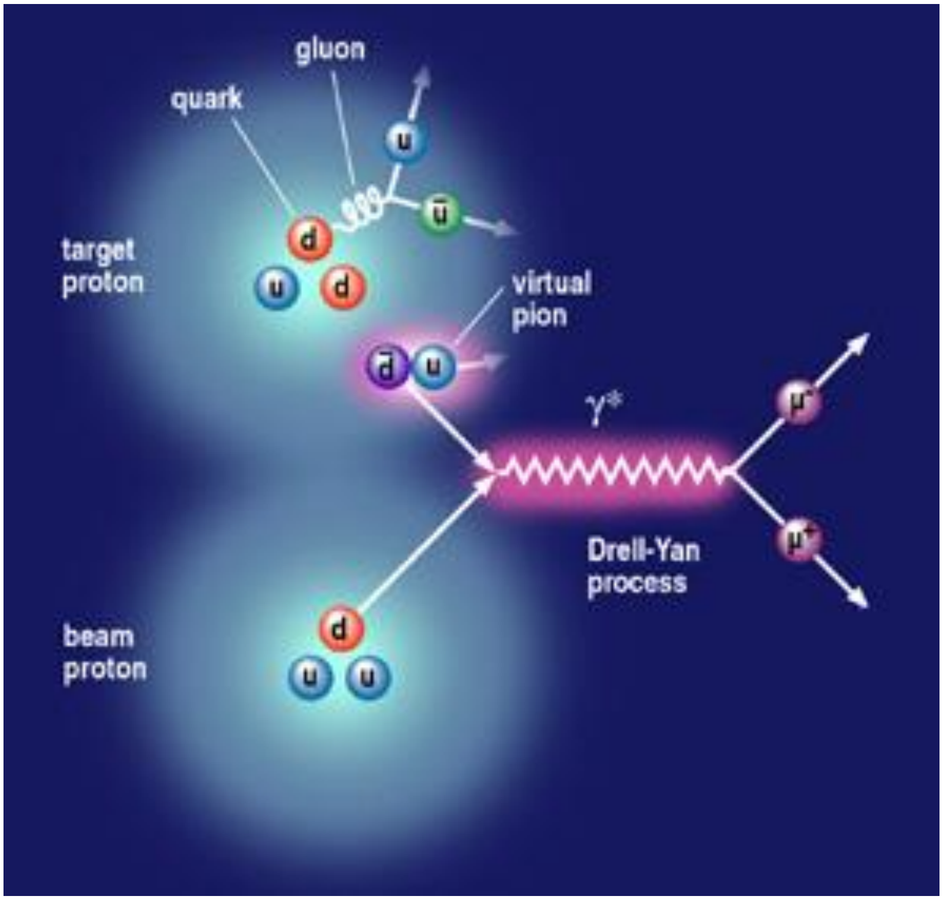
Neutrino Muon Beamline Shielding Assessment Addendum for E1039

Version 2.7

December 18, 2019

C. Johnstone and I. Rakhno

Edited by ES&H Section/RPS Department



Contents

1 Introduction

This document is an addendum to the Neutrino Muon (NM) Beamline Shielding Assessment [1] to accommodate a modified targeting and shielding configuration. The targets used by E906 ("SeaQuest") are replaced by a single liquid-helium-cooled solid ammonia target (6-7% nuclear interaction lengths) for E1039 ("SpinQuest") positioned just upstream of the E906 target location, approximately 300 cm from the front face of the beam absorber steel. Target changeout requirements and the new target location imply a complete redesign of the E906 target cave. Starting with the NM3 target wall (downstream of the target cave), shielding has been increased relative to E906. Further, cryogenic equipment must be located near the target atop the shielding, requiring both new penetrations and increased shielding to protect against neutron damage to solid state components.

The primary beamline from extraction in Switchyard (approximate DUSAF Z = 920) to the new collimator in NM3 (Z = 4353) remains unchanged and is thus not addressed in this addendum (see Figures 1 and 2).

This addendum follows the Incremental Shielding Assessment (ISA) format [2]. Ground and surface water activation calculations, air activation estimates, muon production, residual dose rate predictions, and dose rates associated with skyshine are included. Changes to all other radiological protection considerations, such as those concerning target/absorber cooling systems, are expected to be insignificant and are, therefore, not included.

