MAIN INJECTOR & RECYCLER

SECTION III CHAPTER 07 OF THE FERMILAB SAD

Revision 1 January 2, 2024

This Chapter of the Fermilab Safety Assessment Document (SAD) contains a summary of the results of the Safety Analysis for the Main Injector & Recycler of the Fermilab Main Accelerator that are pertinent to understanding the risks to the workers, the public, and the environment due to its operation.

SAD Chapter Review

This Section III, Chapter 07 of the Fermi National Accelerator Laboratory (Fermilab) Safety Assessment Document (SAD), Main Injector & Recycler was prepared and reviewed by the staff of the Accelerator Direct, Main Injector Department in conjunction with the Environment, Safety & Health Division (ESH) Accelerator Safety Department.

Signatures below indicate review of this Chapter, and recommendation that it be approved and incorporated into the Fermilab SAD.

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Revision History

Printed versions of this Chapter of the Fermilab Safety Assessment Document (SAD) may not be the currently approved revision. The current revision of this Chapter can also be found on ESH DocDB #1066 along with all other current revisions of all Chapters of the Fermilab SAD.

Author	Rev. No.	Date	Description of Change
John E. Anderson Jr. David Capista	0	Initial release of the Main Injector/Recycler Chapter for the Fermi National Accelerator Laboratory Safety Assessment Document (SAD). April 23, 2013	
SAD Committee David Capista	1	January 2, 2024	Update and format change, added MCI

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Acronyms and Abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists
ACNET	Accelerator Control Network System
AD	Accelerator Directorate
AHJ	Authority Having Jurisdiction
ALARA	As Low As Reasonably Achievable
ANSI	American National Standards Institute
APS-TD	Applied Physics and Superconducting Technology Directorate
ARA	Airborne Radioactivity Area
ASE	Accelerator Safety Envelope
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
ASME	American Society of Mechanical Engineers
ASO	Accelerator Safety Order, referring to DOE O 420.2D *Safety of Accelerators*
^{7}Be	Beryllium-7
BLM	Beam Loss Monitor
BNB	Booster Neutrino Beam
BPM	Beam Position Monitor
BY	Boneyard
CA	Controlled Area
CA	Contamination Area
CAS	Contractor Assurance System
CC	Credited Control
CCL	Coupled Cavity Linac
CDC	Critical Device Controller
CERN	European Organization for Nuclear Research
CFM	Cubic Feet per Minute
CFR	Code of Federal Regulations (United States)
Ci	Curie
CLW	Co-Located Worker (the worker in the vicinity of the work but not actively participating)
cm	centimeter
CPB	Cryogenics Plant Building
CSO	Chief Safety Officer
CUB	Central Utility Building
CW	Continuous Wave
CX	Categorically Excluded

D&D	Decontamination and Decommissioning
DA	Diagnostic Absorber
DAE	Department of Atomic Energy India
DCS	Derived Concentration Standard
DocDB	Document Database
DOE	Department of Energy
DOT	Department of Transportation
DR	Delivery Ring
DSO	Division Safety Officer
DSS	Division Safety Specialist
DTL	Drift Tube Linac
DUNE	Deep Underground Neutrino Experiment
EA	Environmental Assessment
EA	Exclusion Area
EAV	Exhaust Air Vent
EENF	Environmental Evaluation Notification Form
EMS	Environmental Management System
EOC	Emergency Operations Center
EPA	Environmental Protection Agency
ES&H	Environment, Safety and Health
Fermilab	Fermi National Accelerator Laboratory, see also FNAL
FESHCom	Fermilab ES&H Committee
FESHM	Fermilab Environment, Safety and Health Manual
FHS	Fire Hazard Subcommittee
FIRUS	Fire Incident Reporting Utility System
FNAL	Fermi National Accelerator Laboratory, see also Fermilab
FODO	Focus-Defocus
FONSI	Finding of No Significant Impact
FQAM	Fermilab Quality Assurance Manual
FRA	Fermi Research Alliance
FRCM	Fermilab Radiological Control Manual
FSO	Fermilab Site Office
FW	Facility Worker (the worker actively performing the work)
GERT	General Employee Radiation Training
GeV	Giga-electron Volt
^{3}H	Tritium
HA	Hazard Analysis

HAR	Hazard Analysis Report
HCA	High Contamination Area
HCTT	Hazard Control Technology Team
HEP	High Energy Physics
HFD	Hold for Decay
HLCF	High Level Calibration Facility
HPR	Highly Protected Risk
Hr	Hour
HRA	High Radiation Area
HSSD	High Sensitivity Air Sampling Detection
HVAC	Heating, Ventilation, and Air Conditioning
HWSF	Hazardous Waste Storage Facility
Hz	Hertz
IB	Industrial Building
IBC	International Building Code
ICW	Industrial Cooling Water
IEPA	Illinois Environmental Protection Agency
IEEE	Institute of Electrical and Electronics Engineers
INFN	Istituto Nazionale di Fisica Nucleare
IMPACT	Integrated Management Planning and Control Tool
IPCB	Illinois Pollution Control Board
IQA	Integrated Quality Assurance
ISD	Infrastructure Services Division
ISM	Integrated Safety Management
ITNA	Individual Training Needs Assessment
KeV	kilo-electron volt
kg	kilo-grams
kW	kilo-watt
LBNF	Long Baseline Neutrino Facility
LCW	Low Conductivity Water
LHC	Large Hadron Collider
LLCF	Low Level Calibration Facility
LLWCP	Low Level Waste Certification Program
LLWHF	Low Level Waste Handling Facility
LOTO	Lockout/Tagout
LPM	Laser Profile Monitor
LSND	Liquid Scintillator Neutrino Detector

LSO	Laser Safety Officer
m	meter
mA	milli-amp
MABAS	Mutual Aid Box Alarm System
MARS	Monte Carlo Shielding Computer Code
MC	Meson Center
MC&A	Materials Control and Accountability
MCR	Main Control Room
MEBT	Medium Energy Beam Transport
MEI	Maximally Exposed Individual
MeV	Mega-electron volt
MI	Main Injector
MINOS	Main Injector Neutrino Oscillation Search
MMR	Material Move Request
MOI	Maximally-Exposed Offsite Individual *(Note: due to the Fermilab Batavia Site being open to the public, the location of the MOI is taken to be the location closest to the accelerator that is accessible to members of the public.)*
MP	Meson Polarized
mrad	milli-radian
mrem	milli-rem
mrem/hr	milli-rem per hour
MT	Meson Test
MTA	400 MeV Test Area
MTF	Magnet Test Facility
^{22}Na	Sodium-22
NC	Neutrino Center
NE	Neutrino East
NEC	National Electrical Code
NEPA	National Environmental Policy Act
NESHAPS	National Emissions Standards for Hazardous Air Pollutants
NFPA	National Fire Protection Association
NM	Neutrino Muon
NMR	Nuclear Material Representative
NOvA	Neutrino Off-axis Electron Neutrino (ve) Appearance
NPH	Natural Phenomena Hazard
NRTL	Nationally Recognized Testing Laboratory
NIF	Neutron Irradiation Facility

