MUON CAMPUS

SECTION III CHAPTER 10
OF THE FERMILAB SAD

Revision 2 January 20, 2024

This Chapter of the Fermilab Safety Assessment Document (SAD) contains a summary of the results of the Safety Analysis for the Muon Campus segment 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 10 of the Fermi National Accelerator Laboratory (Fermilab) Safety Assessment Document (SAD), *Muon Campus*, was prepared and reviewed by the staff of the Accelerator Directorate, Beams Division, External Beam Delivery 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 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
Jerry Annala	2	January 20, 2024	• Updated to align with updated SAD format • Expanded to include Risk Matrix and hazard discussion • Incorporation of Electrostatic septa operations • Incorporation of maximum credible incident for a radiological hazard and a description of the credited/defense-in-depth controls that mitigate it. • Updated Section III-10.1.3, Description of the Muon Campus
Jerry Annala Maddie Schoell	1	February 11, 2020	• Update of Muon Campus Chapter for addition of operating mode to transport beam to the Diagnostic Absorber in the M4 beamline. • Updated References
Jerry Annala John E. Anderson Jr.	0	February 2017	Initial release of the Muon Campus and g-2 Chapter for the Fermi National Accelerator Laboratory Safety Assessment Document (SAD)

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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
MCI	Maximum Credible Incident
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
NASH	Non-accelerator specific hazard
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-10. Muon Campus

III-10.1. Introduction

This Section III, Chapter 10 of the Fermi National Accelerator Laboratory (Fermilab) Safety Assessment Document (SAD) covers the Muon Campus segment of the Fermilab Main Accelerator.

III-10.1.1 Purpose/Function

The Muon Campus Area provides 3.1 GeV muons to the g-2 experimental apparatus, as well as 8 GeV protons to the Mu2e experiment. The accelerator is not capable of operating both experiments simultaneously, so the complex, described in the next sections, will be configured in one mode or the other. Although operating of g-2 calls for sending protons from the Recycler Ring to the AP-0 target where only 3.1 GeV secondary particles are captured, it is possible to bypass the target with the primary protons for commissioning and periodic tuning of the beamline and Delivery Ring (DR). For this reason, it is possible to operate with 8 GeV protons in a portion of the Muon Campus while in the g-2 configuration.

In the g-2 mode of operation, the AP-0 target accepts a pulsed primary proton beam of 8 GeV consisting of 1 x 10^{12} protons/pulse at an average repetition rate of 12 pulses per second. The pulse trains are structured in bursts of 8 pulses separated by 10 milliseconds. Two groups of 8 pulses strike the target every 1.4 seconds. 3.1 GeV secondary particles from the target are transported to and captured in the DR. After proton removal, 3.1 GeV muons are delivered to the g-2 experimental hall.

The Mu2e mode of operation is being commissioned in stages. The current stage of operation is limited to 13 watts of 8 GeV protons (3.60 x 10^{13} protons/hr). The proton beam bypasses the AP-0 target and is transported through the DR to the DR abort absorber or to the Diagnostic Absorber (DA) near the end of the M4 beam line. The beam may enter the M4 line as a single bunch, or as a pulse train driven by resonant extraction.

The magnet circuit that steers beam around the AP0 target is disabled when configured in the g-2 mode to prevent the higher beam power cycles from entering the downstream beam lines. The Mu2e cycles are repetition rate limited in the Timeline Generator hardware to ensure the frequency of commissioning cycles remains low.

The radiation protection throughout the Muon Campus will be upgraded in the future allowing up to 8 kW of beam, although only 170 watts will be allowed to be directed to the DA. When the Muon Campus is configured for beam to the Mu2e experiment, the primary proton delivery will consist of 8 pulses every 1.4 seconds at 8 GeV. This beam will be resonantly extracted from the DR and transported to the Mu2e target station. This version of the Safety Assessment Document only covers the initial stage of commissioning with 13 watts of beam delivered only as far as the DA in the M4 line. Until the beam power upgrades are complete and approved, safeguards will remain in place to limit the beam power of the 8 GeV beam cycles.

III-10.1.2 Current Status

The Muon Campus segment of the Fermilab Main Accelerator is currently: **operational**.

III-10.1.3 Description

The Muon Campus area consists of: 5 beamlines (named M1, M2, M3, M4 and M5) originating in the Tevatron tunnel at F17, a target station at AP-0, Delivery Ring (DR), six service buildings (named F23, AP-0, F27, AP-10, AP-30, and AP-50) and the two Muon Campus experimental areas (MC-1 and Mu2e Detector Hall). This chapter of the SAD covers the M1 beam line from the point it exits the Tevatron enclosure, and all other enclosures listed here up to the experimental equipment owned by g-2 and Mu2e. Figure 1 shows the location of these beamlines and buildings. The MC-1 building and Mu2e building are experimental halls but do contain some accelerator equipment.

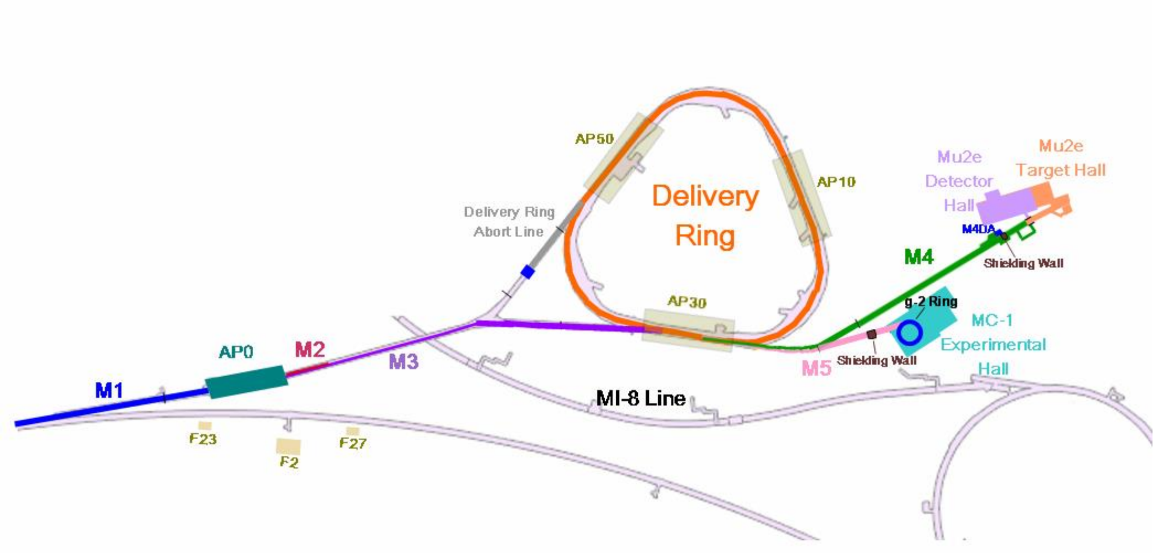


Figure 1. Muon Campus Layout and Associated Beamlines for g-2 and Mu2e Diagnostic Absorber Operation.

The M1 beamline begins in the Tevatron enclosure at F17 and runs through the Pre-Target and Pre-Vault enclosures to the AP-0 target. The M3 line splits from the M1 line just upstream of the AP-0 target. It runs around the target vault and meets the DR under the AP-30 service building. This beamline is 309 meters in length and is comprised of 100 magnets. The M2 beamline begins downstream of the AP-0 target and runs 50 meters where it merges with the M3 beamline.

The DR is essentially the repurposed Debuncher ring formerly used for the Tevatron Collider. The DR is 500 meters in circumference and has beam transfer inserts for injection, extraction, and the abort. The end of the old AP-2 injection line is used to transport beam from the DR to the DR abort. The physical enclosures for all beamlines mentioned to this point are unchanged from the former Tevatron Collider Antiproton Source operation.

The Extraction Enclosure and M4 Enclosure are new beam enclosures that house the M4 beamline, and most of the M5 beamline. The M4 line exits the DR under the AP-30 service building and runs through these two enclosures to the Mu2e experiment enclosure.

The M4 line has a branch point just 30 meters downstream of the DR. At that point the M5 line splits from the M4 line and runs to the g-2 storage ring in the MC-1 Enclosure. The MC-1 building is covered in Section IV Chapter 8, Muon g-2 Storage Ring, of the Fermilab SAD.

50 meters upstream of the Mu2e enclosure, there is a horizontal dipole that can direct beam into a 22-meter-long beamline that terminates at the DA. Beam is prevented from being transported to the Mu2e enclosure during the DA commissioning phase by two beam stops upstream of the shield wall in the M4 beamline that will remain closed. The Mu2e Experimental Hall SAD Chapter will be developed before beam commissioning to the Mu2e experiment.

III-10.1.4 Location

The Muon Campus of the Fermilab Main Accelerator is located on the Fermilab site in Batavia, IL.

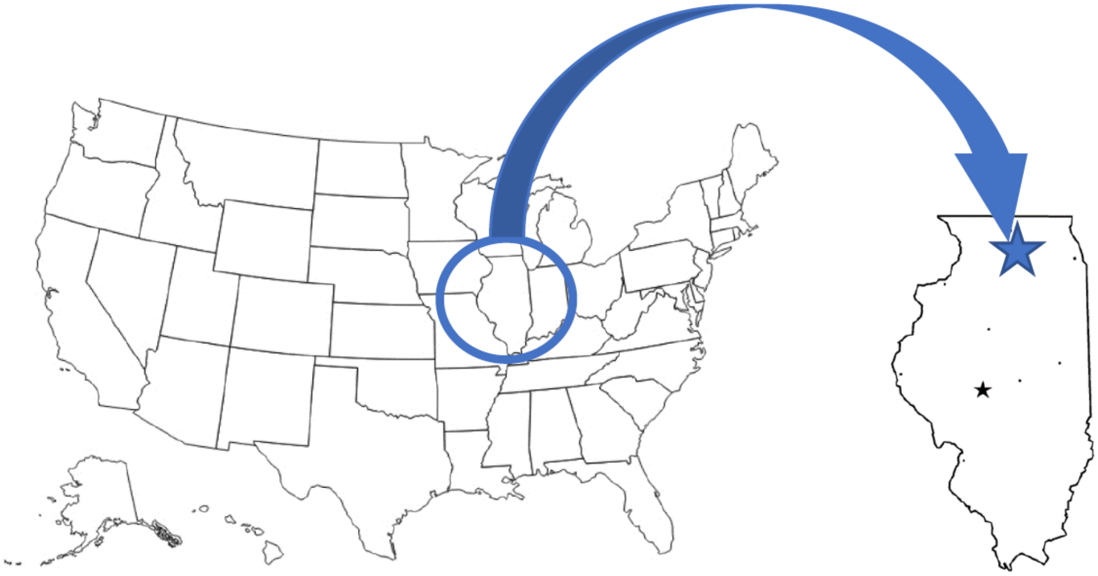


Figure 2. Regional view showing the location of the Fermilab site in Batavia, IL.

The Muon Campus is located west of the Tevatron enclosure between the Booster and Main Injector on the Fermilab site.

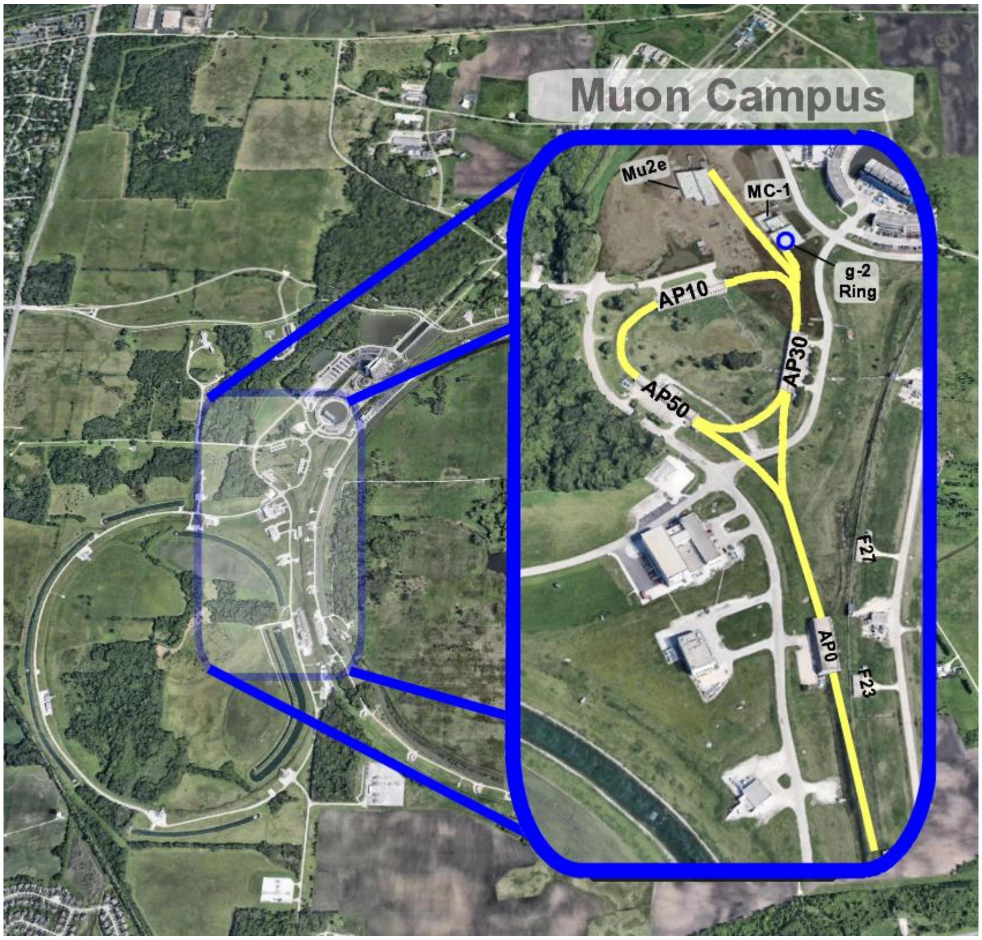


Figure 3. Aerial view of the Fermilab site, indicating the location of the Muon Campus.

