding at least every five years against applicable design specifications and FSAD requirements and general conditions. RCD shall record the status of structural shielding, along with the expiration date for the status determination, in UITF Beam Authorization Tool (BAT).

Acceptable compensatory measures:
If, during RCD inspection, shielding for the accelerator enclosure is found to be less than the values specified in the FSAD, the shielding shall be evaluated by the RCD and compensatory measures, (such as additional access control, installation of temporary shielding, etc.) if necessary, shall be used to maintain performance specified in the Jefferson Lab Shielding Policy for Ionizing Radiation until the shielding is restored to the values specified in the FSAD or the FSAD is amended. The SCMB shall review and evaluate RCD recommendations using the ASE Violation/USI Review Process. The design, approval, and use of compensatory measures for permanent shielding shall be subject to the Jefferson Lab Shielding Policy for Ionizing Radiation.

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

Applicability: When beam delivery is possible.

Specific Controls: Movable shielding.

Management and Surveillance:
The RCD shall record the Movable Shielding status, along with the expiration date for the status determination, in the UITF BAT before beam delivery.

1. Credited Passive Engineered Controls	Event ID No.	Highest Unmitigated Risk Rating

The design, approval, and use of Movable Shielding shall be subject to the *Jefferson Lab Shielding Policy for Ionizing Radiation*. For non-PSS interlocked Movable Shielding locking devices and/or tags installed according to ES&H Manual Chapter 6111, Administrative Control Using Locks and Tags, shall be used to maintain correct placement of moveable shielding. Correct placement of moveable shielding shall be verified in accordance with the Jefferson Lab *Radiation Control Department Procedures* specified in *HPP-OPS-002, Performance of Periodic Routines*. Credited movable shielding shall be robustly labeled as such.

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 Jefferson Lab Shielding Policy for Ionizing Radiation.

1.3. **Nitrogen Gas Supply Orifices**	5d, 5g	**UNACCEPTABLE**

Applicability: When an affected system is charged with gas and personnel are in the affected area within the accelerator enclosure.

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

Management and Surveillance:

- Orifice in place and labeled consistent with ES&H Manual Chapter 6111 Administrative Control Using Locks and Tags.
- Facilities Management and Logistics shall record the Nitrogen Gas Supply Orifice status, along with the expiration date for the status determination, in the UITF BAT before beam delivery.

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

1.4. **ODH Vents, Lintels and Facility Configuration Credited**	5d, 5g	**UNACCEPTABLE**

Applicability: When Quarter Cryomodule is supplied with cryogens or Target is supplied with cryogens

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

Management and Surveillance:

- No surveillance is required for features that are part of UITF poured concrete structures.
- Passive vents, incorporated into moveable shielding and identified as Credited Controls, are visibly labeled consistent with ES&H Manual Chapter 6111 Administrative Control Using Locks and Tags and verified after movement.
- Facilities Management and Logistics shall record the status of passive vents incorporated into moveable shielding and identified as Credited Controls, along with the expiration date for the status determination

1. Credited Passive Engineered Controls	Event ID No.	Highest Unmitigated Risk Rating
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. [a]	Highest Unmitigated Risk Rating
2.1. **PSS Access Controls**	1b, 1d, 1e, 1g, 1h	UNACCEPTABLE
Applicability: When beam delivery is possible. **Specific Controls:** The UITF PSS shall have no loss of safety function during beam delivery. (Loss of safety function is considered to be failure of both independent interlock chains.) **Management and Surveillance:** • Interim changes to the PSS are reviewed and approved in accordance with the PSS Configuration Control Policy 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. • UITF PSS components shall be visibly labeled consistent with ES&H Manual Chapter 6111 Administrative Control Using Locks and Tags. • The Safety Systems Group shall verify the status of the UITF PSS, along with the expiration date for the status determination, in the UITF BAT by before beam delivery.		
2.2. **PSS Beam Containment Controls**	1b, 1d, 1e, 1g, 1h, 1p	UNACCEPTABLE
Applicability: When beam delivery beyond the quarter cryomodule is possible. **Specific Controls:** The UITF PSS shall have no loss of safety function during beam delivery (Loss of safety function is considered to be failure of both independent interlock chains.) **Management and Surveillance:** • UITF PSS components shall be visibly labeled consistent with *ES&H Manual Chapter 6111 Administrative Control Using Locks and Tags* • Interim changes to the PSS are reviewed and approved in accordance with the PSS Configuration Control Policy 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 UITF BAT before beam delivery.		
2.3. **ODH System Controls**	5d, 5g	UNACCEPTABLE
Applicability:		