NTSB	Neutrino Target Service Building, see also TSB
NuMI	Neutrinos at the Main Injector
NW	Neutrino West
ODH	Oxygen Deficiency Hazard
ORC	Operational Readiness Clearance
OSHA	Occupational Safety and Health Administration
pCi	pico-Curie
pCi/mL	pico-Curie per milliliter
PE	Professional Engineer
PIN	Personal Identification Number
PIP	Proton Improvement Plan
PIP-II	Proton Improvement Plan - II
PHAR	Preliminary Hazards Analysis Report
PPD	Particle Physics Directorate
PPE	Personnel Protective Equipment
QA	Quality Assurance
QAM	Quality Assurance Manual
RA	Radiation Area
RAF	Radionuclide Analysis Facility
RAW	Radioactive Water
RCT	Radiological Control Technician
RF	Radio-Frequency
RFQ	Radio-Frequency Quadrupole
RIL	RFQ Injector Line
RMA	Radioactive Material Area
RMS	Root Mean Square
RPCF	Radiation Physics Calibration Facility
RPE	Radiation Physics Engineering Department
RPO	Radiation Physics Operations Department
RRM	Repetition Rate Monitor
RSI	Reviewed Safety Issue
RSIS	Radiation Safety Interlock System
RSO	Radiation Safety Officer
RWP	Radiological Work Permit
SA	Shielding Assessment
SAA	Satellite Accumulation Areas
SAD	Safety Assessment Document

SCF	Standard Cubic Feet
SCFH	Standard Cubic Feet per Hour
SEWS	Site-Wide Emergency Warning System
SNS	Spallation Neutron Source
SR	Survey Riser
SRF	Superconducting Radio-Frequency
SRSO	Senior Radiation Safety Officer
SSB	Switchyard Service Building
SSP	Site Security Plan
SWIC	Segmented Wire Ionization Chambers
TLM	Total Loss Monitor
TLVs	Threshold Limit Values
TPC	Time Projection Chamber
TPES	Target Pile Evaporator Stack
TPL	Tagged Photon Lab
TSB	Target Service Building, see also NTSB
TSCA	Toxic Substances Control Act
TSW	Technical Scope of Work
T&I	Test and Instrumentation
UPB	Utility Plant Building
UPS	Uninterruptible Power Supply
USI	Unreviewed Safety Issue
VCTF	Vertical Cavity Test Facility
VHRA	Very High Radiation Area
VMS	Village Machine Shop
VMTF	Vertical Magnet Test Facility
VTS	Vertical Test Stand
WSHP	Worker Safety and Health Program
μs	micro-second

III-7. Main Injector and Recycler

III-7.1. Introduction

This Section 03, Chapter 07 of the Fermi National Accelerator Laboratory (Fermilab) Safety Assessment Document (SAD) covers the Main Injector & Recycler segment of the Fermilab Main Accelerator.

III-7.1.1 Purpose/Function

The MI provides a primary proton beam to various end-users from 8 Giga-electron volt (GeV) and at higher energies up to 120 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 can currently provide 5.5×10^{13} protons/pulse, at a 1.067 second cycle time, for an hourly intensity of 1.86×10^{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 and to the Muon facility.

III-7.1.2 Current Status

The Main Injector & Recycler segment of the Fermilab Main Accelerator is currently: Operational.

III-7.1.3 Description

The MI/Recycler enclosure is approximately 3319 meters in circumference.

The Recycler accelerator is comprised of permanent combined function magnets that provide both bending and focusing forces to the proton beam. RF cavities are used to capture and manipulate the beam structure to accommodate the downstream machines. There are many trim magnets in this machine that are used to control the orbit of the beam around the accelerator and to control the higher order effects.

The Main Injector accelerator uses electromagnets to provide the bending and focusing forces for the accelerator. RF systems are used for acceleration of the beam. There are many trim magnets in this machine that are used to control the orbit of the beam around the accelerator and to control the higher order effects.

III-7.1.4 Location

The Main Injector & Recycler is located on the Fermilab site in Batavia, IL.

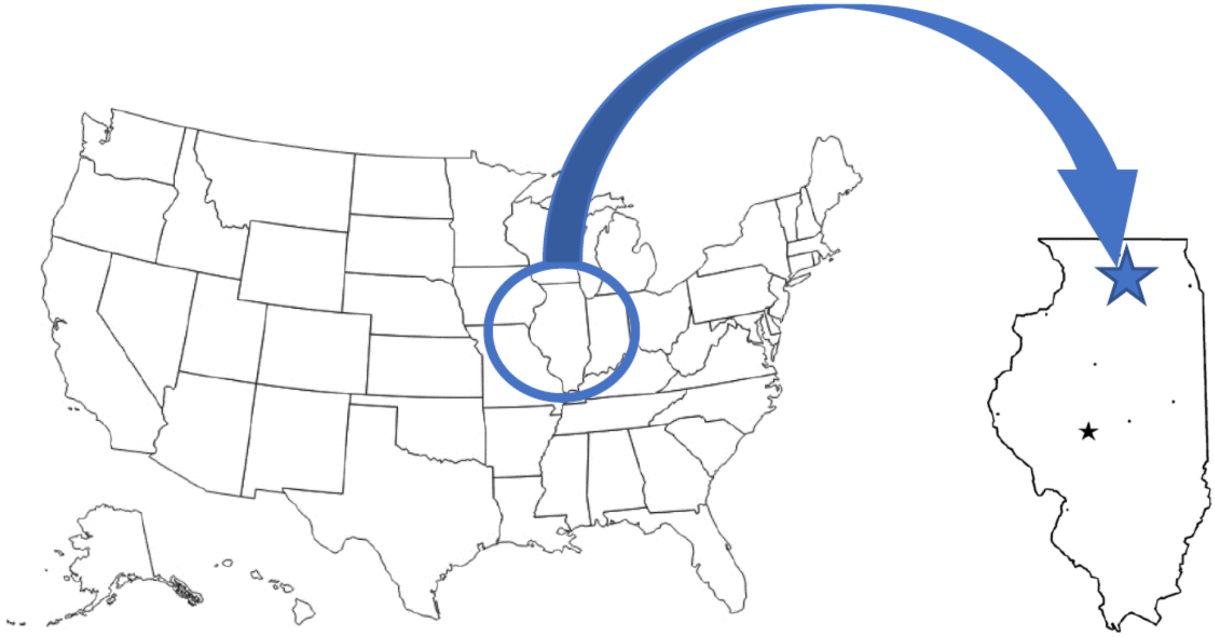

Figure 1. Regional view showing the location of the Fermilab site in Batavia, IL.

The Main Injector & Recycler are located in the located south of 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.