III-10.1.5 Management Organization

The Muon Campus is managed by the External Beam Delivery Department of the Accelerator Directorate. The g-2 experiment (now inactive) was served by beam from the Muon Campus. Construction for the Mu2e experiment is being completed and the experiment will accept beam from the Muon Campus once that is approved. The beam line to g-2 extends into the MC-1 experimental hall which is managed by the Particle Physics Directorate. The beamline to Mu2e terminates at the production target which is within the production solenoid. The production solenoid is the responsibility of the Particle Physics Directorate. The area of the Mu2e facility containing the production solenoid is managed by the Accelerator Directorate. Other areas of the Mu2e facility beyond the production solenoid area and to the south are managed by the Particle Physics Directorate.

III-10.1.6 Operating Modes

The Muon Campus Area is designed to provide 3.1 GeV muons to the g-2 experimental apparatus, as well as 8 GeV protons to the Mu2e experiment. The accelerator is not capable of operating both experiments simultaneously, so the complex, described in this section, will be configured in one mode or the other.

In the g-2 mode of operation, the AP-0 target accepts a pulsed primary proton beam at 8 GeV consisting of 1 x 10^{12} protons/pulse at a maximum repetition rate of 12 pulses per second. The pulse trains are structured in bursts of 8 pulses separated by 10 milliseconds. Two groups of 8 pulses strike the target every 1.4 seconds. 3.1 GeV secondary particles from the target are transported to and captured in the DR. After the secondary protons are directed to the DR beam absorber, 3.1 GeV muons are delivered to the g-2 experimental hall.

The Mu2e mode of operation is being commissioned in stages. The first stages have begun with 13 watts of 8 GeV protons (3.60 x 10^{13} protons/hr). The proton beam bypasses the AP-0 target and is transported through the DR to the Diagnostic absorber located in the M4 beam line upstream of the Mu2e experiment. Beam can alternatively be sent to the DR beam absorber. The beam is extracted toward the DA either using single turn extraction, or by resonant extraction. The magnet circuit that steers beam around the target is disabled when g-2 cycles are detected to prevent the higher beam power cycles from entering the downstream beam lines. The Mu2e cycles are repetition rate limited in the Timeline Generator hardware to ensure the frequency of commissioning cycles remains low.

The radiation protection throughout the Muon Campus will be upgraded in the future allowing up to 8 kW of beam, although only 170 watts will be allowed to be directed to the DA. When the Muon Campus is fully configured for beam to the Mu2e experiment, the primary proton delivery will consist of a maximum of 8 pulses every 1.4 seconds at 8 GeV. This beam will be resonantly extracted from the DR and transported to the Mu2e target station. This version of the Safety Assessment Document only covers the initial stage of commissioning with 13 watts of beam delivered only as far as the DA in the M4 line. Until the beam power upgrades are complete and approved, safeguards will remain in place to limit the beam power of the 8 GeV beam cycles. The operating mode currently in use are detailed further in the rest of this section.

g-2 Operation

The g-2 experiment has completed and further running in this mode is not anticipated. The analysis of this mode remains relevant in the case that it is decided to resume this operation.

Single bunches of protons are delivered to the Muon Campus from the Recycler Ring in an irregular pattern. 16 bunches are sent to the Muon Campus every 1.4 second cycle with the individual bunches separated by 10 msec. The intensity of each bunch is 1 x 10^{12}, with a bunch length of 120 nsec. When the idle time between cycles is included, the average pulse rate is 11.4 Hz. Reduction of beam power is accomplished by either reducing the intensity of individual bunches, or by reducing the frequency of the beam delivery.

Protons are delivered to the Muon Campus from the Recycler Ring via the P1 and P2 beamlines that were used for the Tevatron Collider operations. These two beamlines together provide a path from the MI/Recycler all the way to the beginning of the M1, shown in Figure 1. Conversion of the beamlines from Collider operation to the Muon Campus operation includes an extraction insert in the Recycler and a short beamline connecting the Recycler to the P1 line. Several magnets were replaced in the existing transfer line to improve the aperture for Muon Campus operation. The beamline transported both 8 GeV and 120 GeV protons during collider operations. Transfers to the Muon Campus are limited to the lower energy, so limiting aperture magnets were replaced trading reduced field capability for better beam transmission.

Beam is introduced in the Muon Campus downstream of F17 where the M1 beam line exits the Tevatron enclosure. the M1 line continues to the AP0 target. The only significant change to the M1 line is the final focus for the target which was altered to form a more compact triplet closer to the target.

The 8 GeV protons strike the target in the AP-0 target vault. The focus and momentum selection magnets downstream of the target direct 3.1 GeV, positively charged particles into the M2 line. The M2 line merges with the M3 line 50 meters downstream of the target by energizing a switch magnet named D:H812. The beamline then continues to the DR injection area. Along the entire path, pions decay into muons and neutrinos. The optics of the beamlines are designed to capture the maximum number of decayed muons at 3.094 GeV/c.

A pulsed septa and kicker magnet combination are used for injection into the DR. The beam circles the DR 4 times before the muons are extracted. By this time, all the pions have decayed so the beam consists mainly of muons and protons. Because the relativistic beta of the protons and muons differ, after 4 revolutions in the DR, the two particle types are separated by 70 nsec. This time difference is enough separation for a kicker to rise between the particles. On the 4th revolution, the extraction kicker and abort kicker are both fired such that the protons are sent to the DR cleanup abort, and the muons are extracted into the M4 line. The muon beam continues in the M4 line for 30 meters where a switch magnet named D:V907 directs the beam up into the M5 line for transport to the g-2 storage ring in the MC-1 building.

8 GeV Protons through the Delivery Ring for Commissioning

Commissioning the DR with 8 GeV protons is accomplished by turning on the switch magnet (D:H700) that directs beam around the AP0 target station, and then sending the beam to the DR Absorber by use of the abort kicker. This mode is used for commissioning and for accelerator improvement efforts. The M3 beamline downstream of the AP0 target station, as well as the DR can be powered to the appropriate levels to transport either the 3.1 GeV muons or the 8 GeV protons. Beam can be stored in the DR for diagnostic work for an arbitrary length of time. Running in this mode is done at a much-reduced repetition rate consistent with the Accelerator Safety Envelope[14] and the Antiproton Source 2000 Shielding Assessment[1]. This mode is used for commissioning Mu2e operations as well as investigating g-2 operational improvement.

3.1 GeV Secondary Beam for g-2 Commissioning

A variation of the g-2 operating mode that is used for commissioning and diagnostics is to alter the number of DR revolutions of the 3.1 GeV secondary beam. The number of revolutions can vary from zero to storage for an indefinite time. If less than 4 revolutions are made in the DR, both protons and muons are sent to the g-2 storage ring as there is not enough time separation to direct the two beams into separate beamlines. The Muon g-2 Shielding Assessment [3] includes this operation.

Mu2e Operation

The normal High Energy Physics (HEP) mode of Mu2e operation will be described followed by variations used for commissioning and machine development studies. The approval of this version of the Safety Assessment Document will allow only a limited subset of the commissioning variations, and not allow for beam delivery to the Mu2e experiment.

In the final Mu2e configuration of the Muon Campus, eight 8 GeV proton bunches will be delivered to the Muon Campus from the Recycler every 1.4 seconds. The train of 8 bunches will be separated in time by 48 msec followed by a 1 second wait for the cycle to repeat. The proton bunches will bypass the AP-0 target station and be injected into the DR. The beam will then be resonantly extracted over the span of 43 msec. The extraction point is just downstream of the injection point, where beam enters the M4 line. The first 30 meters of the M4 line is common to both g-2 and Mu2e beam delivery.

30 meters into the M4 beamline, the V907 switch magnet is configured to direct beam to the Mu2e experiment. The downstream end of the magnet is oriented in alignment with the M4 beam line when configured in Mu2e mode. The magnet polarity and operating strength is also set for transport to Mu2e. In the future, the M4 beam line will end at the production solenoid which contains the Mu2e target. The particles surviving beyond the Mu2e target terminate in a dedicated proton absorber, which is designed for the full Mu2e beam power.

Commissioning the M4 Line to the Diagnostic Absorber

The initial stages of commissioning the beamline to Mu2e occurs while the experimental apparatus is being installed. This commissioning activity takes advantage of the DA placed upstream of the experiment during civil construction. This absorber is shielded sufficiently to allow access into the experimental area for installation during beam operation. The DA will be the only destination for beam extracted from the DR until the Mu2e experiment comes online.

Directing beam into the M4 beamline can be done in a single pulse by either directing the beam from the M3 injection line directly into the field region of the extraction Lambertson, or by firing the extraction kicker to similarly direct the beam. The extracted beam is directed toward the Mu2e area and away from the g-2 area by properly configuring the switch magnet (D:V907).

Directing beam to the DA is accomplished by powering a switch magnet (D:HDA01) located 175 meters into the M4 beamline. The DA is located 22 meters downstream of this switch magnet. The switch magnet must be on and operating in a narrow current window before the beam will be permitted down the M4 beamline. Between the switch magnet and the Mu2e hall is a 15-foot-thick shield wall and beam stops that are locked in the closed position. These beam stops will eventually be used as critical devices for the Mu2e experimental area.

Resonant extraction can be used to direct the beam into the M4 beamline as an alternative to single pulse extraction. The resonant extraction mode will be the operational mode for the experiment. Resonant extraction utilizes two sextupole circuits and a set of extraction quadrupoles to properly establish the resonant conditions required. A pair of electrostatic septa are used to slowly split beam from the edge of the circulating beam and direct it into the field region of the Lambertson. The path of the extracted beam in this mode is identical to the path take for single turn extraction.

For all the operating modes in the Muon Campus, the DR injection devices are triggered by the same clock events that initiate extraction from the Recycler. This method is employed to allow extraction from the Recycler and injection into the DR to be treated as a single transfer operation.

III-10.1.7 Inventory of Hazards

The following table lists all of the identified hazards found in the Muon Campus enclosure and support buildings. Section III-10.9 *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 III-10.2 *Safety Assessment.*

Prompt ionizing radiation and Oxygen Deficiency Hazards due to cryogenic systems within accelerator enclosures 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 Muon Campus. Accelerator specific controls are identified as **purple/bold** throughout this Chapter.

All other hazards present in the Muon Campus 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 the Muon Campus.

Radiological		**Toxic Materials**	
☒	**Prompt Ionizing Radiation**	☐	Lead Shielding
☒	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
☐	Magnet 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	☒	Noise
☒	Vacuum Pumps	☒	Silica
☒	Material Handling	☐	Ergonomics
Access & Egress		☐	Asbestos
☒	Life Safety Egress	☐	Working from Heights

Lithium was identified as an additional hazard in use at Muon Campus that was not identified in the Hazard Identification Table above. Lithium will be covered at the end of the "Other Hazards" portion of the Safety Assessment below.

III-10.2. Safety Assessment

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

III-10.2.1 Radiological Hazards

The Muon Campus presents radiological hazards in the form of prompt ionizing radiation, residual radiation, groundwater activation, surface water activation, radioactive water (RAW) systems, air activation, soil interactions, radioactive waste, contamination, beryllium 7 production, and radiation generating devices. There are also non-ionizing radiation sources used within the Muon Campus. A detailed shielding assessment [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)[4].

The shielding assessments [1, 2, 3, 12] for the Muon Campus begin at the switch dipole located at the end of the P2 line at F-17. The Antiproton Source Assessment from the year 2000[1] includes the beamlines from F-17 to the DR, and the DR itself. The Muon g-2 Shielding Assessment [3] includes the external beamline where it exits the DR at the 30 straight section, through the MC-1 Enclosure. The Muon g-2 Assessment [3] also includes the DR cleanup abort. The Muon Campus Shielding Assessment for 8 GeV Beam Transmission to the Diagnostic Absorber [12] includes the M4 beamline through the Extraction Enclosure and M4 Enclosure up to the DA only. The assessments [1, 2, 3, 12] do not consider future Mu2e operation which will allow primary beam intensities several orders of magnitude higher, and the operation of the Mu2e beamline downstream of the Extraction Enclosure.

