Main Injector/Recycler

Revision 0
April 23, 2013

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Revision History

Author	Description of Change	Revision No. & Date
John E. Anderson Jr. David Capista	Initial release of the Main Injector/Recycler Chapter for the Fermi National Accelerator Laboratory Safety Assessment Document (SAD).	Revision 0 April 23, 2013

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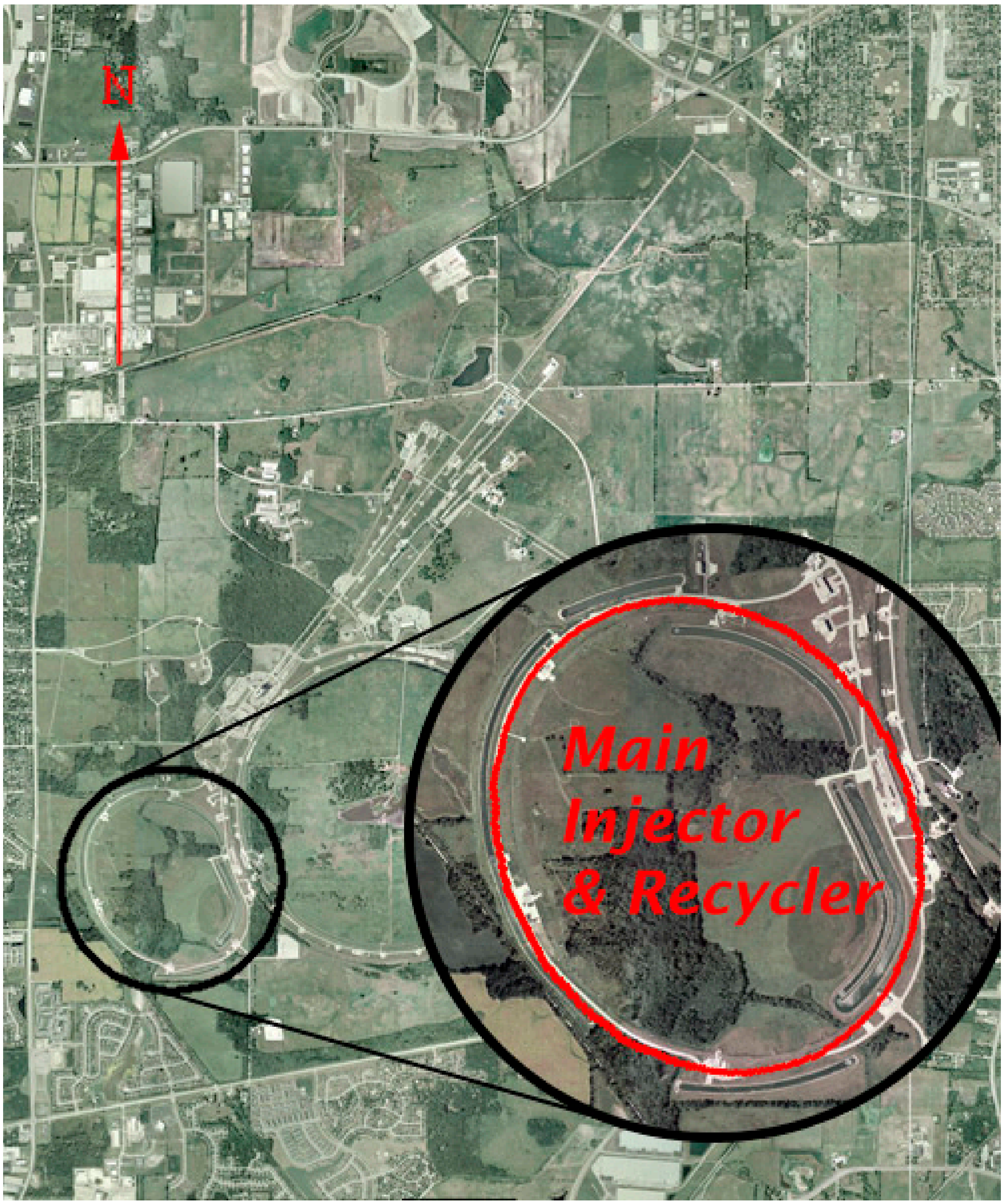
II - 6 Main Injector (MI) /Recycler Area

II - 6.1 MI/Recycler Location on Fermi National Accelerator Laboratory (Fermilab) Site

The following aerial photograph shows the location of the MI/Recycler in relationship to the Fermilab site.



II - 6.2 Inventory of Hazards

The following table lists the identified hazards found in the MI/Recycler enclosure and support buildings. All hazards with an asterisk (*) have been addressed in Chapters 1-10 of the Fermilab Safety Assessment Document (SAD) and are not addressed in this section of the SAD.

