5 RADIATION SAFETY[1]

5.5 Introduction

Chapter 4 of this Handbook presented technical designs for each of the subsystems required to produce the neutrino beam for the NuMI physics program. Inherent in the designs is the fact that radiation protection is of the greatest importance in both primary and secondary beam areas. The purpose of this chapter is to present the various radiation-related matters, to explain the methodology that has guided the designs of the radiation protection systems in the project and to show the results.

The design of the Fermilab Main Injector (MI) permits the acceleration of numbers of protons not previously encountered in the energy regime above 100 GeV. The NuMI Facility design assumes that Main Injector protons will be transported to the target at a maximum intensity of 4×10^{13} protons every 1.87 seconds. This is called the Safety Envelope. Normal running will be allowed up to 10% less than this safety envelope. Physics goals of the MINOS experiment assume a value for beam on target of 3.7×10^{20} protons per year. For the purposes of designing radiation protection for the NuMI Facility, the above intensities translate to a maximum instantaneous proton rate of 2.1×10^{13} protons per second and an annual "dc" average (assuming 55% efficiency for beam) of $\sim1\times10^{13}$ protons per second.

As discussed in Chapter 4, an important consideration in the design of the NuMI Facility has been the desire to maintain the flexibility to accommodate a variety of neutrino beam configurations. This flexibility includes designing a Target Hall in which the location of the beam line components such as the target and the focusing horns may vary depending on the desired range of neutrino energy. Maintaining this flexibility has an impact on the design of the radiation shielding because of the desire to minimize the need to reconfigure the Target Hall shielding after the facility has begun operation.

There are four types of radiation that are of concern in the design of a facility such as NuMI. These are 1) the prompt radiation field, 2) the residual radiation field, 3) airborne activation and 4) soil/rock and groundwater activation. All these will be discussed. We have also included a section on Decontamination and Decommissioning (D&D).

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[1] The approved NuMI/MINOS SA can be found on the web; it contains the most up to date information on radiation safety. Contact Nancy Grossman for access to this password protected document.

The program MARS[2] has been adopted as the Fermilab standard shielding code. Thus the design of the NuMI shielding is based on the use of the MARS simulation code. The "output" of the MARS program can be converted to activation level or, dose equivalents, used to determine the probability of radionuclide production in the air, soil or rock in which the nuclear interactions occur. These doses can then be compared to the various regulatory limits for each type of radiation exposure.

Evaluation of the radiation protection requirements for the NuMI facility has shown that various radiation safety factors drive the design of the facility. The design of the shielding for the target/focusing region (except the top), decay region, and two sides of the Hadron Absorber are driven by groundwater activation. Residual activation levels drive the shielding on top of the target/focusing region, and two sides of the Hadron Absorber. The level of primary beamline losses allowed are driven by groundwater or residual dose rate concerns, depending on the region of the primary beam. The air within the target chase is highly activated and thus must be contained in the target chase to the extent possible. This drives some design issues with the target chase shielding. Similarly the air in the region of the Hadron Absorber is highly activated and must be minimized and allowed to decay in transit to the vent.

Figure 5-1 shows a conceptual drawing of the NuMI Project. Radiation safety items are shown such as interlocked gates and doors, air monitoring locations, and labyrinths and penetrations. Refer to this picture when locating items described in the text.

[2] N. V. Mokhov, “The MARS Code System User’s Guide”,Fermilab-FN-628 (1995); Update Version 13(98), February, 1998