The assessments [1, 2, 3, 12] consider groundwater and surface water activation; calculates air activation; estimates annual release, and release points; considers muon production; considers bulk shielding requirements; summarizes labyrinth and penetration calculations; calculates residual dose rates when significant; and specify active shielding controls and monitoring.

III-10.2.1.1 Prompt Ionizing Radiation

Prompt ionizing radiation is the principal radiation hazard when beam is transported through the Muon Campus beamlines. 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-10.3.1.1. 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-10.4. The conclusion of these analyses is that the mitigated dose level associated with prompt ionizing radiation due to beam loss is acceptable.

III-10.2.1.2 Residual Activation

Since the Muon Campus beamlines downstream of the AP-0 target will either transport low intensity secondary beams, or a less frequent 8 GeV proton commissioning cycles, the residual radiation dose will be minimal. The beamlines upstream of the AP-0 target have the potential for higher residual activity. The area in and around the AP-0 target vault will have the highest levels of residual radioactivity. With the completion of the g-2 experiment, residual radiation levels upstream of the AP0 target should not increase.

The AP-0 target station utilizes a closed loop cooling water system commonly denoted as “RAW” (radioactive water) system for target station components. The predominant isotopes in the activated water have half-lives between 2 and 20 minutes. A chipmunk radiation monitor located in the water cage monitors the radiation levels due to the activated water. Access to the water cage is controlled by the assigned Radiation Safety Officer (RSO) and is not generally permitted until sufficient radiation cooling time has elapsed following beam operation.

As documented in the Muon Campus Shielding Assessment for 8 GeV Beam Transmission to the Diagnostic Absorber [12], the residual dose rate on the upstream face of the DA itself is estimated to be 76 mrem/hr following 30 days of continuous 13-watt operation followed by one day of cooldown.

When the Muon Campus is not in operation, personnel access to beamline enclosures are administratively controlled by an entry control system consisting of access control procedures, key entry systems, and Radiological Work Permits (RWPs). The control measures include training and training verification, and centralized access authorization.

RWPs and ALARA plans must be written and followed in accordance with the FRCM requirements. 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. Members of the ES&H Section Radiation Physics Operations Department will supervise these tasks under the direction of the assigned RSO.

III-10.2.1.3 Groundwater Activation

Operation of the Muon Campus beamlines will activate ground and surface water primarily in the vicinity of the AP-0 target and the DR clean up absorber, which is downstream of the AP-50 straight section. Most of the activation occurs within 1 to 2 meters of the tunnel walls.

Primary beam power on the AP-0 target for g-2 operation is a factor of 4 lower than the operating beam power during Tevatron Collider Operation. The secondary beam power to g-2, and the primary beam power used for early commissioning of the Muon Campus, are both very low by comparison.

By scaling groundwater concentration estimates from collider era operation[[5]], potential groundwater activation levels near the AP-0 target during Muon g-2 operations after 10 years of operation are estimated to be approximately 1.7 E-7 pCi/ml-yr for tritium and 3.4 E-12 pCi/ml-yr for sodium-22, or less than 0.01% of the combined United States Environmental Protection Agency and Derived Concentration Standard release limit. Similarly, by scaling enclosure sump sampling measurements, potential surface water tritium activation levels are estimated to be less than 40 pCi/ml, or approximately 2% of the Derived Concentration Standard release limit.

The DR clean up abort and the DA are the only other areas of the Muon Campus to consider for ground and surface water activation. Estimates for groundwater activation levels [3] after 10 years of operation to the DR Abort would be approximately 5.0 E-6 pCi/ml-yr for tritium and 9.9 E-11 pCi/ml-yr for sodium-22, or less than 0.01% of the combined limit. Potential surface water tritium activation levels are estimated to be less than 50 pCi/ml-yr for tritium and 4.42 pCi/ml-yr for sodium-22, or less than 1% of the Derived Concentration Standard release limit if enclosure sump discharge were to occur once per week.

Groundwater zones are regularly monitored as part of the Fermilab Environmental Monitoring Program [[6]]. Sump discharges to surface waters are sampled at certain locations and frequencies [[7]]. The assigned RSO is responsible for acting on these results. Initial 13 watt beam to the DA during occasional commissioning periods will result in ground water activation levels that are 1.2E-8 of the activation limit, even after 20 years of running at much higher than anticipated hours per year[12].

III-10.2.1.4 Surface Water Activation

Surface Water Activation is address in section III-10.2.1.3 along with ground water activation.

III-10.2.1.5 Radioactive Water (RAW) Systems

Components in the AP0 target vault are cooled by a radioactive water (RAW) system. The components cooled are located directly in the beam path in a target vault. Radiation protection of these devices are more comprehensive than needed by the water system. The pumps and heat exchangers are located within a secured cage area. Access to the cage is controlled by the radiological protection organization. The water in the cage is activated by beam on target, and the activation decays quickly (on the order of an hour). Before access keys are issued, a cooldown period is required, and a radiation monitoring device (Chipmunk) is used to determine that rates are at an acceptable level. Access into the water cage area is then supervised by a radiation control technician (RCT). Only trained radiation workers are allowed in the water cage.

III-10.2.1.6 Air Activation

Illinois state regulations and the Fermilab registration in Registration of Smaller Sources (ROSS) program, administered by the Illinois Environmental Protection Agency (IEPA), govern releases of airborne radionuclides. The regulations limit the effective dose equivalent delivered to a member of the public to 10 mrem/year [[8], [9]]. Fermilab has established a secondary goal of keeping the maximum effective dose equivalent at the site boundary due to air emissions under 0.1 mrem/yr.

The principal radionuclides of concern to air activation are carbon-11 (which has a 20-minute half-life), nitrogen-13 (which has about a 10-minute half-life), oxygen-15 (which has about a 2-minute half-life), tritium (which has a 4500 day half-life), and argon-41 (with a 1.83 hour half-life). The Muon Campus primary proton beam for g-2 operation is transported in a vacuum except for the beam exiting the beam pipe, through a vacuum window at the AP-0 target station. The secondary beam likewise is transported in vacuum except for the exit at a vacuum window at the abort absorber and at the vacuum window between the accelerator beamline and the muon storage ring. During 13 W beam commissioning to the DA, the primary proton beam will exit the vacuum pipe through a window and travel through 3 meters of air before reaching the DA. Both the secondary beam to g-2 and the primary proton beam to the DA pass through two windows at the V907 switch magnet. These windows were removed after the g-2 experiment completed and the mode became inactive.

The release of activated air from the AP-0 target station has been monitored during collider operation [[10]]. The design beam power on target for g-2 operation is 22% of the actual beam power delivered during collider operation. Air activation near the target will scale with the beam power, so will also be 22% of the activation of the air during collider operation.

Air activation due to operating the DR clean up abort from 2.29 GeV protons has been calculated [[3]]; the summary of the calculation is shown in Table 2.

Energy (GeV)	Power (W)	Duty factor	Absorber entrance port (Ci/yr)	Enclosure air (Ci/yr)	Total (Ci/yr)
2.29	0.6	63.40%	0.0103	0.0084	0.0187
8	12.8	5%	0.1543	0.0512	0.2055
Total Activity released (mCi/yr) =			**224**		
Dose to Maximally Exposed Offsite Individual=				**0.093**	**micro-rem/yr**

Table 2: Summary of annual air activity released calculation for the Delivery Ring abort in support of the g-2 experiment.

Beam delivered to the DA is expected to result in a total release of 0.13 Ci/yr based on an estimate of 100 hours of operation per year at 13 W[12].

III-10.2.1.7 Closed Loop Air Cooling

N/A.

III-10.2.1.8 Soil Interactions

Scattered beam or beam lost in an absorber or target has potential to activate soil at low levels calculated in the shield assessment. This usually occurs very near the walls of the enclosure at the point of the beam loss. Beam loss monitoring is used to keep beam losses low to minimize these interactions.

III-10.2.1.9 Radioactive Waste

Radioactive waste produced in the course of Muon Campus operations will be managed within the established Radiological Protection Program (RPP) and as prescribed in the FRCM.

Radioactive waste is a standard radiological hazard that is managed within the established Radiological Protection Program (RPP) 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 Muon Campus, 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-10.2.1.10 Contamination

Contamination can be created when beam or beam loss strike dust or debris on or near the accelerator. This typically occurs in the area of high beam loss. The AP0 target, the DR beam absorber, and the Diagnostic absorbers are the most likely areas for contamination creation. Injection and extraction devices are also common locations for contamination creation, but the beam power allowed in the Muon Campus makes this unlikely. Beam loss monitoring helps maintain low beam loss and thus minimizes the creation of contamination.

Minimizing the possibility of exposing individual to contamination if it is present is implemented in several ways. RWPs must be written and followed in accordance with the FRCM requirements. During controlled access to the beam enclosures, individuals are required to wear appropriate PPE for their work, and they are required to use a log survey meter to identify locations of activation. When an individual enters an enclosure under supervised access, they are required to review the radiation survey maps made since beam was last present. An RWP for enclosure access is used to inform personnel of radiological hazards for any enclosure access.

When exiting the enclosure, individuals are required to use a frisker on themselves and on items being removed from the enclosure. Accessing an enclosure requires either that the individual is a trained radiation worker, or they are escorted by a radiation worker and receive a radiation briefing before accessing.

III-10.2.1.11 Beryllium-7

Beryllium-7 can be created if the proton beam passes through air, or if there are very high losses in air. This can occur at the AP0 target or at the location of vacuum windows. The consequence to the minimal level of this hazard is negligible but is difficult and time consuming to detect. For this reason, areas where Be-7 have been detected are treated as roped off contamination areas until measurements can be made to verify that the hazard is no longer present. All vacuum windows employ a guard that keeps human interaction away from surfaces that are difficult to monitor through use of wipes.

III-10.2.1.12 Radioactive Sources

N/A.

III-10.2.1.13 Nuclear Material

N/A.

III-10.2.1.14 Radiation Generating Devices (RGDs)

There are two electrostatic septa used for resonant extraction from the Delivery Ring. These septa can generate X-rays high voltage is applied. When access to the enclosure is permitted, the safety system clamps the voltage below the X-ray producing threshold.

III-10.2.1.15 Non-Ionizing Radiation Hazards

The metrology department employs a laser tracker (class II laser) for their alignment work in the Muon Campus. When in use, the alignment personnel work in groups of 3 or more and are able to alert any nearby workers. The consequence of an accidental exposure to a class II laser is minimal as a person’s blink reflex is fast enough to avoid serious injury.

III-10.2.2 Toxic_Materials

Beryllium windows and Fluorinert are both used within the Muon Campus. Details are described below.

III-10.2.2.1 Lead Shielding

N/A.

III-10.2.2.2 Beryllium

There are beryllium windows on devices within the AP0 target vault. This hazard has been evaluated as a standard industrial hazard within the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.2.2.3 Fluorinert & Its Byproducts

Hydrofluoric Acid and PFIBs are potential decomposition products from Fluorinert used for a high voltage dielectric in electrical feedthroughs in the resonant extraction electrostatic septa, and in the kicker systems. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in the Delivery Ring enclosure involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use." if the level of hazard will change in future running modes.

III-10.2.2.4 Liquid Scintillator Oil

N/A.

III-10.2.2.5 Pseudocumene

N/A.

III-10.2.2.6 Ammonia

N/A.

III-10.2.2.7 Nanoparticle Exposures

N/A.

III-10.2.3 Flammables and Combustibles

The Muon Campus contains cables and some building materials that are flammable and/or combustible. These hazards have been evaluated as standard industrial hazards within the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.2.3.1 Combustible Materials

The Muon Campus contains cables and some building materials that are combustible. These hazards have been evaluated as standard industrial hazards within the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.2.3.2 Flammable Materials

The Muon Campus contains cables and some building materials that are flammable or combustible. Various cleaning products used throughout the facility are flammable. These hazards have been evaluated as standard industrial hazards within the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.2.4 Electrical Energy

Many power supplies are used throughout the Muon Campus. In addition, electrical distribution equipment is used extensively.

III-10.2.4.1 Stored Energy Exposure

A subset of the power supplies used in the Muon Campus contain capacitors that can store energy even when the power supplies are off. These power supplies all implement dedicated written LOTO procedures. This hazard has been evaluated as standard industrial hazards within the common risk table in Section I Chapter 04 of this document. No unique controls used.

III-10.2.4.2 High Voltage Exposure

Many power supplies produce voltage above 50 volts. This includes more than just magnet power supplies such as ion pumps and various pieces of instrumentation. This hazard has been evaluated as standard industrial hazards within the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.2.4.3 Low Voltage, High Current Exposure

N/A.

