MI - 0247

Shielding Assessment of the Main Injector Complex

(Revision to MI Note: 0225)

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VII. Selected References Included as Attachments

Attachment A1 Dugan Criteria " Shielding Requirements for the Main Injector Era ", (1997).

Attachment B "Study of Attenuation of Radiation Level in Free Space in a Beamline Enclosure" C. M. Bhat, April 1997.

Attachment C "Radiation Shielding of the Main Injector" , Bhat, C. & Martin, P. <u>Proceedings of the 1995 Particle Accelerator Conference and International Conference on High Energy Accelerators</u>. May 1-3, (1995) Dallas, TX. pg. 2105.

Attachment D1 Shielding of the West Booster Tower Building from the Radiation Arising from the Operational losses of 8 GeV proton Beam at the Booster Extraction region during Main Injector Era", C.M. Bhat and P. Martin (June 15, 1994).

D2 "Radiation Shielding of MI8 Beamline", Memo by J. Lackey (Oct. 1996).

Attachment E "Interlock gates for MI - 8 service building", Memo from C.M. Bhat to Phil Martin and John Anderson,(Nov. 14, 1996).

Attachment F "8 GeV shielded Hatch", Memo by C. M. Bhat to Tom Pawlak, Feb. 13, 1996.

Attachment G "Radiation Dose on the 8 GeV Beam-line Berm due to Sight Riser", C. M. Bhat. September 20, 1995.

Attachment H "Shielding Requirements Around the Intersection of AP2 and 8 GeV Beamlines", by C.M. Bhat (April 7, 1994).

Attachment I "Radiation Level in the Intersection Region of AP2 and 8 GeV Beam-line, Due to Beam loss in the AP2 Beam-line", C.M. Bhat and P. Martin, MI Note - 0.0148, (1995).

Attachment J "Temporary, Partial Transport Enclosure Shielding Assessment and Suggested Entry Controls to Permit Personnel Access to the MI-8 Enclosure During Transport Beam Operations" , Memo from Tony Leveling to R. Pasquinelli, Dated Nov. 1 1996.

Attachment K1 "An evaluation of radiation shielding for MI service building, labyrinth and penetrations" , C.M. Bhat, (April 1993, Updated Nov. 1997).

K2 EXIT2A calculations for MI Enclosure, C.M. Bhat, (Nov.1997).

K3 MI60 Circular Labyrinth C.M. Bhat, (June.1998).

K4 Labyrinth calculations for MI60 and F0 region, C.M. Bhat, (Sept.1998).

Attachment L "Desigh of steel shielding for F0", Philip Martin and Chandra Bhat, Oct. 25, (1994).

Attachment M "GROUND WATER, AIR-BORNE AND SOIL ACTIVATION FROM THE OPERATION OF THE MI" C.M. Bhat (REVISED MI Note 0219) (1998)

Attachment N "BD Shielding Review Committee Item,"A memo from Phil Martin to Steve Holmes, dated September 25, 1998.

I. Introduction

Goal of the Fermilab accelerator complex in the next few years is to achieve the ppbar luminosity in the Tevatron collider in excess of 20 x 10^{31} cm^{-2} sec^{-1} to increase its potential to search for new physics. This luminosity will be about ten times more than that achieved during the last collider run. The major limitation to reach this goal arose primarily from the beam intensity limitations in the Main Ring. Hence, a new high intensity 150 GeV proton synchrotron, the Fermilab Main Injector (FMI) [1,2], is being built in a separate tunnel. The FMI which will replace all functionalities of the Main Ring as well as provide high intensity 120 GeV proton beam for fixed target experiments, year-round.

In order to re-use 80-90% of the pbars that are left unused during collider runs, an 8-GeV antiproton storage ring (built using permanent magnets), Recycler Ring (RR) [1], is also being built. Recycling the pbars involves deceleration of the pbars in the Tevatron and in the Main Injector and, storing and cooling them in the Recycler Ring. The RR will be located in the same enclosure as that of the Main Injector. The FMI project includes the construction of both the Main Injector and the Recycler Ring as well as their injection and extraction beamlines.

The purpose of this assessment report is to ensure that the Main Injector accelerator, the Recycler Ring, and associated beamline enclosures are built in conformance with the requirements of the Fermilab Radiological Control Manual (FRCM) [3] and all applicable regulatory requirements.

Construction and completion of the Main Injector/Recycler Ring is broadly classified into three stages from the point of view of shielding assessment:

a) 8-GeV beamline,
b) the Main Injector and Recycler Ring enclosure,

c) the transfer lines between MI and the Tevatron in the vicinity of F0 straight section of the Tevatron and MR remnant up to F17.

The 8 GeV beamline tunnel consists of a remnant of the AP4 line (location 800 to 803) and of a newly built under-ground enclosure (locations 803 to 850) with a total length of about 2600 ft [1,2]. The primary purpose of the beamline is to transport 8 GeV proton beam from the Fermilab Booster accelerator to the Main Injector. A plan view of the beamline is shown in drawing 6-6-12 SC-1. The 8 GeV beamline site plan and its cross sections are shown in drawings 6-6-9 C3 (also see drawing 6-6-12 C11) and 6-6-9 C4, respectively. For purposes of this assessment, locations like 803 is defined as, the point between 803 and 804 where new civil construction began, that is, just downstream of the AP4 dump. Since this beamline consists of old and the new constructions, a multi-faceted approach to the shielding assessment was necessary.

Historically, control of radiation levels in and adjacent to the West Booster Building due to extraction beam losses has been achieved with a combination of interlocked detectors, radiological postings, and occupancy limitations. For the Main Injector operational scenarios, upto 6 ft of steel shielding has been added under the West Booster Tower Building i.e., above the beam extraction region and the shielding assessment is presented elsewhere [ref 27].