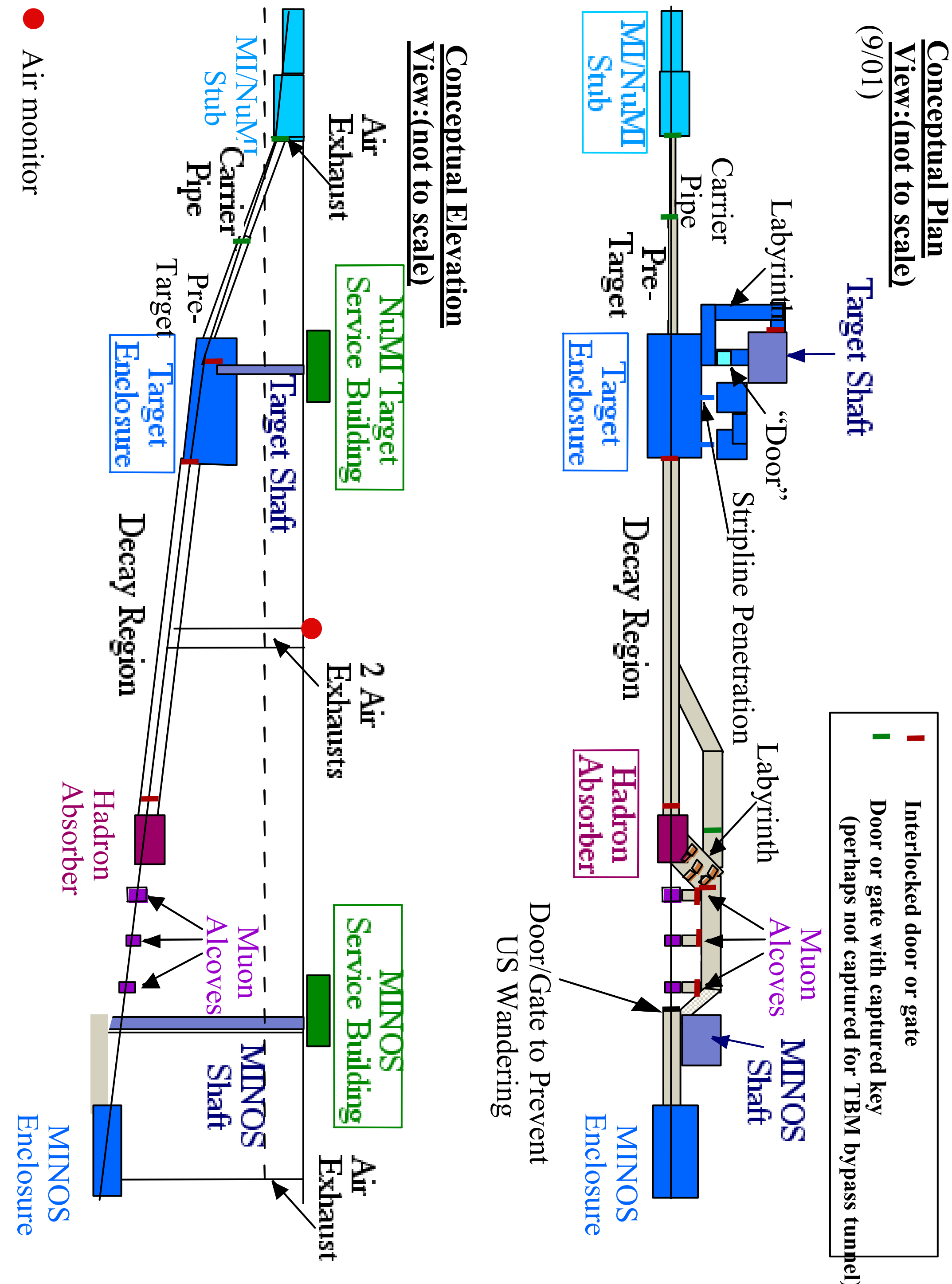

Figure 5-1 Conceptual Drawing of the NuMI Project, showing Radiation Safety Items

5.2 Access Requirements and Interlocks

The personnel safety interlock system is fail safe and redundant. The primary critical device for NuMI will be the Lambertson string (LAM601, LAM6023) located in MI-60. The secondary critical device will be the set of bend magnets HV102. (**Need MARS runs of this.)**

The personnel safety interlock system will "request" the abort signal required to stop NuMI extraction, in those situations when a radiation or critical equipment protection limit has been exceeded. The interlocks for the portions of the NuMI facility in the MI enclosure, NuMI Stub Enclosure, and lined section of the carrier tunnel will be an integral part of the MI interlocks system.

The NuMI safety interlock system will prevent personnel access, when the beam is enabled, to the Carrier Tunnel unlined section, Pretarget and Target Hall area, decay pipe tunnel, Hadron Absorber area and muon alcoves. There will also be interlocked detectors that will disable the beam if the radiation levels become too high in the power supply room, upstream shaft area and bypass tunnel.

5.3 Groundwater

Groundwater activation and contamination can occur when radionuclides produced in the soil or rock surrounding an accelerator or beam line enclosure have a finite probability of getting into water passing through the soil or rock. Groundwater activation also can occur when the beam produces radionuclides, namely tritium, directly in the water contained in the soil or rock. This activated water can then migrate to a potential source of potable water.

