Maximum Credible Incident Analysis for the Neutrino Muon Beamline

Version 2.1

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Contents

1 Introduction

The Neutrino Muon Beamline extends includes 120-GeV primary beam enclosures G1 stub in enclosure C, G2, NM1, NM2, NM3 and NM4. Figure 1 shows these enclosures. A buried beam pipe under vacuum connects all these respective enclosures including the transition from Switchyard (Z=920') to G1, except for NM3/NM4 enclosures, described next. The back face of the primary beam absorber shielding which is stacked inside and around F magnet defines the transition between NM3 and NM4. Although NM3 extends into the experimental hall, this section, surrounded by the NM4 enclosure, is physically separated by extensive shielding. NM4 starts at the upstream wall of the experimental hall and ends at the downstream wall.

The SpinQuest experiment utilizes a liquid-helium-cooled solid ammonia target housed in a shielding cave in NM3 approximately 300 cm from the front face of the beam absorber steel. The target cave location has been changed relative to E906 (SeaQuest) and shielding has been increased significantly relative to E906 with updated radiological drawings and a shielding assessment addendum. The cryogenic equipment, located near the target atop the shielding, requires both penetrations and increased shielding to protect against neutron damage to solid state components.

2 MCI Analysis and Boundaries

The NM boundaries for the purpose of analysis begin at extraction in Switchyard extend from an approximate DUSAF Z = 920 to the end of NM4 at Z=4503, as shown in Figures 1 and 2. E1039 (SpinQuest) modifications to the primary beamline begin at a new collimator installed in NM3 at Z = 4353. E906 incremental Shielding Assessments (ISA) in format [2] therefore are used to assess the Maximum Credible Incident up to this Z location. From the new E1039 collimator to the end of the NM4 experimental hall at Z=4503 is subsequently analyzed using the E1039 spreadsheets.

NM3, which extends from Z = 4113 to 4390, varies from 7 to 20 feet wide, and is at least 16 feet below grade. The last 30 feet of NM3 to the downstream end of the absorber steel extends into the experimental hall but is physically isolated in the 40 ft wide hall by steel and concrete shielding blocks. NM4 extends from Z = 4390 to 4503, is correspondingly 40 feet wide (the full width of the hall) and consists of poured concrete to grade level and metal panel to roof height. Its floor is 24 feet below grade and its roof is 29 feet above grade.

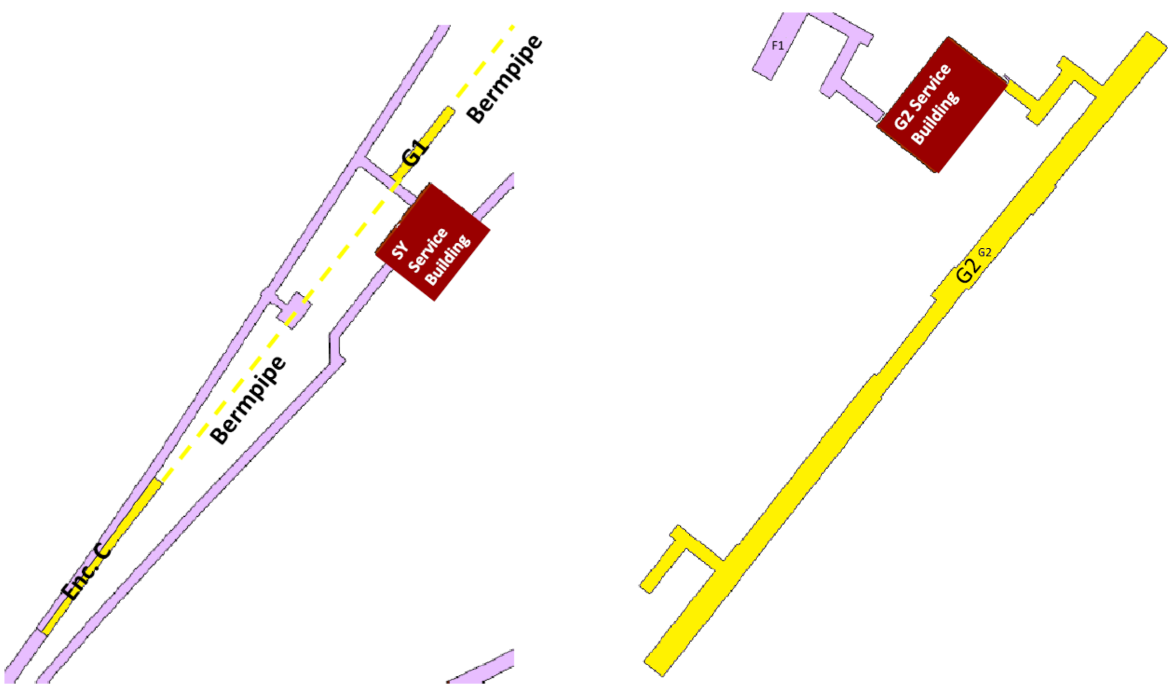


Figure 1: NM Switchyard enclosures C and G1 stub (left) and G2 stub (right) extend from DUSAF Z = 920 to 1708 (G1 end), and from 2070’ to 2420’ (G2 end), respectively. Enclosures are connected by berm pipes. The enclosures and connecting berm pipes shown in yellow ARE NOT PART OF THIS ADDENDUM AND ARE SHOWN FOR INFORMATIONAL PURPOSES ONLY.