2 Addendum Boundaries

This addendum covers the modified beamline in NM3 (from Z = 4353) to the end of the NM4 experimental hall (at Z = 4503).

NM3 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, although it 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. All values are typical; refer to Radiation Safety drawings 9-8-6-13 C-1 through C-14 (Attachment K) for details.

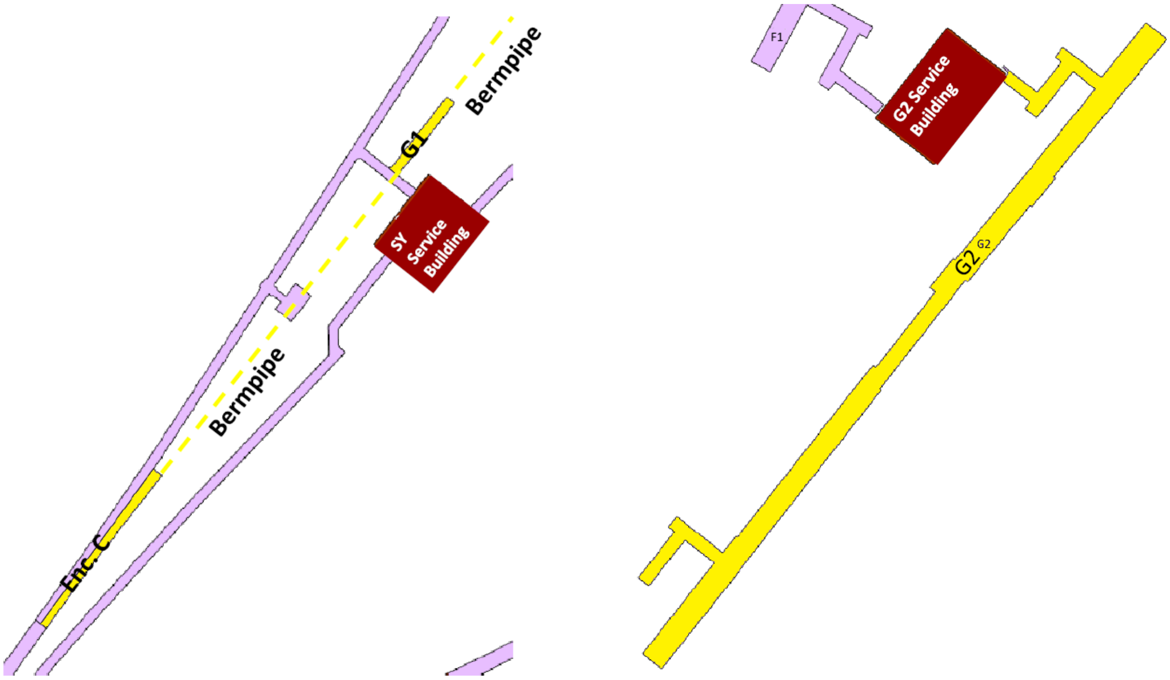


Figure 1: NM Switchyard enclosures C and G1 stub (left) and G2 stub (right) extend from DUSAF Z = 920 to 1708 (G1 end), and from 2070’ to 2420’ (G2 end), respectively. Enclosures are connected by berm pipes. The enclosures and connecting berm pipes shown in yellow ARE NOT PART OF THIS ADDENDUM AND ARE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