The NuMI primary proton beam, and the secondary hadron beam, must be directed toward the MINOS far detector in Soudan, implying a 58 mradian downward slope. As a consequence the Target Hall and much of the hadron decay region pass through the local aquifer. This has led to careful consideration and analysis of the processes that might lead to potential contamination of the groundwater resources. The key issue for NuMI is that radionuclides produced in the rock and water surrounding part of the beam line are produced in the groundwater resource. Thus we cannot take credit for decay in transit to the groundwater resource, as other facilities not constructed so deeply have. Several analyses and designs[3,4,5] laid the groundwork for the present model, which has resulted in the understanding of the problem. A Fermilab TM describing this methodology has been completed and is being circulated for approval. It takes into consideration the flow rate of water within the aquifer. Previous methodologies assumed static water conditions, which is extremely unrealistic within the aquifer. In the unlined sections of the NuMI tunnel, all the water nearby is captured by the tunnel and thus cannot make it to a well for consumption.

5.5.1 Specifications

Table 5-1 gives the limits on the concentrations of ^{22}Na and ^{3}H allowed.

	^{22}Na (pCi/ml)	^{3}H (pCi/ml)
Groundwater	0.4	20
Surface Water	10	2000

Table 5-1 Regulatory limits on allowed radionuclide concentrations in groundwater and surface water.

The sum of the fractions of radionuclide contamination (relative to the regulatory limits) must be less than one for all radionuclides;

$$\sum_i \frac{C_i}{C_{reg\ i}} \leq 1$$

where the sum is over radionuclides, i, C_i is the concentration of radionuclide *i* in the water and $C_{reg\ i}$ is the regulatory limit concentration.

Fermilab ES&H policy requires that a facility design must demonstrate that beamline operation will *not* result in activation levels above the regulatory limits, including all uncertainties in the methodology and input parameters. Verification that such limits are not violated is accomplished during the facility operation through the Lab-wide monitoring program (FESHM).

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3 A.Wehman, S. Childress, "Tritium Production in the Dolomitic Rock Adjacent to NuMI Beam Tunnels", Draft (1998) NuMI-B-495A(1999)

4 B. Freeman, "A NUMI Wide-Band Beam Shield Design That Meets the Concentration Model Groundwater Criteria, NuMI-B-155, June 13, 1995.

5 A. Wehmann,et.al.,"Groundwater Protection for the NuMI Project, FERMILAB-TM-2009, October 10, 1997.

5.5.2 Primary Beam Region

The primary beam region is separated into seven different sections based on the geology and geometry of the sections. Both geometry and geology affect the water flow rates. **Figure 5-2** shows the seven sections. The sections of main concern are the lined sections 1 and 2.

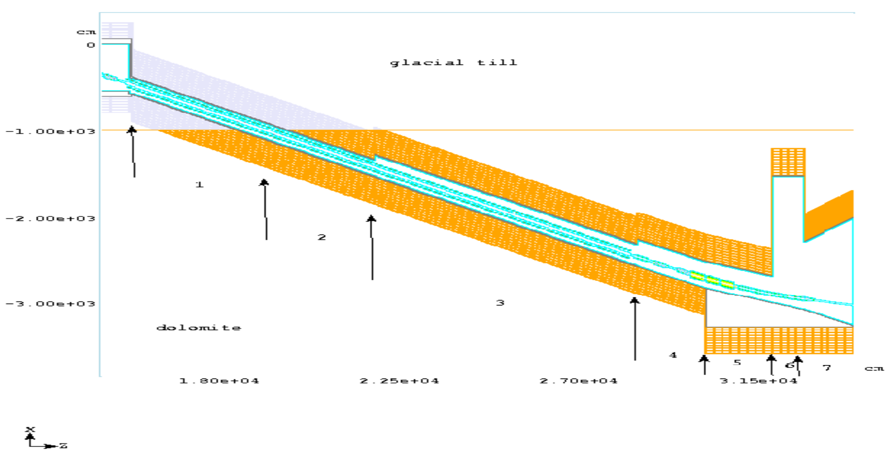

Figure 5-2: Seven Groundwater Sections of the NuMI Primary Beam

Section 1, the glacial till region, is not in the aquifer and the water travels slowly (cm/yr) through the soil to the aquifer. Thus much of the radioactivity has decayed by the time the water reaches the aquifer. Section 2, where the tunnel is lined, in the aquifer and in the mixed rock glacial till, is the area of the utmost concern. Here predicting the water velocity is difficult due to the variable nature of the geology in this region. We conservatively assume the water flows with the regional gradient towards the Fox River. This velocity (4 to 50 feet per year) is slow enough to allow activation of the water near the tunnel. The remaining sections (3 through 7) are unlined and have high water inflow velocities (several hundred feet per year), thus not allowing the water to get very activated and not allowing the water to get to a well. In all cases the inflow rates assumed in the calculations is below that measured in May 2002.