The MI/RR enclosure is an oval shaped under-ground tunnel with a total length of about 10900 ft [1,2]. The 8 GeV beam from the MI-8 beamline will be injected into the Main Injector at location MI-101. A plan view of the MI/RR beam enclosure is shown in drawing 6-6-2 TITLE-1 AS-2. A typical cross section of the enclosure indicating the MI and RR is also shown. The horizontal plane of the RR is about 57 in. above that of MI and about 12 in. below the tunnel ceilings at most of the places.

The elevation of the surface above the MI enclosure is about 746 ft and that of the ceiling of the MI enclosure is about 721.5 ft. Thus, the soil equivalent shielding thickness is about 24.5 ft. This is in accordance with Preliminary Safety Analysis Report of Main Injector [4]. (This means 26.5 ft of soil equivalent at 67 deg relative to the beam direction.) However, the enclosure is built to support a soil weight of 26.5 ft which could be used for future MI intensity upgrades. A number of exit stairs, culverts and service buildings very near to the MI berm with many penetrations complicate the shielding assessment .

The RR is closer to the ceiling than MI accelerator. As a result of this, any passive (or active) shielding established (based on the Dugan criteria) for Main Injector 8 GeV proton beam loss conditions, will not be adequate for RR (if one assumes same amount of beam is lost in the RR). Hence, a special administrative step is required to limit the amount of proton beam delivery to the RR (discussed later in section I.d.ii). In the rest of the report, we concentrate only on MI operating conditions and its shielding requirements unless otherwise stated.

a) Basic Shielding Requirements

The Main Injector Preliminary Safety Analysis Report [4] specifies that a minimum of 24.5 ft soil equivalent shielding is required over the MI and its beamline enclosure to achieve unlimited occupancy at the surface for both accidental as well as normal operational beam loss (see table II) conditions. This specification was derived from the Dugan Criteria [Ref. 5, i.e., Attachment -A1] which applies to all locations along the tunnel. The Dugan criteria also suggests a consistent way of usage of interlock detectors to limit beam losses at any point in the accelerator or beamlines where the passive shielding is not sufficient to meet the shielding criteria suggested by ref. [4].

Dugan criteria [5] is developed using the results of Monte Carlo calculations carried out with CASIM [6,7] and assuming a 3 ft radius tunnel. However, the radial distance between MI ring /beamline and the tunnel ceiling is more than 5.65 ft. This difference in the tunnel radii gives us an additional safety margin [ref. 8, Attachment B] in shielding for which we do not take any credit in the present shielding assessment.

b) Analysis Requirements for Disturbances in Passive Shielding

Regions in which passive shielding is disturbed by exit stairways and labyrinths, drop hatches, cable penetrations, site risers, transport enclosure overpass, shielding media and enclosure step changes, culverts, and other locations with complicated structure cannot be analyzed by simple review of basic shielding criteria. These disturbances require special analysis discussed in refs. [6, 7] and refs. [9 Attachment C, 10]. Wherever the soil shielding is less than 24.5 ft, we have added steel. We have assumed that replacing every foot of soil by steel adds 1.89 ft of extra soil i.e., one foot of steel is equivalent to 2.89 ft [11] of soil (this result is derived from CASIM calculations).

c) Radiation Safety Requirements

The shielding criteria described in Ref. 5 are for accidental beam loss conditions for circulating beam or in transfer lines. They are developed in accordance with the Fermilab Radiological Control Manual [3]. Exhibits I - III shown below are taken from Ref. 3 (version of January 1997), and are used in the rest of the report. (By the time this report was written, a revised version of the Fermilab Radiological Control Manual is released. The revisions do not affect the present assessment)*.

*Comments : However, we are using the current version of FRCM for posting and operational controls.

Exhibit I

TABLE 2-6 Control of Outdoor Accelerator/Beamline Areas Against "Normal" Radiation Levels (from FRCM, January 1997)

Dose Rate	Level of Precaution
DR < 0.050 mrem/hr	No precaution needed, no occupancy limit imposed.
0.050 < DR < 5 mrem/hr	See Article 232 for posting
5 < DR < 10 mrem/hr	Signs (Caution - Radiation Area) with chains and/or fencing to define the perimeter, area must have minimal occupancy.(On a temporary basis, ropes may be substituted for fences/chains.)
10 < DR < 100 mrem/hr	Signs (Caution - Radiation Area) and fences (at least 4' high)with locked gates. For beam-on radiation, access is restricted to authorized personnel only.
100 < DR < 250 mrem/hr	Signs (Danger- High Radiation Area), 8 ft. high fences with locked gates the keys to which are interlocked. Fences with no gates are a permitted alternate. No beam-on access permitted.
250 < DR < 1000 mrem/hr	Signs (Danger- High Radiation Area), 8 ft. high fences with locked and interlocked gates and visible flashing lights warning of the hazard. No beam-on access permitted.
DR > 1000 mrem/hr	Not Allowed

Exhibit II

Table 2-7A Control of Outdoor Accelerator/Beamline Areas Against Accident Radiation Levels: Radiation Interlocks Not Used (from FRCM, January 1997)**