Radiation Ionizing radiation Residual activation Groundwater activation Surface water activation Air activation Soil interactions Radioactive waste	**Kinetic Energy** Power tools * Pumps and motors *
Toxic Materials Lead shielding * Beryllium components *	**Potential Energy** Crane operations * Compressed gases * Vacuum / pressure vessels * Vacuum Pumps *
Flammable & Combustible Materials Cables *	**Magnetic Fields** Fringe fields *
Electrical Energy Stored energy exposure * High voltage exposure * Low voltage, high current exposure *	**Gaseous Hazards** Confined spaces *
Thermal Energy	**Access / Egress** Life Safety Egress *

II - 6.3 Introduction

This Section II, Chapter 6 of the Fermi National Accelerator Laboratory (Fermilab) SAD covers the MI Accelerator, Recycler Ring, and beam absorber areas. The chapter has been prepared by the staff of the Fermilab Accelerator Division (AD) MI Department.

II - 6.3.1 *Purpose of the MI/Recycler Area*

The MI provides a primary proton beam to various end-users from 8 Giga-electron volt (GeV) and at higher energies up to120 GeV in support of the Fermilab high energy physics (HEP) programs. While the accelerator is capable of 150 GeV operations, there are no current plans to utilize energies above 120 GeV. The MI provides 5.16×10^{13} protons/pulse, at a 1.333 second cycle time, for an hourly intensity of 1.39×10^{17} protons at 120 GeV. Beam used for studies purposes in the MI beam line is sent to the MI-40 abort absorber.

The Recycler has been repurposed from its original design as an antiproton storage ring. In its current operational mode, the Recycler is used to collect and transport 8 GeV protons from the Booster accelerator to the MI. Protons from the Recycler are sent directly to the MI via a transfer line in the MI30 straight section. The Recycler is capable of operating at up to 2.25×10^{17} protons/hr at 8 GeV. Beam used for studies purposes in the Recycler is sent to the MI-40 abort absorber.

II - 6.3.2 *Description of the MI/Recycler Area*

The MI/Recycler accelerators are located south of the Wilson Hall. The MI/Recycler accelerator enclosure consists of: an injection line, two circular machines approximately 3319 meters in circumference, two extraction beam lines, a beam abort absorber, and 10 support service buildings. The 8 GeV injection line from the Booster accelerator connects to three areas: the Booster Neutrino beam line, the MI, and the Recycler. Beam can be extracted from the MI enclosure to the Neutrino beam line, the switchyard beam line, the Muon campus, or the MI-40 abort absorber.

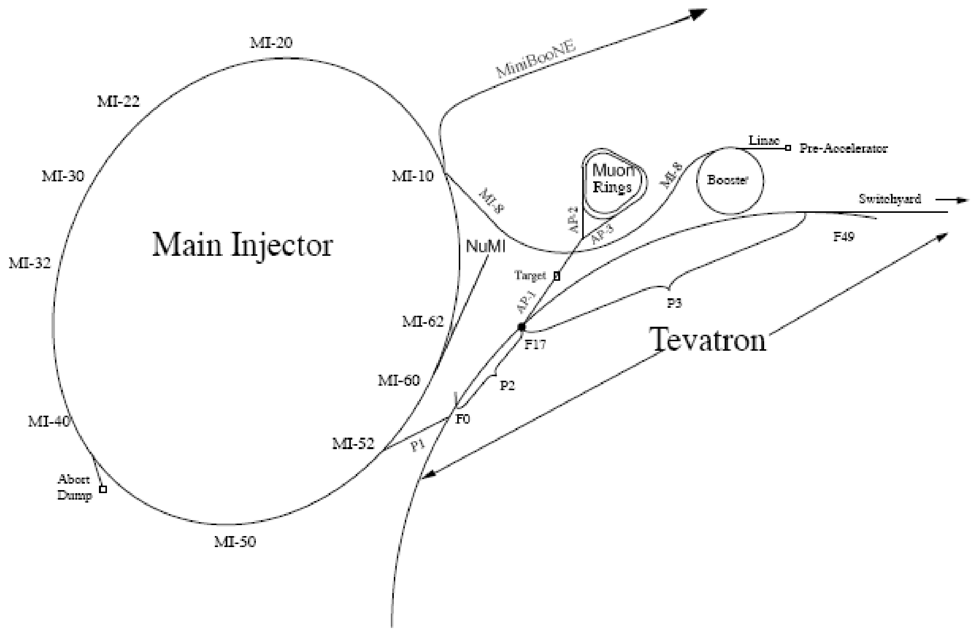


Figure 1 Main Injector Accelerator Layout and Associated Beam Lines

II - 6.3.3 *Operating Modes*

The MI and Recycler are multipurpose machines and have many operating modes. The MI-8 beam line is used to inject beam into one of three areas; the Recycler which accumulates Booster protons for delivery to the MI; the MI which supplies protons to the Fermilab HEP experimental program; or the Booster Neutrino beam line. Both the MI and Recycler machines have beam study cycles that direct beam to the MI-40 abort absorber.

Beam is delivered from the Booster to the MI-8 beam line and passes two switch magnets that further direct the Booster beam to the Booster Neutrino beam line, the Recycler, or to the MI. Booster beam is sent to the MI-8 beam line at a maximum rate of 15 Hertz (Hz), supplying one Booster batch of beam each cycle. Beam can be directed to any of the three beam lines, Booster Neutrino beam line, the Recycler, or to the MI on any given Booster batch.