One should also note that the unlined tunnel downstream collects a large amount of water from the critical section 2. This is because two drainpipes were installed under the lined carrier tunnel. These two pipes extend ~50 feet and 6 feet respectively from the unlined section upstream into the lined section. They collect water in this region at a rate of **~5 gpm** (update value) as of March 2002. The groundwater activation calculation conservatively assumes the tunnel collects none of the water in section 2.

Table 5-2 shows the calculated residency time of the water in each of the 7 sections, based on conservative (slow) flow rates. The last two columns show the number of accident pulses allowed in each section, and the accident condition that can cause such an accident pulse. These results are all based on comparison to the groundwater limit. This table is being updated for the new beam optics. It is envisioned that the results will not change significantly. The region of most concern, as expected, is region 2. The final column in the table shows that power supply regulation is very important. (See Section 4.3.1). In order to have stable, controllable beam, the power supplies will be regulated at least an order of magnitude below that which is shown to create these accident conditions.

The radiation safety system will have interlocked detectors to watch losses in the primary beam. If excessive losses are seen, it will trip the critical devices and remove the beam permit. Also the beam permit system will check the power supply current at flattop before each pulse, losses on the last pulse and many other status items. The permit system will not allow extraction if anything is not within tolerance (See Section 4.1). All of this will make the occurrence of more than one accident pulse very unlikely.

Region	Water residency time (years)	Water residency time (days)	Lost pulses allowed in residency time	Accident Condition
1. Lined Carrier Pipe GT Accident	8.00000	2920.00	4.E+11	V105, 0.6%
2. Lined Carrier Pipe (Interface) Accident	1.50919	550.85	125	V104-2, 30%
3. Unlined Carrier Pipe Accident	0.00487	1.78	204	V104-2, 13%
4. Pre Target Accident (US)	0.01082	3.95	178	V105, 0.2%
5. Pre Target Accident (Mid)	0.01821	6.65	656	V105, 0.2%
6. Pre Target Accident (Shaft)	0.04618	16.86	5799	V105, 0.2%
7. Pre Target Accident (DS)	0.04028	14.70	16693	V105, 0.2%

Table 5-2 Primary Beam Accident Conditions and Lost Pulses Allowed

Due to all the mitigating factors for accident pulses, the DC or normal operational losses are of the biggest concern. These are the continually occurring losses that one can run with while still meeting all the regulatory requirements and not overly irradiating the components that personnel need to access. These are estimated using MARS, to be at a level of 10^{-4} of 4E13ppp (at 1.87 sec per pulse) for all regions, but region 2 where it is 10^{-6}. MARS simulations show that with the required power supply regulation no beam normal beam losses should occur, assuming 500π beam at $1x10^{-3}\Delta p/p$. As described in Section 4.1,the NuMI beam optics is designed to accept the largest beam the MI can provide.

5.5.3 Secondary Beam Region

Similar to the primary beam, the secondary beam is broken down into 5 different regions. Table 5-3 shows the estimated star densities from MARS simulations of the secondary beam components and shielding, and the resulting estimates of activation of the water flowing into the tunnel relative to the groundwater regulatory limit. **Figure 5-3** shows the activation levels of the inflow waters relative to the groundwater regulatory limits, including uncertainties. In all areas we are below the groundwater regulatory limit, including uncertainties.

Region	Star Density (stars per cm3/p)	Star Density Limit (stars/cm3/p)	Average Value Relative to Limit (% Uncertainty)
Target Hall	1.33E-11	4.10E-11	0.185 (75%)
DK Middle Silurian	4.58E-11	6.80E-11	0.402 (66%)
DK Lower Silurian	2.02E-11	4.80E-11	0.258 (64%)
DK Upper Ordovician	1.23E-11	5.40E-11	0.142 (61%)
Hadron Absorber	7.8e-12	4.7e-11	0.101 (64%)