III-10.2.5 Thermal Energy

Thermal Energy hazards can be present in the Muon Campus when work involving welding or brazing is done.

III-10.2.5.1 Bakeouts

N/A.

III-10.2.5.2 Hot Work

Repair or installation work in the Muon Campus often involves welding, brazing, soldering, torch-cutting and grinding. These operations can leave surfaces at dangerously high temperatures at the time of, and after the work. These hazards have been evaluated as standard industrial hazards within the common risk table in Section I Chapter 04 of this document. No unique controls used.

III-10.2.5.3 Cryogenic Liquids

N/A.

III-10.2.6 Kinetic Energy

A variety of tools and equipment employed in the Muon Campus are sources of Kinetic energy. The hazards from these sources are listed below.

III-10.2.6.1 Power Tools

Tools used within the Muon Campus can involve moving blades, bits, or hydraulics and can pose a risk of cutting or crushing. These hazards have been evaluated as standard industrial hazards within the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.2.6.2 Pumps and Motors

Water pumps and some vacuum pumps locate in the muon campus contain rotating or reciprocating parts that can pose a mechanical hazard. These hazards have been evaluated as standard industrial hazards within the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.2.6.3 Motion Tables

There are many magnets, collimators, instruments, etc. that utilize powered motion controls. These devices can be a pinch or crush hazard or move a device to an unstable condition. These hazards have been evaluated as standard industrial hazards within the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.2.6.4 Mobile Shielding

The high intensity Mu2e beam in the future will require shielding carts to be installed in front of some high loss devices. The carts are already in the tunnel and are considered a tip hazard that require proper handling. This hazard has been evaluated as standard industrial hazards within the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.2.7 Potential Energy

Many sources of potential energy exist throughout the Muon Campus in the form of cranes loads, compressed gasses, vacuum pressures, etc. Details of these hazards are enumerated below.

III-10.2.7.1 Crane Operations

A building crane is installed in the AP0 service building. There is also a crane in the experimental pit under AP50 and a rail crane on the enclosure ceiling at the end of the M4 line enclosure. Mobile cranes and lifting devices are occasionally used when required. These hazards have been evaluated as standard industrial hazards within the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.2.7.2 Compressed Gasses

The Muon Campus has distribution lines of air, nitrogen, and ArCO2. These gasses are used to operate pneumatic devices such as beam valves, let up vacuum systems, and feed instrumentation respectively. Bottles of compressed gas are also used for welding and brazing operations. These hazards have been evaluated as standard industrial hazards within the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.2.7.3 Vacuum/Pressure Vessels/Piping

The beam tubes in the Muon Campus operate at a pressure between 10-6 torr and 10-10 torr. To accomplish this, vacuum pumps and equipment is located extensively throughout the Muon Campus. These hazards have been evaluated as standard industrial hazards within the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.2.7.4 Vacuum Pumps

This hazard has been evaluated as standard industrial hazards within the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.2.7.5 Material Handling

Installation and repair of devices in the Muon Campus often requires the lifting or moving of heavy materials. Cranes, fork trucks, etc. are used and pose a crush hazard. These hazards have been evaluated as standard industrial hazards within the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.2.8 Magnetic Fields

III-10.2.8.1 Fringe Fields

Magnets in the Muon Campus have their power and thus their field removed before access is made. However, some permanent magnets, such as with ion vacuum pumps, exist in the campus with external fields greater than 5 Gauss. Fields are nominally only hazardous to people who have heart pacemakers. The likelihood of the fringe field causing a malfunction to the pacemaker is reduced by work planning. These hazards have been evaluated as standard industrial hazards within the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.2.9 Other Hazards

III-10.2.9.1 Confined Spaces

In the Muon Campus, there are sump pump pits, electrical vaults, and a trench across the AP30 parking lot and into the service building that are classified as Confined Spaces. These hazards have been evaluated as standard industrial hazards within the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.2.9.2 Noise

The flow of the LCW in the upstream end of the M4 beamline enclosure produces a high level of noise when two pumps are operating at CUB. Noise levels can also be high when tools or equipment is operated. These hazards have been evaluated as standard industrial hazards within the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.2.9.3 Silica

Construction and installation activities often require drilling or cutting cement. This produces a hazard of inhalation of silica dust. These hazards have been evaluated as standard industrial hazards within the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.2.9.4 Ergonomics

Performing work including office work in awkward positions, or for long periods of time can result in injury. Common ergonomic concerns are present throughout the Muon Campus. These hazards have been evaluated as standard industrial hazards within the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.2.9.5 Asbestos

N/A.

III-10.2.9.6 Working at Heights

There is much equipment in the Muon Campus that is located at heights. Many require the use of ladders or lifts to access. These hazards have been evaluated as standard industrial hazards within the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.2.9.7 Lithium

The AP0 target station employs a pulsed lithium lens for focusing the beam coming off the target. Lithium is a reactive element and produced Lithium Hydroxide when reacting in air and water. The lithium in the lens is well contained. There is a supply of extra lithium in case additional lenses would need to be fabricated. The extra lithium supply is stored in an oil filled container. That container is stored in a locked flammable material cabinet the AP0 service building.

III-10.2.10 Access & Egress

III-10.2.10.1 Life Safety Egress

Almost all interior areas of the Muon Campus have multiple exit points for emergency egress. The only areas where a person get more than 50 feet from multiple egress routs are on either side of the Delivery Ring absorber. This hazard has been evaluated as standard industrial hazards within the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.2.11 Environmental

III-10.2.11.1 Hazard to Air

Airborne release of radionuclides is possible from the Muon Campus. In particular, this occurs as a result of protons impinging on the AP0 target. This hazard has been evaluated as standard industrial hazards within the environmental section of the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.2.11.2 Hazard to Water

Radionuclides can be released into surface water on site. This hazard has been evaluated as standard industrial hazards within the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.2.11.3 Hazard to Soil

Activation of the soil directly outside of the accelerator enclosure can occur in the area of high beam loss. This hazard has been evaluated as standard industrial hazards within the common risk table in Section I chapter 04 of this document. No unique controls used.

III-10.3. Maximum Credible Incident Scenario(s) for the Accelerator Specific Hazard(s)

III-10.3.1 Definition of a Maximum Credible Incident

This section of the Muon Campus SAD evaluates the maximum credible incident (MCI) scenario that could happen in various parts of the Muon Campus. 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-10.3.1.1 Radiological Hazard

The Muon Campus is designed to both transport 8 GeV protons from the end of the P2 line to the Mu2e experiment, or to transport protons from the end of the P2 line to the AP0 target and then transport the resulting secondary beam to the g-2 experiment. There are many devices in the beam lines designed to steer, focus, or measure the beam along the length of the beam lines. Misdirection of the beam or failure of a large number of devices can cause the beam to be lost on the accelerator components causing prompt ionizing radiation. The MCI is defined as the loss of the maximum amount of beam that could credibly be delivered to a location and lost on a component at that location. The maximum beam intensity that could be delivered depends on the location in question.

The designed operating scenario for the Mu2e experiment is to deliver 8 bunches of protons, each bunch containing 1 E12 protons at 8 GeV kinetic every 1.33 seconds. The 1.33 second repetition rate is a result of the accelerator complex operating the 120 GeV Neutrino program. It would be possible to program the complex to operate Mu2e at a faster rate without operating the Neutrino program. The Recycler could deliver 8 bunches of 1 E12 protons at 8 GeV to the Delivery Ring every 0.52 seconds. This delivery of 1.5 E13 protons/sec is the highest credible rate at which the Recycler could be set up to transfer beam synchronously to the Muon Campus. The term synchronous in this case means that the Delivery Ring can be set up to accept these proton bunches with its injection system. 1.5 E13 protons/sec is the synchronous MCI intensity for the Muon Campus.

A higher rate of proton delivery could occur if the need for synchronous transfer is eliminated. This could be accomplished if a correction dipole in the Recycler were mistuned (to about 12 amps). With this situation, all the beam that is delivered into the Recycler could be steered into the Recycler extraction channel on the first turn in the recycler without the need for the extraction kicker to fire. If the beam was steered close enough to the Recycler extraction trajectory, it could possibly survive all the way to the injection point in the Delivery Ring. Since this beam delivery scenario is not synchronized by transfer clock events, the Delivery Ring injection devices would not trigger, and beam would be lost in the 30 straight section of the Delivery Ring. The maximum beam deliver rate into the Recycler would occur If every Booster cycle delivered beam at its maximum intensity of 7 E12. In that scenario, the beam delivered to the Muon Campus would be 1.05 E14 protons/sec. This is defined as the asynchronous MCI intensity for the Muon Campus. The asynchronous MCI applies only to the portion of the Muon Campus from F17 in the Tevatron to the 30 straight section in the Delivery Ring.

A third MCI condition applies to the g-2 operating mode. This mode is presently inactive through configuration control, but it could be activated again with some effort. In considering this mode, it should be noted that the M5 beam line is incapable of transporting 8 GeV beam. Since all Muon Campus beam comes via the Recycler at 8 GeV, the only beam that could be transported by the M5 line is a beam of secondary particles that originate from the AP0 target station. The only reasonable energy to consider is that of the g-2 experiment which is 3.1 GeV.

Extensive simulations show that the maximum number of secondary particles that can survive from the AP0 target to the M5 line is 1.5 E-4 times the number of protons on target. The maximum number of protons that could be focused on target in the g-2 mode of operation would be 3.1 E13 protons/sec. This rate would be as fast as the beam transfer systems and the rf could operate and be 5 times faster than any scenario proposed. This would be the limit of the possible rate of beam transfers to the AP0 target. Realizing this particle flux would require the following conditions. It would take 100 msec to inject two Booster batches into the Recycler, 90 msec to form the bunch structure for transfer, and then 70 msec to transfer the 8 bunches that are prepared. Since the Booster is limited in its operation to 15 Hz, this scenario would use 4 full Booster cycles and so this process could repeat every 0.268 seconds allowing 3.1 E13 protons/sec on target. The number of 3.1 GeV secondary particles that could reach the M5 line would be 4.5 E9 particles/sec. From the TVL spreadsheet tool, we find that the required berm thickness without active controls is 4 e.f.d. The minimum berm thickness in the M5 line is over 6.5 e.f.d., so 4 e.f.d. of shielding is credited and 1.5 e.f.d. are defense in depth.

All locations upstream of the Delivery Ring injection area could potentially experience beam loss under the maximum asynchronous condition. All points downstream of the Delivery Ring injection area could only experience losses at the level described in the synchronous transfer scenario except downstream areas of the M5 beamline which could only experience intensities at the g-2 MCI intensity. Prompt radiation beyond enclosure shielding is maximum when the beam strikes a solid object. Calculations of maximum dose under accident conditions were studied by striking solid components with beam and scaling measured doses on the surface up to the MCI beam conditions appropriate for the area.

Assuming no shielding is present, the asynchronous incident would result in a dose to any individual higher than 1.26 E10 mrem/r and the synchronous incident would result in a dose to an individual higher than 1.8 E9 mrem/hr. These results show that the uncontrolled baseline qualitative risk level associated with these accidents are 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.
- 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-10.4.

The accumulated dose outside of the shielding on the Muon Campus 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 Muon Campus enclosures is the west parking lot. 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.

A change in the MCI for upstream segments will be evaluated for its effect on the Muon Campus through the USI process.

III-10.4. Summary of Credited Controls

This section describes the credited controls that are required to reduce the risk associated with the maximum credible incident to the conditions outlined in Section III-1.3.1.1.