The Recycler is a fixed energy machine in which its bending magnets are based on permanent magnet technology and can only capture, store and accumulate Booster protons. A maximum of 12 Booster batches are possible for capture and storage in this machine. Once the Booster beam is injected into the Recycler, it will be either sent to the MI or to the MI-40 abort.

The MI accepts beam from either the Booster or the Recycler. When the MI is accepting beam directly from the Booster, the fill time is dominated by the 15 Hz cycle time of the Booster. When beam is transferred from the Recycler, the MI can be filled in a single turn. For high power operations, these two machines work in tandem where the Recycler will fill with 12 Booster batches, while the MI is ramping and extracting. Beam from the Recycler will be transferred to the MI in a single turn, starting the cycle over again. Operation in this manner eliminates the fill time for the MI thus reducing the MI cycle time.

Beam from the MI can be delivered to several experimental areas. The highest power beam is sent to the NOvA target at an energy of up to 120 GeV. The MI also supports Switchyard slow spill which is 120 GeV beam delivered to the Meson and Neutrino experimental areas over a several second duration. Beam to the Muon campus can be either 8 GeV or up to 120 GeV. Various study cycles are supported in the MI and Recycler that will deliver beam to the MI-40 abort absorber. The MI study cycles can be at energies between 8 GeV and 150 GeV where the Recycler beam energy is fixed at 8 GeV.

The MI is assessed to provide 5.16×10^{13} protons/pulse, with a 1.333 second cycle time, delivering up to 1.39×10^{17} protons/hr at 120 GeV. The MI operates 95% efficient with approximately 80% of the “lost” protons absorbed at collimators and 20% “kicked” to the MI-40 abort absorber.

The Recycler is assessed to provide 2.25×10^{17} protons/hr at 8 GeV. The Recycler is 99% efficient with beam losses during Booster injection sent to the MI-40 abort absorber by gap clearing kicker magnets.

II - 6.4 Safety Assessment

The unique beam line specific hazards for the MI and Recycler area are analyzed in this section. The radiological hazards include ionizing radiation, residual activation, groundwater and surface water activation, air activation, soil interactions, and radioactive waste.

II - 6.4.1 *Radiological Hazards*

The MI/Recycler beam lines present radiological hazards in the form of prompt and residual ionizing radiation from particle beams, residual radiation due to activation of beam line components, and environmental radioactivity in the form of potential groundwater, surface water, air and soil activation resulting from the operation of the beam transport systems.

Detailed shielding assessments and post assessment documents address these hazards [1, 2]. The assessments provide a detailed analysis of the MI/Recycler facility demonstrating the required shielding, controls and interlocks to comply with the Fermilab Radiological Control Manual (FRCM) [3]. Residual activation of components has a substantial impact on the ability to occupy the MI/Recycler enclosure where recurring access is required for routine maintenance.

The shielding assessments for the MI and Recycler begin at the MI and Recycler injection points at Cell 100 near the MI-10 service building. The assessments include both rings as well as the Recycler to MI transfer line. The shielding assessments include the P150 extraction line beginning at the Extraction Lambertson magnet (I:Lam52) and progressing toward switchyard. The shielding assessments end at the P150 shield wall that separates the MI and Tevatron F-Sector enclosures, and the MI-40 absorber.

The assessments consider groundwater and surface water activation, lists surface water discharge points and monitoring locations; calculates air activation, estimates annual release, and release points; considers muon production; considers longitudinal and transverse shielding requirements; summarizes labyrinth and penetration calculations; calculates residual dose rates; and specifies active shielding controls and monitoring.

II - 6.4.1.1 Ionizing Radiation

Prompt ionizing radiation is the principle radiation hazard when beam is transported through the MI and Recycler beam lines. In order to protect workers and the general public, the enclosures and beam pipes are surrounded either by sufficient amounts of shielding (soil, concrete, or iron), and/or networks of interlocked detectors to keep any prompt radiation exposure within acceptable levels.

Detailed shielding assessments have been compiled and reviewed by the Fermilab Shielding Review Subcommittee to address these concerns. The assessments provide a detailed analysis of the beam line, demonstrating the required overburden or soil shielding, use of signs, fences, and active interlocks to maintain any prompt radiation within acceptable levels.

Shielding assessments for the MI and Recycler beam lines have included analyses of injection, circulation, extraction, and absorption areas. The assessments require that:

- *All penetrations must be filled with shielding as specified.*
- *All movable shielding blocks must be installed as specified.*
- *The average beam intensity in the MI shall not exceed 1.39x10^{17} protons/hr.*
- *The average beam intensity in the Recycler shall not exceed 2.25x10^{17} protons/hr.*
- *The radiation safety interlock system must be certified as working.*
- *Radiation detectors around the MI/Recycler enclosure are installed and interlocked to the radiation safety interlock system.*

II - 6.4.1.2 Residual Activation

Five radiation surveys dating from July 18, 2010 to May 1, 2012 taken within hours after stopping beam operations were used to estimate future residual dose rates for the MI/Recycler area. Residual dose rates of 80-100 milli-rem/hr (mrem/hr) had been regularly found at MI injection and extraction regions in previous operations. For 700 kilo-Watt (kW) operations, these regions are expected to be at the 150-200 mrem/hr level. Collimation locations, recently surveyed at 500-1500 mrem/hr, are expected to be in the 900-2600 mrem/hr range with 700 kW operations.

