Maximum Credible Incident Analysis for the Neutrino Muon Segment

Sue McGimpsey, January 22, 2024

Maximum Credible Incident (MCI) 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 Neutrino Muon (NM)beam line areas. References [2-7] provide additional material on the NM segment. The Radiation Safety Interlock System (RSIS) is used to keep individuals out of the NM enclosures during beam operations. A change to the NM MCI or the MCI for upstream segments will be evaluated for its effect on the NM segment through the USI process.

The operating condition required for producing the NM MCI scenario: maximum beam power operations, directing all of the Main Injector output into the NM segment via the Switchyard segment, and the beam is mis-steered away from the design trajectory to cause very large losses.

A maximum credible incident would be one that also produces the greatest beam loss for the longest period of time. The NM MCI is dependent on the MCI intensity of the Switchyard segment. After careful evaluation, it has been determined that the Switchyard MCI, with respect to beam intensity, has the following beam parameters. At 120 GeV, Switchyard can achieve a maximum of 4.2 E13 protons/pulse, with a 55 second cycle time that is limited by the repetition rate limiter located in Switchyard on the VH94 power supply. A repetition rate limiter is used to protect against the delivery of 120GeV beam more than once every 55 seconds. This device has been used for many years and has been refined by the AD Power Electronics Systems Department (PESD) and the ES&H Interlocks Group. This device is a Credited Control. The following scenarios will disable the Switchyard CDC by turning off S:HP3US & S:HP3DS, inhibiting beam transport:

- If the magnet power supply S:VH94 is excited for more than seven seconds in a sixty second period.
- If the magnet power supply S:VH94 is excited more than once in a 60 second period.
- If a fault occurs with the Repetition Rate Limiter Hardware Input Module, Output Module, or Analog monitoring Module.

See the Switchyard SAD chapter on maximum credible incident scenario(s) for the accelerator specific hazard(s) for more information.

As a result, the maximum beam intensity output that can be achieved from the NM beamline is 2.75E15 protons/hour, with 4.2E13 protons/pulse at a 55 second cycle time. For this MCI intensity to be delivered to the NM beam line, the power supply for V100 would need to be energized continuously, which would bend the beam vertically down, away from the Switchyard absorber and into the Neutrino Muon beam line. Additionally, no beam would be delivered to the Meson area. This could be achieved by having the Meson Critical device (S:MLAM) locked off. A maximum credible incident would be one that produces the greatest beam loss for the longest period of time. The NM MCI occurs when 2.75E15 protons/hour is lost and continuously incident on the beam pipe or a beamline component that is both the closest to the thinnest section of permanent shielding and the farthest away from interlocked radiation detectors in the NM beamline for one hour. This MCI in NM can be a result of the misdirection of the beam so that it impacts the beam pipe and surrounding structures inside the accelerator enclosure, which can occur from a single failure of one or more devices or power supplies, or erroneous operation of them.

Prompt radiation causes hazardous radiation fields directly and indirectly through material effects. Assuming no shielding is present, this incident would result in a dose that far exceeds acceptable levels for radiation exposure to workers or members of the public. Previous MARS simulations [2] finds that a peak dose rate in excess of 10,000 mrem/hr would occur in areas on the NM berm adjacent to the NM beamline and experimental area in this accident condition. Without any preventative or mitigative measures, the prompt radiation dose level associated with this accident is not acceptable.

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

- 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.
- Less than 5 rem in one hour in any area accessible by facility workers or co-located workers

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 NM 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 NM 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 NM segment that take direct human intervention to remove. The permanent shielding encompasses the structural elements surrounding the beamline components and experimental hall. The amount of permanent shielding for the enclosure is documented in the NM Beam Line SA and addendum [2][6].

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 areas. If these amounts of shielding exist, then a person outside of the beamline areas and right next to the shielding will receive at most a dose of 500 mrem within one hour from the assumed one hour of maximum beam power operations. In locations where there is more than the required amount of shielding, that shielding is a credited control. Any areas along the NM beamline with less than the required amount of shielding, will require active controls as described below in addition to the existing shielding. In the locations with less than the required amount of shielding, 0.5 ft less than the values in table 2 will be taken as the credited control along with the interlocked detector. The trip setting for the interlocked detector will be set to account for this lessor amount of shielding taken as a credited control. There are currently eight locations in the NM3 and NM4 areas that already require the use of interlocked detectors for normal operating conditions and compliance with 10CFR835 and the Fermilab ALARA program. For the MCI described above, only one of these interlocked detectors is needed. This is the detector on the NM3 berm at the longitudinal location covering the Z (ft) range from 4353-4368. This interlocked detector also protects the transverse locations 4354-4370. See Tables 2 and 3. 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 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 MCI dose limits of this SAD.

