BOOSTER NEUTRINO BEAM

SECTION III CHAPTER 06
OF THE FERMILAB SAD

Revision 1 January 2, 2024

This Chapter of the Fermilab Safety Assessment Document (SAD) contains a summary of the results of the Safety Analysis for the Booster Neutrino Beam of the Fermilab Main Accelerator that are pertinent to understanding the risks to the workers, the public, and the environment due to its operation.

SAD Chapter Review

This Section III, Chapter 6 of the Fermi National Accelerator Laboratory (Fermilab) Safety Assessment Document (SAD), *Booster Neutrino Beam*, was prepared and reviewed by the staff of the Accelerator Directorate (AD), Beams Division, External Beam Delivery Department in conjunction with the Environment, Safety, and Health (ES&H) Division Accelerator Safety Department.

Signatures below indicate review of this Chapter, and recommendation that it be approved and incorporated into the Fermilab SAD.

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Revision History

Printed versions of this Chapter of the Fermilab Safety Assessment Document (SAD) may not be the currently approved revision. The current revision of this Chapter can also be found on ES&H DocDB #1066 along with all other current revisions of all Chapters of the Fermilab SAD.

Author	Rev. No.	Date	Description of Change
John E. Anderson Jr. & Craig Moore	0	January 23, 2013	Initial release of the Booster Neutrino Beam Chapter for the Fermi National Accelerator Safety Assessment Document (SAD).
Jason D. Crnkovic	1	January 2, 2024	Updated document format and new consideration of Non-Accelerator Specific Hazards. Addition of MCI for radiological hazards with a description of the credited and defense-in-depth controls to mitigate it.

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Acronyms and Abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists
ACNET	Accelerator Control Network System
AD	Accelerator Directorate
AHJ	Authority Having Jurisdiction
ALARA	As Low As Reasonably Achievable
ANSI	American National Standards Institute
APS-TD	Applied Physics and Superconducting Technology Directorate
ARA	Airborne Radioactivity Area
ASE	Accelerator Safety Envelope
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
ASME	American Society of Mechanical Engineers
ASO	Accelerator Safety Order, referring to DOE O 420.2D *Safety of Accelerators*
^{7}Be	Beryllium-7
BLM	Beam Loss Monitor
BNB	Booster Neutrino Beam
BPM	Beam Position Monitor
BY	Boneyard
CA	Controlled Area
CA	Contamination Area
CAS	Contractor Assurance System
CC	Credited Control
CCL	Coupled Cavity Linac
CDC	Critical Device Controller
CERN	European Organization for Nuclear Research
CFM	Cubic Feet per Minute
CFR	Code of Federal Regulations (United States)
Ci	Curie
CLW	Co-Located Worker (the worker in the vicinity of the work but not actively participating)
cm	centimeter
CPB	Cryogenics Plant Building
CSO	Chief Safety Officer
CUB	Central Utility Building
CW	Continuous Wave
CX	Categorically Excluded
D&D	Decontamination and Decommissioning
DA	Diagnostic Absorber

DAE	Department of Atomic Energy India
DCS	Derived Concentration Standard
DocDB	Document Database
DOE	Department of Energy
DOT	Department of Transportation
DR	Delivery Ring
DSO	Division Safety Officer
DSS	Division Safety Specialist
DTL	Drift Tube Linac
DUNE	Deep Underground Neutrino Experiment
EA	Environmental Assessment
EA	Exclusion Area
EAV	Exhaust Air Vent
EENF	Environmental Evaluation Notification Form
EMS	Environmental Management System
EOC	Emergency Operations Center
EPA	Environmental Protection Agency
ES&H	Environment, Safety and Health
Fermilab	Fermi National Accelerator Laboratory, see also FNAL
FESHCom	Fermilab ES&H Committee
FESHM	Fermilab Environment, Safety and Health Manual
FHS	Fire Hazard Subcommittee
FIRUS	Fire Incident Reporting Utility System
FNAL	Fermi National Accelerator Laboratory, see also Fermilab
FODO	Focus-Defocus
FONSI	Finding of No Significant Impact
FQAM	Fermilab Quality Assurance Manual
FRA	Fermi Research Alliance
FRCM	Fermilab Radiological Control Manual
FSO	Fermilab Site Office
FW	Facility Worker (the worker actively performing the work)
GERT	General Employee Radiation Training
GeV	Giga-electron Volt
^3H	Tritium
HA	Hazard Analysis
HAR	Hazard Analysis Report
HCA	High Contamination Area
HCTT	Hazard Control Technology Team
HEP	High Energy Physics

HFD	Hold for Decay
HLCF	High Level Calibration Facility
HPR	Highly Protected Risk
Hr	Hour
HRA	High Radiation Area
HSSD	High Sensitivity Air Sampling Detection
HVAC	Heating, Ventilation, and Air Conditioning
HWSF	Hazardous Waste Storage Facility
Hz	Hertz
IB	Industrial Building
IBC	International Building Code
ICW	Industrial Cooling Water
IEPA	Illinois Environmental Protection Agency
IEEE	Institute of Electrical and Electronics Engineers
INFN	Istituto Nazionale di Fisica Nucleare
IMPACT	Integrated Management Planning and Control Tool
IPCB	Illinois Pollution Control Board
IQA	Integrated Quality Assurance
ISD	Infrastructure Services Division
ISM	Integrated Safety Management
ITNA	Individual Training Needs Assessment
KeV	kilo-electron volt
kg	kilo-grams
kW	kilo-watt
LBNF	Long Baseline Neutrino Facility
LCW	Low Conductivity Water
LHC	Harge Hadron Collider
LLCF	Low Level Calibration Facility
LLWCP	Low Level Waste Certification Program
LLWHF	Low Level Waste Handling Facility
LOTO	Lockout/Tagout
LPM	Laser Profile Monitor
LSND	Liquid Scintillator Neutrino Detector
LSO	Laser Safety Officer
m	meter
mA	milli-amp
MABAS	Mutual Aid Box Alarm System
MARS	Monte Carlo Shielding Computer Code
MC	Meson Center

MC&A	Materials Control and Accountability
MCI	Maximum Credible Incident
MCR	Main Control Room
MEBT	Medium Energy Beam Transport
MEI	Maximally Exposed Individual
MeV	Mega-electron volt
MI	Main Injector
MINOS	Main Injector Neutrino Oscillation Search
MMR	Material Move Request
MOI	Maximally-exposed Offsite Individual *(Note: due to the Fermilab Batavia Site being open to the public, the location of the MOI is taken to be the location closest to the accelerator that is accessible to members of the public.)*
MP	Meson Polarized
mrad	milli-radian
mrem	milli-rem
mrem/hr	milli-rem per hour
MT	Meson Test
MTA	400 MeV Test Area
MTF	Magnet Test Facility
^{22}Na	Sodium-22
NC	Neutrino Center
NE	Neutrino East
NEC	National Electrical Code
NEPA	National Environmental Policy Act
NESHAPS	National Emissions Standards for Hazardous Air Pollutants
NFPA	National Fire Protection Association
NM	Neutrino Muon
NMR	Nuclear Material Representative
NOvA	Neutrino Off-axis Electron Neutrino (ve) Appearance
NPH	Natural Phenomena Hazard
NRTL	Nationally Recognized Testing Laboratory
NIF	Neutron Irradiation Facility
NTSB	Neutrino Target Service Building, see also TSB
NuMI	Neutrinos at the Main Injector
NW	Neutrino West
ODH	Oxygen Deficiency Hazard
ORC	Operational Readiness Clearance
OSHA	Occupational Safety and Health Administration
pCi	pico-Curie

pCi/mL	pico-Curie per milliliter
PE	Professional Engineer
PIN	Personal Identification Number
PIP	Proton Improvement Plan
PIP-II	Proton Improvement Plan - II
PHAR	Preliminary Hazards Analysis Report
PPD	Particle Physics Directorate
PPE	Personnel Protective Equipment
QA	Quality Assurance
QAM	Quality Assurance Manual
RA	Radiation Area
RAF	Radionuclide Analysis Facility
RAW	Radioactive Water
RCT	Radiological Control Technician
RF	Radio-Frequency
RFQ	Radio-Frequency Quadrupole
RIL	RFQ Injector Line
RMA	Radioactive Material Area
RMS	Root Mean Square
RPCF	Radiation Physics Calibration Facility
RPE	Radiation Physics Engineering Department
RPO	Radiation Physics Operations Department
RRM	Repetition Rate Monitor
RSI	Reviewed Safety Issue
RSIS	Radiation Safety Interlock System
RSO	Radiation Safety Officer
RWP	Radiological Work Permit
SA	Shielding Assessment
SAA	Satellite Accumulation Areas
SAD	Safety Assessment Document
SCF	Standard Cubic Feet
SCFH	Standard Cubic Feet per Hour
SEWS	Site-Wide Emergency Warning System
SNS	Spallation Neutron Source
SR	Survey Riser
SRF	Superconducting Radio-Frequency
SRSO	Senior Radiation Safety Officer
SSB	Switchyard Service Building
SSP	Site Security Plan

SWIC	Segmented Wire Ionization Chambers
TLM	Total Loss Monitor
TLVs	Threshold Limit Values
TPC	Time Projection Chamber
TPES	Target Pile Evaporator Stack
TPL	Tagged Photon Lab
TSB	Target Service Building, see also NTSB
TSCA	Toxic Substances Control Act
TSW	Technical Scope of Work
T&I	Test and Instrumentation
UPB	Utility Plant Building
UPS	Uninterruptible Power Supply
USI	Unreviewed Safety Issue
VCTF	Vertical Cavity Test Facility
VHRA	Very High Radiation Area
VMS	Village Machine Shop
VMTF	Vertical Magnet Test Facility
VTS	Vertical Test Stand
WSHP	Worker Safety and Health Program
µs	micro-second

III-6. Booster Neutrino Beam

III-6.1. Introduction

This Section III, Chapter 06 of the Fermi National Accelerator Laboratory (Fermilab) Safety Assessment Document (SAD) covers the Booster Neutrino Beam (BNB) segment of the Fermilab Main Accelerator.

III-6.1.1 Purpose/Function

The original purpose of the BNB segment was to provide an intense source of neutrinos to definitively explore the neutrino oscillation signal reported by the Los Alamos Liquid Scintillator Neutrino Detector (LSND) experiment which took data from 1993-1998. The LSND experiment found evidence that muon neutrinos oscillate into electron neutrinos.

Additional experimental facilities (SciBooNE Hall, Liquid Argon Test Facility, Short Baseline – Near, Short Baseline – Far), have been constructed. The SciBooNE and MiniBooNE Dark Matter experiments have been supported. The beamline is currently supporting the Short-Baseline Neutrino (SBN) Program at Fermilab, which includes the MicroBooNE (finished collecting data), ICARUS (collecting data), ANNIE (collecting data), and SBND (data collection anticipated in CY2024) experiments. The facility is capable of being configured for a variety of 8 GeV physics.