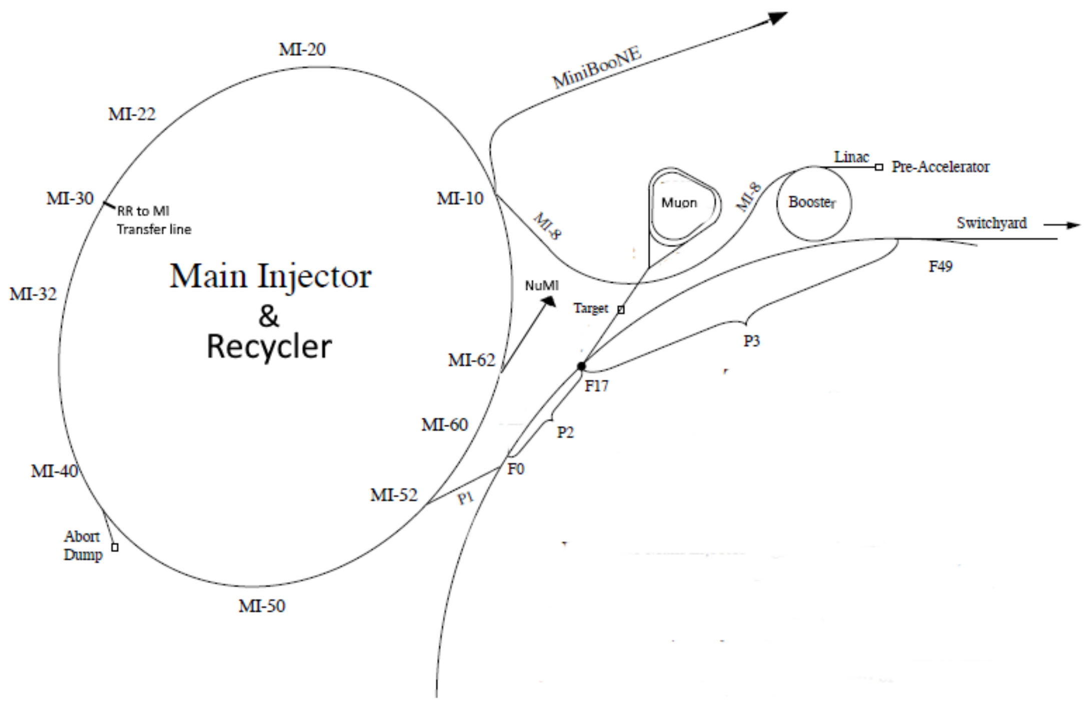

Figure 2 Main Injector Accelerator Layout and Associated Beam Lines

III-7.1.5 Management Organization

The Main Injector & Recycler are managed by the Accelerator Directorate, Main Injector department. Various support departments assist in operations and maintenance such as: Operations Department, Mechanical support, Power Electronics Systems Department, Survey and Alignment, Safety, and Infrastructure Services Division (ISD).

III-7.1.6 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. The MI40 abort is also used by the gap clearing kickers to remove the out of bucket beam (DC beam) that drifts into the kicker gap.

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 Muon area, 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 experimental areas over a several second duration. 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 120 GeV where the Recycler beam energy is fixed at 8 GeV.

III-7.1.7 Inventory of Hazards

The following table lists all of the identified hazards found in the Main Injector & Recycler enclosure and support buildings. Section III-7.9 *Appendix – Risk Tables describes* the baseline risk (i.e., unmitigated risk), any preventative controls and/or mitigative controls in place to reduce the risk, and residual risk (i.e., mitigated risk) for facility worker, co-located worker and Maximally Exposed Offsite Individual (MOI) (i.e., members of the public). A summary of these controls is described within Section I.1.4 *Safety Assessment*.

Prompt ionizing radiation and Oxygen Deficiency Hazards due to cryogenic systems within accelerator enclosures that is subject to particle beam have been identified as accelerator specific hazards, and as such their controls are identified as Credited Controls. The analysis of these hazards and their Credited Controls will be discussed within this SAD Chapter, and their Credited Controls summarized in the Accelerator Safety Envelope for the Main Injector & Recycler Accelerator specific controls are identified as **purple/bold** throughout this Chapter.

All other hazards present in the Main Injector & Recycler are safely managed by other DOE approved applicable safety and health programs and/or processes, and their analyses have been performed according to applicable DOE requirements as flowed down through the Fermilab Environment, Safety and Health Manual (FESHM). These hazards are considered to be Non-Accelerator-Specific Hazards (NASH), and their analysis will be summarized in this SAD Chapter.

Table 1. Hazard Inventory for Main Injector & Recycler

	Radiological		Toxic Materials
☒	**Prompt Ionizing Radiation**	☒	Lead
☒	Residual Activation	☒	Beryllium
☒	Groundwater Activation	☒	Fluorinert & Its Byproducts
☒	Surface Water Activation	☐	Liquid Scintillator Oil
☒	Radioactive Water (RAW) Systems	☐	Ammonia
☒	Air Activation	☐	Nanoparticle Exposures
☐	Closed Loop Air Cooling		**Flammables and Combustibles**
☒	Soil Interactions	☒	Combustible Materials (e.g., cables, wood cribbing, etc.)
☒	Radioactive Waste	☒	Flammable Materials (e.g., flammable gas, cleaning materials, etc.)
☒	Contamination		**Electrical Energy**
☒	Beryllium-7	☒	Stored Energy Exposure
☐	Radioactive Sources	☒	High Voltage Exposure
☐	Nuclear Material	☒	Low Voltage, High Current Exposure
☐	Radiation Generating Devices (RGDs)		**Kinetic Energy**
☒	Non-Ionizing Radiation Hazards	☒	Power Tools
	Thermal Energy	☒	Pumps and Motors
☒	Bakeouts	☒	Motion Tables
☒	Hot Work	☒	Mobile Shielding
☐	**Cryogenics**		**Magnetic Fields**
	Potential Energy	☒	Fringe Fields
☒	Crane Operations		**Other Hazards**
☒	Compressed Gasses	☒	Confined Spaces
☒	Vacuum/Pressure Vessels/Piping	☒	Noise
☒	Vacuum Pumps	☒	Silica
☒	Material Handling	☒	Ergonomics
	Access & Egress	☐	Asbestos
☒	Life Safety Egress	☒	Working at Heights

III-7.2. Safety Assessment

All hazards for the Main Injector & Recycler segment of the Fermilab Main Accelerator are summarized in this section, with additional details of the analyses for accelerator specific hazards.

III-7.2.1 Radiological Hazards

The Main Injector & Recycler presents radiological hazards in the form of: Prompt Ionizing Radiation, Residual Activation, Groundwater Activation, Surface Water Activation, Radioactive Water (RAW) Systems, Air Activation, Soil Interactions, Radioactive Waste, Contamination, Beryllium-7, Non-Ionizing Radiation Hazards. A detailed shielding assessment [1] and post assessment documents [2] addresses these hazards and provide a detailed analysis of the facility demonstrating the required shielding, controls and interlocks to comply with the Fermilab Radiological Control Manual (FRCM)[3].

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. 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 F-Sector enclosures, and the MI-40 absorber. This assessment also includes the NuMI transfer line starting at the extraction Lambertson (Lam62) and progressing toward the NuMI beamline to the Orc gate located at the NuMI 112 location.