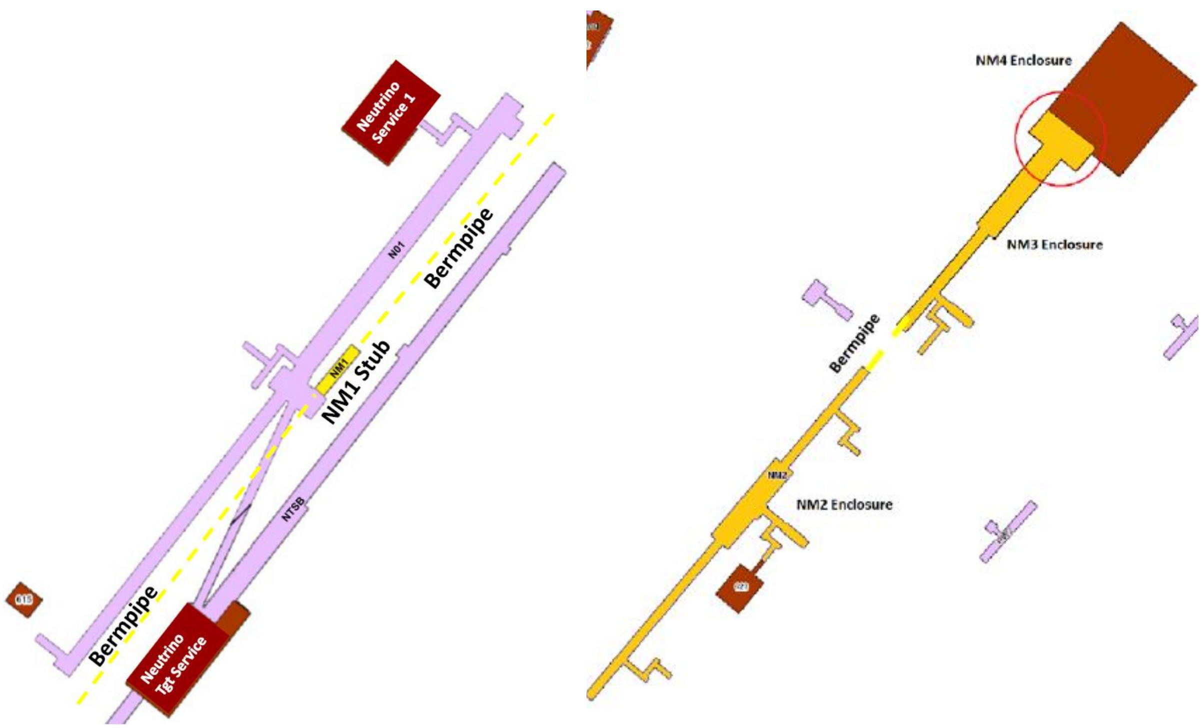


Figure 2: Enclosures NM1 (DUSAF Z = 3179 to 3216) through NM2 (3630 to 4020), NM3 (4113 to 4390), and NM4 Experimental Hall (4390 to 4503). <u>All targeting and shielding changes for E1039 are limited within the area circled in red</u>. The NM enclosures and berm pipes shown in yellow ARE NOT PART OF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

3 Assessment Parameters

This section describes the beam parameters used in this addendum. They are the same as those used for E906 and are reiterated here.

3.1 Normal and Accident Conditions

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

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

This intensity limit is controlled through a Beam Permit, Running Condition, and an interlocked Repetition Rate Monitor (RRM). Under normal operating conditions, ~92% of the beam is incident on the experimental target. The remainder is lost at various upstream points along the beamline, with no loss more than 1.5% occurring at a single location. The maximum normal operating dose rates are estimated using MARS and assume 1.67 x 10^{11} protons per second.

The shielding required under accident conditions (100% beam loss) assume 1.0 x 10^{13} protons per pulse lost on a magnet, a beam pipe in an enclosure, or a buried beam pipe and located arbitrarily along the beamline. An accident is assumed to last for one hour, unless its duration is limited by the use of interlocked detectors.

3.2 Yearly Protons

The beamline is assessed at the maximum, 100% duty factor, or 5.26 x 10^{18} protons per year.

4 Shielding Requirements

The revised shielding requirements are specified in *NM E1039 ISA Summary* (Attachment A) and, as above, are calculated for 120 GeV protons at 1.0 x 10^{13} protons per pulse and 60 pulses per hour (6.0 x 10^{14} 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 areas within the NM4 enclosure that are beyond the massive FMAG beam absorber (from Z = 4390 to 4503), no significant hadronic component of secondary beam remains and, therefore, ISA shielding requirements do not apply. Nevertheless, the secondary beam parameters (30 GeV; 10^{-5} yield) assumed for E906 are carried forward in this addendum for consistency.

Configuration control for moveable shielding will be applied as necessary to prevent its inadvertent removal.

5 Longitudinal Shielding Summary

Since there have been no changes in upstream areas for E1039, the longitudinal summary sheet within Attachment A lists 16 ranges from the fixed collimator assembly in NM3 to the end of NM4 with varying amounts of shielding.