III-6.1.2 Current Status

The BNB segment of the Fermilab Main Accelerator is currently: **Operational.**

III-6.1.3 Description

The BNB segment is a multi-purpose experimental facility located north of the Main Injector (MI) near the MI10 Service Building (see figure 1). The BNB segment accepts beam from the 8 GeV Line (MI8) segment, where the 8 GeV Line is covered under a separate SAD chapter. The BNB segment begins at the downstream wall of the BNB extraction stub, near the downstream end of the MI8 enclosure at cell 851. This segment includes the Beam Pipe downstream of the Main Injector Enclosure. Bending and focusing magnets in MI transport the extracted beam from a switching magnet to the Beam Pipe (buried MI-12A carrier pipe) that connects the MI to the 8 GeV Fixed Target beamline, which includes the MI-12A and MI-12B enclosures. The beamline continues through the MI-12A and MI-12B enclosures to the BNB target station under the MI-12 Service Building. Following the target station are the decay region, 25-m and 50-m beam absorbers, MI-13 enclosure, and MI-13 electronics shed. This chapter assesses the carrier pipe; MI-12A, MI-12B, and MI-13 enclosures; target pile; decay pipe; 25-m and 50-m absorbers; MI-12 Service Building; and MI-13 electronics shed.

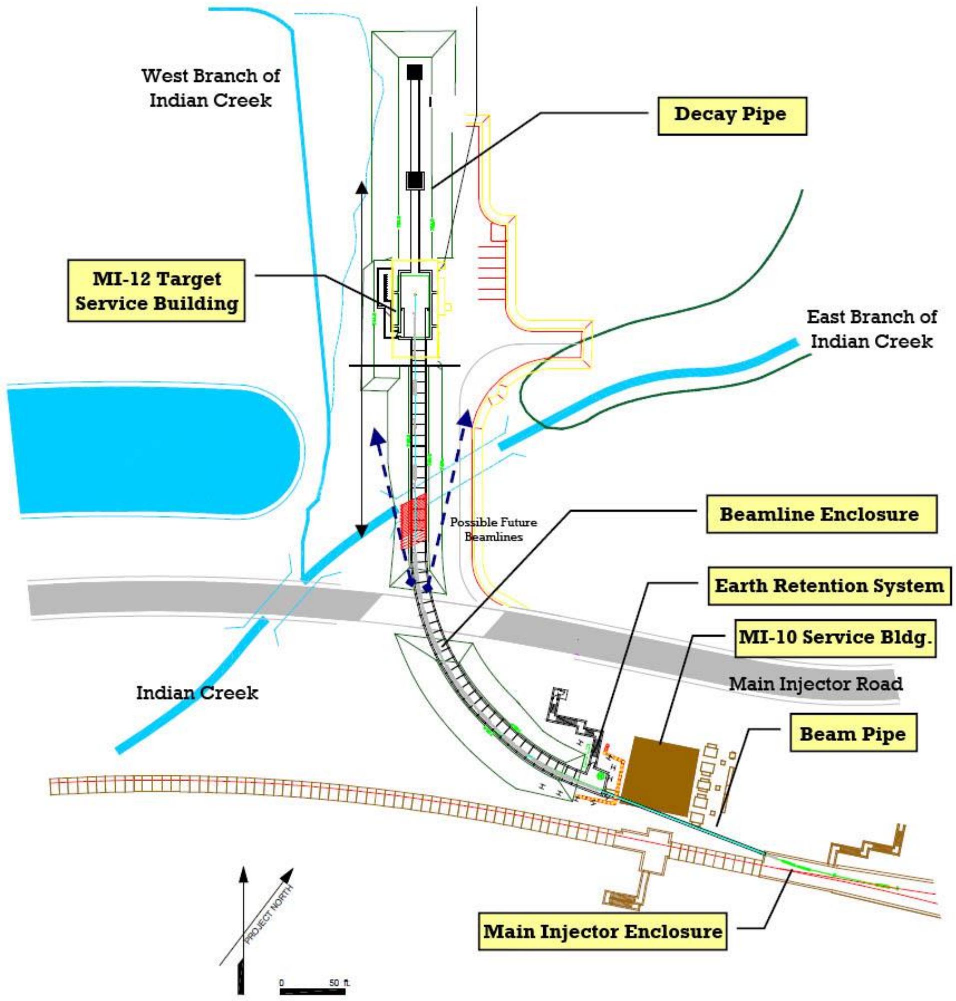

Figure 1. Booster Neutrino Beam (BNB) Layout Figure. The BNB segment begins with the Beam Pipe that starts at the end of the Main Injector Enclosure.

III-6.1.4 Location

The BNB segment of the Fermilab Main Accelerator is located on the Fermilab site in Batavia, IL (see Figure 2). Specifically, this segment is located north of the MI segment (see Figure 3).

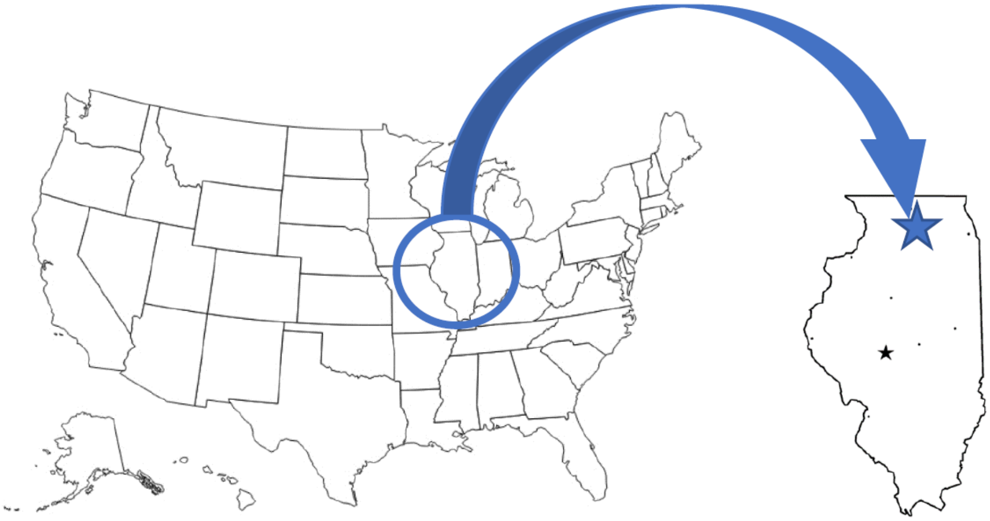

Figure 2. Regional view showing the location of the Fermilab site in Batavia, IL.

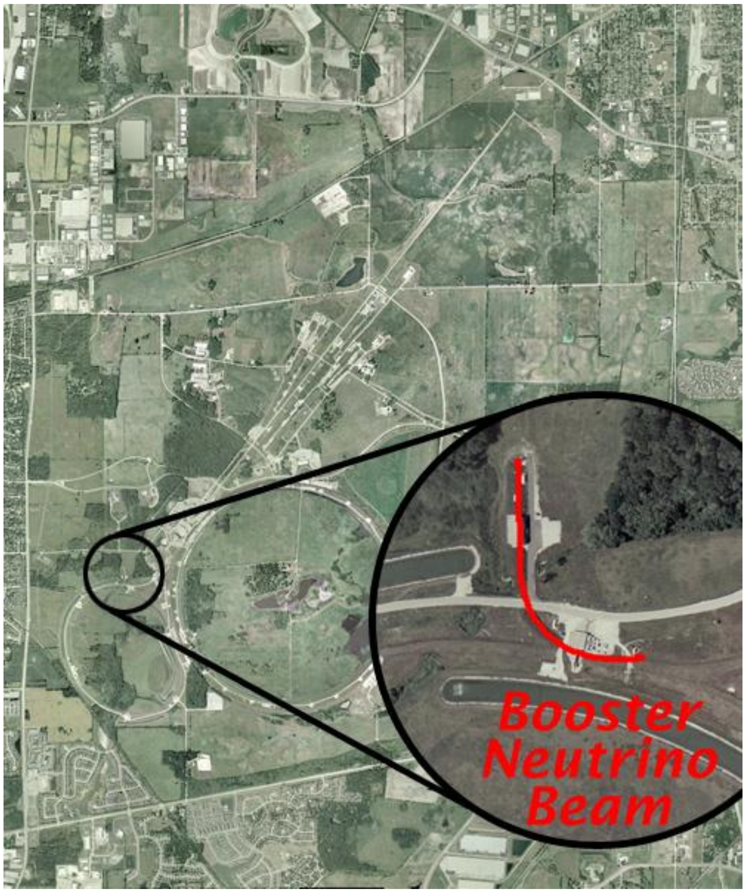

Figure 3. Aerial view of the Fermilab site, indicating the location of the Booster Neutrino Beam (BNB).

III-6.1.5 Management Organization

The BNB area is managed by AD, the Beams Division, and the External Beam Delivery Department.

III-6.1.6 Operating Modes

The BNB line is capable of both on-target and off-target running. Proton transport up to the target is common for both modes.

Common to Both Modes

The BNB segment accepts 8 GeV proton beam from the Booster segment. The 8 GeV beam leaves the Booster enclosure as it would for the MI segment, down the MI8 beamline. It travels in the MI8 beamline through Q851. A switch magnet, MBEX (E:H851), located downstream of Q851 deflects selected Booster batches into the MI-12A and MI-12B enclosures. The next three quadrupoles, Q860, Q861 and Q862, capture the beam and focus it for transport through the 42-m drift tube (Jack Pipe) under the MI10 Service Building. Before the drift tube is also where BNB leaves the MI enclosure near the 101 location. After the drift tube, quadrupoles Q864, Q865 and Q866 match the beam to the Focus-Defocus (FODO) cells of the arc that provide the major bend to direct the beam toward the SBN experimental area.

On-Target Mode

Protons from the primary beam strike a beryllium target. The target is located within and concentric with the magnetic focusing horn, but it is physically separated from the horn. Pions produced in the beryllium target by the 8 GeV protons make a large range of angles with respect to the incident beam direction. The neutrinos produced by the pion decays move nearly collinear with the parent pion direction. Unless the pions are focused toward the detectors, many of the neutrinos would miss the detectors and be lost to the experiments. The pions coming off of that target may be focused by the toroidal magnetic field generated from a high-current-carrying horn. The horn preferentially selects pions with beam energies from 0.75 to 3.75 GeV, which are of interest to the SBN Program. The horn operates at up to a 7.5 Hz repetition rate.

The horn focuses pions into a 50-m steel decay pipe that has a 1.8-meter diameter. At the end of the decay pipe is a beam absorber, which stops all secondary particles except the neutrinos. Located 25 m from the target is an intermediate absorber that can be lowered into the beam. This feature was introduced to provide a test signal versus the background.

The neutrinos will travel 440 m through the ground to the detectors used in the SBN Program (covered under separate SAD chapters). These neutrinos will range in energies from 0.3 to 1.5 GeV.

Off-Target Mode

Protons from the primary beam do not strike a beryllium target; instead, they are transported through the decay pipe, and are stopped at either the 25 m absorber or the 50 m absorber. The protons interact in the absorber, resulting in secondary particles. The secondary particles quickly interact before the majority can decay. The resulting neutrinos travel through the ground to the downstream detectors. This mode provides a test of "prompt" signal versus signal due to decay-in-flight. The horn is not pulsed in this mode.