Since the Recycler has been repurposed from its designed use as an antiproton accumulator, the repurposed operations will result in greater residual activity than previously. The Recycler residual dose rates are expected however to be smaller than those associated with the MI. The MI is a machine with larger losses that can be present at higher energies than those from the Recycler. Since the MI and the Recycler share the same enclosure, the dominant residual dose rates for the enclosure will be from the MI [1].

Each of the MI/Recycler service buildings include large Low Conductivity Water (LCW) supply and return headers. Significant MI beam loss can result in the production of short-lived radioisotopes within the LCW system. Significant beam loss in the Recycler can also result in the production of short-lived radioisotopes within the LCW system even though most Recycler elements are air-cooled and do not require the LCW. These short-lived radioisotopes can result in doses above normal background when transported to the service buildings via the LCW piping.

Radiation detectors have been installed to monitor the dose rates near the return piping at each of the MI service buildings. Although no significant dose rates associated with normal operation of the MI have been observed since the detectors were installed, these detectors are interlocked to protect against unintentional beam loss.

When the MI/Recycler is not in operation, the enclosure area will remain radioactive and access to these components will be tightly controlled with the level of control dependent on the level of residual radiation. The control measures include training and training verification, centralized access authorization, and key entry. Controls required for different levels of residual radiation are specified in the FRCM [3], and are detailed in the Radiological Work Permit (RWP) for the work to be performed.

In most situations, general RWPs for accesses will suffice. A job-specific RWP and an as-low-as-reasonably-achievable (ALARA) plan will be required for work on any highly activated equipment with a potential individual exposure greater than 200 mrem or potential job exposure greater than 1000 person mrem. These tasks will be supervised by members of the AD Radiation Protection Group under the direction of the AD Radiation Safety Officer (RSO).

II - 6.4.1.3 Groundwater and Surface Water Activation

The MI beam losses occur at the injection/extraction locations, distributed around the beam line, and at the abort absorber at MI-40. Radiation surveys of injection/extraction locations indicate that losses are highest at the collimators near MI-30. The interaction of the beam with water molecules produces tritiated water. The majority of potentially activated water is collected in drains around the MI and discharged to the site-wide Industrial Cooling Water system, which contains the tritiated water to the Fermilab site.

The 700 kW MI release estimate for surface and groundwater shows that the annual distributed beam loss of 2.51x10^{19} protons will produce combined ^{3}H (tritium) and ^{22}Na (sodium-22) concentrations that are 45.0% of the surface water limits and a negligible fraction of the groundwater limits respectively [1]. The 6.28x10^{18} protons sent to the MI-40 abort produce combined ^{3}H and ^{22}Na concentrations that account for 0.3% of the surface water limit and a negligible fraction of the groundwater limits [1].

The assessment of releases to groundwater and surface water are based upon a beam intensity of 6.28x10^{20} protons per year injected into the Recycler Ring. Up to 0.3% of the total beam may be lost in the Recycler Ring, which is equivalent to a distributed loss of 1.88x10^{18} protons per year. It is also estimated that a maximum of 1.5% of the total beam will be sent to the MI-40 abort absorber during gap-clearing, which is equivalent to 9.42x10^{18} protons per year.

Annual estimates for groundwater and surface water for a distributed beam loss of 1.88x10^{18} protons from the Recycler will produce combined ^{3}H and ^{22}Na concentrations that account for 3.4% of the surface water limit and a negligible groundwater concentration [2]. Annual estimates for the 9.42x10^{18} protons sent to the MI-40 abort will produce combined ^{3}H and ^{22}Na concentrations that account for only 0.4% of the surface water limit and a negligible groundwater concentration [2].

The combined annual MI/Recycler concentration estimates and release fractions for ^{3}H and ^{22}Na surface water and groundwater releases are given in Table 1.

Table 1: Combined Annual MI and Recycler Surface Water and Groundwater Release Fractions

Description	Annual Concentration Limits ((pico Curie (pCi)/millilitre (ml))		Annual Concentration Estimate (pCi/ml)		Fraction of Annual Limit
	^3H	^{22}Na	^3H	^{22}Na	$^3H + ^{22}Na$
Surface Water (Distributed)	1900	10	51.6	4.84	5.11×10^{-1}
Groundwater (Distributed)	20	0.4	3.44×10^{-5}	6.88×10^{-10}	1.72×10^{-6}
Surface Water (Abort)	1900	10	0.77	0.07	7.4×10^{-3}
Groundwater (Abort)	20	0.4	8.9×10^{-8}	1.81×10^{-12}	4.45×10^{-9}

Groundwater is sampled routinely as part of the Fermilab Environment, Safety, Health, and Quality Section Environmental Monitoring Program. The sump discharges and pond surface waters are routinely sampled as part of the AD Routine Monitoring Program (ADDP-SH-1003).