Maximum Dose Equivalent per One Hour (D)	Level of Precaution
D < 1 mrem	No precaution needed, no occupancy limit
1 < D < 5 mrem	No precaution needed, area must have minimal occupancy
5 < D < 100 mrem	Signs (Caution - Radiation Area)with chains and/or fencing to define the perimeter, area must have minimal occupancy. (On a temporary basis, ropes may be used in place of chains.)
100 < D < 500 mrem	Signs (Danger - High Radiation Area) and fences (at least 4' high) with locked gates. Access by authorized personnel only
500 < D < 1000 mrem	Signs (Danger - High Radiation Area), 8 ft high fences with locked gates the keys to which are interlocked. Fences with no gates are a permitted alternate. No beam-on access permitted.
D > 1000 mrem	Not Allowed

**See comment on page 9

Exhibit III

Table 2-7B Control of Outdoor Accelerator/Beamline Areas Against Accident Radiation Levels: Radiation Interlocks Used (from FRCM, January 1997)

Maximum Dose Equivalent in one hour (D)	Level of Precaution
D < 1 mrem	No precaution needed, no occupancy limit
1≤ D ≤5 mrem	Area must have minimal occupancy
5 ≤ D < 100 mrem	Signs (Caution - Radiation Area) with chains and/or fencing to define the perimeter and area must have minimal occupancy. On a temporary basis ropes may be used in place of chains.
100 ≤ D < 500 mrem	Signs (Danger- High Radiation Area) and fences at least 4' high) with locked gates. Access by authorized personnel only.
500 ≤ D < 1000 mrem	Signs (Danger- High Radiation Area), 8 ft. high fences with locked gates the keys to which are interlocked. Fences with no gates are a permitted alternate. No beam-on access allowed.
D ≤ 250 mrem/trip	See Article 238.4 (Special Circumstances)

d) Beam Intensity Limits

i. Main Injector [1]

The total beam intensity to be transported through the 8 GeV beamline and accelerated in the MI during RUN II is shown in the first row of Table I. This is based upon the design requirements of the Main Injector operation cycles and the beam used by the antiproton production cycle. The Main Injector has five different types of operation cycles with one mixed mode [1,2]. The details of each of the Main Injector cycle and the beam intensity requirements are shown in Table I

I. **Table I**

Main Injector and Recycler Ring Operation Cycles and Design Beam Intensities[1,2,3]

Operation Mode	Number of Booster Batches	Energy	Cycle (sec)	Flattop (sec)	Proton/cycle (Proton/hr)
Antiproton Production	1	120 GeV	1.5	0.04	5E12 (1.2E16)
Fixed Target Injection	6	150 GeV	2.4	0.25	3E13(3.6E15)**
Collider Injection	1	150 GeV	4.0	1.45	5E12
High Intensity slow spill	6	120 GeV	2.9	1.0	3E13 (3.7E16)
High Intensity fast spill (NuMI Intensity)	6	120 GeV	1.9	0.04	3E13 (5.7E16)
Recycler Ring	-	8 GeV pbar	-	-	3E12
	1	8 GeV p	0.2	-	5E12 (9E16)*

* G. Jackson, (private communication). However, the beam intensity is administratively controlled to be less than 1.5E16p/hr.

** During the Tevatron fixed target operation, two Main Injector cycles (each 2.4 sec long) are used to fill the Tevatron once every 60 sec. Hence, total beam/hr = 60 x 3E13 x 2 = 3.6E15 protons/hr

Table II

8 GeV Beam Losses[4]

Category	Energy	Protons	
Operational Losses	8 GeV	1.0 E19/year#	1.67E15/hour
	120 GeV	4.1 E18/year	6.83E14/hour
Accidental Losses	8 GeV	5.7E16/Accident	
	120 GeV	8.5E15/Accident@	

@ Dugan criteria uses 9.6E15 proton loss/accident instead of 8.5E15proton loss/accident.
# We assume 1 year = Operational 6000 hours

From past experience with the operation of the accelerator complex, an average annual operational beam loss and beam losses per accident are projected for the Main Injector operational conditions. These losses include beam losses at extraction, injection and beam scraping etc. The expected beam loss in each of the two categories is listed in Table II. In the case of operational beam loss, the beam losses are distributed throughout the accelerator with relatively larger losses near extraction and injection sections. However, in estimating radiation shielding we assume that the maximum beam power loss may occur at any point near the region of interest.

ii. Recycler Ring [1]

Operating modes of the RR can be broadly categorized as:

a) accelerator study mode using 8 GeV proton beam,
b) antiproton storage mode.

During the forthcoming commissioning stage of the Recycler Ring a small amount of 8 GeV proton beam will be injected from the MI at MI-32 using an antiproton extraction Lambertson. Every injection is expected to have beam intensity of one Booster turn (6E11 protons). Then the beam is extracted at MI-400 and sent to the MI-40 beam absorber. Since the accidental beam loss condition for RR may be same as that for the MI and, the RR ring is only 1 ft from the enclosure ceiling, the Dugan criteria demands soil equivalent shielding to be more than that established for MI (i.e., between 24.5 - 27 ft of soil). Hence, we administratively limit the total amount of 8 GeV proton beam injection into the Recycler Ring to be less than 1.5E16/hour using beam budget monitor.

During antiproton storage in RR, the maximum intensity will be 3E12 per storage. An accidental beam loss in this case has a maximum loss of 3E12 antiproton which is far less than that for proton accidental beam loss conditions. During the anti-proton store in the Recycler Ring no personnel are allowed in the MI enclosure. Hence, this is not a concern from radiation safety point of view.

II. Passive Shielding

We define the passive shielding as the shielding around the accelerator/beamline enclosure which is either soil or shielding material like steel or combination of both. Steel is almost transparent to low energy neutrons; in most of the cases, whenever steel is used as shielding material, a minimum of 3 ft of soil/concrete is used between the steel and the region of minimal or unlimited occupancy region. The amount of steel and soil is decided based upon the CASIM calculations. When the hadronic shower is fully developed we found that 1 ft of shielding steel is equivalent to about 2.89 ft of soil [11].