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.

Unmitigated radiological risks for the Main Injector & Recycler are a level I risk. After mitigation all risks have been reduced to a level III or IV, (risk tables 11.1-11.3).

III-7.2.1.1 Prompt Ionizing Radiation

Prompt ionizing radiation is the principal 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. Operation of the area conforms to the FRCM to maintain exposures for operating personnel as low as reasonably achievable (ALARA).

This hazard has been evaluated via a Maximum Credible Incident (MCI) analysis that is described in Section III-7.3.1.1. This analysis specifies that Fermilab uses Credited Controls that flow down to the Accelerator Safety Envelope (ASE) to mitigate the consequences of the MCI to at or below the acceptable dose levels described in SAD Section I Chapter 4. A detailed description of each of the Credited Controls and their function is provided in Section III-7.4. The conclusion of these analyses is that the mitigated dose level associated with prompt ionizing radiation due to beam loss is acceptable.

III-7.2.1.2 Residual Activation

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.

Each of the MI/RR 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 Radiation Protection Group under the direction of the Radiation Safety Officer (RSO).

III-7.2.1.3 Groundwater Activation

It is assumed that beam loss around the Main Injector is primarily limited to injection/extraction locations distributed around the beamline and the abort absorber near MI-40. Of the injection/extraction locations, routine radiation surveys indicate that losses are highest at the collimators near MI-30.

^{3}H (tritium), a radioisotope of hydrogen, is biologically most hazardous when in the form of tritiated water. The US Environmental Protection Agency (EPA) sets the maximum contamination levels for the groundwater at 20 pCi/ml for tritium and 0.4 pCi/ml for ^{22}Na. However, because of the State of Illinois “non-degradation of a natural resource” requirement [35 IAC 620-392(C)], the limits used for this calculation are the regulatory standard detection levels [40 CFR Part 141.25], which are 1 pCi/ml for tritium and 0.04 for ^{22}Na. Below these levels, these radionuclides are considered “non-detectable”. Due to the presence of under-drains around the entire Main Injector, the majority of potentially radioactivated water is collected and released to surface waters. Since this fact is not considered in the groundwater analyses, their estimated radioactivity levels are conservative upper limits.

The annual limits for ^{3}H and ^{22}Na with respect to surface water and groundwater are given in Table 1. The 1500 kW estimates for surface and ground waters show that a distributed beam loss of 3.63×10^{19} protons during a year of operation will produce ^{3}H and ^{22}Na concentrations combined that account for 1.3% of the annual surface water limit if sump pumps discharge to the surface once per week and 0.1% of the groundwater limit, as shown in MI 1500 kW Distributed Groundwater and Surface Water 03-06-18 (Attachment G).

The 1500 kW estimates for surface and ground waters show that 1.56×10^{19} protons sent to the MI-40 abort during a year of operation will produce ^{3}H and ^{22}Na concentrations combined that account for 0.01% of the annual surface water limit if sump pumps discharge to the surface once per week and a negligible groundwater concentration to the aquifer, as shown in MI 1500 kW ABORT Groundwater and Surface Water 03-06-18 (Attachment H).

Table 1: Surface Water and Groundwater Summary

Description	**Annual Concentration Limits (pCi/ml)**		**Annual Concentration Estimate (pCi/ml)**		**Fraction of Annual Limit**
	^{3}H	**^{22}Na**	**^{3}H**	**^{22}Na**	**$^{3}H + ^{22}Na$**
Surface Water (Distributed)	1900	10	69	6.2	1.3×10^{-2}
Groundwater (Distributed)	1	0.04	5.8×10^{-4}	1.8×10^{-5}	1.0×10^{-3}
Surface Water (Abort)	1900	10	0.77	0.07	1.4×10^{-4}

Groundwater (Abort)	1	0.04	1.1×10^{-6}	3.4×10^{-8}	1.9×10^{-6}

Groundwater is sampled annually as part of the ES&H Division Environmental Monitoring Program and the surface water sampling locations and frequency are documented in ES&H RPO Routine Monitoring Programs.

III-7.2.1.4 Surface Water Activation

It is assumed that beam loss around the Main Injector is primarily limited to injection/extraction locations distributed around the beamline and the abort absorber near MI-40. Of the injection/extraction locations, routine radiation surveys indicate that losses are highest at the collimators near MI-30.

Surface water activation details are discussed in the above section Groundwater Activation (III-7.2.1.3)

Sump sample trending reports from the Main Injector indicate surface water concentrations less than 5 pCi/ml from CY 2015 to CY 2017 when average beam power was less than 700 kW.

Groundwater is sampled annually as part of the ESH Division Environmental Monitoring Program and the surface water sampling locations and frequency are documented in ES&H RPO Routine Monitoring Programs.

III-7.2.1.5 Radioactive Water (RAW) Systems

Radioactive Water in the Main Injector is located at the MI40 abort absorber. The water in this system is closed loop and does not flow into other systems. This water is heat exchanged with the Main Injector LCW system. This area is locked within the enclosure to prevent general access. The absorber room has containment to prevent this RAW from leaving the room in the event of an LCW leak.

III-7.2.1.6 Air Activation

The Main Injector has six major air supplies and six air exhaust vents. Each supply point flows 5000 cubic feet per minute of fresh air into the tunnel and, because of this, the concentration of the air activity at any exhaust location is below the level of detection. Therefore, the annual emission is estimated based on the annual proton beam loss rates. In the lab's annual emissions reports, Main Injector emissions are reported as an unmonitored source.

The yearly scaled estimate for 1500 kW operation based on an expected annual 3% beam loss is 5.19×10^{19} protons from a total of 1.73×10^{21} protons delivered, resulting in approximately 35 Ci being released from the Main Injector. Such a release would be a reasonable addition to the overall integrated Fermilab yearly site discharge of approximately 200 Ci.

The MI-40 Absorber Room Ventilation Stack is locked off with a Radiation Safety Officer (RSO) padlock and is not allowed to operate during beam transport. Since activated air created in the absorber room is not exhausted locally, it mixes with enclosure air after an increased transit time and is eventually exhausted at other locations.

III-7.2.1.7 Closed Loop Air Cooling

Hazard not applicable to the Main Injector & Recycler enclosures

III-7.2.1.8 Soil Interactions

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. 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. 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.

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. 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)[4].

III-7.2.1.9 Radioactive Waste

Radioactive waste produced in the course of Main Injector & Recycler operations will be managed within the established Radiological Protection Program (RPP) and as prescribed in the Fermilab Radiological Control Manual (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 Main Injector & Recycler 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.

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.

III-7.2.1.10 Contamination

Activated dust and debris within the Main Injector & Recycler enclosure results in spreadable material. This hazard is controlled using decontamination practices, PPE, radiations surveys, signs, and barriers.

III-7.2.1.11 Beryllium-7

7Be is produced in areas with high beam losses, such as the collimation area, due to interactions with air. 7Be decays through the electron capture process and only 10% of the decays produce a gamma ray that is hazardous to the worker. This makes the 7Be contamination undetectable to our field survey equipment. The areas that have been measured positive for 7Be are roped off and special access requirements are put in place.