II - 6.4.1.4 Air Activation

The concentration of radionuclides in the MI/Recycler enclosure is below the limit of detection due to very large amounts of air flowing in and out of the MI/Recycler enclosure. The annual emission calculation is based on the annual proton beam loss rates which reflect the output of the Beam Budget Monitor system and various Accelerator Controls Network (ACNET) data loggers. MI emissions are reported as an unmonitored source in the Fermilab Radionuclide Air Emissions Annual Reports [4] provided to the DOE Fermi Site Office for transmission to State and Federal regulatory agencies in accordance with Regulations.

The yearly scaled estimates for 700 kW operation based on the same 4.2% beam loss are 3.0×10^{19} protons from a total of 7.0×10^{20} protons delivered, resulting in an estimated 20.4 Ci being released from the MI. The release of 20.4 Ci in a year from the MI is 1% of the Fermilab allowable total average activity release specified in the Fermilab Lifetime Operating Air Pollution permit issued by the Illinois Environmental Protection Agency (IEPA).

The Recycler beam will be transmitted cleanly. Beam will be intentionally absorbed only at the MI-40 absorber. The MI-40 absorber will be used for kicker gap clearing during injection from the Booster and for aborting the beam if the established beam permit is lost. Gap clearing losses are estimated to be at 1-1.5% [2]. The MI-40 absorber room ventilation stack is locked-off with a RSO padlock and is not allowed to operate during beam transport. Any air activation that might occur due to incidental losses of circulating beam is expected to be minimal.

The reported 2010 release for the MI enclosure was 11.4 Ci [5]. This release resulted from an annual loss of 1.68×10^{19} protons or 6.79×10^{-19} Ci/proton. If the same production rate is assumed for the repurposed Recycler operations, then an estimated 6.4 Ci/yr will be released for an estimated number of 9.42×10^{18} lost protons/yr [2]. Recycler releases are expected to be less than 0.5% of the overall integrated Fermilab Lifetime Operating Air Pollution permit issued by the IEPA. There are no intended air-release points.

II - 6.4.1.5 Particle Interactions in Soil

Muons resulting from MI/Recycler operations penetrate into the soils surrounding the MI/Recycler enclosure. Most of the muons created by beam line losses of 120 GeV MI protons remain below grade since the majority of the MI lies in a horizontal plane. There is one location however with a 24-milliradian vertical bend for extraction into the P150 beam line at MI-52. The 120 GeV protons lost at that location could produce muons above grade.

The steepest upward trajectory in the MI beam line occurs between quadruple magnets Q701 and Q702 [1]. Muons from the Q701-Q702 region represent the greatest opportunity for muon exposure to personnel above grade. While there are downstream portions of the P150 line that also rise vertically, the upward trajectory is at a shallower angle. Since muons generated from losses along these other downstream locations of the MI beam line will encounter a longer path through soil, these locations are of less significance.

The range of 60 GeV muons in soil of density 2.0 grams/cm^3 is approximately 361 feet [6]. A distance of 400 feet of soil is adequate to range out muons with energies below 60 GeV. The flux of muons at energies higher than 60 GeV in the MI is negligible [7].

The path of secondary particles that enter the P150 tunnel intersects the ceiling of the enclosure about 320 feet downstream of Q701 in the P150 beam line. The muons travel about 480 feet downstream beneath the F0 Service Building to emerge near the Tevatron ring road or cooling pond. The bank of the Tevatron cooling pond is at the end of this path where the level of soil drops away. A conservative estimate of the range of the secondary particles is about 400 feet assuming soil shielding of density 2.24 grams/cubic centimeter (cm^3).

The Recycler beam also operates in a horizontal plane. The Recycler does not have any significant upward vertical bends. Any muons generated by Recycler losses will therefore remain below grade until the muons are absorbed. No Recycler muons will have energy greater than 8 GeV. The range of 8 GeV muons in soil of density 2.0 grams/ cm^3 is approximately 66 feet [6]. The Recycler muons are thus absorbed in the soil.

At injection, protons from the Booster are conveyed by the MI-8 injection line and are deflected upward by 32.8 milliradians near Cell 848. Losses here could give rise to muons that penetrate the ceiling about 168 feet downstream of the bend. In the vicinity of the Recycler tunnel, grade elevations are 740 feet or more and the berm is higher. Consequently there are 560 feet or more of soil in the path of any muons from Recycler operations before emerging at grade level. In traversing the soil above the ceiling, muons will travel 66 feet and be entirely absorbed before the muons have ascended no more than 2.0 feet vertically.

Downstream of the first vertical bend is a second vertical bend, reducing the angle of the rising beam from 32.8 milliradians to 19.2 milliradians. This shallower angle would offer an even longer path through soil for muons which would rise less than 0.8 feet vertically in traveling 66 feet.

The soil surrounding MI/Recycler enclosure including that at the MI-40 absorber will be sampled during decommissioning to document activation levels, as required by the Fermilab ES&H Manual (FESHM) [8].