A. MI 8 Beamline

During March 1997, a part of this beamline was assessed and commissioned [12]. In this report we assess the MI-8 beamline in connection with the commissioning and operation of the Main Injector complex.

a) Booster Beam Extraction Region and Region Between Locations 800 and 803

As mentioned earlier, 4.5 ft to 6 ft of Steel shielding is added under the West Booster tower and shielding assessment is done in a separate effort[ref. 27} (Additional information on this is given in Ref. 13 [Attachment-D1 and D2].)

b) Beamline in the Region Between 803 to 810

The geometry of the beamline tunnel from location 803 to 810 is very complicated. Plan, elevation and cross section views of this region are shown in drawings 6-6-12 C-22 and 6-6-12 C-23. Extensive shielding evaluations were carried out depth with 3D ray tracing computer codes [9] and also with CASIM [6,7]. Through these evaluations, available in a separate folder [14], we have determined the shielding "deficits"@ . Additional shielding thickness has been provided by using steel absorber in addition to earth.

The calculations of the amount of steel required in those areas where there was insufficient earth shielding were generally done twice; P. Martin used an EXCEL spreadsheet, written with the full geometry of the tunnel enclosure, beam elevation, berm geometry and up to eight blocks of steel. This spreadsheet could be used to rather quickly determine the approximate steel dimensions of each layer, and then calculate through a fairly coarse two-dimensional matrix of loss points along the beam vs. azimuthal angle, with a one-dimensional polar angle array being calculated for each point in the matrix. The steel dimensions were then increased if any deficits were found. The geometry was then given to C. Bhat, who used a FORTRAN 3D-program [9] to check the results, with somewhat finer resolution in the loss coordinates and angles. Both of these programs were ray-tracing, i.e. they calculated the amount of shielding along a vector in space. Considerable effort in developing these programs went into correctly formulating the equations (using results of CASIM calculations) for determining the path length through the steel, especially as the vector is moving past the edge of the steel in one coordinate or the other.

In both cases, the following assumptions were made. First, it was assumed that one foot of steel was equivalent to 2.89 feet of soil [11]. In that reference, it is shown that the soil-equivalency of steel depends upon the star density in the shower; the value 2.89 feet lies in the middle of the range. Second, it was assumed that the desired amount of

@ the "deficit" is defined as the difference between the measured thickness of the soil and the required soil equivalent thickness in that direction.

shielding depends upon the polar angle of the point on the surface relative to the loss point [9]. The peak of the star densities vs. radial distance in CASIM calculations occurs at around a 70 degree angle measured from the beam direction (or 20 degrees relative to the radial direction). Fitting the density vs. angle for the isodose contour corresponding to the allowed dose yielded the formula for the desired shielding (in feet) of 22 plus 0.2 times the angle (in degrees) relative to the radial direction. As an example, this formula requires 26 feet of shielding at an angle of 20 degrees. Note that this also agrees with the Dugan criteria which were formulated for uniform shielding topology: 24.5 feet divided by the cosine of 20 degrees gives 26 feet. It is important to note that in non-uniform geometries such as we are considering here, to use 24.5 feet as a thickness at all angles would greatly under-shield in the forward direction, and would over-shield at 90 degrees and in the backward direction.

Steel of thickness upto 6 ft is buried in the berm over the beamline from location 803 to 810 to achieve a minimum soil equivalent shielding of 24.5 ft.

c) Beamline in the Region 810 to 850

The beamline in this region is typically at an elevation of 715.8 ft with the enclosure ceiling at 721.5 ft. The surface berm elevation is no less than 746 ft, hence total soil thickness is 24.5 ft. Local disturbances in the typical configuration are evaluated separately in following sections.

Airborne activity due to the MI beam in the tunnel is also estimated [Ref. 26]. We find that airborne activity is an unlikely source of significant committed effective dose equivalent (CEDE). Confirmatory airborne radioactivity measurements will be made during early commissioning and operation of the MI.

d) Exit Stairs and Penetrations

There are five exit stairs in the 8 GeV beamline; these are needed to comply with Life Safety Code requirements. They are at approximate locations 808, 818, 828, 842, and 852. Four of the five exit stairs have similar structures (drawings 6-6-9 SC-13 and SC-14); the one near location 808 is unique (drawings 6-6-9 SC-2 and SC-8). We have estimated the radiation dose near both types of exits at the surface using EXIT2A [10]. Independent of this, we have also used the ray tracing program [9] with exact geometry for each exit stairs and surrounding area to find out whether there is sufficient shielding. Where deficits in the original design were found, recommendations were made for changes in the design of the exit stairs and they were implemented. Thus the expected radiation dose near the exits at surface level in the worst case accident scenario meet or are below that required for unlimited occupancy (see Table III).

The utility penetrations at service buildings are also of concern from the radiation dose point of view. There are two types of utility penetrations in the MI-8 service building (drawing 9-6-6-9 C-4). One type consists of straight, 45-foot long, 8-inch diameter penetrations. The second type consists of three legs of 6-inch diameter conduit with a total length of approximately 55-feet. There are 24 penetration conduits separated by a minimum distance of 0.5 ft of concrete. The estimated radiation levels in the MI-8 service building arising from these penetration are also listed in the Table III. The radiation levels at the exits of these penetrations are well below those required for unlimited occupancy.