III-7.2.1.12 Radioactive Sources

Hazard not applicable to the Main Injector & Recycler enclosure.

III-7.2.1.13 Nuclear Material

Hazard not applicable to the Main Injector & Recycler enclosure.

III-7.2.1.14 Radiation Generating Devices (RGDs)

Hazard not applicable to the Main Injector & Recycler enclosure.

III-7.2.1.15 Non-Ionizing Radiation Hazards

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard due to RF in the MI-60 and MI-30 areas implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.2 Toxic Materials

Hazard not applicable to the Main Injector & Recycler enclosure.

III-7.2.2.1 Lead

The primary lead hazard is in the form of lead solder from older electronics still in use. Lead radiation shielding is used in several areas in the Main Injector, typically in the form of encased lead blankets. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.2.2 Beryllium

Beryllium has been used for vacuum windows in the past. These windows have been replaced however, there are still areas where beryllium contamination may be present. These areas are clearly marked in the tunnel. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.2.3 Fluorinert & Its Byproducts

Fluorinert is used in the MI/RR for cooling of kickers. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.2.4 Liquid Scintillator Oil

Hazard not applicable to the Main Injector & Recycler enclosure.

III-7.2.2.5 Ammonia

Hazard not applicable to the Main Injector & Recycler enclosure.

III-7.2.2.6 Nanoparticle Exposures

Hazard not applicable to the Main Injector & Recycler enclosure.

III-7.2.3 Flammables and Combustibles

The MI/ RR has limited amounts of these hazards. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.3.1 Combustible Materials

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.3.2 Flammable Materials

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.4 Electrical Energy

Electrical hazards are controlled by the MI/RR LOTO procedures. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.4.1 Stored Energy Exposure

Electrical hazards are controlled by the MI/RR LOTO procedures. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.4.2 High Voltage Exposure

Electrical hazards are controlled by the MI/RR LOTO procedures. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.4.3 Low Voltage, High Current Exposure

Electrical hazards are controlled by the MI/RR LOTO procedures. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.5 Thermal Energy

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.5.1 Bakeouts

Bakeout areas are controlled by barriers, signage, and flashing lights. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.5.2 Hot Work

Qualified welders occasionally work in the MI/RR tunnel to repair waterlines and other metalwork. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.5.3 Cryogenics

Hazard not applicable to the Main Injector & Recycler enclosure.

III-7.2.6 Kinetic Energy

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.6.1 Power Tools

Power tools are commonly used when working on MI/RR equipment in the gallery and tunnel. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.6.2 Pumps and Motors

Standard industrial pumps and motors are utilized throughout the MI/RR area for water cooling and vacuum systems. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.6.3 Motion Tables

Technicians use mechanical motion tables to install equipment and improve ergonomics when conducting maintenance or repairs. This hazard has been evaluated within the common Risk Matrix table included in

SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.6.4 Mobile Shielding

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.7 Potential Energy

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.7.1 Crane Operations

Trained technicians utilize various hoists lifts, and bridge cranes to move, maintain, and install equipment in the MI/RR gallery and tunnel. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.7.2 Compressed Gasses

Compressed nitrogen, and argon are present in MI/RR areas to facilitate machine operations. Compressed gas cylinders are stored, used, and moved throughout the MI/RR gallery and tunnel. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.7.3 Vacuum/Pressure Vessels/Piping

Vacuum vessels are present in MI/RR in the form of beam pipes, RF cavities, power amplifier tubes, and other beamline components. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use. MI/RR has a number of air compressor tanks which are pressure vessels. They are located in the service buildings. Fermilab follows the rules laid out in FESHM Chapter 5031. This chapter points to the ASME BPVC (Boiler and Pressure Vessel Code) Section VIII (Division 1 or Division 2) for compliance.

III-7.2.7.4 Vacuum Pumps

Vacuum pumps are used throughout the MI/RR to maintain vacuum on beamline and RF generating components. This hazard has been evaluated within the common Risk Matrix table included in SAD Section

I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.7.5 Material Handling

Trained personnel operate forklifts, stackers, and hand carts to move materials throughout the MI/RR area. Additionally, heavy equipment may be moved short distances utilizing team lifts. Individual lifting is limited to items 50 pounds or less. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.8 Magnetic Fields

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.8.1 Fringe Fields

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.9 Other Hazards

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.9.1 Confined Spaces

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.9.2 Noise

Operating cooling water systems creates a potential noise hazard in the MI/RR gallery and tunnel. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.9.3 Silica

Silica dust may be created when drilling into concrete floors or walls. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the

Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.9.4 Ergonomics

Work involving the MI/RR accelerators may involve sitting or standing for long periods of time, repetitive motion, cramped conditions, and other ergonomic concerns. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.9.5 Asbestos

Hazard not applicable to the Main Injector & Recycler enclosure.

III-7.2.9.6 Working at Heights

MI/RR technicians utilize ladders, step stools, and mobile work platforms to conduct maintenance in MI/RR areas. Utilizing fall protection equipment, trained personnel may work on top of equipment where there is a chance of falling. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.10 Access & Egress

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.10.1 Life Safety Egress

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.11 Environmental

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.11.1 Hazard to Air

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.11.2 Hazard to Water

Transformer oil found in MI/RR has the potential to leak or spill and spread contamination. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.2.11.3 Hazard to Soil

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Main Injector & Recycler enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-7.3. Maximum Credible Incident Scenario(s) for the Accelerator Specific Hazard(s)

III-7.3.1 Definition of a Maximum Credible Incident

This section of the MI/RR SAD evaluates the maximum credible incident (MCI) scenario that could happen in the lifetime of the MI/RR. Consideration and analysis of this MCI is focused on an onsite facility worker, onsite co-located worker, and a maximally exposed off-site individual (MOI).

III-7.3.1.1 Radiological Hazard

The MI/RR are designed to transport and accelerate protons to downstream machines. There are many devices in these accelerators that accelerate, focus, and shape the beam pulses to ensure that a maximum number of protons reach the intended destination. Misdirection of this beam so that it impacts surrounding structures inside the accelerator enclosure can occur from a single failure of many of these devices or erroneous operation of them. An MCI would be one that produces the greatest prompt ionizing radiation from the beam loss.

There are effectively an infinite number of individual beam loss events that can be postulated. The energy of these accelerators ranges between 8 and 120 GeV. The accelerators receive beam from the Booster accelerator at a maximum rate of 15Hz and a maximum intensity of 7E12 protons per pulse. Beam loss can occur at any energy, but the MCI for these accelerators will be that of 120 GeV beam loss. These accelerators are capable of delivering 12 Booster batches of 120 GeV beam every 1.067 seconds. Using these parameters and 100% transmission efficiency in the accelerators gives us:

12[Booster batches/MI cycle] * 7E12[protons/batch] * 3600[seconds/hr] / 1.067[seconds/MI cycle] = 2.83E17 protons per hour.