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Table 1. Longitudinal Shielding Spreadsheet

Long. Range	Location	Category	Curr. shielding	Req. Shielding	Interlocked detector
Z (ft)			efd	efd	Needed?
4353-4357	NM3 collimator	4A	17.5	13.9	Y – already in place
4357-4360	NM3	4B	11.4	11.4	Y – already in place
4360-4368	Target Cave	4A	11.7	13.9	Y – already in place
4368-4373	Target Wall	4A	29.9	13.9	N
4373-4374	Pre-FMAG	4A	31.4	13.9	N
4374-4378	FMAG US	4C	31	16.3	N
4378-4381	FMAG US	4C	28.8	16.3	N
4382-4388	FMAG DS	4C	26	16.3	N
4388-4389	FMAG DS	4C	22.4	16.3	N
4389-4390	FMAG DS	4C	28.5	16.3	N
4390-4391	Post-FMAG	4A	3.54	3.0	N
4391-4392	Post-FMAG	4A	8.9	3.0	N
4392-4394	Post-FMAG	4A	3.54	3.0	N
4394-4454	NM4	4A	0	3.0	N
4454-4490	NM4	4A	7.08	3.0	N
4490-4503	NM4	4A	8.85	3.0	N

Table 2. Transverse Shielding Spreadsheet

Transverse Location (ft)	Location	Category	Curr. Shielding efd	Req. Shielding efd	Interlocked detector Needed
4354-W	NM3 Collimator	4A	17.5	13.9	Y – already in place
4354-E	NM3 Collimator	8A	17.5	4.7	Y – already in place
4357-W	NM3	8B	16.9	3.0	Y – already in place
4357-E	NM3	8B	16.9	3.0	Y – already in place
4360-W	Target Cave	9A	4.0	3.0	Y – already in place
4360-E(dn)	Target Cave	4A	19.8	13.9	Y – already in place
4360-E(up)	Target Cave	8A	5.0	4.7	Y – already in place
4361-W	Target Cave	8A	8.4	4.7	Y – already in place
4361-E(dn)	Target Cave	4A	23.6	13.9	Y – already in place
4361-E(up)	Target Cave	8A	11.4	4.7	Y – already in place
4364-W	Cryo Line	8A	11.0	4.7	Y – already in place
4364-E(dn)	Cryo Line	4A	23.6	13.9	Y – already in place
4364-E(up)	Cryo Line	8A	11.4	4.7	Y – already in place
4367-W	Target Cave	8A	6.7	4.7	Y – already in place
4367-E(dn)	Target Cave	4A	32.6	13.9	Y – already in place
4367-E(up)	Target Cave	8A	11.4	4.7	Y – already in place
4368-W	Target Cave	8A	18.5	4.7	Y – already in place
4368-E(dn)	Target Cave	8A	33.5	4.7	Y – already in place
4368-E(up)	Target Cave	8A	20.3	4.7	Y – already in place
4370-W	Target Wall	8A	22.9	4.7	Y – already in place
4370-E(dn)	Target Wall	4A	32.8	13.9	N
4370-E(up)	Target Wall	4A	20.5	13.9	N
4373-W	Pre-FMAG	8C	25.9	7.0	N
4373-E(dn)	Pre-FMAG	4C	29.4	16.3	N
4373-E(up)	Pre-FMAG	4C	24.3	16.3	N
4376-W	FMAG Face	4C	31.0	16.3	N
4376-E(dn)	FMAG Face	4C	37.4	16.3	N
4376-E(up)	FMAG Face	4C	31.0	16.3	N
4378-W	FMAG	4C	28.8	16.3	N
4378-E(dn)	FMAG	4C	39.9	16.3	N
4378-E(up)	FMAG	4C	28.8	16.3	N
4380-W	FMAG	4C	26.0	16.3	N
4380-E(dn)	FMAG	4C	39.9	16.3	N