This summary sheet indicates that adequate shielding exists for these longitudinal ranges describing the modified beamline, with one exception: at the most upstream secondary beam range in NM4 from Z = 4394 to 4454 with no overhead shielding at all. This exception is remediated by referring to more detailed simulation results, as described in Attachment B1.

6 Transverse Shielding Summary

Similarly, the transverse summary sheet within Attachment A lists 58 selected stations and summarizes the radial distribution of shielding that surrounds the modified beamline. The transverse stations are identified by their distances in feet along the beamline from a designated origin (“DUSAF”). An “E” or “W” suffix designates east or west sides of the beamline that have different requirements for occupancy. 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 such east station, there are two entries: one each for elevation above (“up”) and below (“dn”) the counting house roof.

This summary sheet indicates that adequate shielding exists at all transverse stations of the beamline, with these five exceptions: those at 4390-E(up), 4394-W, 4394-E(up), 4411-E(up), and 4411-W. These exceptions are remediated by referring to more detailed simulation results, as described in Attachments B2 through B6.

7 MARS Simulations

7.1 Overview

MARS [4] simulates electromagnetic and hadronic showers, including processes such as gamma emission following neutron capture.

Attachment C documents MARS calculations for prompt and residual dose rates and source terms for ground and surface water radionuclide concentrations during normal operations. It assumes a 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
- 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

7.2 Neutron Skyshine

The NM4 experimental hall has a thinly shielded roof, thus an estimate of neutron skyshine at various distances is desirable to ensure that dose rates at remote locations are sufficiently low. This is particularly important for nearby and potentially continuously occupied areas, such as the NM4 counting house.

An analysis for two areas (200 cm and 1200 cm downstream of the target) in the NM4 counting house are included in Attachment C and indicate a dose rate < 0.2 mrem/hour. For more remote areas, dose rates are expected to decrease as shown in Attachment 5 of the E906 assessment, “Neutrino Muon (NM) Skyshine”. In this case, the point source on the NM4 roof is estimated at 10 mrem/hour and its effective area is conservatively assumed to be 255 m^2 (i.e., 50% of the roof). It is additionally assumed that neutron energy is 100 MeV and the attenuation length is 390 meters in air. Following the standard methodology for distances greater than 20 meters [5], the dose rates at varying distances from the source are all less than 0.5 mrem/hour as shown in Table 1. Also shown is that skyshine dose rates at distances greater than 100 m are less than 0.05 mrem/hour, as required for public areas with continuous occupancy.

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 rate as a function of distance from NM4

7.3 Prompt Dose Rates

The target station and beam absorber in NM3 are known loss locations and Attachment C 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 points and compared to FRCM Table 2-6, *Control of Accelerator/Beamline Areas for Prompt Radiation Under Normal Operating Conditions* [6]. Table 2 and Figure 3 summarizes these dose rates and their location, which are all less than the maximum allowed by their current postings.

Point	Location	Dose Rate (mrem/hr)	FRCM (mrem/hr)
A	Outside NM4 building at upstream end - Beam left	1.0	5 ≤DR≤100
B	Outside NM4 building at upstream end - Beam right	0.1	.05 ≤DR≤.25
C	Inside NM4 building at Gas Shed - Beam right	0.2	.05 ≤DR≤.25
D	Outside NM4 building at roof – Beam center	1.0	5 ≤DR≤100

Table 2: Summarized dose rates at four points of interest around the NM4 building