II - 6.4.1.6 Radioactive Waste

MI/Recycler radioactive waste hazards and waste disposal will be managed within the program established for the Fermilab accelerator complex and as prescribed in the FRCM. Waste minimization is an objective of the equipment design and operational procedures. Although production of radioactive material is not an operational function of the MI/Recycler area, beam loss and, in the case of some beam diagnostics devices, intentional interception of the beam will result in activation of beam line elements. Reuse of activated items will be carried out when feasible. Activated items that cannot be reused will be disposed of as radioactive waste in accordance with the FRCM requirements.

II - 6.5 Credited Controls

II - 6.5.1 *Passive Controls*

Passive controls are accelerator elements that are part of the physical design of the facility that require no action to function properly. These passive controls are fixed elements of the beam line that take direct human intervention to remove. The MI/Recycler area enclosure is designed as a concrete and earth covered radiation shield to protect personnel from radiological exposure during beam operations.

II - 6.5.1.1 Permanent Shielding

The MI/Recycler shielding requirements for 700 kW operations have been documented which scale from the Standard Reitzner Category Table developed from MARS [9] simulations of thick shielding [1, 2].

The MI Standard Category Table is based on a model with the beam located 3 feet from the tunnel ceiling. Since MI ceiling heights vary but are typically 5.7 feet or more above the beam, the MI table will thus overestimate shielding requirements.

The MI longitudinal shielding summary indicates that all longitudinal ranges provide adequate shielding for 700 kW operations [1]. The shielding summary for the abort line indicates no failures[1]. All transverse locations provide adequate shielding and conform to guidance specified in the FRCM.

The MI has no thinly-shielded sections where neutron skyshine would potentially be a problem at large distances from the source. A calculation has been performed due to its proximity to the site boundary [1]. The Illinois Prairie Path represents the closest off-site location to the MI at approximately Cell 320 and is 85 meters away. Calculations show that if all MI beam is continuously lost on a magnet at this location for one year, the skyshine contribution to site boundary dose would be 1.6 mrem/yr for continuous occupancy. The Fermilab site boundary dose limit is 10 mrem/yr.

The Recycler Standard Category Table for the stated operating parameters is based upon the following models; beam incident on a magnet 3 feet from the enclosure wall, a beam pipe 3 feet from the enclosure wall, and a pipe buried in soil. The Recycler is typically only 1.5 feet below the enclosure ceiling. A model with beam incident on a buried pipe was selected since other models would tend to underestimate the required shielding.

The Recycler longitudinal shielding summary indicates that all longitudinal ranges provide adequate shielding and are within FRCM requirements for operations up to 2.25×10^{17} protons/hr [2]. The shielding summary for the abort line indicates no failures [2]. All transverse locations provide adequate shielding and conform to guidance specified in the FRCM.

The Recycler Ring has no thinly-shielded sections where neutron skyshine would potentially be a problem at large distances from the source. A calculation has been performed due to its proximity to the site boundary [2]. The Illinois Prairie Path again represents the closest off-site location to the Recycler Ring at approximately 85 meters away from Cell 320. Calculations show that if all Recycler beam is continuously lost on a magnet at this location for one year, the skyshine contribution to site boundary dose would be 0.2 mrem/yr for continuous occupancy. The Fermilab site boundary dose limit is 10 mrem/yr.

II - 6.5.1.2 Labyrinth and Penetration Shielding

The details of the MI labyrinth and penetration assessments have been documented [1]. The shielding summary details the mitigations necessary for each penetration to comply with the requirements of the FRCM. Individual analyses of penetrations for electrical power distribution conduits and sump discharge piping have not been performed. Limiting cases for each type of penetration have been analyzed to determine that all locations fall within dose rate requirements established in the FRCM.

Recycler labyrinth and penetration assessments have been documented [2]. The Recycler shielding summary typically represents configurations necessary to mitigate doses from MI losses alone. In most cases, the MI mitigation requires additional shielding over and above the shielding required for Recycler mitigation. Therefore, solutions developed to mitigate doses as a result of the MI shielding assessment are generally adequate to protect against Recycler losses for operation at 2.25×10^{17} protons/hr [2].

There are a few locations where Recycler losses generate a higher dose than MI losses [2]. An example is the large penetration K145B in Room 117 at the south end of the MI-60 service building. In these cases, the solutions reflect the shielding requirements for Recycler operation [2].

II - 6.5.1.3 Movable Shielding

The Main Injector enclosure has four areas where movable shielding is used. Two of these areas are shield walls that have been constructed to separate the MI enclosure from the Tevatron enclosure in the middle of the A150 and P150 transfer line areas. The other two areas are in the Tevatron enclosure where movable shielding has been added to attenuate doses from Recycler losses that could pass through the short circuit emergency exit stairwell that connects between the MI and Tevatron tunnels near the MI-60 region. In all four cases, the shielding has been clearly labeled and secured in place by the AD RSO.

II - 6.5.2 *Active Controls*

Active engineered controls are systems designed to reduce the risks from accelerator operations to acceptable levels. These automatic systems limit operations, shutdown operations, or provide warning alarms when operating parameters are exceeded. The active controls in place for the MI/Recycler area are presented.

