Neutrino Muon Beamline Shielding Assessment

Version 1.3

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1 Introduction

The Neutrino Muon (NM) beamline transports a 120 GeV/c proton beam from Switchyard to a beam absorber located at the downstream end of NM3. The beam absorber removes all primary particles and their products except for muons, neutrons, and neutrinos. A magnetic field sweeps muons horizontally, leaving only high-energy muons in the forward direction. Scattered neutrons are present in the background. Neutrino production is not considered. The experiment is located in NM4.

E906 (“SeaQuest”), the present occupant of the NM4 experimental hall, makes use of these high-energy muons to investigate Drell-Yan physics. Two cryogenic liquid (hydrogen and deuterium) and various solid (carbon, calcium, tungsten, iron) targets will be used. Their nuclear interaction lengths are 6.9%, 12.0%, 9.2%, 9.9%, 9.6%, and 11%, respectively. This shielding assessment supersedes the previous one for the NM beamline as done for E799/E832 (“KTeV”), however the majority of the beamline upstream of enclosure NM3 remains unchanged. The main modifications have been:

- Relocate the target station from NM2 to NM3
- Transport primary beam further downstream to new target station in NM3
- Relocate physical interface between NM3 and NM4

This Shielding Assessment follows the Incremental Shielding Assessment format[1]. Air and groundwater activation calculations, residual dose rate predictions, and dose rates associated with skyshine and muon production are included.

2 Assessment Boundaries

This assessment covers the NM beamline from extraction in Switchyard to the end of the SeaQuest experimental hall (approximate DUSAF Z = 920 to 4503). This includes enclosures C, Switchyard beam absorber, G1 stub, G2, N01/NM1, NM2, NM3, and NM4, as well as the buried beampipes connecting them.

With the exceptions of NM3 and NM4, all enclosures are made of concrete and are located underground. NM3 extends from DUSAF Z= 4113 to 4390, varies from 7 to 20 feet wide, and is 15 feet below grade. The last 30 feet of NM3 extends into the experimental hall and is formed by steel and concrete shielding blocks. NM4 (the experimental hall) extends from DUSAF Z= 4390 to 4503, is 40 feet wide, 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. All values are typical; refer to Radiation Safety drawings 9-8-6-12 C-1 through C-17 for details.

3 Assessment Parameters

This section describes the beam parameters used in the assessment.

3.1 Normal and Accident Conditions

Shielding for the NM beamline is evaluated for 120 GeV/c protons at 6.0×10^{14} per hour, which is derived as follows:

$$60 \frac{pulses}{hour} \times 1.0 \times 10^{13} \frac{protons}{pulse} = 6.0 \times 10^{14} \frac{protons}{hour}$$

This intensity limit is controlled through a Beam Permit, Running Condition, and an interlocked Repetition Rate Monitor (RRM). The maximum normal dose rate is calculated assuming 6.0×10^{14} protons per hour under nominal running conditions. The maximum accidental dose rate is calculated assuming 6.0×10^{14} protons per hour lost on a 15 cm radius, 90 cm long iron cylinder located arbitrarily along the beamline.

Under normal operating conditions 92-97% of the beam will be interacted on the experiment target. The remainder will be lost at various points along the beamline (see attachment 12) with no more than 1.5% occurring at a single location. This means that the accident condition determines the shielding requirements at all points along the beamline upstream of the target station.

3.2 Yearly Protons

The beamline is assessed at 100% duty factor, resulting in 5.256×10^{18} protons per year.

4 Shielding Requirements

Shielding requirements are calculated for 120 GeV/c protons at 1.0×10^{13} protons per pulse and 60 pulses per hour. The amount of shielding is scaled from standard categories ("Cossairt Categories") tabulated for 1000 GeV/c protons at 2.0×10^{13} protons per pulse and a 57 second cycle time. Shielding requirements are summarized in Attachment 1, "Neutrino Muon Scaling Shielding 03-23-11".

5 Longitudinal Shielding Summary

The first part of the beamline, from DUSAF Z= 920 to 4360, is underground. This part has some sections of minimal occupancy with no barriers or postings and other sections located behind four-foot high rigid barriers with locked gates that are posted as a Radiation Area.

The second part of the beamline, from DUSAF Z= 4360 to 4390, is located in a shielding-block cave inside the NM4 experimental hall. The interlocked doors of the enclosure are posted as a Radiation Area.

Attachment 2, "Neutrino Muon Longitudinal 12-20-11", lists the longitudinal ranges, enclosure types, required shielding and actual shielding for the primary and secondary sections of the beamline. Required shielding in secondary beamline areas where spreadsheet scaling laws are not applicable are indicated "N/A".