III-10.4.1 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-10.4.1.1 Passive Credited Engineering 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 Muon Campus enclosures are 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-10.4.1.1.1 Permanent Shielding Including Labyrinths

The permanent shielding encompasses the structural elements surrounding the Muon Campus beamlines. This includes the walls, ceilings, doors, berms, labyrinths in the following areas of the Muon Campus:

- The M1 line beginning at the point downstream of F17 where the beam line exits the Tevatron tunnel. The M1 line passes through a pipe buried under 22.5 feet of soil shielding. In this location, 20.3 e.f.d. are required and credited and 2.2 e.f.d. are defense in depth.
- The M1 line then passes through the Pre-Target and Pre-Vault enclosures which have a 19’ and 20.5 e.f.d. of shielding respectively. 17.9 e.f.d. are required so there are 1.1 e.f.d. of defense in depth for the Pre-Target enclosure, and 2.6 e.f.d. for Pre-Vault.
- The M1 line enters the AP0 target vault at the end of the Pre-Vault enclosure. The AP0 target vault is constructed of concrete and steel shielding designed to shield the AP0 service building during high power targeting operation. The shielding specified in the Shielding Assessment is credited shielding.
- The M3 line splits off from the M1 line 50 feet upstream of the end of the Pre-Vault enclosure and bypasses the target vault under the AP0 service building.
- The M3 line continues beyond the AP0 target vault through the entire Transport enclosure which is buried under at least 13 e.f.d. shielding berm. The upstream portion of the Transport enclosure has an extra e.f.d. of shielding. We employee TLM protection with the same trip limits in both parts of the enclosure. With the TLM, the credited shielding amount in the over the Transport enclosure is 11 e.f.d. with 3 e.f.d. of defense in depth in the upstream portion of Transport, and 2 e.f.d. of defense in depth in the downstream portion.
- The M2 line begins just downstream of the target vault in the Transport enclosure and runs 50 feet before it merges with the M3 line. The beam lines are next two each other for the entire length of the M2 line so the credited controls are the same.
- The M3 leaves the Transport enclosure and enters the Delivery Ring enclosure. The M3 line runs for 350 feet in the Delivery Ring enclosure before it merges with the Delivery Ring synchrotron. The berm over the M3 line is 13 e.f.d. thick in the Delivery Ring enclosure. With the TLMs in use, 10 e.f.d. of shielding is credited and 3 e.f.d. are defense in depth.
- The M3 beamline passes under Indian Rd where the berm is cut down for the passage of the road. The road passes 9.5 feet above the enclosure ceiling, but instead of a uniform layer of soil, there are several slabs of steel over the enclosure. The weakest point of this shielding is where the shielding thickness is 13 e.f.d. This area is protected by the same TLM referred to in the downstream transport description, so 10 e.f.d. are credited and 3 e.f.d. are defense in depth.

- The Delivery Ring synchrotron is 500 meters in circumference and passes under 3 service buildings in the straight sections. Between the Deliver Ring enclosure and the service buildings floor is 10 feet of gravel and concrete shielding. The gravel has a density of 2g/cc so the DR has at least 8 e.f.d. of shielding between the enclosure and the building floor. Chipmunks are used as credited controls in the service buildings, so 5 e.f.d. of shielding are credited and 3 e.f.d. are defense in depth.
- The arcs of the DR are under a soil berm that is 13 e.f.d. thick. TLMs are used in the arcs and 10 e.f.d. of shielding is credited and 10 3 e.f.d. are defense in depth.
- The Deliver Ring abort line diverges from the DR vertically under the AP50 service building and then is directed back downward into a steel abort absorber. The berm over this line is 13 feet thick. There is a small building (a gas shed) constructed at the edge of the berm over this beamline.
- The M4 beam line diverges vertically from the DR under the AP30 service building and travels 90 feet before it leaves the DR enclosure and enters the Extraction enclosure. The first portion of this beam line is in the Delivery Ring enclosure with the credited controls already listed for that enclosure.
- The M4 beamline exits the DR enclosure is under the edge of the AP30 service building. The extraction enclosure is covered by berm that is 16 e.f.d. In this area 15.1 e.f.d. are required, so 0.9 e.f.d. is defense in depth. The M4 line continues through the M4 enclosure protected by the same thickness shielding berm and a TLM with the same trip limit. 15.1 e.f.d. of shielding are credited and 0.9 e.f.d. is defense in depth.
- The end of the M4 line is directed into a Diagnostic Absorber (DA). The absorber is constructed of steel and was built as part of the construction of the enclosure and is under the 16-foot-thick berm. This area is documented in the Muon Campus Shielding Assessment for 8 GeV Beam Transmission to the Diagnostic Absorber [12]. This area of the Muon Campus is illustrated in Figure 5 below.
- Just downstream of the point where the M4 beamline enters the Extraction enclosure, the M5 beamline diverges vertically from the M4 beamline. The M5 beamline is used to transport a low intensity muon beam to the g-2 experiment inside of the MC-1 experimental hall. This beamline can only transport low intensity 3.1 GeV particles and the required shielding thickness is 4 e.f.d. The berm over the M5 line is a minimum of 6.5 e.f.d. thick so 4 e.f.d. are credited and 2.5 e.f.d. are defense in depth.
- The M5 line terminates at the g-2 storage ring in the experimental hall. The shielding for the g-2 experiment is documented in section IV chapter 8 of this SAD. The MC-1 enclosure is illustrated in Figure 4 below.

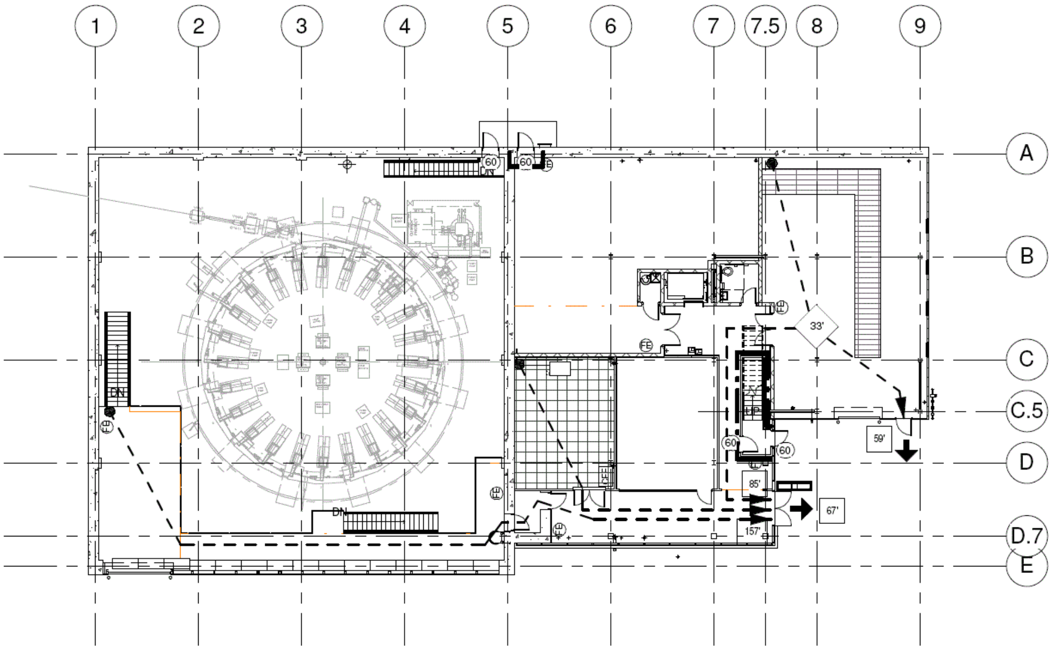


Figure 4. MC-1 Building Layout.

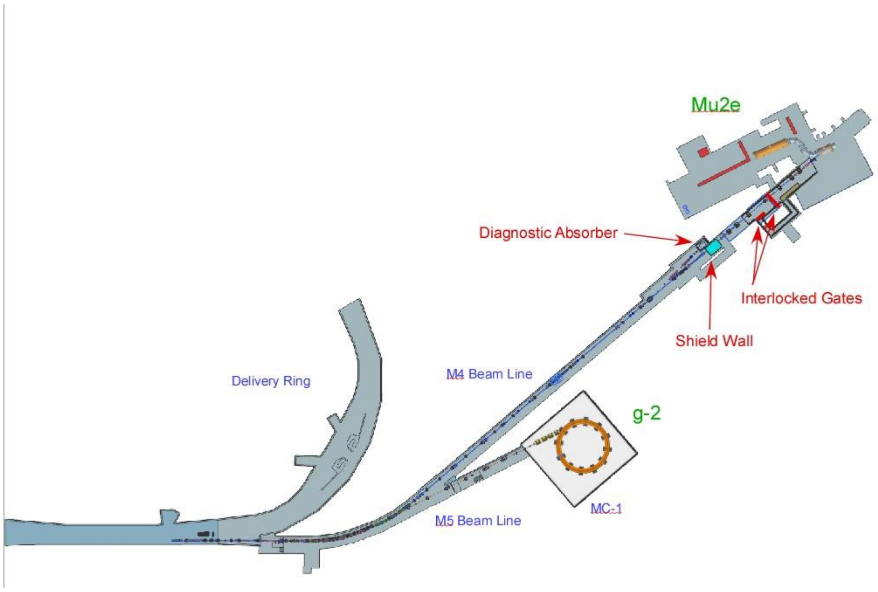


Figure 5. M4 Beamline Details.

The permanent shielding for the enclosures is documented in References [[1], [2], 3, 12]. In some cases, the earth overburden must be supplemented by active controls such as interlocked radiation detectors to maintain compliance with the posting requirements of the FRCM under the assessed beam conditions.

III-10.4.1.1.2 Movable Shielding

The Muon Campus has several areas with removable shielding. There are two drop hatches in the AP-0 building with crane coverage to the tunnel below. There are also 4 drop hatches into the DR enclosure from the outside. There is a drop hatch near the DA in the M4 enclosure. These hatches are filled with concrete shielding blocks. The assigned RSO controls locks for the shielding to these drop hatches and ensures that they are properly filled and secured before permitting beam.

The AP-0 target station consists of several beamline elements suspended from steel modules that provide shielding. Above the steel module are concrete shielding blocks. Surrounding the target vault area is a wall constructed of concrete blocks that allow occupancy of the building during beam operation. The assigned RSO controls access to the area within the concrete block wall; access is not permitted while beam is operable.

There are stackable shield walls in the Extraction Enclosure and the M4 Enclosure. The Extraction Enclosure contains a shield wall at the downstream end of the M5 line that protects the MC-1 Enclosure from beam showers originating from the DR or the M4 line. The shield wall in the M4 enclosure protects the Mu2e area from radiation produced transporting beam to g-2 or to the DA.

The assigned RSO specifies the configuration management measures to be taken to insure the placement of all moveable shielding structures.

III-10.4.1.1.3 Penetration Shielding

The Muon Campus contains many penetrations and labyrinths. Table 3 lists by area the number of such penetrations by type in each section of the Muon Campus.

Beamline Enclosure	Penetration count by type
Pre- Target/Pre-Vault	Stair well (2) Cable penetration (20) to F23 Cable penetration (4) to AP-0 Ventilation stack (1)
Vault	Cable penetration (32) to AP-0
Transport	Stair well (1) Cable penetration (20) to F27 Cable penetration (25) to AP-0 24” air duct into AP-0 (1) Water pipe penetrations (4)
Delivery Ring	Emergency exit trunks (3) Air shafts (3) Elevator shafts (3) Stair wells (6) Cable penetrations (440) 18 inch stub room penetrations (5)
Extraction	Stair well (1) Ventilation stack (1)
M4	Cable penetrations to MC-1 (32) Cable penetrations to Mu2e (38) Stairwell (1) Gated entrance to experimental hall (1)

Table 3: List of Penetrations

The Muon g-2 shielding assessment [[3]], the 2000 Pbar Source Shielding Assessment [[1], 2], and the Muon Campus Shielding Assessment for 8 GeV Beam Transmission to the Diagnostic Absorber [12] address all of the listed penetrations.

III-10.4.1.2 Active Engineered Credited Controls

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

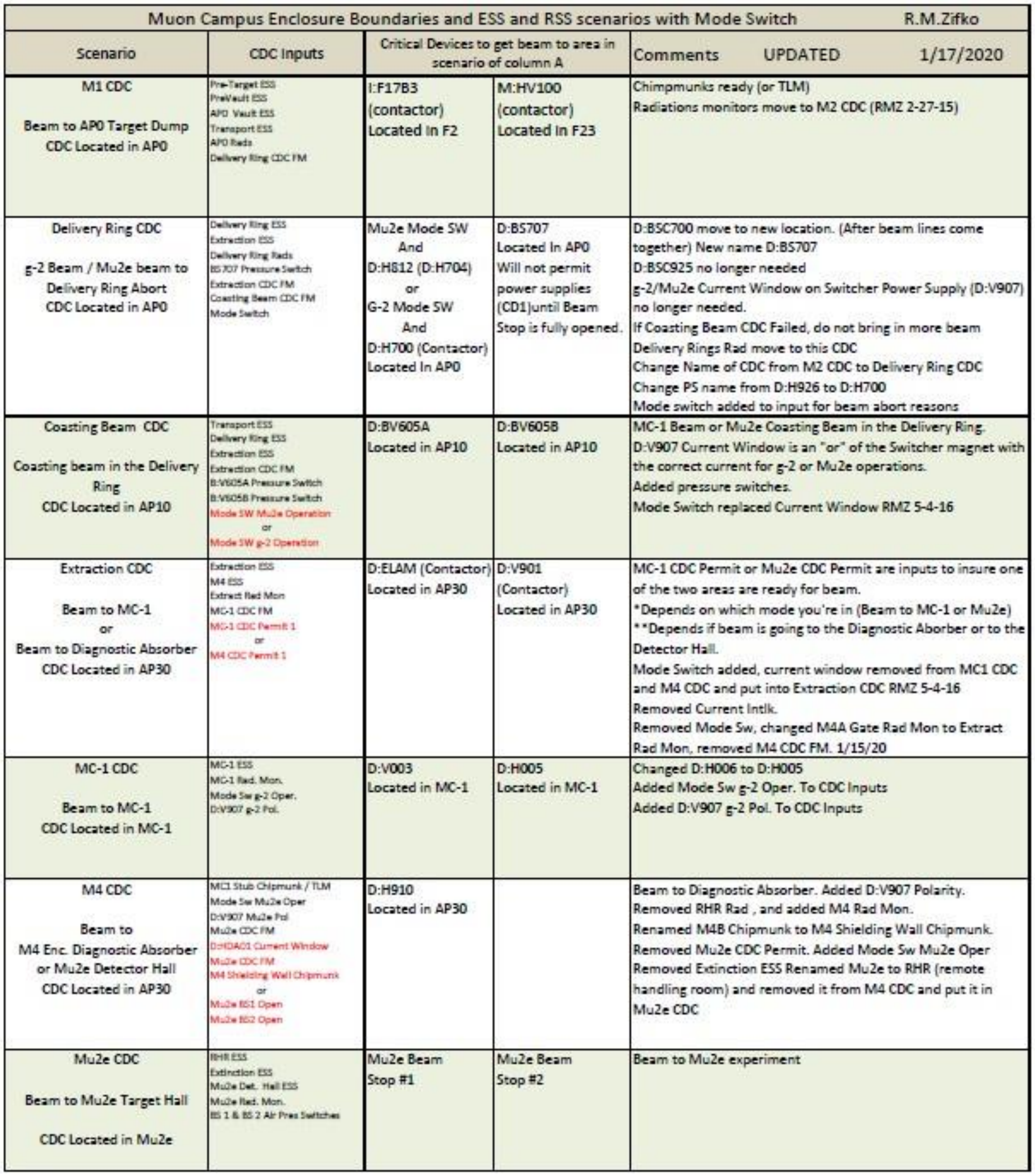
III-10.4.1.2.1 Radiation Safety Interlock System