2. Credited Active Engineered Controls	Event ID No. [a]	Highest Unmitigated Risk Rating

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 in UITF areas.

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

Management and Surveillance:
UITF PSS components shall be visibly labeled consistent with ES&H Manual Chapter 6111 Administrative Control Using Locks and Tags.
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 Safety Systems Group procedures.
ODH sensing devices shall be tested every two years.
The Safety Systems Group shall verify the status of ODH System Controls, along with the expiration date for the status determination, in the UITF BAT by before beam delivery

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. [a]	Highest Unmitigated Risk Rating
3.1. **Doors, Gates, Fences, and other Barriers**	1e, 1g, 1h	UNACCEPTABLE

Applicability: When beam delivery is possible.

Specific Controls:
Entrances to accelerator enclosures shall be interlocked via the PSS Interlocks or locked, barred, or bolted into place to prevent unauthorized access.

Management and Surveillance:
Access shall only be permitted in accordance with approved procedures. Keys shall be controlled and issued to authorized personnel.

Doors, gates, fences, and other barriers serving as Credited Controls shall be clearly identified by visible labels consistent with *ES&H Manual Chapter 6111 Administrative Control Using Locks and Tags*.

Locked, barred, or bolted entrances shall be verified in accordance with the *Radiation Protection Department Procedures* specified in *HPP-OPS-002, Performance of Periodic Routines*. The status, along with the expiration date for the status determination, shall be recorded in the UITF BAT.

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

Applicability:

3. Credited Administrative Controls	Event ID No. [a]	Highest Unmitigated Risk Rating
When beam delivery is possible into the affected segment containing an approved nuclear physics experiment. **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 Otherwise, the *ES&H Manual Chapter 3130 Accelerator Experiment Safety Review Process* shall be used for the review. **Management and Surveillance:** ES&H Manual Chapters are maintained in accordance with *ES&H Manual Chapter 1300 Content Review Process*.		
3.3. **UITF Staffing – Sweep**	1b, 1d, 1f, 1g, 1h	UNACCEPTABLE
Applicability: Applies when UITF is being made ready for PSS state above Open Access. **Specific Controls:** The *UITF Operations Directives* defines minimum requirements for staffing. **Management and Surveillance:** 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 - Operations**	1b, 1d, 1e, 1g, 1h	UNACCEPTABLE
Applicability: Applies when UITF PSS is being made ready for PSS state above Ready. **Specific Controls:** The *UITF Operations Directives* defines minimum requirements for staffing during operations. **Management and Surveillance:** Trained UITF Operators, in the UITF Control Room, perform UITF operations following the steps defined in the *UITF Operations Directives.*		

5.6 Summary

This hazard analysis addresses accelerator-specific hazards in accordance with DOE O 420.2C, 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 14 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 13, of Medium to Extremely Low. With the controls in place, the reduced probability and consequence ratings as applied to the risk matrix, Figure 15, reduce risk rating to tolerable or acceptable for each identified hazard event.

6.0 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 like 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-TN87-057[25] 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 re-use, disposal or recycle (with consideration for restrictions imposed by DOE on release of metals for recycling)[27]. This approach considers both surface contamination and volume activated materials. The approach for volume activated material is conservatively based on the principle that measured radioactivity content is "indistinguishable from background". 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 Jefferson Lab 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.