Transverse Location (ft)	Location	Category	Curr. Shielding efd	Req. Shielding efd	Interlocked detector Needed
4380-E(up)	FMAG	4C	26.0	16.3	N
4382-W	FMAG	4C	26.0	16.3	N
4382-E(dn)	FMAG	4C	33.9	16.3	N
4382-E(up)	FMAG	4C	26.0	16.3	N
4388-W	FMAG	4C	22.4	16.3	N
4388-E(dn)	FMAG	4C	37.7	16.3	N
4388-E(up)	FMAG	4C	22.4	16.3	N
4389-W	FMAG	4C	26.1	16.3	N
4389-E(dn)	FMAG	4C	37.0	16.3	N
4389-E(up)	FMAG	4C	26.1	16.3	N
4390-W	Post-FMAG	4A	2.5	3.0	N
4390-E(dn)	Post-FMAG	4A	16.9	3.0	N
4390-E(up)	Post-FMAG	4A	2.2	3.0	N
4392-W	Post-FMAG	4A	10.4	3.0	N
4392-E(dn)	Post-FMAG	7A	24.6	3.0	N
4392-E(up)	Post-FMAG	4A	10.1	3.0	N
4394-W	Post-FMAG	4A	2.2	3.0	N
4394-E(dn)	Post-FMAG	4A	16.9	3.0	N
4394-E(up)	Post-FMAG	4A	2.2	3.0	N
4411-E(dn)	Post-FMAG	4A	12.4	3.8	N
4411-E(up)	Post-FMAG	4A	0.0	3.0	N
4411-W	Post-FMAG	4A	0.0	3.0	N
4482-E(dn)	Post-FMAG	4A	16.4	3.8	N
4482-E(up)	Post-FMAG	4A	6.6	3.0	N
4482-W	Post-FMAG	4A	6.6	3.0	N
4502-E(dn)	Post-FMAG	4A	14.8	3.8	N
4502-E(up)	Post-FMAG	4A	7.7	3.0	N
4502-W	Post-FMAG	4A	7.7	3.0	N

Movable and Penetration Shielding

The downstream portion of Enclosure NM3 extends into the experimental hall NM4. The NM4 experimental hall contains the target cave and the additional shielding that surrounds it. This target cave area, or "target station", consists of a combination of steel and concrete shielding blocks and the primary beam absorber. The steel and concrete shielding blocks and absorber (Z=4362-4387), mitigate the prompt radiation dose from targeting beam to below 500 mrem/hr and are also credited controls. These 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 NM4 crane. The shielding for this area is defined in the shielding assessment and addendum[2][6]. The AC power disconnect switch for the NM4 crane is locked out and configuration controlled by the assigned RSO.

Penetrations along the NM beam line have been analyzed in the shielding assessments. The 2012 shielding assessment found that no penetrations were identified as exceeding the allowed dose rate limits. The 2019 shielding assessment reassessed penetrations impacted by reconfiguration for E1039 and found that the exit dose rates of all labyrinths and penetrations conform to guidance specified in FRCM. This situation remains unchanged under the new MCI analysis and dose rate limits stated above.

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 NM enclosures employ a Radiation Safety Interlock System (RSIS). The characteristics of the system are described in Section I of the Fermilab SAD. There are interlocked doors at all entrance points to N01/NM1, NM2 and NM3 enclosures. The interlock system inhibits transport of beam into the NM beam line except when the NM beam line is properly secured and locked.

The RSIS inhibits beam by controlling redundant critical devices. For this beam line, the two critical devices, V100 and MuLam, are used to inhibit beam from entering the NM beam line. V100 consists of two vertically bending dipole magnets, wired in series, and energized by a single power supply. The critical device controller is the contactor which energizes the magnets. Similarly, MuLam consists of three horizontally bending dipole magnets, wired in series, and energized by a single power supply. The critical device controller is the contactor which energizes the magnets. Disabling either of these devices will preclude delivery of beam to the NM beam line. Both V100 and MuLam are in the Switchyard Area upstream of the Neutrino Area beam lines. Compromising the radiation safety interlock system for N01/NM1, NM2, NM3, or NM4 or exceeding the trip setting of any interlocked chipmunks will disable the critical devices, thus preventing transport of primary beam into N01/NM1, NM2, and NM3. An interlocked repetition rate monitor, used to limit beam spill frequency and spill duration, will be in used during beam transport to the NM area. This repetition rate limiter is a credited control. For additional information on the repetition rate monitor, see the Switchyard SAD chapter.

The RSIS includes requirements for hardware and system testing, inventory of interlock keys and procedures for maintenance of interlock systems. The RSIS hardware enforces the Search and Secure and Controlled Access processes. The RSIS is designed, installed, and configuration managed in conformance with the requirements stated in the FRCM. The “search and secure” process consists of a thorough exploration of the enclosure to ensure that the NM RSIS area is not occupied. This process is completed by resetting the interlock boxes and a prescribed order in preparation for beam delivery. Trained and qualified personnel from the AD Operations Department are required to search and secure the enclosure before permits from the RSIS may be reestablished following any personnel access to the enclosure, except under strictly specified controlled access conditions.

As mentioned above, with the NM MCI having an intensity of 2.52E15 protons/hr, the amount of permanent shielding needed to keep an individual exposure below 500 mrem in an hour is 13.9, 11.4 and 16.3 e.f.d. depending on the beam line location and category. This is the shielding between the interior surface of the enclosure walls or buried beam pipe and the nearest areas accessible by any individual.