This analysis concludes that the maximum credible incident for the Fermilab MI/RR is a beam with an intensity of 2.83E17 protons per hour at an energy of 120 GeV persistently incident on a beamline component for one hour.

Event Causes:

1. The Booster accelerator is delivering beam with intensity of 7E12 protons per pulse.
2. Beam transmission through the MI8 beamline, Recycler, and Main Injector is 100%.
3. Beam mis-steered at 120 GeV continually via any of the following events:

a. Failed magnet.
b. Operator error.
c. Autotune error.

Assuming no shielding is present, this incident would result in a dose to any individual higher than 5.23E7 rem. The result is that the uncontrolled baseline qualitative risk level associated with this accident is not acceptable.

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

- Less than 500 mrem in one hour in all Laboratory areas to which the public is assumed to be excluded
- Less than 100 mrem in one hour at Fermilab's site boundary and/or in any areas onsite in which the public is authorized (which includes Batavia Road, Prairie Path, parking lots open to the public, and general access areas including Wilson Hall, Ramsey Auditorium.
- Less than 5 rem in one hour in any area accessible by facility workers or co-located workers

These credited controls are discussed in Section III-7.4.

The accumulated dose outside of the shielding on the Main Injector berm is mitigated, by use of Credited Controls, to less than 500 mrem in an MCI. The closest possible location of a member of the public to the MI/RR enclosure is the site boundary. This location is more than five feet away from the berm, which would result in dose of less than 100 mrem applying a conservative dose reduction of 1/r.

III-7.4. Summary of Credited Controls

This section describes the credited controls that are required to reduce the risk associated with the maximum credible incident to a negligible consequence level.

III-7.4.1 Credited Engineering Controls

The purpose of this section is to provide the information necessary to understand the engineering controls that are used to prevent or mitigate the consequences of the maximum credible incident. Engineering controls can be classified as passive or active. This section presents a separate discussion of the engineering controls that fall under each classification.

III-7.4.1.1 Passive Credited Controls

Passive controls are elements of facility design that require no action to function properly. These are fixed elements of the beam line that take direct human intervention to remove. The MI/RR enclosure is designed and constructed as a permanent concrete and earth-covered radiation shield that uses a combination of permanent shielding, movable shielding, and penetration shielding to protect personnel from radiological exposure due to the MCI.

III-7.4.1.1.1 Permanent Shielding

Permanent shielding encompasses the structural elements surrounding the beam line components and extraction lines.

This includes the walls, ceilings, doors, berms, shielding labyrinths and shielding blocks. Topographical surveys of the MI/RR enclosure and berm conclude that there is a minimum of 21.6 Equivalent Feet of Dirt (e.f.d.) shielding between the interior surface of the enclosure walls and the surface of the berm.

The efficacy of this permanent shielding has been quantitatively analyzed and constructed to simulate the MCI as defined in Section III-7.3.1.1. This analysis finds that, under the conditions present in the MCI, a peak dose rate of 500mrem/hr would occur on the berm on the MI/RR which is a non-public area of the campus. In this condition, a MOI would receive a dose of 500 mrem in one hour if there were 20.7 e.f.d.

The credited control for the permanent shielding is thus defined as 20.7 e.f.d. shielding between the interior surface of the enclosure walls and the surface of the berm. As mentioned above, the MI/RR enclosure has 21.6 e.f.d. The credited shielding present on the berm of the MI/RR enclosure is therefore adequate to protect the MOI from receiving a dose of 500 mrem of dose in an hour under an MCI condition.

III-7.4.1.1.2 Movable Shielding

The MI/RR has no movable shielding to the outside areas. There are concrete blocks that separate the MI/RR enclosure from the F0 enclosure along the P1 line and the decommissioned A1 line. There are also concrete blocks that shield the MI31 service building from the decommissioned Pelletron beam line. These concrete block walls are considered permanent shielding.

III-7.4.1.1.3 Penetration Shielding

The Main Injector has sight riser penetrations which are used for survey and alignment to connect the survey network in the tunnel to the outside. These penetrations have been analyzed and filled with steel plugs and poly beads to provide the required shielding to keep the MCI below the 500mr limit.

Table 2: Credited penetration shielding

Location	Shielding Type	Quantity	Purpose	Preferred Method of Configuration (if specified)	Comments
MI-609	Steel and Poly	1	Site Riser penetration		a steel cylinder 11 5/8” dia x 62 5/8” long followed by a poly bead plug 11” dia. x 30” long
MI-601	Steel and Poly	1	Site Riser penetration		a steel cylinder 11 5/8” dia x 62 5/8” long

					followed by a poly bead plug 11" dia. x 30" long
MI-116.5	Steel and Poly	1	Site Riser penetration		a steel cylinder 11 5/8" dia x 62 5/8" long followed by a poly bead plug 11" dia. x 30" long
MI-633	Steel and Poly	1	Site Riser penetration		a steel cylinder 11 5/8" dia x 62 5/8" long followed by a poly bead plug 11" dia. x 30" long
MI-207	Steel and Poly	1	Site Riser penetration		a steel cylinder 11"dia. X 8' long followed by a poly bead plug 12" dia. X 3' long
MI-301	Steel and Poly	1	Site Riser penetration		a steel cylinder 11"dia. X 8' long followed by a poly bead plug 12" dia. X 3' long
MI-309	Steel and Poly	1	Site Riser penetration		a steel cylinder 11"dia. X 8' long followed by a poly bead plug 12" dia. X 3' long
MI-332	Steel and Poly	1	Site Riser penetration		a steel cylinder 11"dia. X 8' long followed by a poly bead plug 12" dia. X 3' long
MI-416	Steel and Poly	1	Site Riser penetration		a steel cylinder 11"dia. X 8' long followed by a poly bead plug 12" dia. X 3' long
MI-507	Steel and Poly	1	Site Riser penetration		a steel cylinder 11"dia. X 8' long followed by a poly bead plug 12" dia. X 3' long

Shielding is present in many penetrations from the MI/RR service buildings to the tunnel when exposure to prompt dose has been evaluated to be a concern to workers. This shielding is in the form of sandbags, poly beads, and poly blocks.