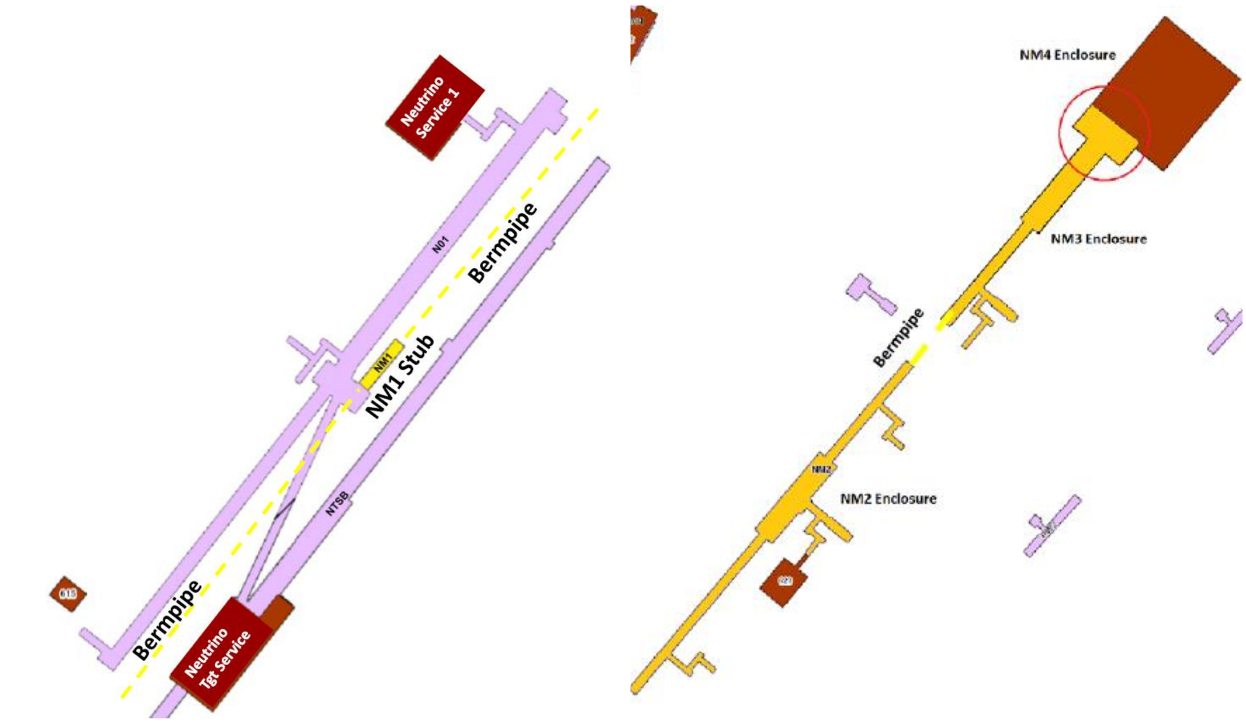


Figure 2: Enclosures NM1 (DUSAF Z = 3179 to 3216) through NM2 (3630 to 4020), NM3 (4113 to 4390), and NM4 Experimental Hall (4390 to 4503). All targeting and shielding changes for E1039 are limited within the area circled in red. The NM enclosures and berm pipes shown in yellow ARE NOT PART OF THIS ADDENDUM AND ARE SHOWN FOR INFORMATIONAL PURPOSES ONLY.

3 Assessment Parameters

This section describes the underlying beam parameters and assumptions used to determine the MCI and what is required for ASE compliance. For the Neutrino Muon beam line, these limits are 5000 mrem/hr within the area behind the locked fence and 500 mrem/hr just in the other side of the fence.

3.1 Normal and Accident Conditions

The NM beam is operated on a single ~4sec beam spill from the Main Injector. Shielding for the NM beamline therefore is evaluated for 120 GeV protons at 4.2 x 10^{13} per 55 sec and calculated as follows based on the shortest supercycle timeline of 55 sec:

$$1\,\frac{spill}{55\,sec} \times 3600\frac{sec}{hour} \times 4.2 \times 10^{13}\,\frac{protons}{spill} = 2.75 \times 10^{15}\,\frac{protons}{hour}$$

This intensity limit is controlled through a Beam Permit, Running Condition, and an interlocked Repetition Rate Monitor (RRM).

The Most Credible Accident condition (100% beam loss) then assumes 4.2 x 10^{13} protons per spill per 55 sec lost on a magnet, a beam pipe in an enclosure, or a buried beam pipe and located arbitrarily along the beamline. For the NM beamline, a buried beam pipe represents a significant radiological category as buried beam pipe connects all enclosures in Figure 1 except NM3 to NM4. An accident is assumed to last for one hour, unless its duration is limited by the use of interlocked detectors. The highest prompt dose is generated by beam loss on a beam pipe; the next highest is for beam striking a magnet or experimental targets, at locations with the least amount of installed shielding.

4 Shielding Requirements

The shielding requirements are specified in *NM E906 ISA Summary and NM E1039 ISA Summary* for Z=902’-4353’ and Z=4353’-4503’ and are calculated for 120 GeV protons at 4.20 x 10^{13} protons per spill with a spill every 55 sec (2.75 x 10^{15} protons per hour). The amount of shielding is scaled from a set of generic shielding criteria developed from Monte Carlo simulations [3] tabulated for 120 GeV protons at 1.6 x 10^{14} protons per pulse and 2700 pulses per hour. The scaling assumes that dose rates decrease by an order of magnitude for every 3.38 feet of soil-equivalent shielding.

