# Maximum Credible Incident Analysis for the Booster Neutrino Beam Segment

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**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. References [1-8] provide background material on the BNB segment and Ref. [9] provides a link to the *Fermilab Radiological Control Manual* (FRCM). The Radiation Safety Interlock System (RSIS) 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, directing all the Booster output into the BNB segment via the 8 GeV Line segment, 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 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 document 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.

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).

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.

**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.

**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.

**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 using incremental shielding assessment (ISA) spreadsheets along with Refs [1,3]. A base case of 120 GeV protons, 1.64E+14 protons-per-pulse, and a 1.33 second accelerator cycle time is assumed for the scaling spreadsheet when determining the longitudinal and transverse shielding requirements. Similarly, a base case of 8 GeV protons, 5E+12 protons-per-pulse, and a 0.13 second accelerator cycle time is assumed for the labyrinth and penetration dose rate spreadsheet. These spreadsheets allow scaling of both energy and intensity to the MCI. Hence, dose rates for the MCI are obtained from the spreadsheets by using them with the beam conditions discussed in the section describing the MCI scenario.

An ISA scaling spreadsheet is 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.

**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 Stripline Pens at station 569 ft, see Table 1. This location uses the RSIS 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 BNB RSIS 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.

*Table 1. Labyrinth and penetration dose rates during the MCI scenario. These dose rates are obtained from an ISA labyrinths and penetrations spreadsheet except for the Dehumidifier Inlet penetration located at station Outside MI-12 Service Building. The dose rate for the Dehumidifier Inlet case is obtained as follows. Table 4 in Ref. [3] describes radiation exposure for some of the BNB labyrinths and penetrations including the Dehumidifier Inlet penetration, but it does not consider the MCI scenario. The different Dehumidifier Inlet table entries are divided by corresponding table entries for other labyrinths and penetrations in the table. The resulting ratios are then multiplied with corresponding dose rates obtained for labyrinths and penetrations from the ISA labyrinths and penetrations spreadsheet used to consider the MCI scenario. To be conservative, the worst-case estimate has been used in this analysis. Specifically, the ratio used is given by the accident dose for the "MI-12B Dehumidifier Inlet Z=656" divided by the accident dose for the "MI-12B Labyrinth Z=673 outside building" when considering the "15 beam pulses using interlocked detector" case. This ratio is then multiplied by the dose rate for the MI12 Stairs Outside at station 552 ft that is obtained from the ISA labyrinths and penetrations spreadsheet. All the areas outside of labyrinths and penetrations have sufficient shielding to produce a dose less than 500 mrem during one hour of running in the MCI scenario except for the Stripline Pens located at station 569 ft, where this area uses the RSIS to limit the dose during the MCI scenario.*

| Station (ft) | Description | L&P Proposed Eff. Dose Rate (mrem/hour) |
|---|---|---|
| **MI8** | MI8 exist door | 6.63E-1 |
| **MI8** | MI8 stairs | 6.63E-1 |

| | | |
|---|---|---|
| **151-168** | MI10 Stairs | 3.09E-2 |
| **552** | MI12 Stairs Top | 2.80E-3 |
| **552** | MI12 Stairs Outside | 6.16E-1 |
| **133** | MI10 Ducts | 6.47E-7 |
| **153** | Vent Shaft | 6.35E-2 |
| **Outside MI-12 Service Building** | Dehumidifier Inlet | 2.78E+2 |
| **569** | 4 Pens | 2.71E-5 |
| **569** | Stripline Pens | 2.07E+4 |
| **574** | 8 Pens | 5.43E-5 |
| **688** | 90-degree Monitor | 1.18E-2 |
| **698** | 8 x 5-inch Ducts N. Wall | 3.07E-7 |
| **715 & 855** | 6 Monitor Wells | 1.43E-1 |
| **829** | Berm Air Supply | 2.38E-1 |
| **829** | Berm Air Return | 1.58E-2 |
| **855** | Muon Mon. 50m Absorber | 4.45E-7 |
| **875** | MI-13 LMC | 2.75E-1 |

**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 hatch by the 25m absorber 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.

**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 as the penetrations are not required to be filled. These doses were found to be less than 500 mrem except for the Stripline Pens at station 569 ft. This location uses the RSIS to limit the dose during the MCI scenario.

**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.

**Radiation Safety Interlock System**

The BNB enclosures are part of the BNB 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 RSIS 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 BNB RSIS 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 1 shows the location of the credited detectors, and Table 2 summarizes the credited control limits for the credited detectors.

The following gives a summary of the approach used to determine the credited control limit for the detector that monitors the Manhole PMH-PVI-2 [15]. The BNB segment is assumed to produce a loss of 3.78E+17 protons-per-hour, equivalent to 7E+12 protons-per-pulse, at 8 GeV with 15 pulses-per-second.

The Manhole PMH-PVI-2 lies beneath Indian Creek Road near station 444, where the road crosses over the MI-12A tunnel (approximately above the beamline). The total effective shielding thickness of the soil, concrete, and steel at this location is 16.4 e.f.d. The interlocked detector is downstream of the manhole in a doghouse on the toe of the MI-12A berm, where the Fermilab GIS indicates that the detector is positioned 10 feet downstream of the manhole, as determined from an aerial photo.