Table 5-3: Secondary Beam Star Densities and Estimated Activation Levels

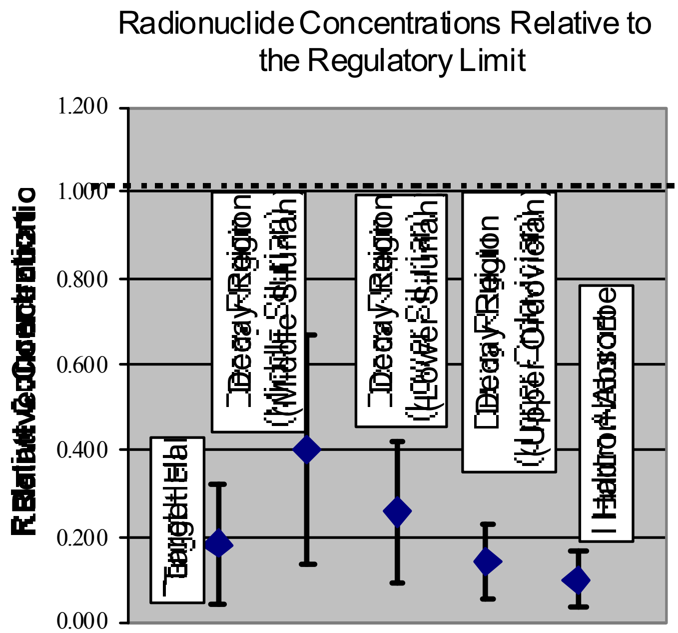

Figure 5-3: Secondary Beam Groundwater Inflow Activation Levels Relative to Regularity Limits

5.3.4 Monitoring

Operation of the NuMI Facility will be included in the comprehensive laboratory-monitoring program. Wells are an integral part of the Fermilab environmental monitoring strategy. Samples of well water would initially be examined every month, with the sampling rate eventually being reduced once NuMI has reached steady-state operation. NuMI, in collaboration with the ES&H Section, is in the process of determining the number and locations of NuMI monitoring wells.

In addition, regular sampling will be done on the water that is pumped from the NuMI downstream shaft region to the surface waters. Regular sampling will also be done for radionuclide levels in cooling water systems, including both the closed loop RAW system serving components experiencing higher activation levels, and the **LCW cooling system** serving conventional beam transport elements. RAW spills are controlled by a combination of continuous water level sensing, secondary containment vessel collection and tightly controlled sump discharge.

5.4 Airborne Activation

Airborne activation results from the interaction of primary and secondary particles directly with target nuclei of the air (or other gaseous medium) in its path. A secondary source of airborne activity is dust, formed by natural erosion or wear or by work on radioactive accelerator components. The third source of airborne radioactivity results from the emission of gaseous radioactivity from liquids irradiated in the accelerator produced radiation environment. For NuMI, the main concern is radioactive air. Activities in radioactive air consist primarily of ^{11}C and ^{13}N with smaller concentrations of ^{15}O and ^{41}Ar; all with relatively short half-lives. ^{11}C, having a 20 minutes half-life, tends to be the dominant concern.

5.5.4 Specifications

Federal regulations, which are further implemented by the State of Illinois, govern the releases of airborne radionuclides, excluding radon and radon progeny, by U. S. Department of Energy Facilities (CFR89)[6]. These regulations place an annual limit of 10 mrem/year on the dose equivalent that can be delivered to a member of the public due to the release of airborne radionuclides from DOE facilities. The methodology for determining the dose equivalent is also specified. The regulations further require the application of continuous monitoring in accordance with U. S. Environmental Protection Agency specifications if the dose equivalent should exceed 0.1 mrem/year. Requirements for monitoring systems that meet these specifications are quite stringent and could tightly constrain Fermilab operations. These limits apply to the total release from the Laboratory.

Consistent with these requirements, in March 1999, Fermilab submitted an application renewal to the Illinois Environmental Protection Agency for its lifetime air pollution-operating permit[7]. This application addressed the radionuclide emissions from NuMI and other Fermilab facilities. It specified that the doses to the public will be kept well below 0.1 mrem/year for all Fermilab operations. The average annual activity release is to be kept less than 100 Ci. In consideration of the overall program of operations at Fermilab, the NuMI project management in consultation with the staff of the Fermilab ES&H Section established an administrative goal for the NuMI project of a maximum annual release of 45 Ci. The corresponding maximum anticipated dose equivalent due to NuMI operations that might be received by an individual hypothetically present full-time at the Fermilab site boundary is estimated to be 0.025 mrem.