For this MCI analysis, the first step will be to determine if any locations exceed 500 mrem in one hour due to the MCI. If 500 mrem is exceeded in one hour, the maximum dose rate in those areas will be determined to see if 5000 mrem is exceeded in one hour behind the locked fence or 500 mrem is exceeded at the fence line in one hour.

There are three categories of beam-material interactions that are considered for the NM shielding requirements for the MCI. The first is beam hitting a magnet in an enclosure, and the second is beam hitting the beam pipe in the enclosure and the third is beam hitting buried beam pipe. These scenarios require 13.9 effective feet of dirt (e.f.d.), 11.4 e.f.d. and 16.3 e.f.d., respectively, to limit the radiation dose rate to less than 500 mrem-per-hour for a person outside of the beamline enclosures. Any N01/NM1 – NM3 areas that fail this criteria, are then evaluated for the highest doses rates possible. The berm/area within the locked fence must stay less than 5000 mrem/hr.

It should be noted that longitudinal and transverse areas downstream of FMAG (Z=4390) are secondary particles and not subject to the ISA shielding spreadsheet requirements, specifically the minimum 3 ft of shielding. Previous beam on studies have been performed to address the secondary particles and the use of the additional interlocked radiation detectors, along with their corresponding trip settings, to comply with the requirements of 10CFR835. This requirement automatically satisfies the MCI dose limits.

5 Longitudinal Shielding Summary

The longitudinal summary spreadsheets, shown in Tables 1 and 2, range from the point of extraction in Switchyard to the end of the NM4 building with E906 spreadsheets required to assess Z=920-4353' and the E1039 updated spreadsheets required to the end of NM4, i.e., for Z=4353-4503'. Installed shielding ranges from 12.5' to over 30' directly above the primary beamline up to Z=4348' and then 11.4 to 31' to the beginning of the secondary beamline at Z=4390', which is the back face of the absorber shielding. The secondary beamline has no hadronic component as discussed above and addressed later in this section.

Based on the new ASE accident intensity (2.75 x 10^{15} versus the previous 6.0 x 10^{14} p/hr) and imposing the ASE condition of 5000 mrem/hr for open spaces that are not accessible by the public, but are behind a locked fence (the NM berm is behind a locked fence and posted as Radiation Area, and the NM4 experimental hall locked), then the two summary sheets, one from E906 and the second from E1039 addendum, indicate that adequate shielding exists from Switchyard through the beam absorber with the exception of the interface between the end of the NM3 berm and the front face of the target cave shield stack. From Z=4348-4360', only 11.4' of shielding is installed upstream and downstream of the E1039 collimator which has steel shielding stacked above the collimator. This location, at the interface between the berm and the NM4 experimental hall, is currently protected using an existing interlocked radiation detector (Chipmunk) for compliance with 10CFR835. This detector can trip the beam within 3 sec, allowing a maximum of 4.2 x 10^{13} protons after detecting an MCI. The credited control trip setting for this interlocked detector will be set to less than 5000 mrem/hr.

Table 1: Longitudinal ISA Spreadsheet from E906

Longitudinal Range	Location	Fixed Shielding (efd)	Movable Shielding (efd)	Current Shielding (efd)	Required (efd)
3179-3216	NM1	19.6		19.6	13.9
3216-3620	Beam Pipe	22.0		22.0	16.3
3620-3829	NM2	18.0		18.0	13.9
3829-3929	NM2	15.5		15.5	13.9
3929-4060	NM2	17.5		17.5	13.9
4060-4113	Beam Pipe	30.8		30.8	16.3
4113-4230	NM3	21.0		21.0	13.9
4230-4334	NM3	21.3		21.3	11.4
4334-4348	NM3	12.5		12.5	11.4
4348-4360	NM3	11.3		11.3	11.4

Table 2: Longitudinal ISA Spreadsheet from E1039

Longitudinal Range	Location	Fixed Shielding (efd)	Movable Shielding (efd)	Current Shielding (efd)	Required (efd)
4353-4357	NM3 collimator	11.4	6.1	17.5	13.9
4357-4360	NM3	11.4		11.4	11.4
4360-4368	Target Cave		11.7	11.7	13.9
4368-4373	Target Wall		29.9	29.9	16.3
4373-4374	Pre-FMAG		31.4	31.4	16.3
4374-4378	FMAG US		31.0	31.0	16.3
4378-4381	FMAG US		28.8	28.8	16.3
4382-4388	FMAG DS		26.0	26.0	16.3
4388-4389	FMAG DS		22.4	22.4	16.3
4389-4390	FMAG DS		28.5	28.5	16.3
4390-4391	Post-FMAG		3.5	3.5	3.0
4391-4392	Post-FMAG		8.9	8.9	3.0
4392-4394	Post-FMAG		3.5	3.5	3.0
4394-4454	NM4		0.0	0.0	3.0
4454-4490	NM4		7.1	7.1	3.0
4490-4503	NM4		8.9	8.9	3.0

6 Transverse Shielding Summary

The two transverse summary sheets, shown on Tables 3 and 4 summarize the radial distribution of shielding that surrounds the primary and the modified E1039 beamline enclosures and the secondary beam range in NM4. The transverse stations are identified by their distances in feet along the beamline from the designated origin. For transverse shielding, there are two sides - an "E" or "W" suffix designates east or west sides of the beamline in locations that exhibit different transverse shielding profiles. Also, for every east transverse station adjacent to the counting house, there is a dependence on elevation. Therefore, for every such east station, there are two entries: one each for elevation above ("up") and below ("dn") the NM4 experimental hall roof. Since the "up" is the "open" space, only this direction is relevant for the MCI analysis.