Air exhaust ventilation ducts (2-foot diameter) are provided at alcoves in the beamline. A drawing of a typical ventilation duct is shown in 6-6-9 M4. The radiation levels at the surface level near the exhaust are found to be well below FRCM limits (see Table III).

e) MI-8 Service Building

The MI-8 service building is the only service building on the 8 GeV transfer line. The drawings 6-6-9 SC-7, SC-8 and SC-9 show plan and section views of the alcove, labyrinth, indoor hatch and stairs in this building. To estimate the radiation dose level in the building we use

Table III.

Estimated Radiation Dose Near Exit Stairs and Penetrations

Location	Radiation Dose	
	Normal Beam loss (mrem/ hr)	Accidental Beam loss (mrem/ accident)
Near Exit door at the surface	<0.025	<0.1
Near far end of straight penetrations (8 in dia)	0.03	1.0
Near far end of the bent penetrations (6 in dia)	<<0.025	<<1.0
Near far end of the air exhaust penetrations	<<0.025	<<1.0

results of Monte Carlo calculations in combination with results of EXIT2A. The estimated radiation dose under the shielded hatch from CASIM is 3.2 $\times 10^{-18}$ rem/proton lost in the beamline. The expected radiation level near the elevator, the top of the hatch, and the top of the stairs are listed in Table IV. The expected radiation levels above and below the hatch listed in Table IV exceed those permitted for unlimited occupancy. However, the MI 8 Service Building is used to store radioactive components, a condition which will require it to be posted as a Controlled Area and locked with a key/core system used for similar existing service buildings. In addition, the region beneath the drop hatch will be posted as a radiation area and will be interlocked to preclude personnel access while beam is operable in the MI 8 line. Adoption of the interlocks, radiological postings, and access controls will be used to ensure that applicable requirements of the FRCM are met [Ref. 15, Attachment-E]. An alternate method may also be employed to control the region. In order to permit access to the drop hatch area , an interlocked detector could be used to limit the dose and duration of an accidental beam loss. If this strategy is adopted, the shielding hatch would not be required and personnel access could be permitted during beam operation. The expected dose per pulse in the accident condition is estimated to be 16μrem and would serve to establish the trip level.

Table IV.

Estimated Radiation Dose Near MI 8 Service Building

Location	Radiation Dose		
	Normal Beam loss (mrem/ hr)	Accidental Beam loss (mrem/ accident)	Inter Locked Detectors
Bottom of the hatch North entrance -A	5.4	182	<0.25 mrem/acc
With 1.5 ft Concrete shielding on the Hatch	0.069	2.3	
Below the hatch East entrance - B	0.25	8.4	
Location - C	0.062	2.1	
Location - D	0.042	1.4	
Near the elevator - E	<0.025	<0.1	
In the Service Building (top of the exit stairs)	<0.025	<0.1	

f) 8 GeV Shielded Hatch

The beamline has a shielded hatch at location 817 for equipment drops. The soil shielding around this hatch is 24.5 ft except near the down stream end of the hatch. Steel is added to the down stream end of the hatch to achieve 24.5 ft [ref. 16 Attachment-F]. Hence the shielded hatch is in compliance with Dugan criteria.

g) Sight Riser (survey points)

There are four sight risers along the 8 GeV beamline viz., near locations 812, 816, between 833 and 834 and one at AP2/8 GeV crossover. The last one is a penetration through the shielding steel above the 8 GeV beamline tunnel as well as the AP2 beamline tunnel. All of these are holes of a maximum 1-foot diameter. We have estimated the radiation level at the surface level from each one of these sight risers using EXIT2A [10] and confirmed the estimate with CASIM calculations. In the case of the sight riser at the AP2/8 GeV crossover the contribution to the radiation coming from the AP2 and AP3 beamline losses have also been taken into account. The radiation levels are as high as 2.5 mrem/hr from normal operational beam losses and ~100 mrem from accidental beam losses [Ref. 17, Attachment-G]. Hence, this penetration is filled with a suitable shielding material (steel and concrete, polyethylene beads, or non-silica sand) to reduce the radiation levels at the surface below the unlimited occupancy limit. The sight risers at other locations are filled with steel and polyethylene plugs to achieve radiation levels at the surface below the unlimited occupancy limit

h) Intersection of the 8 GeV Beamline and AP2 Beamline

Drawings 6-6-10 C-1 and 6-6-10 C-3 display the region between 830 and 831 where the 8 GeV beamline crosses below the AP2 beamline enclosure. These beamlines are at an angle of 49^o with 4.5 ft of shielding in between. Over the AP2 beamline tunnel there is only 14 ft soil equivalent shielding resulting in a 7-foot of soil equivalent shielding deficit over the 8 GeV beamline at the intersection [18, Attachment-H]. Hence, steel is burried in the berm (see drawings 9-6-6-10 C-2) which provides a soil equivalent shielding over 24.5 ft.

Operationally, a special precaution will need to be taken in this region [19, Attachment-I, Ref. 20, Attachment-J]. Whenever there is beam in the 8 GeV line, considerable radiation levels could occur in the AP2 line tunnel. Consequently, to have beam in the MI-8 line, one requires a transport radiation safety system permit which prohibits any personnel to be in the AP2 beamline tunnel.

A less significant radiation hazard may exist in the 8 GeV line between locations 830 and 831 while antiproton beam is transported through the Transport Enclosure [19]. It will not be possible to stack pbars if personnel are present in the MI8 beam line. It will be possible to transfer pbars from Accumulator to MI. The maximum pbars transfer permitted needs to be limited to 95 mA so that the maximum dose of 100mrem/pulse is not exceeded [Attachment N].

i) Man-holes and Utility Ducts

Two manholes and two utility ducts are located near the intersection of the 8 GeV line and South Booster Road. To provide enough shielding to the electric manhole between location 807 and 808, an additional two layers of steel (i.e., 1.5 ft of steel) was placed as shown in drawing 9-6-6-12 C-4. The hand stacked concrete inside the corner of MH14 is also shown. The other manholes for the gas valve box and the two utility ducts are not of concern because they are sufficiently shielded as shown in drawing 9-6-6-12 C-4 (H/C-1).