This spreadsheet indicates that adequate shielding exists along all longitudinal ranges of the beamline. Configuration control will be applied as necessary to prevent shielding from being inadvertently removed.

6 Transverse Shielding Summary

Attachment 3, "Neutrino Muon Transverse 12-20-11", lists the transverse (radial) stations, enclosure types, required shielding and actual shielding for the primary and secondary sections of the beamline. Required shielding in secondary beamline areas where spreadsheet scaling laws are not applicable are indicated "N/A". The transverse stations are designated by the associated enclosure (first three characters) and the DUSAF Z location (final 4 characters). An "E" or "W" suffix designates east or west sides of the beamline that have different requirements. Also, for every east transverse station adjacent to the counting house, there is a difference in the requirement that depends on elevation. Therefore, for every east station, there are two entries: one each for elevation above ("up") and below ("dn") the counting house roof.

This spreadsheet indicates that adequate shielding exists along all transverse stations of the beamline. Configuration control will be applied as necessary to prevent shielding from being inadvertently removed.

7 MARS Simulations

7.1 Overview

MARS15 simulates electromagnetic and hadronic showers, including processes such as gamma emission following neutron capture.

Attachment 4, "E906/SeaQuest MARS15 Simulation", predicts prompt and residual dose rates and source terms for air activation, neutron skyshine, and surface and ground water radionuclide concentrations during normal operation periods. It assumes proton beam intensity of 1.67×10^{11} protons per second, corresponding to 3.2 kW of average beam power. 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
- liquid deuterium target
- detailed model of steel and concrete shielding surrounding FMAG
- borated polyethylene surrounding the target gap
- concrete walls and floor of NM3 and NM4
- NM4 roof
- surrounding soil

Attachment 10, “E906 MARS15 Simulation: Beam Loss Scenarios”, uses the same elements as above and predicts prompt dose rates due to accidental losses at locations upstream of the beam absorber where forward shielding is at its weakest. Attachment 13, Temperature Rise due to Beam Energy in SeaQuest Magnet, provides an ANSYS thermal model of the absorber magnet that predicts the maximum temperature rise inside the beam absorber under full intensity operating conditions.

7.2 Neutron Skyshine

The NM4 experimental hall has a thinly shielded roof, thus an estimate of neutron skyshine is needed to ensure that dose rates at remote locations are sufficiently low. This is particularly important for public areas; the closest such area is Wilson Hall, which is located 1250 meters away. From Attachment 5, “Neutrino Muon (NM) Skyshine”, the point source on the roof is estimated at 10 mrem/hr and its effective area at 255 m^2. Assuming that neutron energy is 100 MeV, the attenuation length is 390 meters in air. Following the Patterson and Thomas formula for distances greater than 20 meters[2], the dose rates at varying distances from the source are all less than 1 mrem/hr as shown in Table 1.

Distance from source (m)	Dose rate (mrem/hr)
20	0.405
25	0.307
30	0.242
35	0.197
40	0.164
45	0.138
50	0.118
75	0.062
100	0.037
150	0.016
200	8.27E-03
250	4.73E-03

500	6.31E-04
750	1.48E-04
1000	4.37E-05
1200	1.82E-05
1500	5.39E-06
2000	8.42E-07

Table 1: Neutron Skyshine Dose Rates

7.3 FMag RAW Skid

The beam absorber for the beamline is at the downstream end of NM3. Attachment 6, "FMAG Cooling Water Activation Levels for the E906-SeaQuest", uses results from Attachment 4 and states that the activity level of the cooling system will require it to be classified as a Radioactive Water (RAW) system. The RAW system skid placement was chosen to be approximately 50 ft. upstream of the beam absorber so that component activation and residual dose rates to workers will be minimized. It is also placed at least 50 ft. from any labyrinths, penetrations, or sumps. The RAW system is monitored via the radiation safety interlock system for volume, pressure, temperature, and flow rate.

7.4 Prompt Dose Rates

The upstream sections of the NM beamline include multiple instrumentation devices that are estimated to have a collective beam loss of approximately 2.5%. In the event that the berm pipe between enclosures G2 and NM1 is filled with helium gas at 1 atm., an additional beam loss of 7.6% is estimated. Prompt dose rates for both estimates are assumed to be negligible due to the small fractional beam loss. For details, see Attachment 12, "Normal running loss estimates for the E906/SeaQuest beamline".

The target station and beam absorber in NM3 are known loss locations and Attachment 4 estimates prompt dose rates under normal running conditions. There are four points of interest associated with the known loss locations, so prompt dose rates are calculated at these four loss points and compared to FRCM Table 2-6, *Control of Accelerator/Beamline Areas for Prompt Radiation Under Normal Operating Conditions*[3]. Table 2 summarizes these dose rates.