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[6] Dagenais (Da84) has provided estimates of the buildup of radon in tunnels made of the rock found at the level of the NuMI facilities on the Fermilab site. These results, including worst-case estimates, indicate occupational exposure to radon and radon progeny under the ventilation conditions present in the NuMI facility to be unimportant compared to the applicable regulatory limits of (CFR93).

[7] In response to this application, Illinois Environmental Protection Agency permit was issued on June 16, 1999.

5.4.2 Air Activation Results for NuMI

Delayed ventilation is used at NuMI to control radioactive air emissions. It is the simplest method and the one historically used at Fermilab. Since the vast majority of the radioactive atoms produced are short lived (20.5 minutes for ^{11}C), a delay time of one hour from production to exhaust will reduce the radioactivity by roughly one order of magnitude at the stack. Since the sealed chase inside the Target Hall is the main source of air activation, the largest delay is from the Target Hall to the vent part way down the Decay Tunnel. The area between the Hadron Absorber and the decay pipe also has high air activation levels. We are in the process of more accurately estimating these levels and determining the best ways to mitigate them. Most likely we will significantly reduce the airflow rate from the Hadron Absorber to the vent and build an aluminum box to contain the air just downstream of the decay pipe. Details of the air activation methodology and its application to NuMI are covered in TM-2089, and draft documents on the updated air activation methodology.

	Ventilation Rate (cfm)	Yearly Release 1% ^{41}Ar (Ci/yr)	Yearly Release 2.5% ^{41}Ar (Ci/yr)
Carrier Tunnel	1000	To be determined	1
Pre-Target Hall	900	To be determined	1
Target Hall	800 (700 leakage rate from chase)	To be determined	40
Upstream 1/2 Decay Region	800	To be determined	0.01
Downstream 1/2 Decay Region	3500	To be determined	0.01
Hadron Absorber	2250 (200 leakage rate from core/aluminum box)	To be determined	Being calculated

Table 5-4 Summary of air emission calculations at NuMI stacks. Note that the ventilation rate in the pre-target area can be reduced if necessary.

5.5 Prompt Radiation

The prompt radiation field at particle accelerators and beam lines exists only while they are in operation. Depending on the configuration of the facility and its components, the prompt radiation fields may include thermal neutrons, fast neutrons, photons and/or muons.

The prompt radiation field must be predicted and mitigated for both normal operations and accident conditions. There are two areas of concern; the radiation field outside of enclosures, which are normally embedded and/or covered by bulk shielding comprised of rock and/or soil, and the "leakage" of radiation through labyrinths and penetrations. For the former it is appropriate to use the results, which have been well established by the simulations done for a relevant set of case studies. These results are documented[8,9] and accepted for use in the design of bulk shielding at Fermilab.

Since most of the NuMI Facility lies deep underground, there are only a few areas where the issue of prompt radiation from NuMI operations must be considered. These areas are the MI/NuMI Stub, power supply room/upstream shaft area and bypass tunnel (see **Figure 5-1**). Interlocks and interlocked detectors will be used in some of these areas. There is also the issue of prompt radiation from the MI in areas where NuMI wishes to have access when NuMI is not operating, but the MI is operating. This includes the unlined section of the Carrier Tunnel and downstream.

5.5.1 Primary Beam

MI/NuMI Stub: In particular, this includes the regions of the Main Injector where the NuMI extraction devices are located, also the NuMI Extraction Stub (Figure A). The design goal is to have the surface areas above all Main Injector related beams be classified as Unlimited Occupancy. The applicable criterion applied to the MI indicates the need for 24.5 feet of soil equivalent over most of the enclosure and 25 feet over extraction regions, with stairways, cable penetrations etc. being treated separately. The as-built drawing which includes the MI-60 extraction region and the NuMI Stub[10] shows that the stated shielding criteria (24.5 and 25 feet) have been satisfied.

[8] A. Van Ginneken and M. Awschalom, "High Energy Particle Interactions in Large targets", Fermilab, 1975, (available from the Publication's Office).

[9] J. D. Cossairt, "A Collection of Casim Calculations", TM-1140, October 22, 1982.

[10] Radiation Safety 9667-C7

Table 5-5 shows the various penetrations and labyrinths in the primary beam region, their dose rates at the exit under normal and accident conditions and the mitigation that will be used. Accident pulses will normally be limited to one pulse due to the beam permit system or radiation safety system detecting the accident condition. Thus the column to look at for the accident condition is the dose rate/pulse. All of these areas have sufficiently low dose rates for their locations.