However, for the MCI, if there are areas along the NM beamline that do not have the required amounts of shielding, Interlocked radiation detectors are employed at those areas so that the same level of protection is provided and a dose to an individual standing in these areas will not receive a dose greater than 500 mrem in one hour. These radiation detectors are interlocked to the critical device controller (CDC), and if any one of them is absent from the CDC loop in the RSIS, beam cannot be transported to the NM beam line.

Interlocked radiation detectors are placed on the berm along the primary beamline and the experimental hall in those areas that are the most likely to be occupied at locations capable of detecting all accident conditions and are credited controls. They also serve to limit prompt dose to ensure compliance with 10CFR835 requirements. Interlocked radiation detector trip limits, for the radiation detectors on the berm, should be set at 500 mrem/hr or less. Chipmunk locations and trip level settings of radiation detectors interlocked to the RSIS must have concurrence from the assigned Radiation Safety Officer.

Interlocked radiation detectors are capable of disabling beam within a maximum of 3 seconds to the NM beam line, allowing only 1 pulse into the NM beamline in the event of an accident condition including initial detection of the event. This therefore limits the total number of protons delivered in an accident condition to 4.2×10^{13}. These interlocked radiation detectors will also protect transverse shielding loss points. Based on the MCI analysis the following interlocked radiation detector is a credited control[6]. While the NM3 and NM4 areas currently employ a total of 8 interlocked detectors, only the detector, shown in Table 4, on the NM3 berm is a credited control and needed to keep the dose to an individual below 500 mrem/hr. The other seven detectors are in place to ensure compliance with the occupancy and posting requirements outlined in the FRCM.

Table 3. Interlocked Radiation Detectors

Credited Control Device	Longitudinal and Transverse Location Protected	Location	Credited Control Limit (mrem/hour)
Chipmunk	4353 - 4368	NM3 Berm	< 500

Administrative Credited Controls

All NM 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 Document

Beam will not be transported to the Neutrino Muon beam line without an approved Beam Permit and Running Condition for the operating area. The Beam Permit specifies beam power limits as determined and approved by the AD Associate Laboratory Director, 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 NM beam line 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 Associate Laboratory Director.

Staffing

MCR must be appropriately staffed to ensure that a valid search and secure is performed for all enclosures, that all interlocked radiation detector trip limits are below the ASE limit and all beam losses stay under one hour in duration.

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: 2.75E15 protons/hr.

Defense-in-Depth Controls

Fermilab employs additional Defense in Depth (DD) controls to further reduce the possibility of an individual being exposed during an MCI. The NM beam line is located in an area in which members of the public are not invited, so that only badges employees have access to this area. Other DD controls in place are locked service buildings and radiological fences to keep individuals off the outside of the beam line berms.

Fencing and Posting

Fences are used and posted to designate potential Radiation Areas during machine operations. The NM Shielding Assessment concluded that the radiation levels that can be expected along the NM beam line require fences with a radiation area posting. The entire NM berm is fenced and posted consistent with its identification as a Radiation Area in accordance with the FRCM.

Training

All personnel engaged in the commissioning, operation, and emergency management of the NM beam line shall have at a minimum Fermilab's Radiological Worker Training, and Radiological Worker Practical Factors Training. Furthermore, personnel approved for access into the NM interlocked enclosures shall have Fermilab's Controlled Access training current as well.

Training in Fermilab's General or system specific Lock Out-Tag Out procedures shall be required to perform troubleshooting and maintenance as applicable.

Summary and Conclusion

Specific hazards associated with commissioning and operation of the Neutrino Areas and NM Beam Line enclosures are identified and assessed in this chapter of the Fermilab Safety Assessment Document. The designs, controls, and procedures to mitigate NM Beam Line specific hazards are identified and described. The Neutrino Areas and the NM Beam Line is subject to the global and more generic safety requirements, controls and procedures outlined in Section 1 of this Fermilab Safety Assessment Document.

The preceding discussion of the hazards presented by NM Beam Line operations and the credited controls established to mitigate those hazards demonstrate that the beam line can be operated in a manner that will produce minimal hazards to the health and safety of Fermilab workers, visiting scientists, and the public, as well as to the environment.

References

[1] Fermilab Radiological Control Manual
[2] Neutrino Muon Beam Line Shielding Assessment, February 2012.
[3] TeamCenter reference EN04847.
[4] G2 and NM1/N01 ODH Evaluation and Classification, B. DeGraff, January 2012.
[5] Fermilab Environment, Safety, and Health Manual
[6] C. Johnstone and I. Rakhno, Neutrino Muon Beamline Shielding Assessment Addendum for E1039, December 18, 2019.
[7] D. Christian, M Geelhoed, N. Mohkov, E906/SeaQuest MARS Simulation, Fermilab-TM-2479.