III-6.1.7 Inventory of Hazards

Table 1 lists all the identified hazards found in the BNB enclosure and support buildings. Section III-6.9 *Appendix – Risk Matrices* describes the baseline (unmitigated) risk, any preventative and/or mitigative controls in place to reduce the risk, and residual (mitigated) risk for facility worker, co-located worker, and Maximally-exposed Offsite Individual (MOI), i.e. a member of the public. Tables 5 and 5.1-5.31 list the baseline and residual risks for hazards. A summary of these controls is described within Section III-6.2 *Safety Assessment.*

Prompt ionizing radiation and Oxygen Deficiency Hazard (ODH) due to cryogenic systems within accelerator enclosures have been identified as accelerator specific hazards, and as such, their controls are identified as Credited Controls. The analysis of these hazards and their Credited Controls will be discussed within this SAD chapter, and their Credited Controls summarized in the Accelerator Safety Envelope (ASE) for the Fermilab Main Accelerator. Accelerator specific controls are identified as **purple/bold** throughout this chapter.

All other hazards present in BNB are safely managed by other Department of Energy (DOE) approved applicable safety and health programs and/or processes, and their analyses have been performed according to applicable DOE requirements as flowed down through the Fermilab Environment, Safety, and Health Manual (FESHM). These hazards are considered to be Non-Accelerator-Specific Hazards (NASHs), and their analysis will be summarized in this SAD Chapter.

Table 1. Hazard Inventory for Booster Neutrino Beam (BNB).

	Radiological		**Toxic Materials**
☒	**Prompt Ionizing Radiation**	☒	Lead
☒	Residual Activation	☒	Beryllium
☒	Groundwater Activation	☐	Fluorinert & Its Byproducts
☒	Surface Water Activation	☐	Liquid Scintillator
☒	Radioactive Water (RAW) Systems	☐	Ammonia
☒	Air Activation	☐	Nanoparticle Exposures
☒	Closed Loop Air Cooling		**Flammables and Combustibles**
☒	Soil Interactions	☒	Combustible Materials (e.g., cables, wood cribbing, etc.)
☒	Radioactive Waste	☐	Flammable Materials (e.g., flammable gas, cleaning materials, etc.)
☒	Contamination		**Electrical Energy**
☒	Beryllium-7	☒	Stored Energy Exposure
☒	Radioactive Sources	☒	High Voltage Exposure
☐	Nuclear Material	☒	Low Voltage, High Current Exposure
☐	Radiation Generating Devices (RGDs)		**Kinetic Energy**
☐	Non-Ionizing Radiation Hazards	☒	Power Tools
	Thermal Energy	☒	Pumps and Motors
☐	Bakeout	☒	Motion Tables
☒	Hot Work	☐	Mobile Shielding
☐	**Cryogenics**		**Magnetic Fields**

Potential Energy		☒	Fringe Fields
☒	Crane Operations	**Other Hazards**	
☒	Compressed Gasses	☒	Confined Spaces
☒	Vacuum/Pressure Vessels/Piping	☒	Noise
☒	Vacuum Pumps	☒	Silica
☒	Material Handling	☒	Ergonomics
Access & Egress		☐	Asbestos
☒	Life Safety Egress	☒	Working at Heights

III-6.2. Safety Assessment

All hazards for the BNB segment of the Fermilab Main Accelerator are summarized in this section, with additional details of the analyses for accelerator specific hazards.

III-6.2.1 Radiological Hazards

BNB has radiological hazards in the form of prompt ionizing radiation (from particle beams), residual activation (from component activation), groundwater activation, surface water activation, radioactive water (RAW) systems, air activation, closed loop air cooling, soil interactions, radioactive waste, contamination, beryllium-7, and radioactive sources. Refs. [1-8] provide background material on the design and safety analysis, including radiological hazards, of the BNB segment. The design and operation of this segment complies with the Fermilab Radiological Control manual (FRCM) [9]. Operating the BNB transport and targeting systems results in environmental radioactivity in the form of air, soil, and potential groundwater activation.

Two detailed shielding assessments and post assessment documents address these hazards. The assessments provide a detailed analysis of the BNB segment and demonstrate that the required overburden for shielding, use of signs, fences, and active interlocks comply with FRCM. Residual activation of beamline components has a substantial impact on the ability to occupy the beamline enclosures where recurring access is required for routine maintenance. The 8 GeV Fixed Target Shielding Assessment region extends from cell 803 in the 8 GeV Line to the front face of the MiniBooNE Target Station. The MiniBooNE Target Station Shielding Assessment region begins at the front face of the target station in the MI-12B enclosure and continues through the decay and absorber regions to the point where the muons range out in the soil 70’ downstream of the 50-meter absorber. The assessments assume an average 7.5 Hz pulse rate of 8 GeV/c protons at an intensity of 6E12 protons/pulse for a rate of 1.62E17 protons/hr.

The assessments consider transverse and longitudinal shielding requirements; summarize labyrinth and penetration calculations; calculate air activation, estimate annual release, and list release points; calculate ground and surface water activation, list surface water discharge points, and monitoring locations; consider muon production; calculate residual dose rates; and specify active shielding controls and monitoring.

III-6.2.1.1 Prompt Ionizing Radiation

Prompt ionizing radiation is the principal radiation hazard when beam is transported through the BNB segment. Sufficient amounts of shielding (earth, concrete or iron) and/or networks of interlocked detectors surround the enclosures and beam pipes to keep any prompt radiation within acceptable levels and to protect workers and the general public from ionizing radiation. Operation of the area conforms to the FRCM to maintain exposures for operating personnel as low as reasonably achievable (ALARA).

This hazard has been evaluated via a Maximum Credible Incident (MCI) analysis that is described in Section III-6.3.1.1. This analysis specifies that Fermilab uses Credited Controls that flow down to the Accelerator Safety Envelope (ASE) to mitigate the consequences of the MCI to at or below the acceptable dose levels described in SAD Section I Chapter 4. A detailed description of each of the Credited Controls and their function is provided in Section III-6.4. The conclusion of these analyses is that the mitigated dose level associated with prompt ionizing radiation due to beam loss is acceptable.

III-6.2.1.2 Residual Activation

Several preventions and mitigations are used to reduce the risk associated with the residual activation hazards, which include the following. General and/or job specific Radiological Work Permits (RWPs) are written by ES&H personnel, and they specify the work that is permitted to be performed, requirements to perform the work, and limitations of radiological exposure. A Log Survey Monitor (LSM) allows for real time monitoring of radiation levels during work, and its use is specified in the relevant RWP when deemed appropriate for the work. Radiological training is an educational system managed by ES&H personnel that establishes basic worker knowledge through presentations and testing. Radiological signage is in various places throughout the accelerator complex, which warns of various hazards and occupancy restrictions. Furthermore, work may be restricted or prevented until sufficient time has passed such that radiation levels are sufficiently low to allow for safer work to proceed. Target pile shielding is material placed between radiation sources in the target pile and the enclosure to be protected. Shielding is also placed between radiation sources and other materials that may come into the close proximity of people. Public access gates will be used to prevent unauthorized access by the public. The following discussion in this section outlines the approach used to reduce the risk associated with residual activation hazards.

By design, residual radiation in the BNB area except at the target station is expected to be low. Beam interaction which would cause a high level of residual radiation would compromise the efficient transport of primaries to the target. Operational losses along the 8 GeV fixed target beamline will result in activation of instrumentation devices and other beam line components that intercept the beam. The activation level and quantity of activated material will not be unique relative to other segments of the Fermilab Main Accelerator.

Residual activation hazards will be managed within the ALARA program established throughout the Fermilab accelerator complex and as prescribed in FRCM. All potential residual activation hazards are handled operationally as in all other primary beam enclosures. These controls include verification of training, centralized authorization, and key entry. The level of control depends on the level of residual radiation. In most cases, a general RWP for accesses will suffice. The RWPs and ALARA plans must be written and followed in accordance with the FRCM requirements for work on any highly activated equipment.

The target and focusing horn, referred to collectively as the "target station", have become highly radioactive during operation. The shielding assessment estimates the dose on target station components of up to 150 rem/hr and dose rates outside the target station shielding of less than 100 mrem/hr after 10 years of running and one day of cool off. No personnel access is allowed into the target station area. Job specific ALARA plans have been developed to install a new horn and remove a failed horn. These tasks will be carried out under the direction of an ES&H Radiation Safety Officer (RSO).

There is no personnel access to the inside of the decay region. The 25-m absorber can be raised and lowered into the beam by accessing the 25-m absorber silo without exposing personnel to the front face or interior steel absorber plates.

Lastly, baseline qualitative risks due to this hazard were assessed, and determined to be risk level I (major concern) for facility workers and co-located worker receptors, but through the use of preventive and mitigative hazard controls, the likelihood and consequence of this hazard is reduced, resulting in a risk level of IV, meaning residual risks are of minimal concern. For the public the baseline qualitative risk due to this hazard are managed through a series of preventive and mitigative controls, which mitigate consequences from the hazard from a baseline risk level III (minor concern) to a residual risk level of IV (minimal concern).

III-6.2.1.3 Groundwater Activation

Several preventions and mitigations are used to reduce the risk associated with the groundwater activation hazards, which include the following. Facility designs employ shielding to mitigate the production of activation products in groundwater. Sump pits/enclosures capture activated water to prevent releases exceeding allowed discharge limits. Sump water is evaluated to determine the presence of tritium or other activation products to prevent exposure to people. The sump water is periodically sampled, and tank draining is performed by Radiological Control Technicians (RCTs) who have specialized training. The highly trained RCTs employ ALARA principles to mitigate exposures during tank draining activities. The following discussion in this section outlines the approach used to reduce the risk associated with prompt ionizing radiation hazards.

The greatest concern is the production of helium-3 (tritium) and sodium-22 radionuclides due to production rate and leachability into the groundwater, as well as the long half-lives of these radionuclides. FRCM provides Fermilab standards pertaining to groundwater activation, and Environmental Protection Notes No. 8 and 17 provide the methodologies used for estimating groundwater activation. The methodology is designed to achieve a conservative estimate of groundwater activation.

Groundwater activation is a concern both in the target and decay pipe areas. The target pile was designed for the specified beam elevation, so as to provide adequate protection of the groundwater below the target pile.

A containment region consisting of crushed aggregate (CA-6) surrounds the 1.8-meter diameter decay pipe. The containment region extends at least ten feet from the beam centerline, i.e. seven feet from the decay pipe wall.

A design excluding water from the containment region was developed to keep groundwater activation outside this volume below the regulatory limits for radionuclides. The intent was to isolate water from the containment region using a double-walled geotextile liner system similar to those used in landfills (Figure 2). Six monitoring wells were installed for dewatering and sampling the three different liner zones. Three monitoring wells, one for each liner zone, are located at the upstream and downstream ends of the decay region on the east side.

The lower half of the liner system was tested in June, 2001, before final backfilling took place, and no leaks were detected. A second set of tests in January, 2002 indicated a failure of both layers, and that the failure is near the bottom of the liner system.