This summary sheet indicates that adequate shielding exists at all transverse stations of the beamline, with one exception: at 4360 – 4367. This location, at the SW corner of the NM4 experimental hall, is currently protected using an (existing) interlocked radiation detector (Chipmunk). This detector can trip the beam within 3 sec, allowing a maximum of 4.2×10^{13} protons after detecting an MCI. The credited control trip setting for this interlocked detector will be set to less than 5000 mrem/hr.

Table 3: Transverse ISA Spreadsheet from E906

Transverse Station (ft)	Location	Fixed Shielding (efd)	Movable Shielding (efd)	Current Shielding (efd)	Required (efd)
NC13176	N01	26.6		26.6	16.3
NC13208	N01	21.8		21.8	16.3
NM23673	NM2	19.0		19.0	16.3
NM23827	NM2	19.5		19.5	16.3
NM23882	NM2	19.0		19.0	16.3
NM24009	NM2	25.5		25.5	16.3
NM24028	NM2	17.9		17.9	16.3
NM24100	Beam Pipe	31.4		31.4	18.7
NM34120	NM3	18.4		18.4	16.3
NM34125	NM3	21.7		21.7	16.3
NM34150	NM3	21.7		21.7	13.9
NM34168	NM3	21.2		21.2	13.9
NM34245	NM3	21.3		21.3	13.9

Table 4: Transverse ISA Spreadsheet from E1039

Transverse Station (ft)	Location	Fixed Shielding (efd)	Movable Shielding (efd)	Current Shielding (efd)	Required (efd)
4354-W	NM3 Collimator	11.4	6.1	17.5	16.3
4354-E	NM3 Collimator	11.4	6.1	17.5	16.3
4357-W	NM3	16.9	0.0	16.9	13.8
4357-E	NM3	16.9	0.0	16.9	13.8
4360-W	Target Cave		4.0	4.0	13.9
4360-E(dn)	Target Cave		19.8	19.8	13.9
4360-E(up)	Target Cave		5.0	5.0	13.9
4361-W	Target Cave		8.4	8.4	13.9
4361-E(dn)	Target Cave		23.6	23.6	13.9
4361-E(up)	Target Cave		11.4	11.4	13.9
4364-W	Cryo Line		11.0	11.0	13.9
4364-E(dn)	Cryo Line		23.6	23.6	13.9
4364-E(up)	Cryo Line		11.4	11.4	13.9
4367-W	Target Cave		6.7	6.7	13.9
4367-E(dn)	Target Cave		32.6	32.6	13.9
4367-E(up)	Target Cave		11.4	11.4	13.9
4368-W	Target Cave		18.5	18.5	13.9
4368-E(dn)	Target Cave		33.5	33.5	13.9
4368-E(up)	Target Cave		20.3	20.3	13,9
4370-W	Target Wall		22.9	22.9	13.9
4370-E(dn)	Target Wall		32.8	32.8	13.9

Transverse Station (ft)	Location	Fixed Shielding (efd)	Movable Shielding (efd)	Current Shielding (efd)	Required (efd)
4370-E(up)	Target Wall		20.5	20.5	13.9
4373-W	Pre-FMAG		25.9	25.9	16.3
4373-E(dn)	Pre-FMAG		29.4	29.4	16.3
4373-E(up)	Pre-FMAG		24.3	24.3	16.3
4376-W	FMAG Face		31.0	31.0	16.3
4376-E(dn)	FMAG Face		37.4	37.4	16.3
4376-E(up)	FMAG Face		31.0	31.0	16.3
4378-W	FMAG		28.8	28.8	16.3
4378-E(dn)	FMAG		39.9	39.9	16.3
4378-E(up)	FMAG		28.8	28.8	16.3
4380-W	FMAG		26.0	26.0	16.3
4380-E(dn)	FMAG		39.9	39.9	16.3
4380-E(up)	FMAG		26.0	26.0	16.3
4382-W	FMAG		26.0	26.0	16.3
4382-E(dn)	FMAG		33.9	33.9	16.3
4382-E(up)	FMAG		26.0	26.0	16.3
4388-W	FMAG		22.4	22.4	16.3
4388-E(dn)	FMAG		37.7	37.7	16.3
4388-E(up)	FMAG		22.4	22.4	16.3
4389-W	FMAG		26.1	26.1	16.3
4389-E(dn)	FMAG		37.0	37.0	16.3
4389-E(up)	FMAG		26.1	26.1	16.3
4390-W	Post-FMAG		2.5	2.5	3.0
4390-E(dn)	Post-FMAG		16.9	16.9	3.0
4390-E(up)	Post-FMAG		2.2	2.2	3.0
4392-W	Post-FMAG		10.4	10.4	3.0
4392-E(dn)	Post-FMAG		24.6	24.6	3.0
4392-E(up)	Post-FMAG		10.1	10.1	3.0
4394-W	Post-FMAG		2.2	2.2	3.0
4394-E(dn)	Post-FMAG		16.9	16.9	3.0
4394-E(up)	Post-FMAG		2.2	2.2	3.0
4411-E(dn)	Post-FMAG		12.4	12.4	3.0
4411-E(up)	Post-FMAG		0.0	0.0	3.0
4411-W	Post-FMAG		0.0	0.0	3.0
4482-E(dn)	Post-FMAG		16.4	16.4	3.0
4482-E(up)	Post-FMAG		6.6	6.6	3.0
4482-W	Post-FMAG		6.6	6.6	3.0
4502-E(dn)	Post-FMAG		14.8	14.8	3.0
4502-E(up)	Post-FMAG		7.7	7.7	3.0
4502-W	Post-FMAG		7.7	7.7	3.0