Access	Normal (mrem/hr)	Accident (mrem/hr)	Accident (mrem/pulse)	Mitigation
Survey Riser SR-1 (498)	1.48	14765.41	7.79	plug
Exhaust Air Vent EAV-1 (935)	0.29	2852.87	1.51	fence
Survey Riser SR-2 (954)	0.29	2852.87	1.51	plug
Target Hall Labyrinth	2.44E-03	24.37	0.013	OK
Target Hall Equipment Door	0.25	2476.83	1.31	OK

Table 5-5: Primary Beam Labyrinth and Penetration Calculations

5.5.5 Secondary Beam

In the secondary beam, two areas will have beam on access. These areas are the power supply room and upstream shaft area adjacent to the Target Hall. The design goal is to have these areas be Controlled Areas. **Table 5-6** shows anticipated levels in these areas due to the transmission line penetration, labyrinth and the equipment door. Two interlocked detectors will be located in this region, one in the Power Supply Room and one in the shaft area.

Access	Normal (mrem/hr)	Accident (mrem/hr)	Accident (mrem/pulse)	Mitigation (possible)
Target Hall Labyrinth	1.36E-03	-	-	OK
Target Hall Equipment Door	0.74	-	-	OK

Stripline Penetration (PS Room)	2.77	-	-	(shield)
Raw Penetration	60.80	-	-	plug
Survey Riser SR-3 (1321)	0.002	-	-	plug

Table 5-6: Secondary Beam Labyrinth and Penetration Dose Rates

Dose rates at the exit of the Hadron Absorber labyrinth are estimated at 7 mrem/hr beam on. Dose rates in the bypass tunnel are estimated at less than 0.05 mrem/hr. When beam is first commissioned at lower intensities, these values will be checked with radiation monitors.

5.6 Residual Dose Rates

The residual radiation field is that which remains after the beam has been shut down. In most situations at Fermilab, the residual radiation field is almost exclusively gamma rays, with the occasional presence of beta rays near a contaminated surface.

Location	Dose Rate (on contact)
Target Hall: concrete floor of work area	< 1 mrem/hr
Target Hall: Top of T-Block (horn 1)	~ 5 mrem/hr
Target Hall: Bottom of concrete "cap"	~ 2 mrem/hr
Target Hall: near work cell	~ 1 mrem/hr
Target Hall: near air handling equipment	~1 mrem/hr
Target Hall: DS horn baffle (old result)	25 rem/hr
Target Hall: bottom of T-Blocks above horn 1 (average)	100 rem/hr
Target Hall: inside cave walls around horn 1	80 rem/hr
Target Hall: horn 1 outer conductor	600 rem/hr
Target Hall: target	6000 rem/hr
Target Hall: upstream wall	~2 mrem/hr
Decay Region: outside edge of concrete	~100 mrem/hr
Decay Region: emergency egress (rock & conc)	~100 mrem/hr
Decay Region: upstream window	5 rem/hr
Decay Region: downstream window	700 mrem/hr
Decay Region: decay pipe	30-200 rem/hr
Hadron Absorber: Core Near Beam	~100's rem/hr
Hadron Absorber: Core Sides	~ 10's rem/hr
Hadron Absorber: Steel Blocks	~1's rem/hr
Hadron Absorber: Front	~ 1's rem/hr
Hadron Absorber: Labyrinth Side	~100 mrem/hr
Hadron Absorber: Non-Labyrinth Side	
Hadron Absorber: Top	
Hadron Absorber: Back	< 30 mrem/hr

Table 5-7: Estimated Residual Dose Rates for Various Beamline Elements

Table 5-7 shows the estimated residual dose rates for various beamline elements. Blank cells are in the process of being estimated. Underlined numbers are being updated.

5.7 RAW Water Systems

Here we describe the results of the calculation of the induced activity in the NuMI Radioactive Water (RAW) Systems. The interaction between the ionizing radiation and water leads to the formation of short-lived radical species (OH, H and electrons mainly) and stable molecular species (O_2, H_2O_2 and H_2). While most of the ions recombine to form water, hydrogen gas and other species are also produced. The amount of hydrogen gas produced is calculated to assess the level of safety precautions required.

The most significant radioisotopes, from a contaminant aspect are ^3H, and to a lesser extent ^7Be, because of their rather long half lives. However, from a dose rate from a RAW system point of view, tritium dose not contribute, because of its very low energy decay beta particle. Only 10% of beryllium decays are via gamma emissions, while 11C, 13N and 15O are positron emitters producing 0.511MeV gamma rays. Therefore, allowing cooling time before getting near a RAW system is very effective way of reducing the dose rates.