APPENDIX A – ACRONYMS

Acronym	Definition	Page
ALARA	As Low as Reasonably Achievable	78
AOD	Accelerator Operations Directives	15
ASE	Accelerator Safety Envelope	1
ASO	Accelerator Safety Order	1
BDCS	Beam-Dump Cooling System	67
BELS	Beam Envelope Limit System	24
CARM	Controlled Area Radiation Monitor	23
CEBAF	Continuous Electron Beam Accelerator Facility	1
CHL	Central Helium Liquefier	10
CLAS12	CEBAF Large Acceptance Spectrometer	3436
COEM	Conduct of Engineering Manual	20
CM	Configuration Management	12
CMTF	Cryomodule Test Facility	12
CNI	Computing and Networking Infrastructure	30
CTF	Cryogenic Test Facility	12
CTOF	Central Time-of-Flight	36
DEQ	Department of Environmental Quality	8
DC	Drift Chambers	36
DOE	Department of Energy	1
EPA	Environmental Protection Agency	70
EPICS	Experimental Physics and Industrial Control System	11
ERR	Experiment Readiness Review	16
ES&H	Environment, Safety and Health	16

Acronym	Definition	Page
ESH&Q	Environment, Safety, Health, and Quality	26
ESNet	Energy Science Network	9
ESR	End Station Refrigerator	12
FCAL	forward electromagnetic calorimeter	37
FM&L	Facilities Management and Logistics	17
FSAD	Final Safety Assessment Document	1
FSD	Fast Shutdown	24
FTOF	Forward Time-of-Flight	36
GeV	Gigaelectron-Volt	32
GHz	Gigahertz	48
GTS	Gun Test Stand	44
HMS	High Momentum Spectrometer	36
HR	Human Resources	25
HRS	High-Resolution Spectrometers	35
HRSD	Hampton Roads Sanitation District	8
HTCC	High Threshold Cherenkov Counter	36
IR	Infrared	41
IT	Information Technology	30
ITS	Injector Test Stand	44
JSA	Jefferson Science Associates, LLC.	Ii
Jefferson Lab	Thomas Jefferson National Accelerator Facility	1
kV	Kilovolt	10
kW	Kilowatt	24
LCW	Low Conductivity Water	8
LERF	Low Energy Recirculator Facility	1
LINAC	Linear Accelerator	11
LOD	LERF Operations Directive	15
LTCC	Low-Threshold Cherenkov Counter	36
mA	Milliamps	41
MCC	Machine Control Center	10
MHz	Megahertz	33
MeV	Million electron Volts	5

Acronym	Definition	Page
MPS	Machine Protection Systems	20
MS4	Municipal Separate Storm Sewer System	8
MVA	megavolt-Amperes	9
MW	Megawatt	24
O2	Oxygen	73
ODH	Oxygen Deficiency Hazard	10
OSP	Operational Safety Procedure	16
PCAL/EC	Calorimeters	36
PPE	Personal Protective Equipment	24
PSS	Personnel Safety System	17
QAP	Quality Assurance Program	27
RBM	Radiation Boundary Monitors	29
RCD	Radiation Control Department	23
RPP	Radiation Protection Program	27
SCMB	Safety Configuration Management Board	23
SF6	sulfur hexafluoride	33
SHMS	Super-High Momentum Spectrometer	26
SME	Subject Matter Expert	29
SREL	Space Radiation Effects Laboratory	5
SRF	Superconducting Radio Frequency	14
SSG	Safety Systems Group	20
SSO	Safety System Operator	17
SURA	Southeastern Universities Research Association	5
SVT	Silicon Vertex Tracker	36
TCC	Threshold Cherenkov Counter	36
THz	Terahertz	41
TOF	time-of-flight	37
UITF	Upgraded Injector Test Facility	1
UPS	Uninterruptible Power Supplies	10
USI	Unreviewed Safety issue	4
UV	Ultraviolet	41
VTA	Vertical Test Area	12

APPENDIX B – HAZARD ANALYSIS FOR TECHNICAL AREAS

Appendix B analyzes the Technical Areas which meet one or more of the elements of the definition of an accelerator.