A detector will measure a dose rate that is a factor of 0.5 or more of the peak dose rate when it and the location of the peak loss have the same amount of shielding. This determination has been made from previous tests using arrays of detectors and deliberate losses from 8 GeV beam and assuming that the detector is 10 feet downstream of the location for peak beam loss that is assumed to be beneath the manhole. The shielding beneath the detector exceeds the manhole shielding by 5.1 e.f.d., which has been estimated by examining the drawing 9-6-7-55 C-1. A difference of 5.1 e.f.d. in shielding thickness will attenuate the measured dose rate by a factor of 1.51E-2. This attenuation calculation assumes a 2.8 ft tenth-value layer (TVL) for soil to be consistent with the TVL value used in Ref. [1]. The current state of the art would typically use a 3.38 ft TVL for soil, and so this analysis is assuming that the soil provides more shielding than the current typical TLV value. The use of a 2.8 ft TVL for soil is a conservative approach, as the detector is expected to trip off at a lower dose or dose rate than calculated by this approach. The detector will measure a factor of 0.5 x 1.51E-2 = 7.55E-3 times the manhole dose given this scenario. Hence, a dose rate of 500 mrem-per-hour at the manhole will cause the detector to measure 7.55E-3 x 500 mrem-per-hour = 3.78 mrem-per-hour.

But, a shielding thickness of 0.5 e.f.d. is taken as defense in depth for the manhole, which means that the shielding beneath the detector is taken to exceed the manhole shielding by 5.6 e.f.d for this problem. This increased difference in shielding leads to an attenuation factor of 1.00E-2 for the measured dose rate. Therefore, a dose rate of 500 mrem-per-hour in the manhole will cause the detector to measure (0.5 x 1.00E-2) x 500 mrem-per-hour = 2.5 mrem-per-hour when using 0.5 e.f.d. of shielding as defense in depth. Thus, a 2.5 mrem credited control limit for the detector will produce at most a dose of 500 mrem in the manhole during one hour of maximum beam power operations.

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.

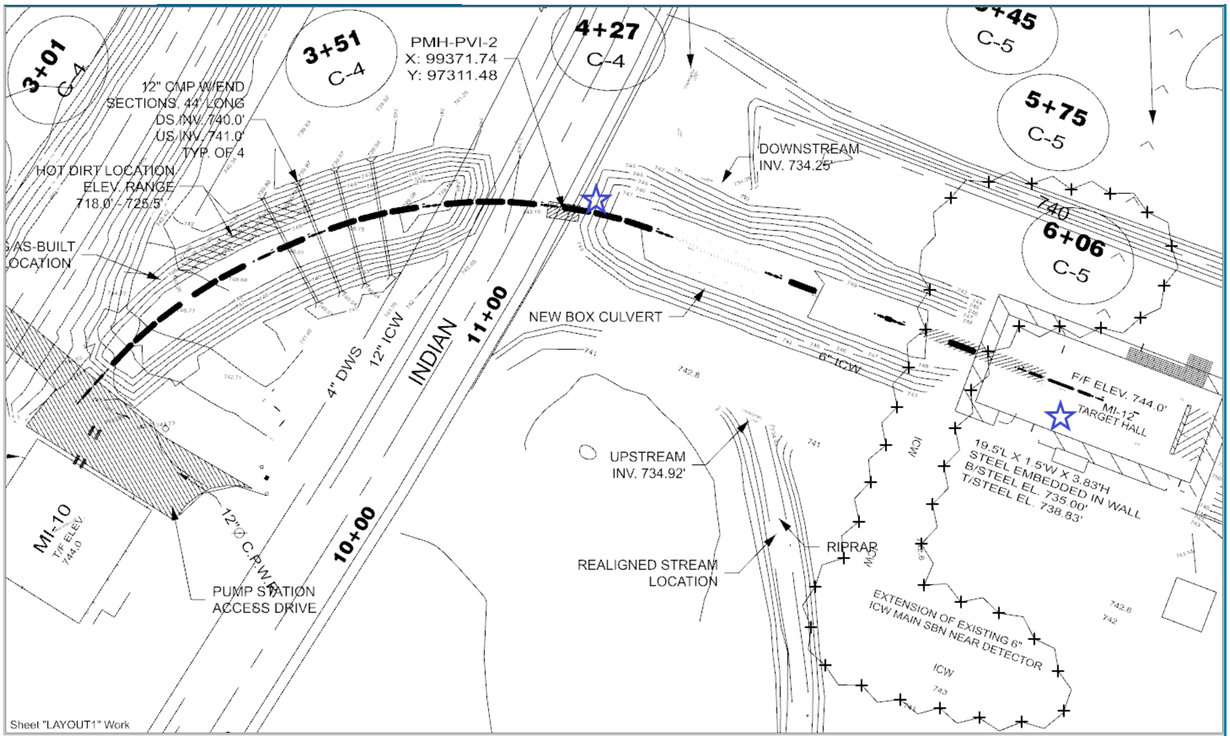


*Figure 1. The approximate locations of the credited detectors for the BNB segment are indicated by the blue five-point stars.*

*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 |

### 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.

### 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.

**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.

**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.

**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. The section describing the MCI scenario 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 RSIS 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. The section describing the MCI scenario 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.

**Summary and Conclusion**

Prompt ionizing radiation hazards associated with commissioning and operating the BNB segment are identified and assessed in this document. 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.

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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