The Muon Campus enclosures employ a Radiation Safety Interlock System (RSIS). The characteristics of the system are described in Chapter I, Section 4.3.2.1 of the Fermilab SAD.

The Muon Campus beamlines are enclosed in nine distinct enclosures, each with their own RSIS. There are interlocked access points, emergency egress exits, and interlocked gates between enclosures in each area. Each RSIS inhibits critical devices upstream of its own enclosure to prevent transport of beam when the enclosure is not ready for beam operation.

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.

Critical devices are used for protecting each of the Muon Campus enclosures. If any of the mentioned Muon Campus radiation detectors reach their trip threshold, a critical device will respond by removing beam from the area that could cause the radiation dose. Table 4 below lists the critical devices necessary to allow each beam operating scenario along with other pertinent information.



Muon Campus Enclosure Boundaries and ESS and RSS scenarios with Mode Switch R.M.Zifko

Scenario	CDC Inputs	Critical Devices to get beam to area in scenario of column A		Comments UPDATED 1/17/2020
M1 CDC Beam to AP0 Target Dump CDC Located in AP0	Pre-Target ESS PreVault ESS AP0 Vault ESS Transport ESS AP0 Rads Delivery Ring CDC FM	I:F17B3 (contactor) Located In F2	M:HV100 (contactor) Located In F23	Chimpmunks ready (or TLM) Radiations monitors move to M2 CDC (RMZ 2-27-15)
Delivery Ring CDC g-2 Beam / Mu2e beam to Delivery Ring Abort CDC Located in AP0	Delivery Ring ESS Extraction ESS Delivery Ring Rads BS707 Pressure Switch Extraction CDC FM Coasting Beam CDC FM Mode Switch	Mu2e Mode SW And D:H812 (D:H704) or G-2 Mode SW And D:H700 (Contactor) Located In AP0	D:BS707 Located In AP0 Will not permit power supplies (CD1)until Beam Stop is fully opened.	D:BSC700 move to new location. (After beam lines come together) New name D:BS707 D:BSC925 no longer needed g-2/Mu2e Current Window on Switcher Power Supply (D:V907) no longer needed. If Coasting Beam CDC Failed, do not bring in more beam Delivery Rings Rad move to this CDC Change Name of CDC from M2 CDC to Delivery Ring CDC Change PS name from D:H926 to D:H700 Mode switch added to input for beam abort reasons
Coasting Beam CDC Coasting beam in the Delivery Ring CDC Located in AP10	Transport ESS Delivery Ring ESS Extraction ESS Extraction CDC FM B:V605A Pressure Switch B:V605B Pressure Switch Mode SW Mu2e Operation or Mode SW g-2 Operation	D:BV605A Located in AP10	D:BV605B Located in AP10	MC-1 Beam or Mu2e Coasting Beam in the Delivery Ring. D:V907 Current Window is an "or" of the Switcher magnet with the correct current for g-2 or Mu2e operations. Added pressure switches. Mode Switch replaced Current Window RMZ 5-4-16
Extraction CDC Beam to MC-1 or Beam to Diagnostic Absorber CDC Located in AP30	Extraction ESS M4 ESS Extract Rad Mon MC-1 CDC FM MC-1 CDC Permit 1 or M4 CDC Permit 1	D:ELAM (Contactor) Located in AP30	D:V901 (Contactor) Located in AP30	MC-1 CDC Permit or Mu2e CDC Permit are inputs to insure one of the two areas are ready for beam. *Depends on which mode you're in (Beam to MC-1 or Mu2e) **Depends if beam is going to the Diagnostic Aborber or to the Detector Hall. Mode Switch added, current window removed from MC1 CDC and M4 CDC and put into Extraction CDC RMZ 5-4-16 Removed Current Intlk. Removed Mode Sw, changed M4A Gate Rad Mon to Extract Rad Mon, removed M4 CDC FM. 1/15/20
MC-1 CDC Beam to MC-1 CDC Located in MC-1	MC-1 ESS MC-1 Rad. Mon. Mode Sw g-2 Oper. D:V907 g-2 Pol.	D:V003 Located in MC-1	D:H005 Located in MC-1	Changed D:H006 to D:H005 Added Mode Sw g-2 Oper. To CDC Inputs Added D:V907 g-2 Pol. To CDC Inputs
M4 CDC Beam to M4 Enc. Diagnostic Absorber or Mu2e Detector Hall CDC Located in AP30	MC1 Stub Chipmunk / TLM Mode Sw Mu2e Oper D:V907 Mu2e Pol Mu2e CDC FM D:HDA01 Current Window Mu2e CDC FM M4 Shielding Wall Chipmunk or Mu2e BS1 Open Mu2e BS2 Open	D:H910 Located in AP30		Beam to Diagnostic Absorber. Added D:V907 Polarity. Removed RHR Rad , and added M4 Rad Mon. Renamed M4B Chipmunk to M4 Shielding Wall Chipmunk. Removed Mu2e CDC Permit. Added Mode Sw Mu2e Oper Removed Extinction ESS Renamed Mu2e to RHR (remote handling room) and removed it from M4 CDC and put it in Mu2e CDC
Mu2e CDC Beam to Mu2e Target Hall CDC Located in Mu2e	RHR ESS Extinction ESS Mu2e Det. Hall ESS Mu2e Rad. Mon. BS 1 & BS 2 Air Pres Switches	Mu2e Beam Stop #1	Mu2e Beam Stop #2	Beam to Mu2e experiment

Table 4: Critical Device list, inputs, and scenarios

Each Muon Campus enclosure is protected by upstream critical devices, which needs to be positively activated to allow beam into the next enclosure. To allow beam in any Muon Campus enclosure, beam must be permitted in all upstream enclosures as well, meaning that access to those areas is not allowed. The following describes how each of the Muon Campus enclosures is protected from beam exposure to personnel. In the Muon Campus, disabling a magnet is done by opening a contactor to a power supply that energizes the magnet. This contactor is controlled by the RSIS. The enclosures are illustrated in Figure 6 below, and a description of what devices protect personnel during permitted access is given in beam order beginning with the M1 line.

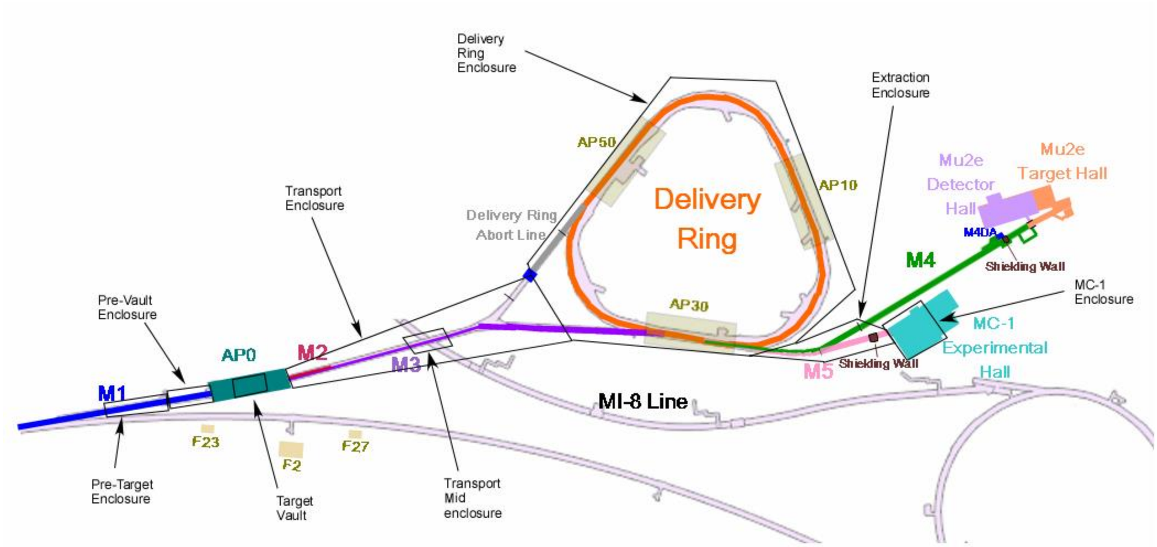


Figure 6. Muon Campus Enclosure Map.

The Pre-Target enclosure is where the M1 line enters the Muon Campus as the beam exits the Tevatron enclosure. If access is permitted in the Pre-Target enclosure, two pairs of critical devices inhibit the transfer of beam from the Main Injector and Recycler into the P1 line. The Recycler extraction Lambertson, R:LAM52, bends the beam down away from the Recycler by 21 mrad. Without current in the R:LAM52 magnet string, beam is lost in the region just downstream. A vertical dipole, R:V703, is a second critical device that bends beam back up 24 mrad onto the P1 line trajectory. Without the R:V703 24 mrad bend, the beam is lost within the R:V703 dipole.

A similar critical device pair prevents beam from transferring from the Main Injector into the P1 line when access is allowed into Pre-Target enclosure. I:LAM52 and I:V701 are bending dipole strings required to bend the beam out of the Main Injector and into the P1 beamline. Turning either of these devices off prevents beam from being transported through F-Sector in the Tevatron enclosure toward either the Muon Campus or the 120 GeV Fixed Target experimental program.

The M1 line continues through the Pre-Vault enclosure. Two critical devices in the very upstream portion of the M1 line, I:F17B3 and M:HV100, have their contactors disabled when access is allowed to the Pre-Vault enclosure. The first of these devices, I:F17B3, is a dipole string in the P2 line that needs to be energized for beam to be bent away from the P2 line trajectory. With I:F17B3 at zero current, the beam passes cleanly into the P3 line and on to the 120 GeV Fixed Target experimental area. The second device, M:HV100, is a dipole string that bends beam horizontally away from the P2 line trajectory toward the target station. With M:HV100 off, nearly all of the beam is lost within the second HV100 magnet, and the beam is 100% extinguished on the next quadrupole downstream which is still within the Tevatron F-Sector enclosure. It is not possible for beam to leave the Tevatron enclosure without both I:F17B3 and M:HV100 magnet strings energized.

When access into the AP-0 target vault area is permitted, the same two critical devices protecting the Pre-Vault area (I:F17B3 and M:HV100) are disabled. There are interlocks associated with access into the vault area, as well as a specific written procedure for entry. Access to the Target Vault is under the control of the assigned RSO.

When access is permitted in the Transport enclosure, which is immediately downstream of the AP-0 target, beam is not permitted in the M1 line. The same two critical devices (I:F17B3 and M:HV100) are disabled as are for permitting access to the Pre-Target enclosure and Target Vault.

In the middle of the Transport enclosure is embedded another enclosure called the Transport Mid enclosure. Being within the Transport enclosure it utilizes the same critical devices (I:F17B3 and M:HV100). In addition, when access is permitted in this enclosure, beam is disabled in the MI-8 beamline, that passes beneath, by disabling B:LAM and B:MH1 by turning off the magnet power supplies through the CDC controller and removing an Enclosure Enter key. Both critical devices are discussed in III-4, Booster Chapter of this SAD.