Technical Areas are evaluated using the same methodology as in Chapter 4 of the FSAD. The analysis process is outlined in Figure B1.

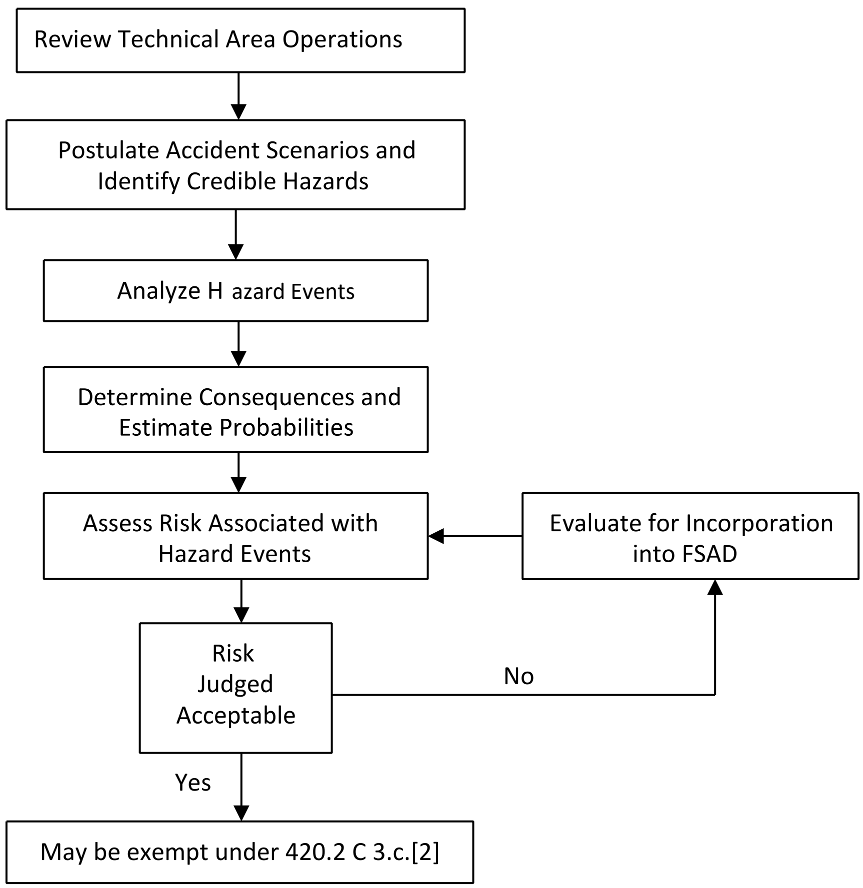

Figure B-1 – Safety Analysis Methodology

As can be seen from Figure B-1, if the unmitigated risk level in a Technical Area is "Tolerable," the Technical Area may be considered for exemption from further requirements under the provisions of 420.2C paragraph 3.c.[2].

The Technical Areas, identified in Chapter 4 of the FSAD as part of the Jefferson Lab Accelerator Facility, under consideration in Appendix B are: CMTF, VTA, and GTS.

- 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 VTA is located next to the CMTF. The VTA contains shielded cryogenic dewars to facilitate performance testing of SRF cavities, and cryogenic testing of other related components. The SRF cavities are the fundamental components used assemble the cryomodules tested in the CMTF.
- The GTS is an enclosure adjacent to the LERF vault. Like the ITC, the GTS is designed to test photo emission gun performance after the application of high voltage processing techniques.

Each of these areas uses engineered and administrative safeguards matched to their intended function to facilitate safe and efficient operation. For internal consistency and ease of use, the methodology found in Chapter 5 of the FSAD is represented below.

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. We have chosen to avoid a completely subjective approach, however well informed it is by professional opinion.

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. The result is in Figure B-1 below.

Table B - 1 – Classification of Radiation and ODH Health Effects

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

Notes:

* Table 4-1 considers health effects for exposure to a worker or workers 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 a prompt ionizing radiation exposure or an oxygen deficient atmosphere or due to Accelerator Facility operations. Therefore, the Health Effect: High does not have an off-site component.