MI-10 SB	Solid Poly & Poly Beads	6" thick solid poly box filled >24" deep with poly beads	Bus penetrations from SB crossover to tunnel alcove	Surrounded by aluminum enclosure	See PPH3-AIP08
MI-10 SB	Poly Beads	> 4' depth	Fill annulus between four 12" dia. carrier penetrations and LCW pipes		See PPH3-AIP09
MI-20 SB	Poly Beads	> 4' depth	Fill annulus between four 12" dia. carrier penetrations and LCW pipes	labels	See PPH3-AIP10
MI-20 SB	Solid Poly & Poly Beads	6" thick solid poly box filled >24" deep with poly beads	Bus penetrations from SB crossover to tunnel alcove	Surrounded by aluminum enclosure	See PPH3-AIP11
MI-30 SB	Solid Poly & Poly Beads	6" thick solid poly box filled >24" deep with poly beads	Bus penetrations from SB crossover to tunnel alcove	Surrounded by aluminum enclosure	See PPH3-AIP12
MI-30 SB	Poly Beads	> 4' depth	Fill annulus between four 12" dia. carrier penetrations and LCW pipes	labels	See PPH3-AIP13
MI-40 SB	Solid Poly & Poly Beads	6" thick solid poly box filled >24" deep with poly beads	Bus penetrations from SB crossover to tunnel alcove	Surrounded by aluminum enclosure	See PPH3-AIP14
MI-40 SB	Poly Beads	> 4' depth	Fill annulus between four 12" dia. carrier penetrations and LCW pipes	labels	See PPH3-AIP15
MI-50 SB	Solid Poly & Poly Beads	6" thick solid poly box filled >24" deep with poly beads	Bus penetrations from SB crossover to tunnel alcove	Surrounded by aluminum enclosure	See PPH3-AIP16
MI-50 SB	Poly Beads	> 4' depth	Fill annulus between four 12" dia. carrier penetrations and LCW pipes	labels	See PPH3-AIP17
MI-52 SB	Solid Poly & Poly Beads	6" thick solid poly box filled >24" deep with poly beads	Bus penetrations from SB crossover to tunnel alcove	Surrounded by aluminum enclosure	See PPH3-AIP18
MI-52 SB	Poly Beads	> 4' depth	Fill one empty and annulus between three 12" dia. carrier	labels	See PPH3-AIP19

			penetrations and LCW pipes		
MI-62 SB	Poly Beads	> 4' depth	Fill one empty and annulus between three 12" dia. carrier penetrations and LCW pipes	labels	See PPH3-AIP20
MI-31 Stub	Steel & Concrete	Many rods & blocks	Protect MI-31 from MI & Recycler		6' long steel rods inside two 6" dia. e-cooling carrier pipes & two 2' thick concrete walls (one wall on each end); this is in addition to the 7' of steel & 4.5' of concrete that was there when e-cooling was in use
P150	Concrete & Poly Beads	Many blocks	Protect F-sector from Recycler losses		In P150 tunnel, voids filled with bags of poly beads
A150	Concrete & Poly Beads	Many blocks	Protect F-sector from Recycler losses		In A150 tunnel, voids filled with bags of poly beads

MI-60 SB	Steel & Solid Poly	20 assemblies	20 single-leg RF penetrations in MI-60 RF gallery		Does not include the unused RF penetrations
MI-60 SB	Steel & Solid Poly	1 assembly	Long 8" dia. LCW penetration		"#2"; in Room 118
MI-60 SB	Steel & Solid Poly	1 assembly	Long 8" dia. LCW penetration		"#5"; in RF gallery
MI-60 SB	Steel & Solid Poly	1 assembly	Long 8" dia. LCW penetration		"#3"; in RF gallery
MI-60 SB	Steel & Solid Poly	1 assembly	Long 10" dia. LCW penetration		"#6"; in RF gallery
MI-60 SB	Steel & Solid Poly	1 assembly	Long 10" dia. LCW penetration		"#4"; in RF gallery
MI-60 SB	Steel & Solid Poly	1 assembly	Long 8" dia. LCW penetration		"#1"; in corner of RF gallery
MI-60 SB	Steel & Solid Poly	1 assembly	Short 8" dia. LCW penetration		"#1"; in Room 118

MI-60 SB	Steel & Solid Poly	1 assembly	Short 8" dia. LCW penetration		"#2"; in corner of RF gallery
MI-60 SB	Steel & Solid Poly	1 assembly on cart	K145A & K145B penetrations in Room 117	PAD-118 lock on cart	Cart has attached chipmunk
MI-60 SB	Steel & Solid Poly	1 assembly on cart	RF5A & RF5B penetrations in Room 118	PAD-118 lock on cart	Cart has attached chipmunk
MI-60 SB	Gravel & Solid Poly	13.2' of gravel & 4" of poly	Unused RF32 penetration in MI-60 RF gallery		
MI-60 SB	Gravel & Solid Poly	15.1' of gravel & 6.5" of poly	Unused RF71 penetration in MI-60 RF gallery		
MI-60 SB	Gravel & Solid Poly	15.1' of gravel & 6.5" of poly	Unused RF114 penetration in MI-60 RF gallery		
MI-62 SB	Solid Poly	1' thick	Three unused bus penetrations		
MI-14 SB	Sand	At least 15.4' in penetration	Two unused single-leg penetrations (#1 & #2)	PAD-118, MI Enter, and Confined Space locks	Penetrations end in vault outside of MI-14 SB
MI-14 SB	Solid Poly & Poly Beads	>3' beads at bottom; 1' solid at top of 1st leg; vault filled with beads	Two penetrations (#3 & #4) into MI-14 SB	PAD-118, MI Enter, and Confined Space locks	Penetrations pass through vault outside of MI-14 SB
MI-39 SB	Sand	At least 15.8' in penetration	Two unused single-leg penetrations (#3 & #4)	PAD-118 and Confined Space locks	Penetrations end in vault outside of MI-39 SB
MI-39 SB	Poly Beads	3' beads at bottom; 3' of beads over penetrations in vault	Two penetrations (#1 & #2) into MI-39 SB	PAD-118 and Confined Space locks	Penetrations pass through vault outside of MI-39 SB

III-7.4.1.2 Active Credited Engineering Controls

Active engineered controls are systems designed to reduce the risks from the MCI to an acceptable level. The active controls in place for MI/RR operations are discussed below.

III-7.4.1.2.1 Radiation Safety Interlock System

The MI/Recycler enclosure is approximately 3319 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, F Sector, Muon Campus Transport, and MI-12A enclosures are properly secured and locked, and the area radiation monitors are made up.

The Radiation Safety Interlock System (RSIS) must prevent entry into the following Exclusion Area(s) during applicable beam operation:

- MI-10
- MI-20—MI62
- TeV F Sector
- MI/TeV Crossovers

Prior to accelerator operations, a Search and Secure is performed to establish the interlock system for the Exclusion Area(s). This Search and Secure ensures no personnel are remaining within the Exclusion Area(s) during accelerator operations.

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.

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.

III-7.4.2 Credited Administrative Controls

All MI/RR accelerator 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. The administrative procedures and programs considered necessary to ensure safe accelerator operations are discussed below.

III-7.4.2.1 Operation Authorization Document

For beam to be transported to the MI/RR enclosure, an approved Beam Permit and Running Conditions document is required. The Beam Permit specifies beam power limits as determined and approved by the AD Associate Laboratory Director, in consultation with the ES&H Radiation Physics Operations

Department Head, assigned RSO, AD Operations Department Head, and AD Main Injector Department Head. The Running Condition for the MI/RR describes the operating configuration as reviewed by the assigned RSO, AD Operations Department Head, and AD Main Injector Department Head and as approved by the AD Associate Laboratory Director.

III-7.4.2.2 Staffing

The MCR must be appropriately staffed according to ensure operations within bounding conditions specified in Operation Authorization Document, and to disable beam operation to the Linac and initiate an immediate response in the event of a determined ASE violation.