II - 6.5.2.1 MI/Recycler Beam Loss Controls

The AD MI Department has documented ten different machine control systems that limit beam losses in the MI/Recycler [10]. The machine controls make up nine systems that fall into four categories; systems that detect beam losses, systems that prevent beam losses, systems that reduce the probability or frequency of beam losses, and software based administrative alarms.

Three of the machine controls create two separate systems that detect excessive beam losses. The Beam Loss Monitor (BLM) system in conjunction with the Beam Permit System detects excessive beam losses through several hundred ionization chambers distributed around the MI/Recycler ring.

The LCW Activation Monitoring, an element of the second system, detects beam loss at or near LCW-cooled elements. Radiation monitors are located adjacent to the LCW piping at each service building. Uncontrolled losses will trip the radiation monitors and disable the Radiation Safety System preventing further beam injection. Seven interlocked detectors are required to monitor LCW piping within service buildings at MI/Recycler area locations MI-10, MI-20, MI-30, MI-40, MI-50, MI-52, and MI-62.

Three machine control systems, the Power Supply Regulation and Permits System and the MI/Recycler Vacuum Interlocks System in conjunction with the Beam Permit System, prevent beam losses from occurring. These machine control systems monitor critical power supplies and vacuum systems preventing further beam from being injected if faults are detected.

Four additional machine controls including the Beam Switch Sum Box, the Time Line Generator, the MI/Recycler Transfer Permit, and the MI/Recycler Orbit Controls insure that the necessary machines are ready to transport beam. These systems determine if the necessary machines are ready to transport beam and maintain the beam near the center of the machine's aperture thus reducing the probability or frequency of beam losses.

The MI/Recycler Alarms and Limits combine software monitoring of devices and monitoring controls. Machine devices are monitored by the ACNET System and device problems are posted on alarm screens in the Main Control Room based upon an established set of limits and priorities for each device.

The combination of these systems provides a defense-in-depth strategy to greatly limit the duration of accidental beam losses. The analysis of these systems and an operating experience review over the past 10 years provided the basis for determining the credible beam loss accident event for the MI and Recycler. Based on this review by the Beam Loss Scenarios Panel, the Fermilab Director approved a two category reduction for the accident condition postings for the MI/Recycler area [11].

II - 6.5.2.2 Radiation Safety Interlock System

The MI/Recycler area is one of the two Booster Radiation Safety Interlock System operating modes. The characteristics of the system are described in Chapter I of the Fermilab SAD.

The MI/Recycler enclosure is approximately 3300 meters in circumference. Spaced around the ring are eight service buildings with interlocked enclosure access points and an additional interlocked equipment access labyrinth at the MI-60 service building. Sixteen interlocked emergency exit stairs that lead directly to the surface are spaced around the ring to minimize the distance between exit points. The enclosure is separated into five separate interlocked boundaries to assist with Search and Secure operations. The interlock system inhibits transport of beam beyond the Booster absorber in the Booster enclosure except when the MI, Tevatron F Sector, Muon Campus Transport, MI-12A, and MI-31 Stub enclosures are properly secured and locked, and the area radiation monitors are made up.

The Radiation Safety Interlock system inhibits beam by controlling redundant critical devices. In the case of the MI operating mode, the primary critical devices are the Booster Extraction Lambertson (ACNET designation B:LAM), and the Horizontal Bend Magnet Power Supply (ACNET designationB:MH1). In the event of a critical device failure, the system has a failure mode function that will reach back and disable the upstream Linac Radiation Safety Interlock System.

Trained and qualified personnel from the AD Operations Department are required to search and secure the enclosure before permits from the radiation safety interlock system may be reestablished following any personnel access to the enclosure, except under strictly specified controlled access conditions. The Radiation Safety Interlock Systems including requirements for hardware and system testing, inventory of interlock keys, search and secure procedures for the beam line enclosure, controlled access procedures, personnel training requirements, and procedures for maintenance of interlock systems, are in conformance with the requirements stated in the FRCM.

II - 6.5.3 *Administrative Controls*

All MI/Recycler area operations with the potential to affect the safety of employees, researchers, or the public or to adversely affect the environment are performed using approved laboratory, division, or department procedures. These procedures are the administrative controls that encompass the human interactions that define safe accelerator operations.

II - 6.5.3.1 Beam Permits and Run Conditions

In accordance with AD Administrative Procedure on Beam Permits, Run Conditions, and Startup (ADAP-11-0001), beam will not be transported to the MI/Recycler without an approved Beam Permit and Run Condition. The Beam Permit specifies beam power limits as determined and approved by the AD Head in consultation with the AD ES&H Department Head, AD RSO, AD Operations Department Head, and AD External Beams Department Head. The run conditions list the operating modes and safety envelope for the MI/Recycler beam line. Run conditions are issued by the AD ES&H department, and are signed by the AD Operations Department Head, AD RSO, and AD Division Head.