** The rem is not a measure of exposure; it is 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 are a function of absorbed radiation dose measured in rad.

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

**** The mean lethal dose to a population of human individuals that, if untreated, will result in death within 30 days is 450 rad.

The consequences of various events are grouped into Consequence Levels as shown in Figure B2. The binning is based on the methodology used in FSAD, Rev. 8a and a consensus standard that addresses occupational hazards and risks in process design. [22]

Table B - 2 – Consequence Rating Levels

Consequence Level	Description Words	Maximum Consequences
H	High	Serious impact on-site or off-site. May cause on-site deaths or loss of facility/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, or minor impact on the environment. Capable of returning to operation.
L	Low	Minor impact on-site with no off-site impact. May cause minor injury, minor occupational illness, or minor impact on the environment.
EL	Extremely Low	Will not result in a significant injury, occupational illness, or provide a significant impact on the environment.

The probability rating levels are shown in Table B - 3 – Probability Rating Levels. 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 hazardous event.

Table B - 3 – Probability Rating Levels

Category	Symbol	Description	Estimated Range of Probability of Accident Descriptive Word Occurrence per Year
High	H	Event is likely to occur several times during the facility or operation lifetime.	$> 10^{-1}$
Medium	M	Event may occur during the facility or operation 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		Probability of occurrence is so small that a reasonable scenario is not conceivable. These	$< 10^{-6}$

		events are not considered in the design or FSAD accident analysis.	

The risk matrix shown in Table B-4 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 accelerator facilities.

Table B - 4 – Risk Matrix

Consequence Level					
	H				
	M				
	L				
	EL				
		EL	L	M	H
		Probability of Occurrence			

Risk rating		
	High	Unacceptable
	Medium	
	Low	Tolerable
	Negligible	Acceptable

Assessment Results

The results of the analysis methodology used in Chapter 5 Hazard Assessment and Mitigation, as applied to the combination of hazards presented by the Technical Areas, is found below in Table B-1. Since Technical Areas are not accelerators, they are not represented in an ASE. However, controls required for Technical Areas are incorporated into Operational Safety Procedures that address the hazards specific to each Technical Area. It should be noted that, in most cases, the same systems that serve as Credited Active Engineered Controls for accelerators are used in Technical Areas. 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.

Table B - 5 – Hazards, Postulated Initiating Events and Worst-Case Accident Scenarios in Technical Areas