7 MARS Simulations

7.1 Overview

MARS [4] simulates electromagnetic and hadronic showers, including processes such as gamma emission following neutron capture. For the studies here, a proton beam intensity of 1.67x 10^{11} protons per second (normal operational intensity) is assumed, corresponding to the current operational limit of 6.0 x 10^{14}p/hr. Prompt dose would need to be scaled to 7.64 x 10^{11} p/sec to convert values to the new MCI intensity. The low energy cutoff for neutrons used in this simulation was 1 meV (milli-electron Volt).

The model consists of the following elements:

- magnetized beam absorber (FMAG), including the re-entrant hole, but excluding the return fields
- areal density targets of 5.1 g/cm^2 frozen LNH_3 and 0.44 g/cm^2 liquid He
- detailed model of steel and concrete shielding including
  - upstream fixed collimator
  - increased dimensions of target cave relative to E906
  - increased shielding starting from target wall through FMAG absorber
- concrete walls and floor of NM3 and NM4
- NM4 roof
- surrounding soil

Below are longitudinal and transverse MARS simulations for the NM4 hall. Note that z(MARS)=0 in the simulation corresponds to the front face of F-mag at Z(DUSAF)=4376'. Prompt dose is calculated for 1.67 x10^{11} p/sec indicating that an increase of a factor of 4.57 is required to scale the prompt dose to the MCI accident intensity.

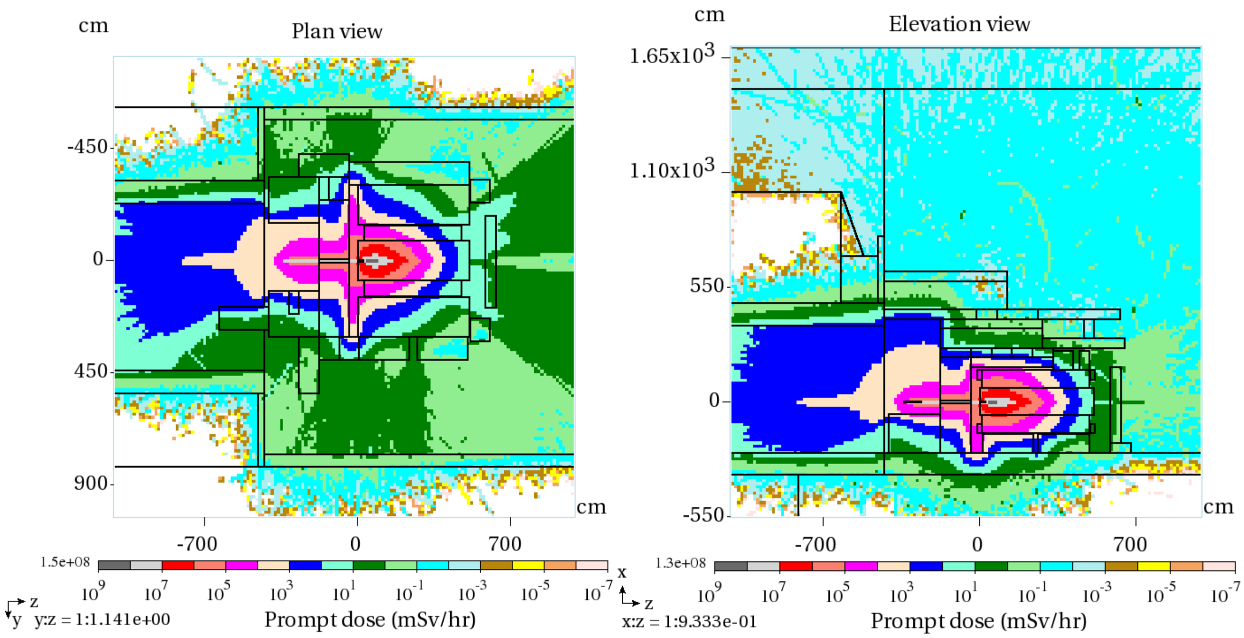


Figure 3: The calculated prompt dose distributions around downstream NM3 and NM4 for elevation and plan views.