B. MI and Recycler Enclosure

a) Main Injector Accelerator

Main Injector is built in a plane at an elevation of about 715.85 ft. The vertical distance between the Main Injector ring and the enclosure ceiling is about 5.65 ft. The MI enclosure is designed to have soil equivalent shielding > 24.5 ft to meet the Dugan criteria [see Attachment A2} for beam intensities listed in Table I.

To collect the water seeping through the MI ring berm underdrains are provided on both sides of the tunnel for the entire MI enclosure. These under drains are at an elevation of about 711 ft. The water is collected in the sumps at several locations around the MI ring. The collected under-drain water (surface water) is pumped to Main Injector cooling pond.

The MI has a total of six injection and extraction regions[1] viz., 8 GeV proton injection at MI-10, one 8-GeV antiproton extraction at MI-22, one 8-GeV antiproton injection at MI-32, 8-150 GeV beam extraction towards the Beam absorber in the vicinity of MI-40, a 120-150 GeV beam extraction at MI-52 (with its associated 120 GeV slow extraction septum around MI-30. Also, this serves as an 8 GeV and 150 GeV antiproton injections region of MI) and 150 GeV antiproton extraction at MI-62. All these extraction or injection regions have enough shielding to protect personnel and the environment at the surface.

Ground-water, surface-water and air activations studies for these extraction and injection regions have been carried out separately [see refs. 4 and 21]. The ground water contamination is not a problem at most of the locations except that at MI30. For MI30 location, a detailed study is being done by extracting geological samples. From air-borne activation point of view Beams Division entry procedure should be followed for entry into the extraction and injection region of the MI enclosure after the beam switch is turned off [ref. 26]. Soil activation is not of concern due to the operation of the MI.

b) MI40 Beam Absorber and the beam abort line

The MI40 beam absorber is installed in a separate enclosure in the vicinity of the MI40 straight section. The enclosure has an exhaust fan which will be off during the beam operation. The drawing 9-6-6-7 C-8, shows that the earth equivalent shielding is enough to keep the radiation level above the berm at unlimited occupancy and hence no posting is needed. Entry into the beam absorber enclosure will be controlled by a Beams Division entry procedure.

The MI40 beam absorber enclosure is provided with separate under drain sump near the entrance. The sump water is pumped to the

[1] A fast resonant extraction around MI-609 for NuMI is not covered in this assessment because this is beyond the scope of the MI project. Among all these extraction or injection regions, this is the only region where the total beam extracted is as high as 5.7E16 protons@120 GeV/hour. As shown in drawing 9-6-6-7 C-7 this region meets Dugan criteria [5] of 25 ft of soil equivalent shielding.

MI under drain system and finally pumped to cooling pond near MI40. The sump in the MI 40 absorber is at the elevation of about 705 ft. CASIM calculations have been made to estimate the tritium concentration in the sump water. We find that the radioactive contamination without annual flushing and with annual flushing is negligible as allowed under the DOE contract for Fermilab. Hence, radioactive contamination in the sump water is not a concern However, the sump water will be studied for radioactive contamination during commissioning and operation.

We have investigated the ground and surface water activation [21, Attachment M] arising due to the operation of the MI absorber. We find that the design of the MI40 beam absorber is quite conservative. The air activation is to be studied in two region : in the vicinity of MI40 extraction region and, in the beam absorber enclosure. Appropriate radiological control will be taken during MI operation phases in compliance with FRCM.

At the time of aborting MI beam of energy 8-150 GeV at MI40, the beam will get a horizontal kick at MI-400. A potential loss point for the aborted beam is near Lambertson at MI-402. Dugan criteria requires 25 ft of earth shielding over the beam extraction region. These locations will be raised to 25 ft before the high intensity operation of MI.

The MI and RR aborted proton beam will be transported to the MI40 beam absorber using two separate beamlines. The former beam line is about 270 ft long. As shown in drawing 9-6-6-7 C-8, about 176 ft of the this beamline is installed in the MI enclosure and about 90 ft the beamline comprises of 2 ft dia buried beam pipe. This beam pipe will be under vacuum (rough vacuum) during the operation of the MI. The beam pipe aligns with the carbon core of the beam absorber. Above the buried beam pipe there is more than 30 ft of soil shielding (Dugan criteria requires 27 ft of soil over the buried beam pipe to protect against accidental beam losses).

We have investigated the possibility of radioactivation of the soil due to the interaction of the aborted beam with the soil. There are three different scenarios that causes beam losses in the beam pipe, *viz.*,

1) beam blowup,
2) misfiring of the kicker,
3) interaction of the beam with the air molecules in the beam pipe.

The maximum value of the β (lattice) function in the abort line is about 144 m. For a 20π -mm-mr beam the maximum rms beam size in the buried beam pipe is expected to be about 0.31 inch which is much smaller then the beam pipe radius. Also, the maximum displacement of the beam at the end of the abort beam line is about 1.2 inches[2] (for 15% error in the kicker strengths), which is well within the acceptance of the buried beam pipe. Hence the beam blowup should not pose potential beam losses in the beam line.

From our previous experience with Main Ring and other accelerators, the possibility of kicking the beam at different strengths or misfiring of the abort kicker during MI operation/commissioning is about once in a month for continuous operation[3]. This implies a beam loss of 3.36E14/year@150 GeV which would give rise to ground water contamination about an order of magnitude smaller than allowed limit of 20 pCi/ml-y. Hence, this is not of concern during the MI operation.