Point	Location	Dose Rate (mrem/hr)	FRCM (mrem/hr)
A	Outside NM4 building at upstream end - Beam left	1.64	5 ≤DR≤100
B	Outside NM4 building at upstream end - Beam right	.092	.05 ≤DR≤.25
C	Inside NM4 building at Gas Shed - Beam left	.0092	.05 ≤DR≤.25
D	Outside NM4 building at roof – Beam center	10	5 ≤DR≤100

Table 2: Summarized Dose Rates around NM4 building with known loss point

In addition, prompt dose rates in the experimental hall for two possible accidental beam loss scenarios where forward shielding is weakest have been simulated (see Attachment 10). For a beam loss duration of 1 hour, the results indicate that potential dose rates could be as high as 100 mSv/hr (10 R/hr) within the fenced areas adjacent to the experimental hall and the limits of FRCM Table 2-7, *Control of Accelerator/Beamline Areas for Prompt Radiation Under Accident Conditions When It is Likely that the Maximum Dose Can Be Delivered*[3], might be exceeded.

Although FRCM Article 236.2(b)(1) states, "Accelerator/beamline areas shall be posted and controlled for the normal operation conditions in accordance with Table 2-6 when the safety analysis documents that delivering the maximum dose to an individual is unlikely", interlocked detectors will be used to limit dose rates to acceptable levels during these unlikely beam loss scenarios.

8 Labyrinths and Penetrations

The labyrinths and penetrations along the NM beamline are listed and described in Attachment 7, "Neutrino Muon Labs and Pens 02-13-12". No labyrinths or penetrations were identified as exceeding the allowed dose rate limits.

9 Air Activation Calculations

The beam transport system is under vacuum; therefore, we do not consider air activation along the beam line. In the target station region, the beam traverses a minimal air gap before interacting in the magnetized absorber. The air activation calculation uses the results of Attachment 4.

Table 3 summarizes expected dose rates due to airborne radionuclides as a function of time. Refer to Attachment 8, **"**Air activation Levels for the E906-SeaQuest Target Hall", for a detailed explanation. The expected rates will be verified with local air monitoring ("stack monitor") and the Accelerator Division Radiation Safety Officer will determine the required operational cool-off periods based on this data during commissioning.

As of this writing, leakage in the NM beam pipe has been problematic. In the event that vacuum cannot be maintained, the pipe between enclosures G2 and N01/NM1 may be temporarily filled with helium until the source of leakage can be identified and fixed. Beam interaction with the helium will produce tritium that has been estimated at 0.34 micro-Curies per month (see Attachment 11). This amount of tritium may be vented to atmosphere and it has been determined by the ES&H Section to be an insignificant addition to the overall integrated Fermilab yearly allowable site discharge.

Cool-off time [minutes]	Dose rate [mrem/hr]
0	7.38
30	1.89

60	0.67
120	0.12

Table 3: Predicted airborne dose rate as a function of cool-off time

10 Activated Air Release Points

Based on 5.256 x 10^{18} protons per year, E906 will release approximately 2 Curies (±30%) per Attachment 8. The natural air exchange rate in the NM4 experimental hall is assumed to be 6327 cfm (one experimental hall volume per hour) through the structure. The calculated 2 Curies is an acceptable addition to the lab's annual budget of activated air release. There are no designated air release points.

11 Ground and Surface Water Activation Calculations

Attachment 4 predicts the peak star density in soil surrounding the NM3 target station to be 100 stars per cubic centimeter per second. Dividing this by the primary beam rate (1.67 x 10^{11} protons per second) gives:

$$\text{Star}_{max} = 100\ \frac{stars}{cm^3\ second} / 1.67 \times 10^{11}\ \frac{protons}{second} = 5.99 \times 10^{-10}\ \frac{stars}{cm^3\ proton}$$

This production value is used as input to Attachment 9, “NM Groundwater – Surface Water 11-04-11”, the results of which are summarized in Table 4.

Description	Annual Concentration Limits (pCi/ml)		Annual Concentration Estimate (pCi/ml)		Percent of Total Limit
	H^3	Na^{22}	H^3	Na^{22}	$H^3 + Na^{22}$
Surface Water	1900	10	3.11E-1	2.76E-2	2.92E-03
Ground Water	20	0.4	3.11E-9	4.13E-12	1.66E-10

Table 4: Comparison of annually predicted H^3 and Na^{22} production to allowed levels.