Abbreviations: WBD – Whole Body Dose, EL – Extremely Low, L – Low, M–Medium

IID	Hazard Type	Event Description	Potential Initiators	Basis/ Assumptions	Results	Location	Unmitigated Risk Rating	Unmitigated Probability	Unmitigated Consequence	Mitigated Risk Rating	Mitigated Probability	Mitigated Consequence
B1	Ionizing Radiation	Personnel gain unauthorized entry during RF operations. RF cavity field emission produces average photon dose rate 110 rem/hr whole body.	• Human error • Unauthorized Operator	• Avoidable • RF operating at max gradient • Few workers exposed to high radiation fields	• Worker exposure of 2 hrs RF (longer than the average run time for cavity testing) 220 rem WBD	• CMTF Cave	**UNACCEPTABLE** • Elevated worker exposure • Detectable health consequences	M	M	**ACCEPTABLE** • Shielding • PSS Access Controls • Alarms and warning devices (lights, signage, etc.), • Radiation Worker training	EL	L
B2	Ionizing Radiation	Personnel present in the VTA, high-power RF applied to a cavity, no shielding. RF cavity field emission dose rate approx. 53 R/h	• Control system failure	• Avoidable • RF operating at max gradient • Few workers exposed to high radiation fields	• 1 hr worker exposure, 53 rem WBD	• VTA Floor Level	**ACCEPTABLE** • Elevated worker exposure • Minimal to undetectable health consequences	M	L	**ACCEPTABLE** • Shielding • PSS Access Controls • Alarms and warning devices (lights, signage, etc.), • Radiation Worker training	EL	L
43	Ionizing Radiation	Personnel present in the GTS while high voltage applied to gun, no shielding. dose rate <2.2 R/h	• Control system failure	• Avoidable • Gun HV at max • Few workers exposed to high radiation fields • Typical 1 hour test	• 1 hr worker exposure • < 2.2 rem WBD	• LERF GTS	**ACCEPTABLE** • Elevated worker exposure • Minimal to undetectable health consequences	M	EL	**ACCEPTABLE** • Shielding • PSS Access Controls • Alarms and warning devices (lights, signage, etc.), • Radiation Worker training	EL	L
B4	**ODH***	Gaseous nitrogen supply fails	• Component failure	• ODH conditions inside enclosure: combination of highest leakage volume, and highest Pi	• Worker exposure to <9 % O2 (worst case) • ODH 2 conditions	• Inside CMTF Cave • GTS	**UNACCEPTABLE** • Worker health effects up to and including death	M	M	**ACCEPTABLE** • ODH System alarms • Nitrogen lines outfitted with flow restricting orifice • ODH Training • PPE	EL	L
B5	**ODH***	Gaseous nitrogen supply fails	• Component failure	• ODH conditions inside Cave: combination of largest spill volume, and highest probability	• Worker exposure to >18% O2 (worst case) • ODH conditions	• Inside CMTF Control Room	**ACCEPTABLE** • Worker health effects up to and including temporary impairment	EL	EL	**ACCEPTABLE** • ODH System alarms • Nitrogen lines outfitted with flow restricting orifice, penetrations to Control Room sealed • ODH training • PPE	EL	EL
B6	**ODH***	Gaseous helium supply fails	• Component failure • Human error	• ODH conditions inside Cave: combination of largest helium spill volume, and highest probability	• Worker exposure to <9 % O2 (worst case) • ODH conditions	• Inside CMTF Cave	**TOLERABLE** • Worker health effects up to an including death	EL	H	**TOLERABLE** • ODH Alarms • Open passive vent at CMTF ceiling • ODH training • PPE	EL	H

Table B - 5 – Hazards, Postulated Initiating Events and Worst-Case Accident Scenarios in Technical Areas

Abbreviations: WBD – Whole Body Dose, EL – Extremely Low, L – Low, M–Medium

IID	Hazard Type	Event Description	Potential Initiators	Basis/ Assumptions	Results	Location	Unmitigated Risk Rating	Unmitigated Probability	Unmitigated Consequence	Mitigated Risk Rating	Mitigated Probability	Mitigated Consequence
B7	ODH*	Gaseous helium supply fails	• Component failure	• ODH conditions inside Cave: combination of largest helium spill volume, and highest probability	• Worker exposure to >18 % O2 (worst case) • ODH conditions	• Inside Barn	**ACCEPTABLE** • Worker health effects up to and including temporary impairment	EL	EL	**ACCEPTABLE** • ODH System Alarms • ODH Training • PPE	EL	EL
B8	Non-Ionizing Radiation	Personnel present in the CMTF, Barn, mezzanine, high-power RF applied to a window test stand.	• RF maintenance work • RF component testing	• Avoidable • RF power not shutdown prior to starting work • RF power applied while waveguide is open	• Workers exposed to RF radiation of 0.5 watt/cm2 at 30 cm (head, upper torso) and 10 watt/cm2 at 5 to 6 cm (fingers, hands) per 1000 W RF power	• Inside CMTF Cave • CMTF Mezzanine • Barn	**UNACCEPTABLE** • Worker suffers eye injury and 2nd degree burns to extremities	M	M	**ACCEPTABLE** • Physical interlock wire confirming waveguide integrity as a condition of klystron high voltage. • RF leakage test • LOTO. • Waveguide bolt up/ tagging procedure	EL	M
B9	Non-ionizing Radiation	RF waveguide or cable open while klystron is on	• RF maintenance work • RF component testing	• Avoidable • RF power not shutdown prior to starting work • RF power applied while waveguide is open • Worst case exposure to workers	• Workers exposed to RF radiation of 0.5 watt/cm2 at 30 cm (head, upper torso) and 10 watt/cm2 at 5 to 6 cm (fingers, hands) per 1000 W RF power	• CMTF • VTA	**UNACCEPTABLE** • Worker suffers eye injury and 2nd degree burns to extremities	M	M	**ACCEPTABLE** • RF leakage test. • LOTO. • Waveguide bolt up/ tagging procedure	EL	M