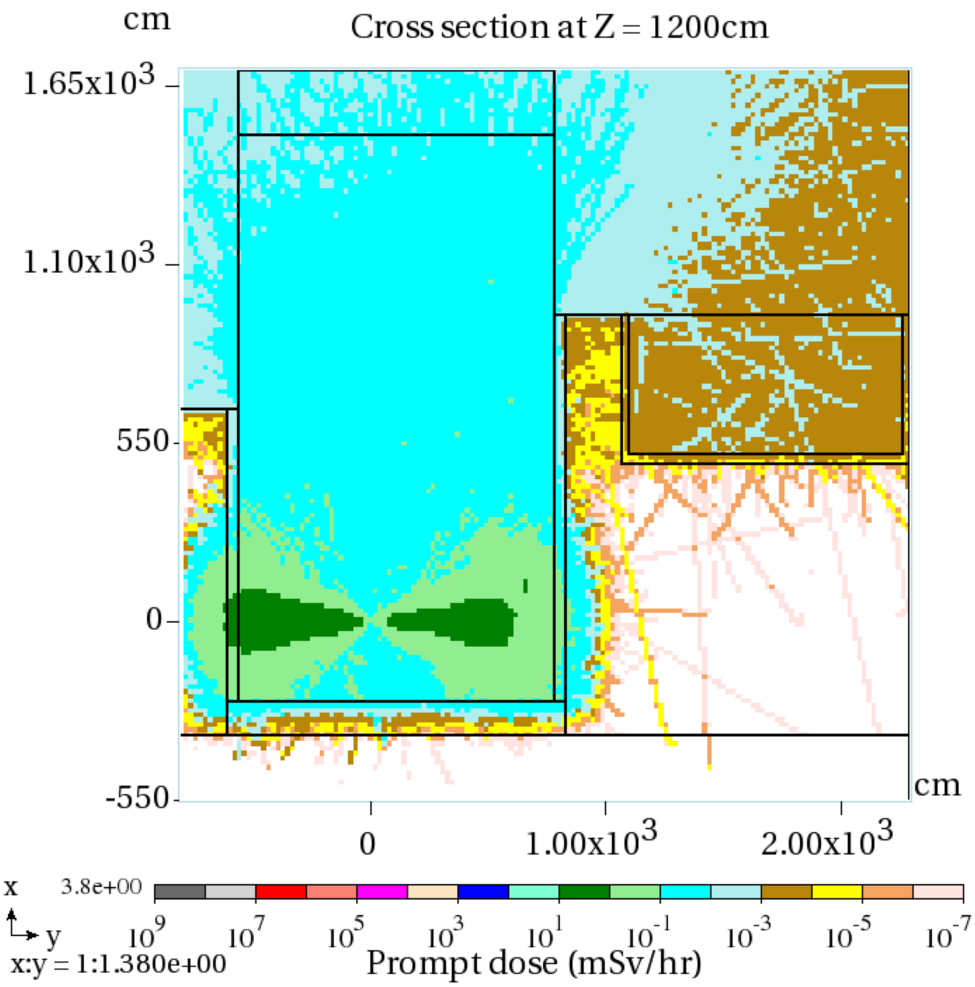


Figure 4: Transverse slice at Z(DUSAF) = 4415' in the secondary beam section of the NM4 hall enclosure showing prompt dose distributions on the roof and also in the counting house.

7.2 Prompt Dose Rates

Prompt dose rates are calculated using the E906/E1039 spreadsheets and also MARS in the NM3 target area and NM4 experimental all to address the dose distributions in outside the shielding (open spaces). ISA spreadsheets are used for prompt doses at the exit of labyrinths and penetrations which for NM only represent enclosed spaces. In NM4, at all roof (longitudinal) and exterior (transverse) locations the dose is significantly less than 10mr/hr for 1.67x 10^{11} protons/sec and <<45.7 mrem/hr for the MCI accident condition of 7.64 x 10^{11} protons/sec - even in the secondary beam section of the enclosure hall where shielding is not installed or minimal.

7.2.1 Unmitigated Peak Prompt Dose Rates

In Table 5 below, the peak prompt dose is estimated for all longitudinal and transverse sections of the NM beamline starting with the NM1 enclosure. Note that there are NM3 locations that fail and must be mitigated with a radiation detector as discussed in the next section.