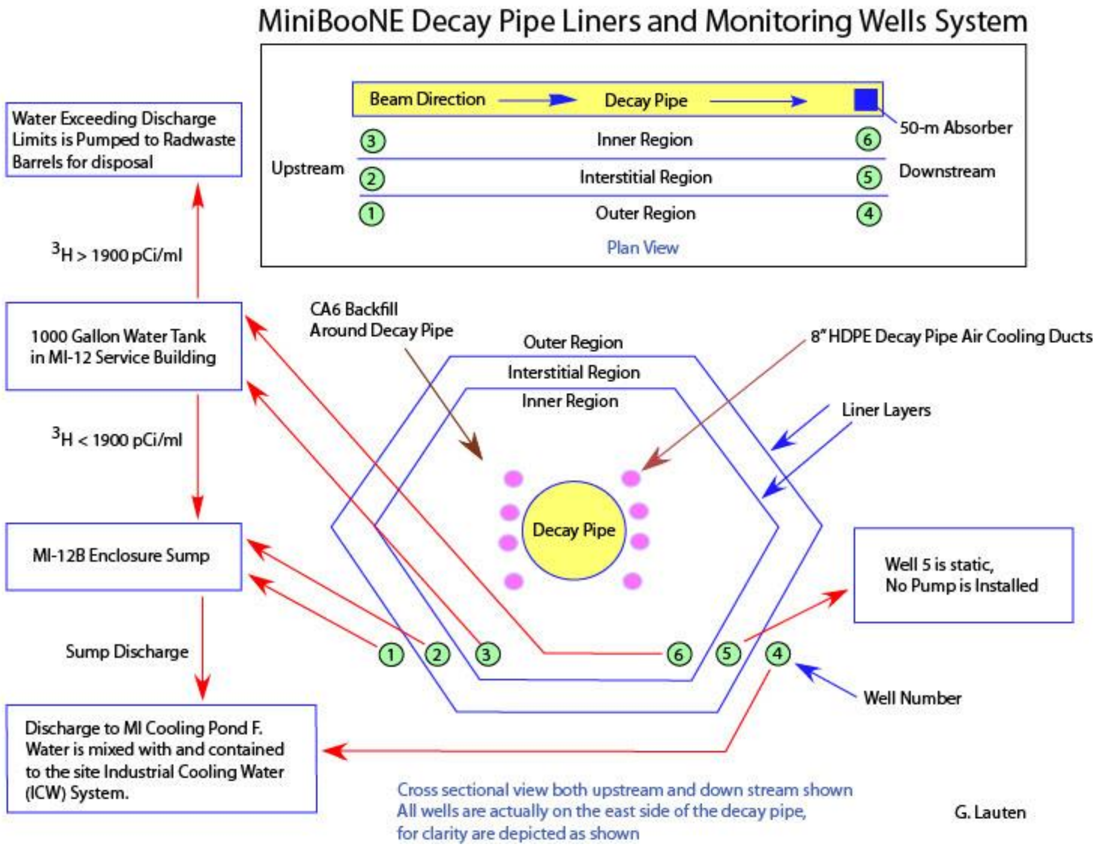

Figure 4. MiniBooNE Deca Pipe Liners and Monitoring Wells System.

These tests could not identify the location of the failure, but they suggest that it is near the MI-12 end of the decay region. The failure likely cannot be repaired at reasonable cost However, the leak prevention functionality of the liner system can be restored by continuously pumping and dewatering the entire volume. A detailed plan for dewatering and monitoring the decay region system has been developed.

The liner tests and the plans for mitigation have been reviewed by the MiniBooNE Safety Committee. The details regarding installation of the equipment, measurement of performance, and documentation of the results are addressed in the Plan for Dewatering and Monitoring the MI-12 Decay Region. Following the dewatering plan keeps groundwater activation outside the liner region below the regulatory limits for radionuclides. However, dewatering also creates a waste stream of tritiated water requiring disposal.

The AD External Beam Delivery Department in conjunction with ES&H continues ALARA efforts to understand and reduce the amount of tritiated water collected from the system. Well and liner tests conducted between July and November, 2012, were part of this effort to reduce the amount of tritiated water collected from the liner dewatering systems. These tests indicated that there are new well casing failures between the outer and interstitial regions of the liner at the upstream monitoring locations at an elevation below the liner. The tests further indicate that there are new well casing failures between all three downstream monitoring wells below the liner region and a likely breech in the liner at the location where the Little Muon Counter (LMC) pipe passes through the liner near the MI-13 enclosure. The suspected breach in the liner at the LMC is likely the source for the slow increase in tritiated water collected from the downstream monitoring wells over the years. These failures between the well casings and suspected liner breach at the LMC do not change the current dewatering plans, but rather provide additional information for the development of strategies to reduce the amount of tritiated water collected requiring disposal.

III-6.2.1.4 Surface Water Activation

Baseline qualitative risk analysis of this hazard determined that for worker, co-located worker, and members of the public receptors, that potential exposures to groundwater activation, although anticipated, from the perspective of frequency of occurrence, carries a negligible exposure consequence, and therefore is rated at a risk level of IV (minimal concern). Through the use of preventive and mitigative measures by the facility, the residual qualitative risk for workers, co-located workers and members of the public, likelihood is reduced to “extremely unlikely”, and a residual qualitative risk of IV (minimal concern).

Several preventions and mitigations are used to reduce the risk associated with the surface water activation hazards, which include the following. Soil, concrete, and/or steel shielding reduces surface water activation. Beam loss monitors in enclosures are used to prevent excessive beam loss during normal operations, as beam loss can produce activated materials. Radiation detectors in enclosures and berms reduce the amount of activation to surface water by promptly disabling the beam when losses go above a threshold value. An off-site discharge limit is applied to any water mixed into onsite surface water, as this prevents surface water concentrations from approaching the Derived Concentration Standard (DCS). Monitoring of potential mixed sources allow for diversion of water, preventing exposure to waters above the DCS. In situations where surface water activation is higher than expected (discovered by monitoring), the facility stops operations until the facility upset condition is resolved. Frequent surface water monitoring at many locations allows for the mitigation of increases in activity approaching the DCS. The following discussion in this section outlines the approach used to reduce the risk associated with surface water activation hazards.

In accordance with the dewatering plan, water from the exterior monitoring wells #1 and #4 is pumped to the MI cooling pond F either directly or via the MI-12B enclosure sump. The MI cooling pond F is part of the site-wide Industrial Cooling Water (ICW) System, thus containing any tritiated water to the Fermilab site. The water levels in the remaining wells are monitored with level indicators, and the water is pumped into a holding tank in the MI-12 Service Building for activation analysis prior to either release to the MI Cooling Pond or appropriate waste disposal. All discharges to surface waters conform to the requirements of DOE Order 458.1. Specifically, water having concentrations in excess of the DCS of DOE Order 458.1 is disposed of as radioactive waste.

The sump discharge locations along the 8 GeV beamline discharge to MI cooling ponds that are part of the site wide ICW System. The sump discharges are routinely sampled.

Baseline qualitative risk analysis of this hazard determined that for worker, co-located worker, and members of the public receptors, that potential exposures to surface water activation, although anticipated, from the perspective of frequency of occurrence, carries a negligible exposure consequence, and therefore is rated at a risk level of IV (minimal concern). Through the use of preventive and mitigative measures by the facility, the residual qualitative risk for workers, co-located workers and members of the public, likelihood is reduced from “anticipated: to “extremely unlikely”, and a residual qualitative risk of IV (minimal concern).

III-6.2.1.5 Radioactive Water (RAW) Systems

Several preventions and mitigations are used to reduce the risk associated with the radioactive water (RAW) system hazards, which include the following. A RAW key control system prevents personnel access to radioactive water systems. Engineered secondary containment prevents unintended exposure to contaminated water. General and/or job specific RWPs are written by ES&H personnel, and they specify the work that is permitted to be performed, requirements to perform the work, and limitations of radiological exposure. A LSM allows for real time monitoring of radiation levels during work, and its use is specified in the relevant RWP when deemed appropriate for the work. The Run Condition gives operating parameters that reduce activation by limiting the total amount of beam that could be delivered. Specifically, this includes an operating limit for protons/hr. A RWP will specify that a RCT or RSO be present during certain kinds of work or work conditions. The radiological expert can make real time decisions to limit, stop, or prevent radiation exposure to personnel. Public access gates will be used to prevent unauthorized access by the public. Radiological shielding is material placed between radiation sources and people, which prevents the close proximity of these sources and people. The following discussion in this section outlines the approach used to reduce the risk associated with RAW system hazards.

The MiniBooNE horn will be cooled by a “closed loop” water system, with its own pumps and purification system, filled from the Low Conductivity Water (LCW) system. The system will reside in the MI-12B enclosure, just upstream of the target pile. The design and construction of this system is similar to many other RAW systems at Fermilab. Water level, flow, and temperature interlocks are an input to the beam permit system. The system will be monitored for tritium build-up in accordance with FRCM. Routine analysis of the RAW system concentration levels, HEP program schedule, operational impact to other parts of the accelerator complex, and ALARA principles will all be considered when determining the appropriate timing of water replacement. The system incorporates a spill pan of sufficient volume to contain the activated water in case of leaks. Any water collected is disposed of in accordance with the FRCM.

The hazard due to Radioactive Water (RAW) Systems was evaluated, for the potential hazards associated with workers, co-located workers and the public potentially being exposed to radioactive water beyond regulatory limits. The baseline, qualitative risks due to this hazard were assessed, and determined to be risk level I (major concern) for workers and co-located workers and risk level III (minor concern) for the public. Through the use of a number of preventive and mitigative hazard controls, the likelihood and consequence of this hazard is reduced, resulting in a risk level of IV to workers and co-located workers, meaning residual risks are of minimal concern. For the public, the baseline qualitative risk due to this hazard are managed through a series of preventive controls (locked facilities, interlocked systems preventing entry), so that the likelihood of experiencing this hazard remains Beyond Extremely Unlikely, with a reduction of overall residual risk of IV, meaning the risk is a minimal concern, not subject to additional evaluation.

III-6.2.1.6 Air Activation

Several preventions and mitigations are used to reduce the risk associated with the air activation hazards, which include the following. Target pile shielding is material placed between radiation sources in the target pile and the enclosure to be protected. Key issuance to enclosures is restricted until after the air monitors show that there is a sufficiently low level of radiation coming from the activated air components. A LSM allows for real time monitoring of radiation levels during work, and its use is specified in the relevant RWP when deemed appropriate for the work. The release of activated air is engineered to reduce potential exposure consequences. The air flow is engineered to dilute the activated air components and provide time for these components to decay away prior to the release of the air from the enclosure. The Run Condition gives operating parameters that reduce activation by limiting the total amount of beam that could be delivered. Specifically, this includes an operating limit for protons/hr. Public access gates will be used to prevent unauthorized access by the public. The following discussion in this section outlines the approach used to reduce the risk associated with air activation hazards.

The shielding assessment for the MiniBooNE configuration estimates that operation of the facility will release no more than 15 Ci/year. The 15 Ci/year will result in a dose at the site boundary of less than 0.015 mrem/year, which is well below the Environmental Protection Agency (EPA) standard of 10 mrem/year and also much less than the EPA’s continuous monitoring threshold of 0.1 mrem/year.