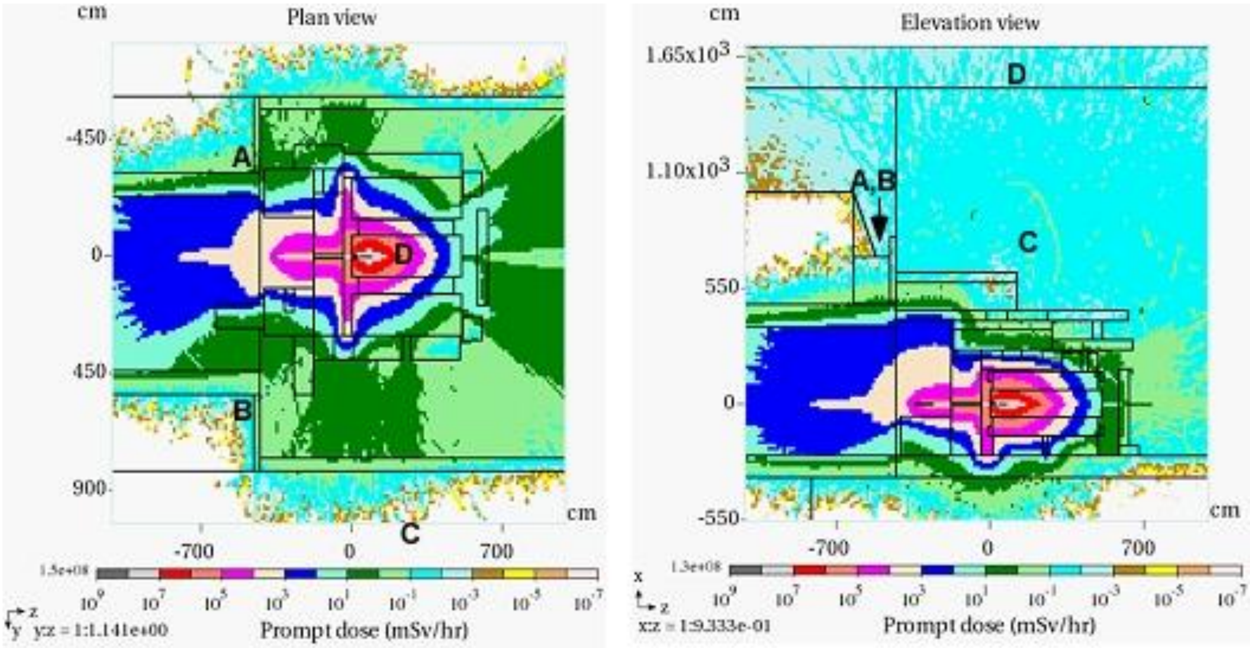


Figure 3: Plan and elevation view locations of points of interest from Table 2. Note that A, B, and C are at grade elevation and D is on the NM4 roof. Beam direction is from left to right.

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 (see Attachments D through I).

The labyrinth and penetration summary sheet within Attachment A indicates that the exit dose rates of all labyrinths and penetrations conform to guidance specified in FRCM.

9 Air Activation Calculations

Since the beam parameters and air exchange assumptions for E1039 are identical to those of E906 and the modified beamline traverses a very similar air gap before interacting with the magnetized absorber, a revised air activation analysis uses the same methodology.

Table 3 summarizes expected airborne activity levels as a function of decay time. Refer to Attachment 8 of the assessment, "Air activation Levels for the E906-SeaQuest Target Hall", for a more detailed explanation. Conservatively, this potentially implies that a 120 minute cool-off period may be imposed to keep personnel exposure below 10% of the Derived Air Concentration (DAC) values so that continuous air monitoring is not required. At the discretion of the assigned

Radiation Safety Officer, the expected levels may be verified with local air monitoring ("stack monitor") and the required operational cool-off periods based on this data during commissioning.

How long to wait before entering the area, after 1 month of irradiation								
DAC(pCi/ml)	2.000E+01	1.000E+01	2.400E+00	2.050E+00	2.700E+00	5.250E+00		
Access concentrations							Dose rate	
T_{wait}(min)	**H-3**	**Be7**	**Carbon11**	**Nitrogen13**	**Oxygen15**	**Argon41**	**(mrem/hr)**	**(mrem/week)**
0	2.69E-05	9.60E-04	1.46E+00	3.54E-01	2.33E-01	2.09E-02	16.86	674.3
5	2.69E-05	9.60E-04	1.23E+00	2.50E-01	4.23E-02	2.02E-02	12.67	507.0
10	2.69E-05	9.60E-04	1.04E+00	1.77E-01	7.70E-03	1.96E-02	10.18	407.3
15	2.69E-05	9.60E-04	8.76E-01	1.25E-01	1.40E-03	1.90E-02	8.34	333.6
20	2.69E-05	9.60E-04	7.40E-01	8.81E-02	2.55E-04	1.84E-02	6.88	275.2
30	2.69E-05	9.60E-04	5.28E-01	4.39E-02	8.44E-06	1.72E-02	4.74	189.6
45	2.69E-05	9.60E-04	3.18E-01	1.55E-02	5.09E-08	1.56E-02	2.77	110.8
60	2.69E-05	9.60E-04	1.91E-01	5.44E-03	3.06E-10	1.42E-02	1.65	66.0
90	2.69E-05	9.60E-04	6.93E-02	6.74E-04	1.11E-14	1.17E-02	0.61	24.4
120	2.69E-05	9.59E-04	2.51E-02	8.36E-05	4.03E-19	9.66E-03	0.24	9.6