Table 5: Unmitigated peak prompt dose calculated for an MCI in the NM beam line

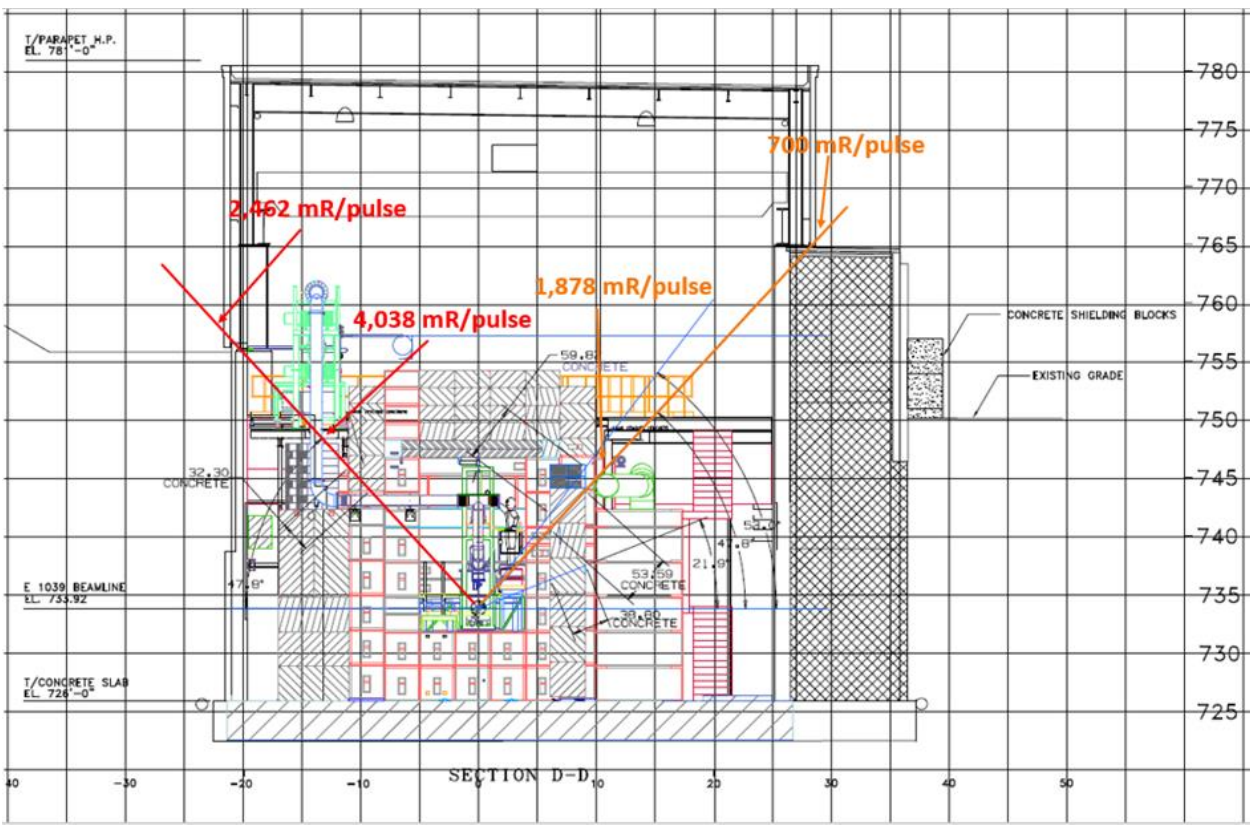
Encl	Z Location	ISA spreadsheet	Shielding efd	MCI peak dose (mrem/hr)
NM1	3179-3216’ 3208’	Longitudinal Transverse	19.6 21.8	7 <2
Beam pipe	3216-3620’	Longitudinal	22	7
NM2	3829-3929 4028’	Longitudinal Transverse	15.5 17.9	117 2
Beam Pipe	4060-4113 4100’	Longitudinal Transverse	30.8 31.4	<1 <1
NM3	4353-4364’ 4360-4367’	Longitudinal Transverse	11.7 4	1,615 262,500
NM4	4394-4454’	longitudinal	0	<45.7 LPH2-NMS001
NM4	4390 – 4394’	transverse	2.2	<45.7 XPH2-NMS001-2
NM4	4411’	transverse	0	<45.7 XPH2-NMS004-5

Figure 5 shows a “slice” at the interaction point at the NM3 target cave and the highest resulting doses. The largest calculated doses are on the East side of the NM4 experimental hall roof and the SW corner of the NM4 experimental hall at grade level. The due East and West side locations were evaluated due to these areas potentially being accessible to personnel on the other side of the locked fence. The dose on the roof is 700 mrem and the dose at the SW corner is 2462 mrem. Both of these locations are only accessible to workers and co-located worker and are less than 5000 mrem. However, these doses result from one pulse of MCI beam intensity. So, the two chipmunks, on the NM3 berm and the SW corner of the NM4 experimental hall, will be credited controls with trip limits set to less than 5000 mrem/hr.

The roof is not accessible to personnel. The fence on the West side is 143 feet away from NM4 and is the closest accessible location. Keeping the berm dose rate to less than 5000 mrem/hr, 1/r would reduce this dose at the fence line to 35 mrem in one hour. Although this is conservative since the NC berm is present between NM4 and the fence, and the highest dose that is not mitigated by any shielding outside of NM4 experimental hall emanates from grade level at approximately a 45-degree angle.

The closest distance a member of the public is allowed to be is on Pine Street, approximately 2000 feet away. Keeping the NM berm dose rate to less than 5000 mrem/hr, 1/r would reduce the dose to a member of the public to 2.5 mrem in one hour.

Figure 4: Scaled doses for the MCI intensity



8 Labyrinths and Penetrations

There are three labyrinths and three sets of penetrations within the boundaries of this addendum. In some cases, individual analysis of every penetration within a group of similar penetrations has not been performed. Rather, limiting cases giving a conservative estimate of dose for penetrations within each group have been identified and analyzed in the Neutrino Muon shielding assessment and addendum [1][2] The labyrinth and penetration summary sheet indicates that the exit dose rates of all labyrinths and penetrations meet the 5000 mrem/hr condition for the enclosed areas.