The air pressure in the buried beam pipe is expected to be 0.001 Torr. During transport of the beam to the absorber we may expect some beam scattering by the air molecules. The scattered beam particles will end up in the beam soil surrounding the beam pipe. We estimate that the total beam scattered by the air molecules is about 6.5 x 10^{-4} % of the total beam aborted. The yearly ground water and the soil activation arising from the beam loss is estimated to be much smaller than that would arise from the MI40 beam absorber. Hence, this is not a concern during the operation of the Main Injector/Recycler Ring.

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[2]Private communication with A. Russell (MID), (December, 1997).

[3] George E. Krafczyk, December, 1997 (private communication)

c) MI Service Buildings and Exit Stairs in the Service Buildings

There are six service buildings: MI-10, MI-20, MI-30, MI-40, MI-50 and MI-60 and, two kicker buildings: MI-52 and MI-62, adjacent to the MI berm. First five of the six service buildings have similar structure. Typical view of a service building and a kicker building are shown in the construction drawings, 6-6-2 Title 1 AS-6, 6-6-2 Title 1 AS-17 and 6-6-2 Title 1 AS-19. Each of these buildings are provided with an exit stair to enter the MI enclosure. As shown in drawing 6-6-2 Title 1 AS-19, the entrance to the exit stairs is a 6 ft wide passage way which is built over the MI enclosure berm. The floor of this passage way is typically at an elevation of 748.5 ft. The exit stairs have two interlocked doors to inhibit entrance of any personnel to the enclosure when there is beam in the MI enclosure. The radiation level at the surface is evaluated and found to be well below the unlimited occupancy limits [22, Attachment K2, page 8].

d) MI60 Service Building

The MI60 service building is situated on the surface at MI-60 straight section of the MI and is about 450 ft long (parallel to MI-60 straight section) and about 50 ft wide. All of the MI low level RF controls and modules are located in the building. Also, this is the only MI service building which has a control room. Part of the building has many offices and is made into unlimited occupancy region.

There are two personnel entrances to the MI enclosure and a 30ft x 8 ft instrument drop hatch inside the building. One of the personnel entrance is an exit stairs and the other is an elevator. At the tunnel elevation there are two entrances to the MI enclosure; one of them is circular labyrinth of about 300 ft (L) x 10 ft (W) x 8 ft (H) and the other one is a labyrinth with four legs. The estimated radiation dose at the end of these labyrinths show that none of these are of concern and they are build in compliance with FRCM [22, Attachment K2 page 17 and K3]

e) Penetrations

Each service building is provided with several four 6" dia PVC penetrations. A typical penetration is shown in drawing 9-6-6-7 C-9 (also see 6-6-2 Title 1 AS-19). The estimated radiation level in the service buildings due to these pènetrations [22] are found to be well below 0.05 mrem/hr. There are also a number of straight penetrations for LCW pipes and for magnet buses. The estimated radiation levels due to these penetrations are well below unlimited occupancy limit and are also listed in ref. [22, Attachment K2 page 1 and 2].

Air exhaust ventilation ducts (2-foot diameter) are provided at alcoves in the MI enclosure. A drawing of a typical ventilation duct is shown in 9-6-6-7 C-10 STA-9+08. The radiation dose rates from these penetrations at the surface level near the exhaust are found to be well below FRCM limits [22, Attachment K2, page 4]. The exhaust ventilation in the MI40 beam absorber enclosure is also assessed in similar way and found to be fully shielded [22, Attachment K2, page 45].

f) Standard Type MI-Exit Stairs

There are eighteen emergency exit stairs in the MI enclosure in addition to that in service buildings and kicker buildings; these are needed to comply with Life Safety Code requirements. They are at approximate locations 114, 124, 208, 216, 227, 315, 326, 336, 414, 422, 508, 516, 624, 634, 527, 601, 609 and 614. Out of these, the first fourteen of the exit stairs have similar structure. A plan view of a typical exit stairs is shown in figure 6-6-7 SC-33. Construction drawings of exit stairs in MI service building are shown in figure 6-6-2 TITLE-1 C-6, 6-6-2 TITLE-1 AS-17, 6-6-2 TITLE-1 AS-19 and 6-6-7 SC-35. The exit stairs near locations MI-527 and MI-614, and near

MI-601 and MI-609 [ref. 23] are displayed in 9-6-6-7 C-7A. Extra steel is buried in the enclosure berm to achieve 24.5 ft of soil equivalent shielding for these four exit stairs. All of these exit stairs are designed to have radiation level at the exit doors near the surface [22, Attachment K2, page 6,7,9-16] well below the unlimited occupancy limit.

h) Sight Risers (survey points)

There are twelve sight riser along the MI enclosure, viz., at locations 116, 128, 207, 301, 309, 332, 416, 507, 532, 601, 609, and 633. All of them have similar structure as explained in section II.A.g. These sight risers will treated similar to MI-8 beamline sight risers to keep radiation levels at the surface well below unlimited occupancy limit.

i) Culverts

There are a total of 13 culverts along the MI enclosure which are built using cement pipes of four different sizes, viz., 4 ft, 3 ft, 2 ft and 1.5 ft dia. Some of these culverts have more than one pipe placed side Some of these culverts have more than one pipe placed side by side and are of varying lengths. The locations, size, lengths and their angles to the MI beam line berm of individual culverts are listed in Table V. Suggestions were made prior to the civil constructions of these regions of the MI enclosure to add necessary steel under them or to extend the culverts or combination of both to keep the radiation level is well below the acceptable limit in compliance with FRCM. We have estimated [24] the radiation level at the end of each type of culvert using CASIM (CASPEN) for accidental beam loss conditions. The table below summarizes the results for each culverts. We conclude that the culverts in the MI regions should not be of radiation concern.