Table 3: Airborne radionuclide activity levels (Ci) as a function of decay time and the dose rates in the E1039 experimental hall. DAC values are for a cloud of 4 m radius.

10 Ground and Surface Water Activation Calculations

Attachment C predicts the peak star density in soil surrounding the E1039 target station to be approximately 100 stars per cubic centimeter per second. This is the same as for E906. Dividing this by the maximum primary beam delivery rate averaged over an hour (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 J, *NM E1039 Groundwater – Surface Water*, the results of which are summarized in Table 4.

Description	Annual Concentration Limits (pCi/ml)		Annual Concentration Estimate (pCi/ml)		Fraction of Total Limit
	H^3	Na^{22}	H^3	Na^{22}	$H^3 + Na^{22}$
Surface Water	1900	10	3.11E-1	2.77E-2	2.93E-03
Ground Water	1	0.04	7.69E-8	5.26E-13	7.69E-08

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

Therefore, groundwater and surface water radionuclide productions for E1039 are expected to be insignificant.

11 Muon Production

A forward cone of energetic penetrating muons exists when a 120 GeV proton beam is absorbed in FMAG. Relativistic kinematics gives the result [5] that the maximum angle between the momentum vector of the muons and that of the parent particles (assumed to be pions) is approximately 22 mrad (1.26 degrees). The location at which these muons potentially penetrate the surface is approximately 305 m (1000 feet) downstream of NM4 and near the NM9 enclosure. Since the range of muons in soil at this energy is less than 250 m (820 feet) [5], muons will not penetrate the surface.

12 Residual Dose Rates

In Attachment C, residual dose rates are estimated between 10 mrem/hour and 100 mrem/hour 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.

13 Intended Active Shielding Controls and Monitoring

13.1 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.

13.2 Radiation Detectors

Radiation detectors will be placed around the experimental hall at several locations, including those that are the most likely to be occupied. Locations and 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. These detectors performed as required during E906 running.

14 Conclusions

The shielding for the modified NM beamline at and beyond the downstream end of the E1039 collimator in NM3 has been analyzed under normal and accident conditions. The analyses and calculations performed for prompt dose rates, skyshine, muon production, and activation of air, ground water, and surface water are all within FRCM requirements and the facility can be operated safely. 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.

15 References

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

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

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

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

[5] *Radiation Physics for Personnel and Environmental Protection*, FERMILAB-TM-1834, J.D. Cossairt, https://esh-docdbcert.fnal.gov/cgi-bin/cert/ShowDocument?docid=1007

[6] *Fermilab Radiological Control Manual* (*FRCM*), http://eshq.fnal.gov/manuals/fcm/

16 Attachments

A. *NM E1039 ISA Summary* 112019

B. 1. LPH2-NMS001
   2. XPH2-NMS001
   3. XPH2-NMS002
   4. XPH2-NMP003
   5. XPH2-NMS004
   6. XPH2-NMS005

C. *Radiation Shielding Calculations for E1039 Spinquest Experiment*, FERMILAB-TM-2674-AD-APC, C. Johnstone and I. Rakhno, December 2, 2019

D. PWKS-NM57 Sight Riser Penetration SR6

E. PWKS-NM58 NM4 Water Pipes to Gas Shed Penetrations

F. PWKS-NM59 NM4 Underfloor Cable Penetrations

G. PWKS-NM60 NM4 West Stairwell Labyrinth

H. PWKS-NM61 NM4 Upstream East Stairwell Labyrinth

I. PWKS-NM62 NM4 Downstream East Stairwell Labyrinth

J. *NM E1039 Groundwater – Surface Water 052418*, W. Schmitt, May 24, 2018

K. Radiation Safety Drawings 9-8-6-13 v5