A fan installed at the exhaust stack near the MI-12A entrance establishes airflow from the target pile end towards the upstream end at ventilation rate of 100 cfm. This rate corresponds to more than a four-hour transit time through the enclosures. Air release data from 2008 through 2011 shows an average annual release of 2.4 Ci/year from the target pile region, well below the assessed estimated release of 15 Ci/year. The dose at the site boundary is based on separate calculations discussed in the MiniBooNE Air Activation

Analysis and scaled to the 1.62E17 protons/hr found in the addendum to the MiniBooNE Target Station Shielding Assessment using historical meteorological data.

ES&H routinely checks a permanent stack monitor installed for purposes of data-logging air emissions. This monitor is an input to the MUX system, and through the connection from MUX to the accelerator control system, can be connected to the beam permit system to shut off the beam in cases of off-normal operation. Following a period of operation and a cool-down period, a RSO determines when it is safe to turn back on the 1000-cfm ventilation systems that release air from the enclosure to the external atmosphere.

The design and construction of the target pile reduces leakage except from around the horn region itself. Potential locations for the release of airborne radionuclides in measurable concentrations are identified and routinely monitored in accordance with standard Fermilab procedures to ensure compliance with applicable standards.

The hazard due to Air activation was evaluated, for the potential hazards associated with workers, co-located workers and the public potentially being exposed to radioactive water beyond regulatory limits. The baseline, qualitative risks due to this hazard were assessed, and determined to be risk level I (major concern) for workers and co-located workers and risk level III (minor concern) for the public. Through the use of a number of preventive and mitigative hazard controls, the likelihood and consequence of this hazard is reduced, resulting in a risk level of IV to workers and co-located workers, meaning residual risks are of minimal concern. For the public, the baseline qualitative risk due to this hazard are managed through a series of preventive controls (locked facilities, interlocked systems preventing entry), so that the likelihood of experiencing this hazard remains Beyond Extremely Unlikely, with a reduction of overall residual risk of IV, meaning the risk is a minimal concern, not subject to additional evaluation.

III-6.2.1.7 Closed Loop Air Cooling

Several preventions and mitigations are used to reduce the risk associated with the closed loop air cooling hazards, which include the following. The Run Condition gives operating parameters that reduce activation by limiting the total amount of beam that could be delivered. Specifically, this includes an operating limit for protons/hr. Engineered containment of the cooling air is used to keep it separate from the breathable air. Target pile shielding is material placed between radiation sources in the target pile and the enclosure to be protected. Key issuance to enclosures is restricted until after the air monitors show that there is a sufficiently low level of radiation coming from the activated air components. A LSM allows for real time monitoring of radiation levels during work, and its use is specified in the relevant RWP when deemed appropriate for the work. Public access gates will be used to prevent unauthorized access by the public. The release of activated air is engineered to reduce potential exposure consequences. The following discussion in this section outlines the approach used to reduce the risk associated with closed loop air cooling hazards.

Air activation is caused by the primary 8 GeV proton beam and secondary radiation interacting with the air in the interior of the MiniBooNE target pile and decay pipe. The principal radionuclides of concern are carbon-11 which has a 20-minute half-life, nitrogen-13 which has a 10-minute half-life, oxygen-15 which has a 2-minute half-life, tritium which has a 12.3-year half-life, and argon-41 (produced by thermal neutron capture on argon-40) which has a 1.8-hour half-life.

Estimates for air activation from the beamline target and decay areas were developed by members of the Neutrinos at the Main Injector (NuMI) collaboration, and their work has been modified for the MiniBooNE target pile geometry. The results from this analysis show that the amount of activated air released to the atmosphere depends upon three factors: (i) how much beam is lost in the 8 GeV Fixed Target beamline enclosures, (ii) how much air from the target pile and decay pipe is mixed with the air in the enclosures, and (iii) how rapidly the air flows through the enclosures (ventilation rate).

The primary solution to controlling radioactive air emissions is to apply reasonable engineering controls to seal the activated region, i.e. the target pile for this case, so as to maximize the decay of the airborne radionuclides in place. Concrete caps the target pile steel on the top, sides, and front in order to contain the air inside the target pile. Voids on the sides, between the steel and concrete, have been filled with Styrofoam sheets. The top and front of the target pile have been made airtight to the extent possible by covering them with aluminum sheeting, as well as caulking between sheets and where the sheets meet the concrete walls of the enclosure. The steel lid covering the 25-m absorber has been sealed with caulk where it meets the concrete side walls to make it as airtight as possible.

The hazard due to closed loop air cooling, was evaluated, for the potential hazards associated with workers, co-located workers and the public potentially being exposed to radioactive water beyond regulatory limits. The baseline, qualitative risks due to this hazard were assessed, and determined to be risk level I (major concern) for workers and co-located workers and risk level III (minor concern) for the public. Through the use of a number of preventive and mitigative hazard controls, the likelihood and consequence of this hazard is reduced, resulting in a risk level of IV to workers and co-located workers, meaning residual risks are of minimal concern. For the public, the baseline qualitative risk due to this hazard are managed through a series of preventive controls (locked facilities, interlocked systems preventing entry), so that the likelihood of experiencing this hazard remains Beyond Extremely Unlikely, with a reduction of overall residual risk of IV, meaning the risk is a minimal concern, not subject to additional evaluation.

III-6.2.1.8 Soil Interactions

Several preventions and mitigations are used to reduce the risk associated with the soil interaction hazards, which include the following. The use of beamline designs that include measures to reduce unwanted beam particle losses, along with the use of beam dump (absorber) designs that minimizes radiological leakage through the use of shielding. The Run Condition gives operating parameters that reduce activation by limiting the total amount of beam that could be delivered. Specifically, this includes an operating limit for protons/hr. General and/or job specific RWPs are written by ES&H personnel, and they specify the work that is permitted to be performed, requirements to perform the work, and limitations of radiological exposure. A RWP may specify that personal protective equipment (PPE) be used during certain kinds of work or work conditions. The PPE limits the likelihood of bodily exposure to activated material and contamination. Public access gates will be used to prevent unauthorized access by the public. The primary concern is with the soil that surrounds the BNB target and decay pipe areas. These soil areas are further discussed in Section III-6.2.1.3, *Groundwater Activation*, of this Chapter.

The hazard due to soil interactions was evaluated, for the potential hazards associated with workers, co-located workers and the public potentially being exposed to radioactive soil beyond regulatory limits. The baseline, qualitative risks due to this hazard were assessed, and determined to be risk level IV (minimal concern). Through the use of a number of preventive and mitigative hazard controls, the likelihood and consequence of this hazard is further reduced, resulting in a reduced likelihood of encountering the hazard, and a a risk level of IV to workers, co-located workers, and the public, meaning residual risks are of minimal concern.

III-6.2.1.9 Radioactive Waste

Several preventions and mitigations are used to reduce the risk associated with the radioactive waste hazards, which include the following. Radiological shielding is material placed between radiation sources and people, which prevents the close proximity of these sources and people. Work may be restricted or prevented until sufficient time has passed such that radiation levels are sufficiently low to allow for safer work to proceed. General and/or job specific RWPs are written by ES&H personnel, and they specify the work that is permitted to be performed, requirements to perform the work, and limitations of radiological exposure. A LSM allows for real time monitoring of radiation levels during work, and its use is specified in the relevant RWP when deemed appropriate for the work. Fermilab has a material survey and release process. Any item exposed to beam-on conditions is surveyed by radiological workers and classified appropriately when removed from an enclosure. Items identified for disposal are surveyed and processed by Radiological Control organization personnel in accordance with FRCM Chapter 4. Public access gates will be used to prevent unauthorized access by the public. The following discussion in this section outlines the approach used to reduce the risk associated with radioactive waste hazards.

Radioactive waste is a standard radiological hazard that is managed within the established Radiological Protection Program (RPP) and as prescribed in FRCM. Waste minimization is an objective of the equipment design and operational procedures. Although production of radioactive material is not an operational function of BNB, beam loss and intentional beam interception, e.g. some beam diagnostic devices, will result in activation of beamline materials. Reuse of activated items will be carried out when feasible. Activated items that cannot be reused will be disposed of as radioactive waste in accordance with the FRCM requirements. For example, radioactive water from the target and horn cooling systems, as well as any water from the decay region dewatering wells having concentrations in excess of the DCS of DOE Order 458.1, is disposed of as radioactive waste in accordance with the FRCM requirements.

The hazard due to radioactive waste was evaluated, for the potential hazards associated with workers, co-located workers and the public potentially being exposed to radioactive water beyond regulatory limits. The baseline, qualitative risks due to this hazard were assessed, and determined to be risk level III (minor concern) for workers, co-located workers and the public. Through the use of a number of preventive and mitigative hazard controls, the likelihood and consequence of this hazard is reduced for all receptors, resulting in a risk level of IV to workers and co-located workers, meaning residual risks are of minimal concern.

III-6.2.1.10 Contamination

Several preventions and mitigations are used to reduce the risk associated with the contamination hazards, which include the following. Shielding for activated contamination is material placed between radiation sources and the personnel to be protected. More generally, radiological shielding is material placed between radiation sources and people, which prevents the close proximity of these sources and members of the public. The RWPs must be written and followed in accordance with the FRCM requirements, where they specify the work that is permitted to be performed, requirements to perform the work, and limitations of radiological exposure. A LSM allows for real time monitoring of radiation levels during work, and its use is specified in the relevant RWP when deemed appropriate for the work. A RWP may specify that PPE be used during certain kinds of work or work conditions. The PPE limits the likelihood of bodily exposure to activated material and contamination. RCTs and RSOs survey for and clean radiological contamination as part of the RWP process. Fermilab has a material survey and release process. Any item exposed to beam-on conditions is surveyed by radiological workers and classified appropriately when removed from an enclosure. Items identified for disposal are surveyed and processed by Radiological Control organization personnel in accordance with FRCM Chapter 4. Public access gates will be used to prevent unauthorized access by the public. Activated contamination leads to radioactive waste, where radioactive waste is discussed in Section III-6.2.1.9, *Radioactive Waste*, of this Chapter.

III-6.2.1.11 Beryllium-7

The baseline qualitative risks due to this hazard were assessed, and determined to be risk level I (major concern) for workers, co-located workers, and the public, but through the use of preventive and mitigative hazard controls, the likelihood and consequence of this hazard is reduced, resulting in a risk level of IV for workers, co-located workers, and the public meaning that the residual risks of this hazard are of minimal concern, and no further evaluation is necessary.

No prevention or mitigation is required for this type of hazard, as beryllium-7 is not hazardous in this pattern of facility use.

III-6.2.1.12 Radioactive Sources

Several preventions and mitigations are used to reduce the risk associated with the contamination hazards, which include the following. Unused radioactive sources are kept in storage, which prevents the close proximity of these sources and people. Furthermore, radioactive sources are kept in locked storage, where key issuance is a controlled process. Unused high activity sources are stored within shielded containers. Radiological training is an educational system managed by ES&H personnel that establishes basic worker knowledge through presentations and testing. Radiological signage on or near source cabinets give warning of the presence of radioactive sources. Public access gates will be used to prevent unauthorized access by the public.