* NOTE: ODH assessment can be found as #JLAB-TN-07-066

Table B - 6 – 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
Non-Ionizing Radiation	Medium	Medium	Unacceptable	Acceptable

Assessment Summary

The impact of each event is highly localized, limited to directly adjacent spaces, and affects limited (in most cases, one) staff. Each of the Technical Areas analyzed present 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.

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2 CEBAF-TN-0058, Workshop on Radiation Safety, April 1986

3 RCD-DEP-18 #001, "Recommendations and Rationale for Beam Loss Assumptions at CEBAF".

4 CEBAF-TN-95-044, Shielding and other radiation safety requirements for the 200 MeV recirculating linac with energy recovery for the UV FEL, G. Neil, G. Stapleton, May 1995

5 CEBAF-TN-95-044, Shielding and other radiation safety requirements for the 200 MeV recirculating linac with energy recovery for the UV FEL, G. Neil, G. Stapleton, May 1995

6 JLAB-TN-18-020, "Radiation Safety Aspects of the Upgraded Injector Test Facility", V. Vylet, June 2018

7 Technical Report Series No. 188, Radiological Safety Aspects of the Operation of Electron Linear Accelerators, WP Swanson, IAEA, Vienna, 1979

8 JLAB-TN-13-023, Radiation Safety Consideration of C100 Cryomodule Operation at Jefferson Lab, P. Degtiarenko, M. Keller, G. Kharashvili, V. Vylet, K. Welch

9 JLab Ops Staytreat 2016, *C100 Activation Status and Projections*, P. Degtiarenko, D. Hamlette, G. Kharashvili, V. Vylet, K. Welch, M. Washington

10 SLAC RADIATION PHYSICS NOTE RP-15-13, July 2015, Radiation Fields from Field Emission at the SCRF cavities of LCLS-II, M. Santana Leitner, Lixin Ge

11 JLAB-TN-08-034 Degtiarenko, P., *Evaluation of Radiation Exposure Around End Stations at Jefferson Lab.* Newport News: Jefferson Lab, 2008.

12 JLAB-TN-08-068, Radiated RF Power from an Open Waveguide Routed to a Superconducting Cavity, Haipeng Wang (Last Updated on October 31, 2008)

13 JLAB-TN-08-076 Hazard from Accelerator Beam Induced RF, R. May (last updated 9-19-13)

14 JLab-TN-13-023, Degtiarenko, P, et al., *Radiation Safety Consideration of C100 Cryomodule Operation at Jefferson Lab*. Newport News: Jefferson Lab, 2013.

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[16] CEBAF-TN-95-044, Shielding and other radiation safety requirements for the 200 MeV recirculating linac with energy recovery for the UV FEL, G. Neil, G. Stapleton, May 1995

[17] *TJNAF Site Environmental Report for Calendar Year 2006 (and reports for prior years).* TJNAF. Newport News, VA.

[18] ibid

[19] JLAB-TN-15-021, "The Impact of modifications to Hall A and C Beam Dump Atmospheric Controls on Radioactive Emissions"

[20] TN 16-016, "Analysis of key accident scenarios for high power beam dump cooling systems"

[21] Robertson, H. SSG Note. *Description of the Jefferson Lab Oxygen Monitoring System.* Newport News, VA: Jefferson Lab SSG, July 19, 2006. Revision 3.0

[22] *Preliminary Safety Analysis Report, Revision 2.* Newport News: Jefferson Lab ESH&Q, October 2, 1989.

[23] *CEBAF Hazards Analysis.* April 27, 1993.

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