The following staffing shall be in place during applicable beam operation:

- At least one member of the AD Operations Department who has achieved the rank of Operator II or higher shall be on duty and on site.
- At least one member of the AD Operations Department shall be present in the Main Control Room (MCR).
- A single person could satisfy both of these conditions.

III-7.4.2.3 Accelerator Operating Parameters

To ensure operations within bounding conditions used in the MCI analysis, the following intensity shall not be exceeded: 2.83E17 protons/hr.

III-7.5. Summary of Defense-in-Depth Controls

The Fermilab MI/RR has additional controls in place that reduce the risk associated with the maximum credible incident, but that are not required to mitigate it. These controls are considered defense-in-depth, and they are defined in the following sections.

III-7.5.1 Defense-in-Depth Engineering Controls

III-7.5.1.1 Passive Defense-in-Depth Engineering Controls

III-7.5.1.1.1 Permanent Shielding

The defense-in-depth control for the permanent shielding is a minimum of 0.9 e.f.d. shielding, present in the MI/RR berm.

III-7.5.1.2 Active Defense-in-Depth Engineering Controls

Chipmunks are located within the MI/RR service building in areas to reduce the possible exposure to working personnel.

Table 3: Defense-in-depth radiation monitors

Type	Location
Chipmunk	MI-10 SB LCW
Chipmunk	MI-20 SB LCW
Chipmunk	MI-30 SB LCW
Chipmunk	MI-40 SB LCW
Chipmunk	MI-50 SB LCW
Chipmunk	MI-52 SB LCW
Chipmunk	MI-62 SB LCW
Chipmunk	MI-60 S Room 117 Pipe & BUS Pen
Chipmunk	MI-60 S Room 110 LCW Pens RF Gal
Chipmunk	MI-60 N Room 110 LCW Pens RF Gal
Chipmunk	MI-60 N Room 118 LCW Pen
Chipmunk	MI-60 N Room 118 Pen

III-7.5.1.2.1 Machine Protection Controls

Accelerator devices, such as loss monitors and power supplies, are connected to a beam permit system to ensure excessive beam loss does not occur. This beam permit system has approximately 200 available inputs to the system. The beam permit loop has been designed in a fail-safe manner and is capable of removing the beam from the accelerator and moving it to the abort absorber in approximately 50 us after detection of a fault in a system. The permit system also monitors the accelerator for potential problems before beam is injected and can detect a single lost pulse from booster limiting the total loss incident in the accelerator to a single Booster batch, defined in the MCI as 7E12.

The machine protection system consists of the following controls:

- Passive control:
    - Destruction of the accelerator components from high intensity beam
        - Beam pipe is 65 mills stainless steel and will melt when exposed to 1MW particle beam. The vacuum will breach. The accelerator will be let up to atmosphere stopping the incident.
- Alarms and Limits
    - Displayed in the MCR for operators. Some alarms require acknowledgement
- Orbit control and monitoring
    - Semi-automated tuning to keep the beam at desired positions. Some critical beam positions are connected to the permit system
    - Reduces beam loss, tunnel activation, and aids ALARA
- Low Conductivity Water (LCW) activation monitoring
    - Protected by chipmunks at the enclosure stairwells

- Accelerator Time-Line generator
  - Programmed timing for accelerator operations. Modules require approval prior to use
- Beam Switch Sum Box
  - Allows or prevents beam from the Linac based on requests from the TLG, Status of beam switches, and status of the beam permit system from all machines involved in the operation
- Beam transfer Permit system
  - Allows or inhibits beam transfers to accelerators. Beam present in an upstream machine will be sent to the Abort absorber
- Vacuum Interlock System
  - Requires vacuum in the accelerator to be adequate to contain the beam. Will close vacuum valves and trip the permit system if the vacuum is poor.
- Power Supply Permits and Regulation
  - Requires critical power supplies to be on with some monitored for regulation. Will trip the permit system if not at the desired configuration
- Beam Loss Monitor System
  - Provides information to operators tor control of beam losses, aids in ALARA
  - Used in conjunction with AI for pattern recognition to locate the source of a tuning problem or accelerator drift
  - Allows for the prediction of tunnel activation for WPC
  - Connected to the Beam Permit System
  - Monitors integrated beam loss through a cycle and if above limit, will drop the beam permit after extraction
  - Monitors instantaneous loss and if over the limit, will drop the beam permit immediately
  - **Limits the accident incident to a single pulse as opposed to the MCI of 3374 pulses**

III-7.5.1.3 Defense-in-Depth Administrative Controls

III-7.5.1.3.1 Training

All personnel engaged in the commissioning, operation, and emergency management of the MI/RR shall have at a minimum, Fermilab's Radiation Worker training current. Furthermore, personnel approved for access into the MI/RR interlocked enclosure shall have Fermilab's Controlled Access training current as well.

Equipment specific to the operation of the MI/RR shall be operated by or with the supervision of the corresponding expert, who ensures that the equipment is being used according to its specifications and unique safety measures.

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

III-7.5.1.3.2 Procedures

As applicable, either Fermilab's General Lock Out-Tag Out or Written Departmental Lock Out-Tag Out procedures shall be used. As per Fermilab's FESHM Chapter 2100, Written Departmental Safety procedures shall be reviewed and re-approved every twelve (12) months, at a minimum, or when the configuration of the equipment has been altered. Re-training for these procedures shall also be carried out every twelve (12) months to remain current.

III-7.6. Decommissioning

No decommissioning is planned in the near future for the Main Injector & Recycler enclosure. DOE Field Element Manager approval shall be obtained prior to the start of any decommissioning activities for Main Injector and Recycler.

III-7.7. 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.

III-7.8. References

[1] W. Higgins, et al., *MAIN INJECTOR 1500 kW Incremental Shielding Assessment*, May 2018.

[2] W. Higgins, *Shielding Analysis of New MI-113 Culvert and Demolition of MI-110 Culvert*, Nov 2020.

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

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

III-7.9. Appendix – Risk Matrices

Risk Assessment methodology was developed based on the methodology described in DOE-HDBK-1163-2020. Hazards and their potential events are evaluated for likelihood and potential consequence assuming no controls in place, which results in a baseline risk. A baseline risk (i.e., an unmitigated risk) value of III and IV does not require further controls based on the Handbook. Events with a baseline risk value of I or II do require prevention and/or mitigation measures to be established in order to reduce the risk value to an acceptable level of III or IV. Generally, preventive controls are applied prior to a loss event, reflecting a likelihood reduction, and mitigative controls are applied after a loss event, reflecting a consequence reduction. For each control put in place, likelihood or consequence can have a single "bin drop", resulting in a new residual risk (i.e., a mitigated risk). This risk assessment process is repeated for each hazard for Facility Workers (FW), Co-Located Workers (CLW), and Maximally-Exposed Offsite Individual (MOI). At the conclusion of the risk assessments, controls that are in place for the identified accelerator specific hazards are identified as Credited Controls and further summarized in Section III-7.4 of this Chapter as well as SAD Chapter VII-A.1 *Accelerator Safety Envelope – Fermilab Main Accelerator*.