In addition, potential ground and surface water activation along the section of buried beam pipe connecting the G2 and NM1 enclosures has been considered. Currently, due to its age and large volume, maintaining sufficient vacuum in this pipe to allow primary beam transport has been problematic. In the event that vacuum cannot be maintained at a level of less than 10 torr (mm-Hg), the feasibility of filling the pipe with helium gas for a one month interval has been investigated. Attachment 11, “Radiological Consequences of E906-SeaQuest Engineering Run with Helium filled beam pipe”, estimates that the surface water tritium concentration approaches 0.4% of the 1900 pCi/ml discharge limit, assuming that no dispersion occurs within the soil and that under-drain sump pumps operate once per day. Contamination of the groundwater due to this level of activation is insignificant.

Beam interaction with the helium in the beam pipe will also produce tritium, estimated at 0.34 micro-Curies per month. Assuming that this tritium is uniformly distributed through the soil, it would add the equivalent of 8.03E-11 stars/cc/proton to the star density, which is much smaller than the contribution of scattered beam interacting in the soil and results in a negligible effect on the groundwater (see Attachment 11).

12 Surface Water Discharge Points

The Neutrino Area sump pumps discharge water into surface ditches. Neutrino sump and retention pit concentrations are regularly sampled as part of the AD/Routine Monitoring Program, procedure ADDP-SH-1003.

13 Muon Production

In Attachment 4, muon production and the associated dose rates are addressed. The MARS15 simulation of the target station and beam absorber indicates that muons remain below grade level.

14 Residual Dose Rates

In Attachment 4, residual dose rates are estimated between 10 mrem/hr and 100 mrem/hr at three locations (NM3, NM3 target station, and NM4) after 30 days of running and one day of cool off. These and other potential residual radiation hazards will be handled operationally via radiological work control documents, such as Radiological Work Permits, as in all primary beam enclosures.

15 Intended Active Shielding Controls and Monitoring

15.1 Enclosure Interlocks

All NM beamline enclosures up to and including the experimental hall are interlocked to the Radiation Safety Interlock System (RSIS). This system is routinely tested and certified to turn off critical device(s) for the beamline within one second of detecting an out-of-range or absent input signal.

15.2 Repetition Rate Monitor

The spill rate to the NM beamline is controlled by a Repetition Rate Monitor (RRM) that is interlocked to the RSIS. This device currently inhibits beam extraction to the Switchyard enclosures if the extraction power supply VH94 is energized for more than four seconds in any sixty second period. Thus, beam cannot be transported to any of the Switchyard 120 experimental areas, including the NM beamline, at a frequency greater that once per minute.

The spill rate interval monitored by the RRM is set by the AD RSO and may change from this initial set point.

15.3 Radiation Detectors

Radiation detectors will be placed around the experimental hall at several locations, including those that are the most likely to be occupied. Trip levels of radiation detectors interlocked to the RSIS will be set by the Radiation Safety Officer to ensure compliance with FRCM requirements. Such detectors are capable of disabling beam within one second of exceeding a predetermined level.

16 Conclusions

We have analyzed the NM beamline shielding under normal and accident conditions. The analyses and calculations performed for prompt dose, skyshine, and activation of air, ground water, and surface water are all within FRCM requirements and the facility can be operated safety. Residual activation near the target station has also been predicted and dose to personnel in the area will be kept As Low As Reasonably Achievable (ALARA) via configuration and radiological work controls.

17 References

[1] W. Higgins & P. Kasper, "Incremental Shielding Assessment Methodology", (1997).

[2] D. Cossairt, "Radiation Physics for Personnel and Environmental Protection", FERMILAB-TM-1834, v10 (2009).

[3] *Fermilab Radiological Control Manual*, Chapter 2 (revised December 2011).

18 Attachments

1) "Neutrino Muon Scaling Shielding 03-23-11" spreadsheet
2) "Neutrino Muon Longitudinal 12-20-11" spreadsheet
3) "Neutrino Muon Transverse 12-20-11" spreadsheet
4) D. Christian, M. Geelhoed, N. Mohkov, "E906/SeaQuest MARS15 Simulation" FERMILAB-TM-2479
5) K. Vaziri, "Neutrino Muon (NM) Skyshine"
6) K. Vaziri, "FMAG Cooling Water Activation Levels for the E906-SeaQuest"
7) "Neutrino Muon Labs and Pens 02-13-12" spreadsheet
8) K. Vaziri, **"**Air activation Levels for the E906-SeaQuest Target Hall"
9) W. Schmitt, "NM Groundwater – Surface Water 11-04-11"
10) N. Mokhov, "E906 MARS15 Simulation: Beam Loss Scenarios"

11) K. Vaziri, “Radiological Consequences of E906-SeaQuest Engineering Run with Helium filled beam pipe”
12) M. Geelhoed, “Normal running loss estimates for the E906/SeaQuest beamline”
13) Zhijing Tang, “Temperature Rise due to Beam Energy in SeaQuest Magnet (2)”