Lastly, the baseline qualitative risks due to this hazard were assessed, and determined to be risk level I (major concern) for workers, co-located workers, and the public, but through the use of preventive and mitigative hazard controls, the likelihood and consequence of this hazard is reduced, resulting in a risk level of IV for workers, co-located workers and the public, meaning that the residual risks of this hazard are of minimal concern, and no further evaluation is necessary.

III-6.2.1.13 Nuclear Material

N/A.

III-6.2.1.14 Radiation Generating Devices (RGDs)

N/A.

III-6.2.1.15 Non-Ionizing Radiation Hazards

N/A.

III-6.2.2 Toxic Materials

BNB has toxic material hazards in the form of lead and beryllium. These hazards are part of NASHs discussed in SAD Section I Chapter 04, *Safety Analysis*.

III-6.2.2.1 Lead

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.2.2.2 Beryllium

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

The MiniBooNE target will be cooled by drawing air from the horn box, through the tube surrounding the beryllium target. The air will pass through a very efficient filter before reaching the blowers to contain any particulates. Beryllium flakes from the target are the primary material that might be collected. Disposal of this filter will be done in accordance with FESHM. The filter is housed inside of a 0.75" thick steel shield. The steel shielding reduces the dose equivalent, on contact, to 36 mrem/hr per 0.1% of total target activity captured by the filter.

III-6.2.2.3 Fluorinert & Its Byproducts

N/A.

III-6.2.2.4 Liquid Scintillator

N/A.

III-6.2.2.5 Pseudocumene

N/A.

III-6.2.2.6 Ammonia

N/A.

III-6.2.2.7 Nanoparticle Exposures

N/A.

III-6.2.3 Flammables and Combustibles

BNB has flammable and combustible hazards in the form of combustible materials. These hazards are part of NASHs discussed in SAD Section I Chapter 04, *Safety Analysis*.

III-6.2.3.1 Combustible Materials

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.2.3.2 Flammable Materials

N/A.

III-6.2.4 Electrical Energy

BNB has electrical energy hazards in the form of stored energy exposure, high voltage exposure, and low voltage, high current exposure. These hazards are part of NASHs discussed in SAD Section I Chapter 04, *Safety Analysis*.

III-6.2.4.1 Stored Energy Exposure

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.2.4.2 High Voltage Exposure

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.2.4.3 Low Voltage, High Current Exposure

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.2.5 Thermal Energy

BNB has thermal energy hazards in the form of hot work. These hazards are part of NASHs discussed in SAD Section I Chapter 04, Safety Analysis.

III-6.2.5.1 Bakeout

N/A.

III-6.2.5.2 Hot Work

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.2.5.3 Cryogenics

N/A.

III-6.2.6 Kinetic Energy

BNB has kinetic energy hazards in the form of power tools, pumps and motors, and motion tables. These hazards are part of NASHs discussed in SAD Section I Chapter 04, Safety Analysis.

III-6.2.6.1 Power Tools

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.2.6.2 Pumps and Motors

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.2.6.3 Motion Tables

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.2.6.4 Mobile Shielding

N/A.

III-6.2.7 Potential Energy

BNB has potential energy hazards in the form of crane operations, compressed gasses, vacuum/pressure vessels/piping, vacuum pumps, and material handling. These hazards are part of NASHs discussed in SAD Section I Chapter 04, Safety Analysis.

III-6.2.7.1 Crane Operations

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.2.7.2 Compressed Gasses

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.2.7.3 Vacuum/Pressure Vessels/Piping

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.2.7.4 Vacuum Pumps

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.2.7.5 Material Handling

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.2.8 Magnetic Fields

BNB has magnetic field hazards in the form of fringe fields. These hazards are part of NASHs discussed in SAD Section I Chapter 04, *Safety Analysis*.

III-6.2.8.1 Fringe Fields

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.2.9 Other Hazards

BNB has other hazards in the form of confined spaces, noise, silica, ergonomics, and working at heights. These hazards are part of NASHs discussed in SAD Section I Chapter 04, *Safety Analysis*.

III-6.2.9.1 Confined Spaces

BNB has two confined spaces: the sump pit in the MI-12B enclosure and the MI-13 enclosure. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.2.9.2 Noise

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.2.9.3 Silica

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.2.9.4 Ergonomics

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.2.9.5 Asbestos

N/A.

III-6.2.9.6 Working at Heights

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.2.10 Access & Egress

BNB has kinetic energy hazards in the form of life safety egress. These hazards are part of NASHs discussed in SAD Section I Chapter 04, *Safety Analysis*.

III-6.2.10.1 Life Safety Egress

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.2.11 Environmental

BNB has environmental hazards related to air, water, and soil. These hazards are part of NASHs discussed in SAD Section I Chapter 04, *Safety Analysis*.

III-6.2.11.1 Hazard to Air

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.2.11.2 Hazard to Water

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.2.11.3 Hazard to Soil

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04, *Safety Analysis*. Work in BNB involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-6.3. Maximum Credible Incident Scenario for Accelerator Specific Hazards

Consideration and analysis of the MCI is focused on an onsite facility worker, onsite co-located worker, and maximally-exposed offsite individual (MOI) that is outside of the BNB areas. The Radiation Safety Interlock System (Section III-6.4.1.2.1) is used to keep individuals out of the BNB enclosures during beam operations. A change to the MCI for upstream segments will be evaluated for its effect on the BNB segment through the USI process.

Three simultaneous operating conditions are required for producing the MCI scenario: maximum beam power operations in the Booster segment (Chapter III-4), directing all the Booster output into the BNB segment via the 8 GeV Line segment (Chapter III-5), and the beam is mis-steered away from the design trajectory to cause very large losses. The Booster could in principle produce up to 7E+12 protons-per-pulse at a 15 Hz pulse rate (6.6667E-2 s accelerator cycle time) during maximum beam power output. This scenario corresponds to 3.78E+17 protons-per-hour with each proton having around 8 GeV of energy. A secondary yield of 1 and secondary beam energy of 8 GeV are also assumed, where secondary particles (e.g. pions or kaons) are produced through proton beam-material interactions.

The MBex switch-magnet is used to direct beam pulses in the 8 GeV Line to the BNB segment, where it has no inherent repetition rate limit. The MBex magnet could direct all the beam pulses in the 8 GeV Line to the BNB segment if the magnet pulse timing was set incorrectly. Specifically, this would occur if MBex pulses on a generic Booster reset event for an accelerating beam cycle instead of a Booster reset event for a MiniBooNE beam cycle.

The beam can be accidentally mis-steered leading to all of it being lost in the segment, which will generate hazardous radiation fields. One hour of total continuous beam loss during maximum beam power operations is considered for this scenario, which leads to 3.78E+17 protons of prompt radiation within the BNB segment. One hour is taken as the maximum credible time interval for total continuous beam loss due to the staffing (Section III-6.4.2.2) requirements for monitoring and operating the Main Accelerator Complex.

This MCI analysis does not consider the beam bunch structure, and it treats the beam pulse structure as the smallest beam features. A proton pulse in the BNB segment is typically comprised of a train of 81 proton bunches, but this level of detail is not needed when calculating doses rates and doses. Prompt radiation causes hazardous radiation fields directly and indirectly through material effects. Three categories of beam-material interactions are considered for the BNB shielding requirements: beam hitting I) a magnet in an enclosure, II) a beam carrier pipe in an enclosure, or III) a beam carrier pipe buried in the ground. The BNB enclosures are designed and constructed with concrete, steel, and earth-covered radiation shielding to protect people from radiological exposure due to the MCI. The thickness of non-dirt shielding materials, e.g. concrete and steel, is typically converted into an effective feet of dirt thickness for comparison and standardization purposes. Most shielding is permanent, but the target station and 25-meter absorber components are protected by movable shielding.

The three beam loss cases discussed in this chapter are based on the generic shielding methodology. Case I is when the beam causes point losses on a pole face of a dipole magnet that is inside of an enclosure. Case II is when the beam causes point losses on an aluminum beam pipe that is inside of an enclosure. Case III is when the beam causes point losses on a steel pipe that is buried in dirt. The enclosures are surrounded by dirt shielding, and in all cases the dirt shielding is surrounded by air. The effective dose-per-proton is determined for the outside air layer. The enclosures and shielding use a cylindrical geometry in all cases, where the enclosures have a 3 ft inner radius and 1 ft thick concrete walls.

The BNB segment is located in a non-public area of the campus, and this incident would result in a dose higher than 500 mrem to an individual when assuming that there is no shielding. The result is that the uncontrolled baseline qualitative risk level associated with this accident is I, as shown in Section III-6.10 Appendix – Risk Tables, Tables 5.1-5.3.

Fermilab uses Credited Controls that flow down to the Accelerator Safety Envelope (ASE) to mitigate the consequences of an MCI to the following conditions:

- Less than 5 rem in one hour in any area accessible by facility workers or co-located workers.
- Less than 500 mrem in one hour in all Laboratory areas to which the public is assumed to be excluded.

- Less than 100 mrem in one hour at Fermilab’s site boundary and/or in any areas onsite in which the public is authorized (which includes Batavia Road, Prairie Path, parking lots open to the public, and general access areas including Wilson Hall, Ramsey Auditorium).

These credited controls are discussed in Section III-6.4.

The accumulated dose outside of the shielding on the BNB berm is mitigated, by use of Credited Controls, to less than 500 mrem in an MCI. The closest possible location of a member of the public to the BNB enclosure is the west parking lot. This location is more than five feet away from the location of the Credited Control radiation monitors, which would result in dose of less than 100 mrem applying a conservative dose reduction of 1/r.

III-6.4. Summary of Credited Controls

Engineered systems and programs/procedures are used to prevent and mitigate hazards through passive and active means. Credited controls flow down to the ASE, which limit MCI radiation doses to less than 5 rem for workers, less than 500 mrem for MOIs in non-public areas of the campus, and less than 100 mrem for areas of the campus where the public is invited. The BNB segment is in an area where members of the public are not invited. Limiting doses to below 500 mrem leads to a negligible consequence level for prompt radiation exposure to workers and members of the public as identified in DOE Handbook 1163, Consequence Matrix Figure C-1 for a radiological hazard.

III-6.4.1 Engineering Credited Controls

Engineering controls are physical devices, elements, features, systems, etc. that isolate people from hazards. Engineering credited controls can be active or passive, and they are used in the BNB segment to prevent or mitigate prompt radiation risks associated with the MCI scenario.

III-6.4.1.1 Passive Engineering Credited Controls

Passive engineering controls are elements that make up parts of the Main Accelerator Complex facility which require no human action to protect people. There are fixed beamline elements that provide radiation shielding in the BNB segment that take direct human intervention to remove.

Cases I, II, and III require 17.9, 15.4, and 20.3 effective feet of dirt (e.f.d.), respectively, to limit the radiation dose rate to between 100 and 500 mrem-per-hour for a person outside of the beamline areas. The beam propagates near the design trajectory during normal operations, and it must interact with a magnet or carrier pipe before producing prompt radiation fields that emanate from the beamline. There are “special cases”, e.g., absorbers, collimators, and targets, but these special cases are effectively case I, as the beam is interacting with a “thick” and “dense” piece of material in an enclosure. Hence, the special cases are treated the same as case I. When there is 17.9 and 20.3 e.f.d. of shielding that surrounds a BNB enclosure and buried beam carrier pipe, respectively, then a person outside of the area and right next to the shielding will receive at most a dose of 500 mrem during one hour of maximum beam power operations.