9 Intended Active Shielding Controls and Monitoring

9.1 Radiation Detectors

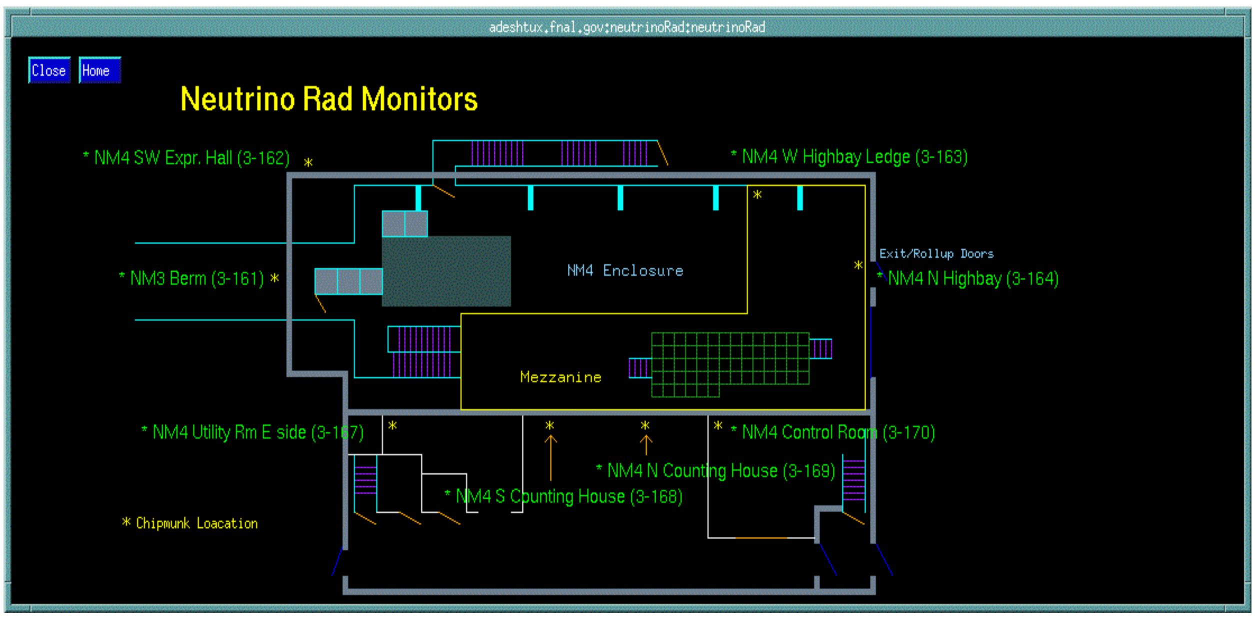
Radiation detectors are placed around the experimental hall including occupied areas at locations capable of detecting all MCI conditions and limiting prompt dose to ensure compliance with the ASE limits. The radiation detectors will be interlocked to the Radiation Safety Interlock System (RSIS). This system is routinely tested and certified to turn off critical device(s) for the beamline and stopping the beam within 3 seconds. The RSIS trip level will be set by the Radiation Safety Officer.

Radiation detectors (chipmunks) are capable of disabling the 120 GeV proton beam to the NM primary beamline within 3 seconds, thus allowing a maximum of 4.2×10^{13} protons once an MCI condition is detected. These detectors protect and limit prompt dose in both the longitudinal and transverse direction as required at locations that have been identified from the shielding or occupancy analyses. Chipmunk locations required to protect against MCI conditions are marked with an asterisk and are credited controls. Other existing chipmunk locations are shown but are not required to protect against an MCI accident condition. All chipmunk locations, coverage, and MCI-relevant settings are listed in Table.

Table 5: Chipmunk locations and coverage regions plus required settings for an MCI.

Chipmunk ID	Location	Coverage per ISA spreadsheets	MCI setting (mrem/hr)
3-161*	NM3 Berm	Long. Z=4353'-4368'	DR≤5000
3-162*	Grd Level, NM4 Exp Hall SW	Trans. Z=4354'-4368' E&W	DR≤5000
3-163	Grd Level, High-bay Ledge W	Trans. Z~4460'	Not required
3-164	Grd Level, NM4 High Bay, N	Trans. Z~4503'	Not required
3-167	Grd Level, Utility Rm	Trans Z~4376'	Not required
3-168	Grd Level, NM4 CH S	Z~4400'	Not required
3-169	Grd Level, NM4 CH N	Z~4425'	Not required
3-170	Grd Level, NM4 Control Room	Z~4445'	Not required

Figure 6: ***Interlocked Chipmunks around NM4 Experimental Hall***



10 Conclusions

The shielding for the NM primary beamline and secondary beam area from Switchyard in Enclosure C to the end of NM4 experimental hall has been analyzed under the MCI intensity conditions, 4.2×10^{13} protons per pulse with one pulse per 55 sec, or 2.75×10^{15} protons per hour. The analyses and calculations performed indicate complete protection against violating the ASE in the event of an MCI at any location based on the berm or concrete shielding combined with the installation of two radiation detectors as described in this document. This analysis also concludes that the credited controls limit the dose to a member of the public to 2.5 mrem in one hour should the MCI occur.

11 References

[1] *Neutrino Muon Beamline Shielding Assessment, v1.3*, T. Kobilarcik and M. Geelhoed, February 24, 2012

[2] C. Johnstone and I. Rakhno, Neutrino Muon Beamline Shielding Assessment Addendum for E1039, December 18, 2019.

[3] D. Christian, M Geelhoed, N. Mohkov, E906/SeaQuest MARS Simulation, Fermilab-TM-2479.

[4] *Incremental Shielding Assessment Methodology*, W. Higgins and P. Kasper, November 10, 1997, https://esh-docdb.fnal.gov:440/cgi-bin/ShowDocument?docid=3843

[5] *Update to the Generic Shielding Criteria,* FERMILAB-TM-2550-ESH, S.D. Reitzner, November 6, 2012

[6] *The MARS Code System User's Guide*, FERMILAB-FN-628 (1995), N. V. Mokhov, https://mars.fnal.gov/