When access is permitted in the DR enclosure, critical devices in both the M2 and M3 line prevent beam from being transported through the Transport Enclosure. Dipole magnet D:H700 is disabled by turning off the magnet power supplies through the CDC controller and removing an Enclosure Enter key, which prevents primary proton beam from being directed out of the M1 line and into the M3 line. With D:H700 at zero current, the M1 line beam continues straight to the AP-0 target vault target. Disabling dipole D:H812 prevents secondary beam from the AP-0 target from entering the M3 line. D:H812 provides a 52.4 mrad bend to put the secondary beam on the trajectory of the M3 line. With D:H812 unpowered, beam is completely lost in the two quadrupoles immediately downstream of H812. Downstream of the point where the M2 and M3 lines merge, is beam stop D:BS707. D:BS707 is the second critical device for both the primary proton beam in the M3 line and the secondary beam from the M2 line. D:BS707 is closed for DR access, preventing any beam transmission beyond the beam stop. The geometry of the Transport enclosure provides sufficient distance and shielding downstream of D:H700, D:H812, and D:BS707 to allow access into the DR enclosure.

When access is permitted in the Extraction Enclosure, the same critical devices that allow access into the DR enclosure (D:H700, D:H812, and D:BS707) are disabled.

When access is permitted in both the MC-1 enclosure or the M4 enclosure, extraction from the DR is not allowed by disabling the extraction Lambertson magnet, D:ELAM, and the dipole, D:V901. If D:ELAM is not energized, the beam kicked into the normal extraction channel stays at the DR elevation and cannot enter the aperture of the C-Magnet in the extraction line. A second critical device is a downward bending dipole, D:V901. With D:V901 not energized, beam travels in a straight line through this sector magnet and is lost on the steel part way through the magnet. It is necessary to energize both D:ELAM and D:V901to transport beam into the Extraction enclosure. The geometry of the Extraction Enclosure provides enough shielding from the DR to allow access into the MC-1 enclosure or the M4 enclosure with D:ELAM and D:V901 disabled. If the Muon Campus is configured for g-2 operation, but access is permitted to the MC-1 Enclosure, extraction from the DR is disabled by the same two critical devices (D:ELAM and D:V901).

If access is permitted to the MC-1 Enclosure, two critical devices in the M5 beamline have their contacts disabled to protect the enclosure if beam is being transported to the DA. D:V003 and D:H005 are both disabled when access is permitted to the MC-1 Enclosure. D:V003 is a 9 degree down bend. With this magnet disabled, beam would continue in an upward direction and exit the vacuum pipe before traversing the next magnetic element. D:H005 is a three-magnet bend string that provides 27 degrees of horizontal bend. With this magnet string disabled, beam would exit the vacuum pipe before it reached the second dipole.

If access is permitted to the M4 enclosure the dipole string critical device named D:H910 is disabled by use of an electrical contactor. This magnet string provides the 41 degrees of horizontal bend required to direct beam toward the M4 beamline and to Mu2e. With this bend string disabled, beam continues in the direction of the beam extracted from the DR toward the extraction enclosure wall. When access to the M4 enclosure is permitted, the status of the D:H910 contactor is monitored to ensure that it is open. If the contactor open status goes away, the Extraction Enclosure Critical Device is disabled as a backup to D:H910.

There is also a coasting beam Critical Device Controller. This safety system device closes two independent beam valves, D:BV605A and D:BV605B, in the DR when access is allowed to the Transport, DR, or Extraction enclosure. The beam valves (D:BV605A and D:BV605B) eliminate the possibility of stored beam being present in the DR.

Trained and qualified personnel from the AD Operations Department are required to search and secure the enclosure before permits from the RSIS may be re-established following any personnel access to the enclosure, except under strictly specified controlled access conditions. The RSIS includes requirements for hardware and system testing, inventory of interlock keys, and procedures for maintenance of interlock systems. The RSIS hardware enforces the administrative Search and Secure and Controlled Access processes. The RSIS is designed, installed, and configuration managed in conformance with the FRCM.

The RSIS utilizes a series of chipmunk radiation detectors and Total Loss Monitor (TLM) radiation detectors to inhibit beam from an area if radiation levels nearby exceed a predetermined level. Table 5 below lists the credited radiation detectors, followed by a description of how they are implemented.

Table 5 Muon Campus credited radiation monitors

Type	Location	CC Limit (mrem/hr for Chipmunks)
Chipmunk	AP-10 North Door	500
Chipmunk	AP-10 Relay Rack A17R05	500
Chipmunk	AP-10 Relay Rack A16R07	500
Chipmunk	AP-10 Relay Rack A16R03	500
Chipmunk	AP-10 D:QS power supply	500

Type	Location	CC Limit (mrem/hr for Chipmunks)
Chipmunk	AP-10 D:QD power supply	500
Chipmunk	AP-10 Relay Rack A14R03	500
Chipmunk	AP-10 Relay Rack A14R0Y	500
Chipmunk	AP-10 Control Room Southwest Door	500
Chipmunk	AP-10 Bay A13 South	500
Chipmunk	AP-10 Bay A12 North	500
Chipmunk	AP-10 Relay Rack A2R01	500
Chipmunk	AP-10 Southwest Rollup Door	500
Chipmunk	AP-10 South Door	500
Chipmunk	AP-30 South Door	500
Chipmunk	AP-30 South Rollup Door	500
Chipmunk	AP-30 D:H744 power supply	500
Chipmunk	AP-30 D:Q303 power supply	500
Chipmunk	AP-30 Relay Rack A35R07	500
Chipmunk	AP-30 Relay Rack A35R01	500
Chipmunk	AP-30 D:ISEP power supply	500
Chipmunk	AP-30 Relay Rack A35R03	500
Chipmunk	AP-30 Relay Rack A33R07	500
Chipmunk	AP-30 Relay Rack A33R01	500
Chipmunk	AP-30 D:ELAM power supply	500
Chipmunk	AP-30 D:V906 power supply	500
Chipmunk	AP-30 NE Rollup Door	500
Chipmunk	AP-30 North Door	500
Chipmunk	AP-50 West Door	500
Chipmunk	AP-50 Relay Rack A57R07	500
Chipmunk	AP-50 Relay Rack A57R01	500
Chipmunk	AP-50 Relay Rack A56R04	500
Chipmunk	AP-50 Relay Rack A55R08	500
Chipmunk	AP-50 Relay Rack A55R02	500
Chipmunk	AP-50 D:SEXV power supply	500
Chipmunk	AP-50 D:VA03 power supply	500
Chipmunk	AP-50 Relay Rack A53R07	500
Chipmunk	AP-50 Relay Rack A53R01	500
Chipmunk	AP-50 Abort Kicker power supply	500
Chipmunk	AP-50 D:ASEP power supply	500
Chipmunk	AP-50 East Rollup Door	500
Chipmunk	AP-50 East Door	500
TLM	Upstream Transport enclosure	100,000 nC/min
TLM	Downstream Transport enclosure into Delivery Ring	100,000 nC/min
TLM	Delivery Ring 20 arc	100,000 nC/min
TLM	Delivery Ring 40 arc	100,000 nC/min
TLM	Delivery Ring 60 arc	100,000 nC/min
TLM	Delivery Ring abort line	100,000 nC/min

The Transport enclosure has two TLM monitors. The downstream monitor continues into the Delivery Ring enclosure, and both monitors react to beam loss in the M3 beamline. Dose measurements have been made over the M3 line with chipmunks placed on the surface above the point where beam was lost, and the TLM response was calibrated against the surface dose. In the upstream portion of the M3 beam line, the shielding is 14 e.f.d. The dose on the surface measured 0.064 mrem/E12 lost on a solid object (a beam stop was used for the study). Under this condition, a constant beam loss at the MCI intensity of 1.05 E14 protons/sec would result in a 500 mrem surface dose in 73.9 seconds. In this interval, the TLM would have experienced 8.7 million counts. With the TLM set to trip at 100,000 counts/min, the limit would be reached in the first second. If it takes the safety system 3 seconds to turn the beam off, the total beam lost would be 420 E12 and the dose on the berm would be limited to 27 mrem. We will credit only 11 e.f.d. of the 14-foot berm. With 11 e.f.d. of shielding, the loss during this interval would be limited to 270 mrem. This provides 3 e.f.d. of shielding as defense in depth.

In the downstream part of the Transport enclosure, the berm thickness reduces to 13 e.f.d. In this part of the enclosure there are 2 e.f.d. of shielding considered defense in depth.

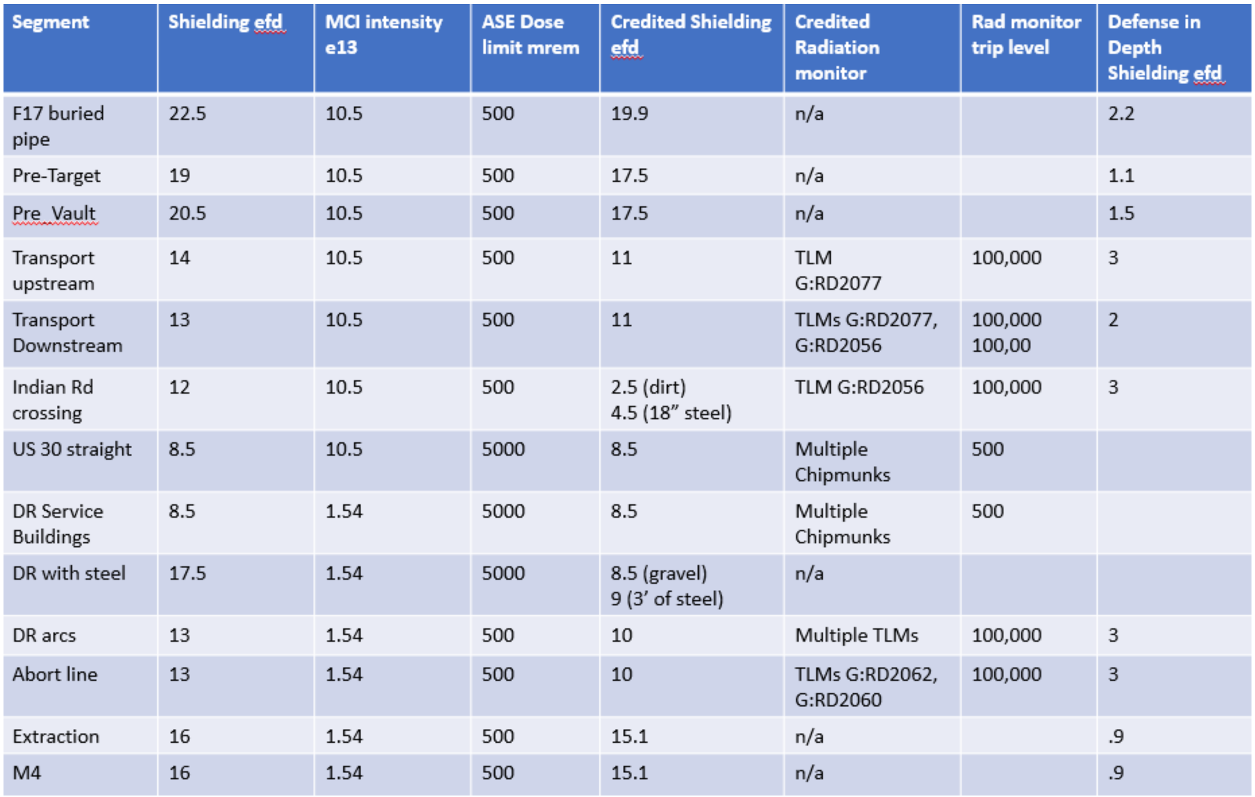
The berm at the Indian Road crossing was similarly calibrated as described in the Transport enclosure. The highest dose on the surface measured 0.019 mrem/E12 lost. Under this condition, a constant beam loss at the MCI intensity of 1.05 E14 protons/sec would result in a 500 mrem surface dose in 250 seconds. In this interval, the TLM would have experienced 26.5 million counts. With the TLM set to trip at 100,000 counts/min, the limit would be reached in the first second. If it takes the safety system 3 seconds to turn the beam off, the total beam lost would be 420 E12 and the dose on the berm would be limited to 8 mrem. We will credit only 10 e.f.d. of the shielding under the road. With 10 e.f.d. of shielding the loss during this interval would be limited to 80 mrem. This provides 3 e.f.d. shielding as defense in depth.

Dose rates in the AP30 service building measured as described in Transport enclosure except that TLMs will not be used under the service buildings. In the service buildings we rely on chipmunk detectors as the credited active controls. The dose rates measured on the chipmunks were 2.32 mrem per E12 lost on a solid object. Constant beam loss at the asynchronous MCI intensity of 1.05 E14 protons/sec would result in a dose of 5000 mrem in the service building in 20.5 seconds. Setting the chipmunk trip level to 500 mrem/hr the trip level would be reached in 5 seconds. If the safety system disabled beam within another 3 seconds, the dose in the service building would be limited to 1950 mrem. Reducing the shielding by 3 e.f.d. would almost double the dose during the incident to nearly 4000 mrem. This demonstrates that we can credit only 5 e.f.d. of shielding along with crediting the chipmunks with a trip setting of 500 mrem/hr. 3 e.f.d. of shielding are defense in depth.