In order to run beam to the MI/Recycler beam line, the MI Enclosure, Tevatron F Sector, Muon Campus Transport, MI-12A, and MI-31 Stub must be secure, seven interlocked detectors used to monitor LCW piping within MI-10, MI-20, MI-30, MI-40, MI-50, MI-52, and MI-62 Service Building locations and five interlocked detectors to monitor prompt radiation at three locations in the MI-60 Service Building must be active.

II - 6.5.3.2 Summary of Beam Operating and Safety Envelope Parameters

The MI/Recycler has been assessed from the standpoint of beam operating and safety envelope parameters. The MI was assessed for beam operating parameters of 5.16×10^{13} protons/pulse, 1.39×10^{17} protons/hr with a 1.333 second cycle time (2700 pulses/hr) at 120 GeV. The Recycler beam operating parameters used in this assessment are of 8.34×10^{13} protons/pulse, 2.25×10^{17} protons/hr with a 1.333 second cycle time (2700 pulses/hr) at 8 GeV.

Accelerator operational approvals shall be obtained by following the AD Procedure on Beam Permits, Run Conditions, and Startup (ADAP-11-0001), administered by the AD ES&H Department and AD Head. Beam Permit and Run Condition documents shall identify the beam power and operating parameters allowed within the current Accelerator Safety Envelope. The

Beam Permit specifies beam power limits as determined and approved by the AD Head in consultation with the AD ES&H Department Head, AD RSO, AD Operations Department Head, and AD Main Injector Department. The Run Condition for the MI/Recycler area describes the operating configuration as reviewed by the AD RSO, AD Operations Department Head, and as approved by the AD Head.

II - 6.6 Summary and Conclusion

Specific hazards associated with commissioning and operation of the MI/Recycler area enclosure are identified and assessed in this chapter of the Fermilab Safety Assessment Document. The designs, controls, and procedures to mitigate MI/Recycler specific hazards are identified and described. In addition to these specific safety considerations, the MI/Recycler area is subject to the global and more generic safety requirements, controls and procedures outlined in Section I of this Fermilab Safety Assessment Document.

The preceding discussion of the hazards presented by MI/Recycler operations and the credited controls established to mitigate those hazards demonstrate that the area can be operated in a manner that will produce minimal hazards to the health and safety of Fermilab workers, visiting scientists, members of the public, as well as to the environment.

II - 6.7 Glossary, Acronyms

ACNET	Accelerator Control Network System
AD	Accelerator Division
ALARA	As Low As Reasonably Achievable
BLM	Beam Loss Monitor
Ci	Curie
ES&H	Environment, Safety and Health
Fermilab	Fermi National Accelerator Laboratory
FESHM	Fermilab Environment, Safety, and Health Manual
FRCM	Fermilab Radiological Control Manual
GeV	Giga-electron volt
HEP	High Energy Physics
Hr	Hour
Hz	Hertz
IEPA	Illinois Environmental Protection Agency
kW	kilo-watt
LCW	Low Conductivity Water
MI	Main Injector
mrem/hr	milli-rem per hour
NOvA	Neutrino Off-axis Electron Neutrino (νe) Appearance
NuMI	Neutrino at Main Injector
RSO	Radiation Safety Officer
RWP	Radiation Work Permit
SA	Shielding Assessment
SAD	Safety Assessment Document

II - 6.8 References

[1] **Main Injector Incremental Shielding Assessment 700 kW,** W. Schmitt, W. Higgins, M. Vincent, R. Zimmermann, August 2012.

[2] **Recycler Ring Incremental Shielding Assessment 2.25x10^{17} protons/hour,** W. Schmitt, W. Higgins, M. Vincent, R. Zimmermann, October 2012.

[3] **Fermilab Radiological Control Manual**. - The web link is: http://esh.fnal.gov/xms/FRCM

[4] **Fermilab Radionuclide Air Emissions Annual Report**. - https://esh-docdb.fnal.gov:440/cgi-bin/ShowDocument?docid=2073

[5] **Calendar Year 2010 Radionuclide Air Emissions Annual Report for Fermilab. -** https://esh-docdb.fnal.gov:440/cgi-bin/ShowDocument?docid=1735

[6] **Radiation Physics for Personnel and Environmental Protection**, D. Cossairt, TM-1834

[7] **Summary of Shielding Estimates for LBNE Transport Line Hadrons & Muons**, K. Vaziri, LBNE-doc-3759-v1, May 18, 2011.

[8] **Fermilab Environment Safety & Health Manual**. - The web link is: http://esh.fnal.gov/xms/FESHM

[9] N.V. Mokhov, **"The MARS Code System User's Guide"**, Fermilab-FN-628 (1995);N.V. Mokhov, O.E. Krivosheev, **"MARS Code Status"**, Proc. Monte Carlo 2000 Conf., p. 943, Lisbon, October 23-26, 2000; Fermilab-Conf-00/181 (2000).

[10] **Main Injector and Beam Loss Controls**, D. Capista, July 2012.

[11] **Approval to Reduce Accident Condition Postings by two categories for the Main Injector and Recycler. -** https://esh-docdb.fnal.gov:440/cgi-bin/ShowDocument?docid=1935