Determination of radiation dose rates due to prompt radiation for the BNB segment are derived Refs [1,3] and incremental shielding assessment (ISA) spreadsheets. Dose rates are calculated using a base case of 120 GeV protons, 1.6E+14 protons-per-pulse, and a 7.52E-1 Hz pulse rate (1.33 s accelerator cycle time) for determining longitudinal and transverse shielding requirements. Dose rates are calculated using a base case of 8 GeV protons, 5E+12 protons-per-pulse, and a 7.69 Hz pulse rate (0.13 s accelerator cycle time) for determining labyrinth and penetration dose rates. These base cases correspond to 4.33E+17 protons-per-hour for shielding requirements and 1.38E+17 protons-per-hour for labyrinths and penetrations, where the base cases are used as reference points for the ISA spreadsheet calculations. These spreadsheets allow for the quick determination of dose rates given different beam operating conditions by using scaling formulas to produce the values of interest from the base case values. Hence, dose rates for the MCI are obtained from the spreadsheets by using them with the beam conditions discussed in Section III-6.3.

An ISA scaling spreadsheet is used for determining shielding thickness requirements, and it based on generic shielding models, where these models have been developed over decades to provide conservative estimates for shielding requirements. Current models have their origins in the use of general rules-of-thumb (ROTs) for concrete and iron, where the use of ROTs eventually transitioned to the use of Monte Carlo simulations based on CASIM [10,11]. The current state of the art now uses models derived from Monte Carlo simulations based on MARS [11,12].

A beam has been directed into either a magnet pole face or pipe that creates an interaction region which generates a radiation field. As the field propagates through an enclosure gap, the dose rate decreases as a function of distance from the interaction region due primarily to a reduction in radiation flux via a geometric dilution. Table 4 gives air gap thicknesses at various locations along the BNB line. As the field propagates through the shielding that surrounds either an enclosure or a pipe, the dose rate decreases as a function of distance from the interaction region due to a reduction in radiation flux via both geometric dilution and material interactions.

An ISA labyrinths and penetrations summary spreadsheet is used for determining dose rates outside of penetrations and labyrinths, and it based on generic dose rate models. Generic penetrations and labyrinth dose rate models have been developed over decades [13,14]. The models are based on analytic approximations and data-based studies done decades ago.

III-6.4.1.1.1 Permanent Shielding Including Labyrinths

The permanent shielding encompasses the structural elements surrounding the beamline components. A buried beam transport pipe separates the BNB concrete structure from the MI enclosures. The permanent shielding includes the beamline enclosure with one personnel exit labyrinth, one major equipment hatch and personnel access labyrinth at the MI-12 Service Building, utility penetrations, and earthen berms and overburden. Radiation dose rates outside of labyrinths and penetrations were calculated for the MCI scenario, where these calculations do not include shielding. These doses were found to be less than 500 mrem except for the MI-12B stripline penetrations at station 569 ft. This location uses the Radiation Safety Interlock System (Section III-6.4.1.2.1) to limit the dose during the MCI scenario.

The shielding has sufficient overburden such that a 500 mrem or greater dose due to prompt radiation cannot occur during the MCI scenario except at 2 locations in the BNB segment. The two locations with insufficient shielding are the Manhole PMH-PVI-2 located at the 441-447 ft z-range and stripline penetrations located at the 569 ft station in the MI-12 Service Building. The MiniBooNE Radiation Safety Interlock System (Section III-6.4.1.2.1) is used to limit the potential radiation doses at these two locations.

A shielding thickness of 17.9 e.f.d. is taken as the credited control for limiting prompt radiation-based exposure to an individual outside of BNB enclosures, except at the Manhole PMH-PVI-2, and any shielding thickness in excess of 17.9 e.f.d. is considered to be defense in depth. A shielding thickness of 15.9 e.f.d. is taken as the credited control for limiting prompt radiation-based exposure to an individual outside of BNB enclosure at the Manhole PMH-PVI-2, where any shielding thickness in excess of 15.9 e.f.d. is considered to be defense in depth. There is 16.4 e.f.d. of shielding at the Manhole PMH-PVI-2.

A shielding thickness of 20.3 e.f.d. is taken as the credited control for mitigating prompt radiation-based exposure to an individual outside of BNB areas that have a buried beam carrier pipe, where any shielding thickness in excess of 20.3 e.f.d. is considered to be defense in depth. Tables 3 and 4 summarize the total, credited control, and defense in depth shielding at various locations along the BNB segment for the permanent shielding.

III-6.4.1.1.2 Movable Shielding

Movable shielding is required to be in place to provide protection against radiation fields during BNB operations, where this type of shielding is not composed of dirt, but is instead made of materials such as concrete, steel, and sandbags. The thickness of non-dirt shielding materials is typically converted into an effective feet of dirt thickness for comparison and standardization purposes.

Within the MI-12 Service Building is an access shaft to the below grade enclosure for rigging beamline elements and target station components into or out of the 8 GeV Fixed Target beamline enclosures. The access shaft is filled with a combination of steel and concrete shielding blocks to mitigate the prompt radiation from targeting to acceptable levels in the MI-12 Service Building.

The 25-meter absorber is constructed with an access shaft to the surface in the center of the decay region. The access shaft is filled with a combination of steel plates that make up the 25-meter absorber and concrete shielding blocks to mitigate the prompt radiation from beam hitting the absorber when in the down position to acceptable levels on the berm.

The large shielding blocks range in weight from approximately 10,000 pounds to approximately 26,000 pounds and cannot be moved without the use of the MI-12 building crane for the building access shaft or an external crane for the 25-meter absorber. The shielding for both areas is defined in the MiniBooNE Target Station Shielding Assessment and post assessment documents. The shielding is locked in-place, and the configuration is controlled by an RSO. Table 3 gives the total, credited control, and defense in depth shielding at various locations along the BNB segment for the movable shielding, where the credited control shielding thicknesses are discussed in the previous section.

III-6.4.1.1.3 Penetration Shielding

The beamline has several utility penetrations routing between the BNB areas and service buildings that may be occupied. Radiation dose rates outside of labyrinths and penetrations were calculated for the MCI scenario, where these calculations do not include shielding. These doses were found to be less than 500 mrem except for the MI-12B stripline penetrations at station 569 ft. This location uses the Radiation Safety Interlock System (Section III-6.4.1.2.1) to limit the dose during the MCI scenario.

III-6.4.1.2 Active Engineering Credited Controls

Active engineering controls are elements that make up parts of the Main Accelerator Complex facility that require human action to protect people, which may include active interaction with, monitoring, or periodic maintenance/calibration of the engineering control.

III-6.4.1.2.1 Radiation Safety Interlock System

The BNB enclosures are part of the MiniBooNE Radiation Safety Interlock System (RSIS). There are interlocked exit labyrinths at both ends of the 8 GeV Fixed Target beamline enclosures with an internal section gate that is used to divide the beamline into two separate boundaries called MI-12A and MI-12B. At the downstream end of the decay region is a small, underground, and interlocked instrumentation enclosure called MI-13. The interlock system inhibits transport of beam beyond the BNB extraction point in the 8 GeV Line except when the MI-12A, MI-12B, and MI-13 enclosures are properly secured and locked, 1000 CFM intake and exhaust fans are off, Target Air Flow Intake Switch is on, and area radiation monitors are made up.

The radiation safety interlock system inhibits beam by controlling redundant critical devices. The critical devices for the BNB segment are the E: HV860 power supply that feeds the extraction magnet and E:BS860 air operated beam stop in the MI enclosure. The system has a failure mode function in the event of a critical device failure, which will inhibit beam to the Booster segment and eliminate the possibility of beam reaching the BNB enclosures.

Shielding is adequate to limit potential MCI radiation doses to less than 500 mrem for an individual outside of the BNB areas except for the Manhole PMH-PVI-2 located at the 441-447 ft z-range and stripline penetrations located at the 569 ft station in the MI-12 Service Building. Tables 3 and 4 summarize the shielding at various locations along the BNB segment. The potential MCI radiation exposure is limited by the use of two credited control detectors: one detector near the Manhole PMH-PVI-2 with a credited control limit of 2.5 mrem and one detector near the stripline penetrations with a credited control limit of 150 mrem. Both detectors are connected to the MiniBooNE Radiation Safety Interlock System and are operated in integrate mode, where this interlock system will inhibit beam to the BNB segment if one of these detectors measures a radiation signal above the trip limit. The detector near Manhole PMH-PVI-2 is located outside of the manhole and on a berm next to the manhole. A credited control limit of 2.5 mrem will limit the MCI dose to be less than 500 mrem in the manhole, where this manhole has not been designed for occupancy during beam operations. A credited control limit of 150 mrem will limit the MCI dose to be less than 500 mrem in the MI12 Service Building due to the stripline penetrations. An RSO may set the detector interlocked trip limits to a value less than the credited control limit given in this section due to other considerations, such as for occupancy requirements in the MI-12B Service Building. Figure 5 shows the location of the credited detectors, and Table 2 summarizes the credited control limits for the credited detectors.

Following any enclosure access by people, except under strictly specified controlled access conditions, trained and qualified personnel from the AD Accelerator Ops Department must search and secure the enclosure before permits from the radiation safety interlock system may be reestablished. The search and secure process consists of a thorough exploration of an enclosure to ensure that it is not occupied. The radiation safety interlock systems are in conformance with FRCM, and include requirements for hardware and system testing, inventory of interlock keys, search and secure procedures for the beamline enclosures, controlled access procedures, training requirements, and procedures for interlock system maintenance.