The AP10 and AP50 service buildings are not subject to the asynchronous MCI intensity, but only the synchronous MCI intensity of 1.54 E13 protons/second. The shielding for these buildings are the same as AP30, so the dose limit of 5000 mrem in those buildings would be reached after total MCI loss on a solid object in 140 seconds. Setting the chipmunk trip level to 500 mrem/hr the trip level would be reached in 13 seconds. If the safety system disabled beam within another 3 seconds, the dose in the service building would be limited to 571 mrem. In these service buildings, we credit 5 e.f.d. of shielding and the chipmunks with a trip setting of 500 mrem/hr (the same as in the AP30 service building). 3 e.f.d. of shielding are defense in depth.

The berm over the Delivery Ring abort line was calibrated the same as described in the other enclosure. The highest dose on the surface measured 0.019 mrem/E12 lost. Under this condition, a constant beam loss at the synchronous MCI intensity of 1.54 E13 protons/sec would result in a 500 mrem surface dose in 95 seconds. In this interval, the TLM would have experienced over 1.4 million counts. With the TLM set to trip at 100,000 counts/min, the limit would be reached after the first second. If it takes the safety system 3 seconds to turn the beam off, the total beam lost would be 62 E12 and the dose on the berm would be limited to 21 mrem. We will credit only 10 e.f.d. of the 13 e.f.d. of berm. With 10 e.f.d. of shielding, the dose in this interval would be 210 mrem. This provides 3 e.f.d. of shielding as defense in depth.

The berm over the Delivery Ring arcs was calibrated the same as described in the other enclosure. The highest dose on the surface measured 0.042 mrem/E12 lost. Under this condition, a constant beam loss at the synchronous MCI intensity of 1.54 E13 protons/sec would result in a 500 mrem surface dose in 780 seconds. In this interval, the TLM would have experienced over 12 million counts. With the TLM set to trip at 100,000 counts/min, the limit would be reached after the first second. If it takes the safety system 3 seconds to turn the beam off, the total beam lost would be 62 E12 and the dose on the berm would be limited to 2.6 mrem. We will credit only 10 e.f.d. of the 13 e.f.d. of berm. With 10 e.f.d. of shielding the dose in this interval would be 26 mrem. This provides 3 e.f.d. of shielding as defense in depth.



Segment	Shielding efd	MCI intensity e13	ASE Dose limit mrem	Credited Shielding efd	Credited Radiation monitor	Rad monitor trip level	Defense in Depth Shielding efd
F17 buried pipe	22.5	10.5	500	19.9	n/a		2.2
Pre-Target	19	10.5	500	17.5	n/a		1.1
Pre Vault	20.5	10.5	500	17.5	n/a		1.5
Transport upstream	14	10.5	500	11	TLM G:RD2077	100,000	3
Transport Downstream	13	10.5	500	11	TLMs G:RD2077, G:RD2056	100,000 100,00	2
Indian Rd crossing	12	10.5	500	2.5 (dirt) 4.5 (18” steel)	TLM G:RD2056	100,000	3
US 30 straight	8.5	10.5	5000	8.5	Multiple Chipmunks	500	
DR Service Buildings	8.5	1.54	5000	8.5	Multiple Chipmunks	500	
DR with steel	17.5	1.54	5000	8.5 (gravel) 9 (3’ of steel)	n/a		
DR arcs	13	1.54	500	10	Multiple TLMs	100,000	3
Abort line	13	1.54	500	10	TLMs G:RD2062, G:RD2060	100,000	3
Extraction	16	1.54	500	15.1	n/a		.9
M4	16	1.54	500	15.1	n/a		.9

Table 6: Segments listed showing the minimum shielding in the area along with any active credited controls for the area.

The following figure shows the locations of the credited chipmunks and the TLMs in the Muon Campus.

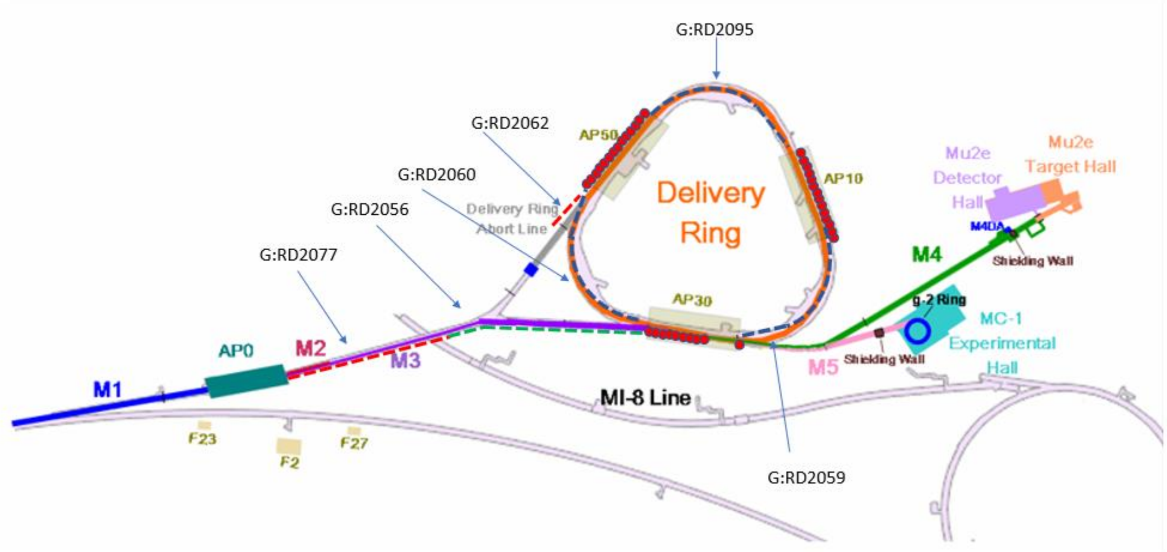


Figure 7. Locations of credited Chipmunk detectors shown as red dots are in the service buildings. The TLMs are shown as broken colored lines with their channel names. The various colors to make clear their location and extent.

III-10.4.2 Credited Administrative Controls

All Muon Campus 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-10.4.2.1 Operation Authorization Document

Beam will not be transported to the Muon Campus without an approved Beam Permit and Running Condition. 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 External Beam Delivery Department Head The Running Condition for the Muon Campus describes the operating configuration as reviewed by the assigned RSO, AD Operations Department Head, and AD External Beams Department Head and as approved by the AD Associate Laboratory Director.

III-10.4.2.2 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 Muon Campus 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-10.4.2.3 Accelerator Operating Parameters

To ensure operations within bounding conditions used in the MCI analysis, the following intensities shall not be exceeded in the areas of the Muon Campus listed here:

- The following intensity shall not be exceeded between F17 in the Tevatron and the injection area in the Delivery Ring 30 straight section: 3.78 e17 protons/hr at 8 GeV.
- The following intensity shall not be exceeded in the Delivery Ring downstream of the 30 straight section, or in the M4 beamline: 5.54 e16 protons/hr at 8 GeV.
- The following intensity shall not be exceeded in the M5 beamline to g-2: 1.67 e13 particles/hr at 3.1 GeV.

III-10.5. Summary of Defense-in-Depth Controls

III-10.5.1 Defense-in-Depth Engineering Controls

III-10.5.1.1 Passive Defense-in-Depth Engineering Controls

III-10.5.1.1.1 Permanent Shielding

The defense-in-depth control for the permanent shielding is defined as 3.0 e.f.d. shielding, present in the Muon Campus berms, in locations that also use active engineered controls. Areas of the Muon Campus that do not require active engineered controls use the additional shielding beyond the credited amount as defense in depth. Additional shielding is placed in some areas of the Muon Campus, such as stacked steel over the extraction devices in the DR, to provide additional defense in depth shielding. Credited controls collectively protect the MOI from receiving an unacceptable dose even if unforeseen modifications to the defense-in-depth permanent shielding were to occur. Such acts could include erosion of the berm or digging into the berm by a human or animal.

III-10.5.1.2 Active Defense-in-Depth Engineering Controls

III-10.5.1.2.1 Machine Protection Controls

The Muon Campus is protected by beam loss monitors, vacuum system monitors, and power supply status monitors.

III-10.5.1.3 Defense-in-Depth Administrative Controls

III-10.5.1.3.1 Fencing and Posting

Fences are used and posted to designate potential Radiation Areas during machine operations. Service building doors remained locked with radiation postings in accordance with the FRCM[4].

III-10.5.1.3.2 Training

All personnel engaged in the commissioning, operation, and emergency management of the Muon Campus shall have at a minimum, Fermilab's Radiation Worker training (FN000731: Rad worker just in time; FN000471: Rad worker practical factors; FN000470: Rad worker classroom (virtual)) current. Furthermore, personnel approved for access into the Muon Campus' interlocked enclosure shall have Fermilab's Controlled Access (FN000311) training current as well.

Equipment specific to the operation of the Muon Campus such as power supplies, RF power amplifiers 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-10.5.1.3.3 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-10.6. Decommissioning

DOE Field Element Manager approval shall be obtained prior to the start of any decommissioning activities for the Muon Campus.

III-10.7. Summary and Conclusion

Specific hazards associated with operation of the Muon Campus accelerators for Muon g-2 and commissioning 8 GeV protons to the M4 DA are identified and assessed through the shielding assessments [1, 2, 3, 12] and summarized in this chapter of the Fermilab SAD. The designs, controls, and procedures to mitigate Muon Campus specific hazards are identified and described. The Muon Campus accelerators are subject to the global and more generic safety requirements, controls and procedures outlined in Section I chapter 04 of the Fermilab SAD.

The preceding discussion of the hazards associated with Muon Campus accelerator operations and the credited controls established to mitigate those hazards demonstrate that the Muon Campus accelerator and beamlines can be operated in a manner that will produce minimal risk to the health and safety of Fermilab workers, researchers, the public, as well as to the environment.

III-10.8. References

[1] **Antiproton Source 2000 Shielding Assessment**, AD/Antiproton Source Department, May 2000 – The Web link is: http://pbar.fnal.gov/documents/Antiproton%20Source%202000%20Shielding%20Assessment/Antiproton%20Source%202000%20Shielding%20Assessment.htm

[2] **Muon Campus Operation Utilizing the Antiproton Source 2000 Shielding Assessment,** A. Leveling, April 2016. - The web link is: https://beamdocs.fnal.gov/AD-private/DocDB/ShowDocument?docid=5081

[3] **Muon g-2 Shielding Assessment,** A. Leveling, February 2017. The Web link is: https://beamdocs.fnal.gov/AD-private/DocDB/ShowDocument?docid=5204

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

[5] **AP0 Target Station Review Committee Report**, June 9, 1997

[6] **Groundwater Management Plan (GMP)**, December 2015 – The Web link is: https://esh-docdb.fnal.gov:440/cgi-bin/ShowDocument?docid=1689

[7] **ESH&Q RPE Routine Monitoring Program**s, ESHQS-RPE-001 – The Web link is: https://fermipoint.fnal.gov/org/eshq/rp/_layouts/15/WopiFrame.aspx?sourcedoc=/org/eshq/rp/Snoop%20Survey%20Program/ESHQS-RPE-001%20ESHQ%20REP%20Routine%20Monitoring%20Programs.pdf&action=default

[8] **Title 40, Code of Federal Regulations, Part 61, Subpart H, "National emissions standard for hazardous air pollutants (NESHAP) for the emission of radionuclides other than radon from Department of Energy Facilities**", 1989.

[9] **Illinois Environmental Protection Agency Registration of Smaller Sources registration memo**, August 21, 2012.

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

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

[12] **Muon Campus Shielding Assessment for 8 GeV Beam Transmission to the Diagnostic Absorber**, A Leveling, February 5, 2020 – The Web link is: https://beamdocs.fnal.gov/AD-private/DocDB/ShowDocument?docid=7983

[13] **M4 line diagnostic absorber MARS simulations to determine exclusion area gate positions**, Leveling RPC, LLC, February 12, 2019 – The Web link is: https://mu2e-docdb.fnal.gov/cgi-bin/private/ShowDocument?docid=3308

[14] **Accelerator Safety Envelope** - The web link is: https://esh-docdb.fnal.gov/cgi-bin/sso/RetrieveFile?docid=1066

[15] **Delivery Ring Cleanup Abort Final Design**, A Leveling, November 2016 – The Web link is: https://beamdocs.fnal.gov/AD-private/DocDB/ShowDocument?docid=5178

III-10.9. Appendix – Risk Tables

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-10.4 of this Chapter as well as SAD Chapter VII-A.1 *Accelerator Safety Envelope - Fermilab Main Accelerator*.