Fermilab Radiological Control Manual (FRCM) suggests keeping the tritium concentrations in the cooling system below 0.67 microCuries/cc. However, some of the NuMI RAW systems may exceed this limit due to high particle fluxes or it may not be feasible to replace the cooling water frequent enough to keep the concentrations below the FRCM value. For these cases, multi-tier containment methods are used, with the proper operational precautions during the handling of the RAW systems. When possible the high tritium concentration water is disposed of as solidified low-level radioactive waste.

Table 5-8 and **Table 5-9** summarize the results for five NuMI RAW systems. One can see that the horn 1 system has the highest levels. These results, are conservatively calculated (reference RAW Note), and thus an overestimate. The table also shows the estimated shielding needed for the RAW systems and DI bottles and tanks. A 1.5' thick concrete wall is planned for the RAW room which houses the horn 1, horn 2, target and decay pipe RAW systems. With this wall, dose rates are estimated at less than 5 mrem/hr outside the room's door.

The flux densities used in calculating activities and dose rates are shown in **Table 5-8** for the decay pipe and Hadron Absorber Systems. For the target system, a flux density of 0.12 hadrons/cm^2/proton was used. This corresponds to 10 times the flux density at the horn 1 neck. This is a conservatively high estimate. For horn 1, the flux density used for the water between the conductors was 0.019 hadrons/cm^2/proton and 0.0053 hadrons/cm^2/proton for the water in the tank under the horn. For horn 2 the flux density used for the water between the conductors is

0.0025 hadrons/cm^2/proton and 0.0019 hadrons/cm^2/proton for the tank under the horn. The target cooling tubes have an inner diameter of 5.4 mm, and thus the amount of water present is extremely small.

Cooling System	Size (gallons)	MARS Flux Density Used (parts/cm2/p)	Tritium (Ci/yr)	Total Activity (Ci/yr) 1 hour Cooldown	Ci/ml/yr (1 hour cooldown)
Target & Baffle	See text	10*Horn1 neck	0.080	0.63	1.65E-06
Horn 1	~105	see text	1.820	14.23	3.76E-05
Horn 2	~105	see text	0.538	4.20	1.11E-05
Decay Pipe	5500	4.66E-05	0.011	0.09	5.27E-09
Hadron Absorber	130	1.30E-05	0.006	0.04	1.00E-07

Table 5-8: RAW System Activity

Cooling System	Size (gallons)	mrem/hr @1' (0 cooldown)	Local Secondary Containment	Hydrogen Gas	DOSE on contact (0 cooldown) (Rad/hr)	DOSE @1' (0 cooldown) (Rad/hr)
Target & Baffle	See text	44 rem/hr with no shielding from horn 1 RAW, with 18" planned concrete shielding, expect < 5 mrem/hr on the outside of the RAW room door.	contained in target	1 cc/day	2.9	0.9
Horn 1	~105		contained in chase shielding and Al liner	3.5 gal/day	66.6	20.0
Horn 2	~105		contained in chase shielding and Al liner	0.6 gal/day	19.7	5.9
Decay Pipe	5500		contained in concrete	52 gal/yr	0.009	0.003
Hadron Absorber	130	87	yes	14 gal/yr	0.185	0.056

Table 5-9 RAW System Dose Rates and Hydrogen Gas Production

Since 4% hydrogen gas in air is considered explosive, a helium purging system will be added to the horn RAW systems. The Hadron Absorber RAW system needs to be vented to the exhaust stack and the Decay Pipe RAW system might need daily purging/venting with small amounts of Helium gas.

5.8 Hot Component Handling

See Section 4.2.

5.9 Decontamination & Decommissioning (D&D)

The guidelines of the FESHM 8070 will be used for the D&D of the NuMI Beamline. No hazardous materials have been used in the construction of the beamline. Items put in the NuMI tunnel during construction are being chemically analyzed for D&D. Therefore, no mixed waste or potential contaminant of the ground water will be produced. The major radioactive isotopes produced will have 2.6 and 5.3 year half-lives. There are sump pumps that remove the water that flows into the NuMI tunnel. This will continue after the conclusion of the experiment. Accidental flooding of the tunnel in the future will not have any detrimental effects on the ground water. All the materials used in the construction of the beamline are naturally occurring in the surrounding soil.