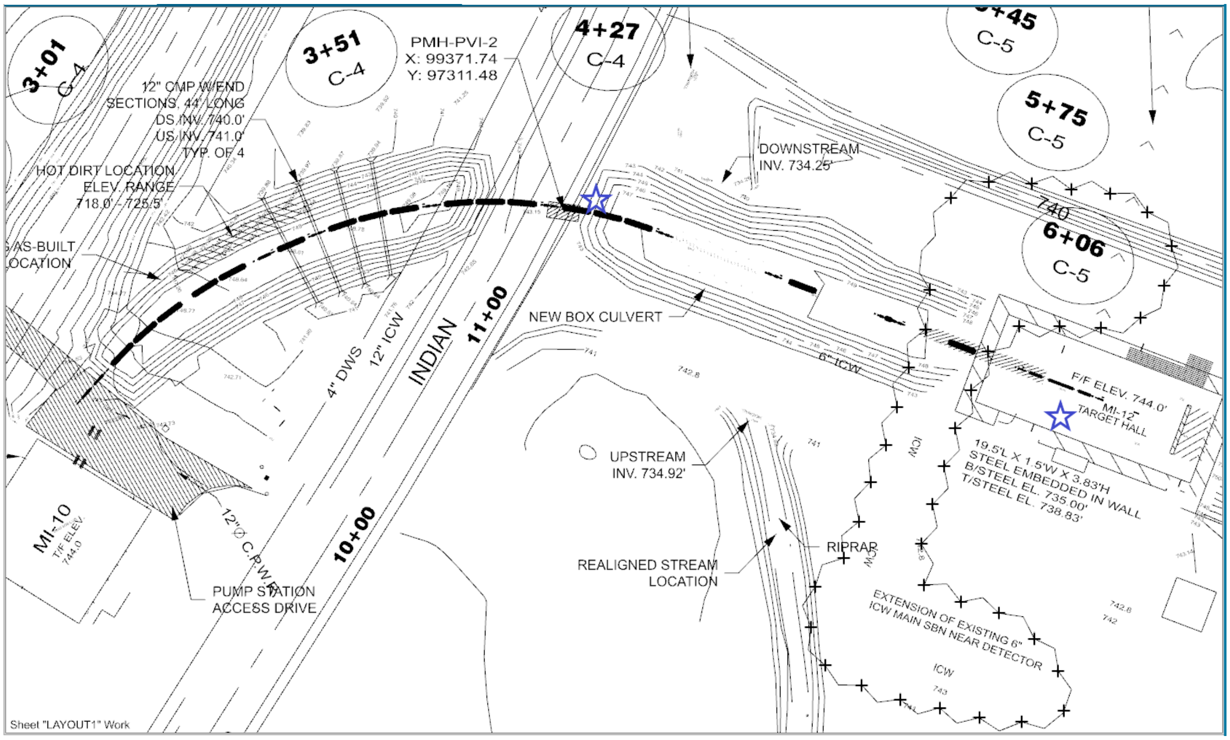

Figure 5. The approximate locations of the credited detectors for the BNB segment are indicated by the blue five-point stars.

Table 2. Credited control detectors used to limit the potential MCI radiation dose for the Manhole PMH-PVI-2 located at the 441-447 ft z-range and stripline penetrations located at the 569 ft station in the MI-12 Service Building.

Radiation Detector Type	Location	Credited Control Limit (mrem)
Chipmunk	MiniBooNE Indian Creek Road	2.5
Chipmunk	MI-12B Stripline Penetrations	150

III-6.4.2 Administrative Credited Controls

All BNB operations with the potential to affect the safety of workers and MOIs, or to adversely affect the environment, are performed using approved laboratory, directorate, division, or department procedures. These procedures and programs are the administrative controls that encompass the human interactions that define safe accelerator operations.

III-6.4.2.1 Operation Authorization Documents

Beam will not be transported to the BNB segment without an approved Beam Permit and Run Condition. The Beam Permit specifies beam power limits as determined and approved by the AD Associate Laboratory Director (ALD), in consultation with the ES&H Radiation Physics Operations Department Head, ES&H Accelerator Safety Department Head, assigned RSO, AD Operations Department Head, and AD External Beam Delivery Department Head. The Running Condition for the BNB segment describes the operating configuration as reviewed by the assigned RSO, AD Operations Department Head, and AD External Beam Delivery Department Head and as approved by the AD ALD.

III-6.4.2.2 Staffing

The MCR must be appropriately staffed according to ensure operations within bounding conditions specified in Operation Authorization Document, and to disable beam operation to the BNB segment and initiate an immediate response in the event of a determined ASE violation.

The following staffing shall be in place during applicable beam operation:

- At least one member of the AD Operations Department who has achieved the rank of Operator II or higher shall be on duty and on site.
- At least one member of the AD Operations Department shall be present in the Main Control Room (MCR).
- A single person could satisfy both of these conditions.

III-6.4.2.3 Accelerator Operating Parameters

To ensure operations within bounding conditions used in the MCI analysis, the following intensity shall not be exceeded: 3.78E17 protons/hr.

III-6.5. Summary of Defense-in-Depth Controls

Defense-in-depth is the collection of non-credited-control methods used to further prevent and mitigate exposure to prompt radiation for individuals and equipment. The defense-in-depth used for the BNB segment include an access gate that prevents unauthorized individuals from approaching accelerators and beamlines, service buildings with locked doors, radiation detectors, temporary guards, temporary ropes, signage, a safety training program, and a radiological ALARA program. Tables 3 and 4 summarize the defense-in-depth shielding for the BNB segment.

Table 3. Longitudinal shielding thicknesses obtained from Refs. [1,3]. Defense in depth shielding thickness is obtained by taking the difference of the current and credited control shielding thicknesses. Section III-6.4.1.1 outlines the framework used to select the credited control shielding thicknesses. All the areas have sufficient shielding to produce a dose less than 500 mrem during one hour of running in the MCI scenario except for the Manhole PMH-PVI-2 located at the 441-447 ft z-range, where this area uses the Radiation Safety Interlock System (Section III-6.4.1.2.1) to limit the dose during the MCI scenario.

Z Range (location) (ft)	Enclosure Type	Fixed Shielding (e.f.d.)	Movable Shielding (e.f.d.)	Current Shielding (e.f.d.)	Credited Control Shielding (e.f.d.)	Defense In Depth Shielding (e.f.d.)
0-100	MI 8 GeV Extraction	23.2		23.2	17.9	5.3
100-217	Buried 24" Carrier Pipe	25.5		25.5	20.3	5.2
217-233	Buried 24" Carrier Pipe	24.5		24.5	20.3	4.2
233-268	Tunnel Beyond MI10	19.4		19.4	17.9	1.5
268-278	Tunnel Under Berm Toe	19.4		19.4	17.9	1.5
278-400	Tunnel Under Berm	24		24	17.9	6.1
400-417	Tunnel Under Berm Toe	19.3		19.3	17.9	1.4
417-441	Indian Creek Road	19.3		19.3	17.9	1.4
441-447	Manhole PMH-PVI-2	16.4		16.4	15.9	0.5
447-475	Tunnel Under Berm Toe	20.2		20.2	17.9	2.3
475-490	Tunnel Under Berm	24.4		24.4	17.9	6.5
490-526	Box Culvert	24.5		24.5	17.9	6.6
526-544	Tunnel Under Berm	25.2		25.2	17.9	7.3
544-595	Tunnel Under Berm	24.0		24.0	17.9	6.1
595-645	Tunnel Upstream of MI-12	26.1		26.1	17.9	8.2
645-656	MI-12	22.8		22.8	17.9	4.9
656-674	MI-12		19.5	19.5	17.9	1.6
656-672	MI-12 Vault		19.5	19.5	17.9	1.6
672-690	Target Pile Upstream		34.6	34.6	17.9	16.7
690-697	Target Pile Collimator		38.0	38.0	17.9	20.1
697-699	Vault Downstream Wall	26.3		26.3	17.9	8.4

699-710	Decay Pipe under MI-12	24.1		24.1	20.3	3.8
710-763	Upstream Decay Pipe	26.2		26.2	20.3	5.9
763-776	Midrange Absorber In Beam		22.5	22.5		4.6
762-776	Midrange Absorber Out		23.3	23.3	17.9	5.4
776-846	Downstream Decay Pipe	26.0		26.0	20.3	5.7
846-856	Permanent Absorber	38.7		38.7	17.9	20.8

Table 4. Transverse shielding thicknesses obtained from Refs. [1,3]. Defense in depth shielding thickness is obtained by taking the difference of the shielding without air and credited control shielding thicknesses. Section III-6.4.1.1 outlines the framework used to select the credited control shielding thicknesses. All the areas have sufficient shielding to produce a dose less than 500 mrem during one hour of running in the MCI scenario.

Transverse Station (location)	Enclosure Type	Shielding Without Air (e.f.d.)	Credited Control Shielding (e.f.d.)	Defense In Depth Shielding (e.f.d.)	Air Space In Enclosure (feet)
101	MI Extraction Stub	24.6	17.9	6.7	5.3
188	MI10 Crossover	25.7	17.9	7.8	1.0
231	Stairway Alcove	26.0	17.9	8.1	5.8
250	Stairway Exit Below Ground	20.0	17.9	2.1	5.7
301	Stairway Exit	24.0	17.9	6.1	5.7
351	Tunnel	23.1	17.9	5.2	5.7
427	Indian Creek Road	19.0	17.9	1.1	5.7
504	Box Culvert	23.2	17.9	5.3	5.7
545	Tunnel Downstream of Culvert	25.7	17.9	7.8	4.9
575	Tunnel	24.0	17.9	6.1	3.9
636	MI12 Upstream	22.0	17.9	4.1	2.0
660	MI12 Pretarget Vault	18.8	17.9	0.9	5.5
685	MI12 Horn Vault	30.0	17.9	12.1	3.3
693	MI12 Collimator	30.0	17.9	12.1	3.3
698	MI12 Downstream Wall	30.0	17.9	12.1	3.3
701	Decay Pipe Under MI12	26.9	20.3	6.6	3.0
765	Midrange Absorber In	31.8	17.9	13.9	0.0
765	Midrange Absorber Out	26.0	17.9	8.1	4.5
829	Decay Pipe	25.6	20.3	5.3	3.0

847	Permanent Absorber	38.2	17.9	20.3	0.0
882	Little Muon Counter Manhole (on 847 drawing)	53.4	17.9	35.5	0.0

BNB also has a machine protection system. Major elements monitored include beam losses, magnet currents, and beam positions.

III-6.6. Decommissioning

DOE Field Element Manager approval shall be obtained prior to the start of any decommissioning activities for the BNB segment.

III-6.7. Summary and Conclusion

Specific hazards associated with commissioning and operating the BNB segment are identified and assessed in this chapter of the Fermilab SAD. The designs, controls, and procedures to mitigate BNB specific hazards are identified and described. In addition to these specific safety considerations, the BNB segment is subject to the global and more generic safety requirements, controls, and procedures outlined in Section 1 of this Fermilab SAD.

The preceding discussion of the hazards presented by BNB operations and the credited controls established to mitigate those hazards demonstrate that the beamline can be operated in a manner that will produce minimal hazards to the health and safety of workers and MOIs, or to the environment.

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III-6.9. Appendix – Risk Matrices

Risk Assessment methodology was developed based on the methodology described in DOE-HDBK-1163-2020. Hazards and their potential events are evaluated for likelihood and potential consequence assuming no controls in place, which results in a baseline risk. A baseline risk (i.e., an unmitigated risk) value of III and IV does not require further controls based on the Handbook. Events with a baseline risk value of I or II do require prevention and/or mitigation measures to be established in order to reduce the risk value to an acceptable level of III or IV. Generally, preventive controls are applied prior to a loss event, reflecting a likelihood reduction, and mitigative controls are applied after a loss event, reflecting a consequence reduction. For each control put in place, likelihood or consequence can have a single “bin drop”, resulting in a new residual risk (i.e., a mitigated risk). This risk assessment process is repeated for each hazard for Facility Workers (FW), Co-Located Workers (CLW), and Maximally-exposed Offsite Individual (MOI). At the conclusion of the risk assessments, controls that are in place for the identified accelerator specific hazards are identified as Credited Controls and further summarized in Section III-6.4 of this Chapter as well as SAD Chapter VII-A.1 *Accelerator Safety Envelope – Fermilab Main Accelerator*.