Table V. Estimated radiation levels near culverts. L = Length of the culverts and T = Total thickness of the material between bottom of the culvert and ceiling of the enclosure.
(Accident = Continuous loss of 5.7E16 p@8 GeV or 8.5E15 p@120 GeV.)

Location of the Culvert	Size (dia)	Length (L) (ft) Thickness (T) (ft)	Angle (deg)	Comments
MI-110	4 ft, 7 pipes are spread in 60 ft region	136(L) 13.5 (T)	48	<1mr/acc 1.5 ft steel
MI-123	4 ft 3 pipes spread in 25 ft region	61(L) 16.5 (T)	57	<1mr/acc 1.5 ft steel
MI-423	4 ft 5 pipes spread in 38 ft region	90(L) 11.5 (T)	~90	<1mr/acc 1.5 ft steel
MI-332	3 ft 3 pipes spread in 25 ft region	110(L) 7.5 (T)	~90	<1mr/acc* 2.25 ft steel
MI-100	2 ft	45(L) 19.5 (T)	90	<1mr/acc No steel
MI-117	2 ft	56(L) 16.0 (T)	90	<1mr/acc No steel
MI-228	2 ft	48(L) 16.0 (T)	90	<1mr/acc No steel
MI-315	1.5 ft	55(L) 14 (T)	90	<1mr/acc No steel
MI-402	1.5 ft	63(L) 11.0 (T)	90	1mr/acc No steel
MI-502	2 ft	55(L) 17.5 (T)	90	<1mr/acc No steel
MI-617	1.5 ft	45(L) 21.0 (T)	90	<1mr/acc No steel
MI-627	2 ft	45(L) 21.0 (T)	90	<1mr/acc No steel
MI-634	2 ft	45 (L) 21.0 (T)	90	<1mr/acc No steel

* With steel

Sectional views of the MI berm in the vicinity of individual culverts are shown along with the as built drawings of MI/RR. The 24.5 ft contours shown on these FESS drawings are indicative of required shielding right above the culverts assuming no disturbance in the shielding by additional structures (like culverts). However, from the CASIM calculations the needed shielding right above the loss point, i.e. 90 deg relative to the beam direction, is about 22.0 ft and at shower maximum i.e., at 67 deg, is about 26.5 ft. The dose at a point on the surface is the sum of doses which occur along an infinite number of trajectories arising from complicated hadronic showers. While the ray through the center of the culvert is under-shielded, this is more than compensated by the many rays which are over-shielded. Hence a local disturbance, like culverts (of small dimensions up to 2 to 3 ft dia and if there are many then they should be sufficiently apart), would not reflect any deficit in the overall shielding.

C The P150 and A150 transfer lines, F0 straight section and Main Ring Remnant from F0 to F17

a) P150 beamline (150 GeV Proton transfer beamline to Tevatron)

This beamline is intended to transfer a) the 150 GeV proton beam from the Main Injector to the Tevatron during the collider runs, b) 120 GeV proton beam from MI for antiproton production and, c) 120 GeV proton beam from MI towards fixed target Switchyard areas using the Main Ring remnant as a beamline, d) 150 GeV unused antiprotons from the Tevatron to the Main Injector and e) 8 GeV antiprotons from Accumulator Ring to MI/RR. The beam line starts at Q522 location in the Main Injector and ends at the center of the four switching Lambertsons in the Tevatron at F0 sector. The beam is elevated from about 715.85 ft at MI52 to 723.375 ft at the Tevatron F0 injection region. The enclosure floor (ceiling) elevates from 713.5 ft (721.5 ft) near MI to 718.5 ft (730.5 ft) at F0. The total length of the beamline is approximately 725 ft. The beamline enclosure is designed to achieve a minimum of 24.5 ft soil equivalent shielding everywhere and 26 ft of soil equivalent shielding over the MI52 extraction location, as per the requirements from the Dugan criteria [see Attachment A2 and drawing 9-6-6-7 C-6]. Hence, the beamline is in compliance with the shielding requirements of Ref.3 for unlimited occupancy during the MI operation.

b) A150 beamline (150 GeV Antiproton transfer beamline to Tevatron)

The A150 beam line is intended for the transfer of 150 GeV antiprotons from the Main Injector to the Tevatron. This beamline also transfers 150 GeV proton beam in reverse direction during beamline tune up. The total amount of beam extracted at MI62 and transported is far less than that with P150 beam line. However, the total shielding over the beam line tunnel is 24.5 ft. Hence, this beam line is in compliance with the shielding requirements of Ref. 3 for unlimited occupancy during MI operation.

c) F0 straight section

The Tevatron enclosure from E48 to F13 is a newly constructed enclosure including the F0 service building at the surface level. This region has many penetrations including eight 9 in diameter RF wave-guide penetrations. For the entire section of the beamline necessary steel is added to meet the criteria of 24.5 ft of soil equivalent shielding thus meeting the requirement for unlimited occupancy [see Attachment L, and refs. 25, 26] . Construction drawings for this region is shown in 6-6-11 - C-3 to C-23. The estimated radiation dose [see Attachment K2 page 18] near the end the penetration (in the F0 service building) is as high as 4 mrem/accident without adding 4 ft of shielding. The service building is posted as controlled area in compliance with FRCM.

d) MI and Tevatron RF Cavity Regions

The Tevatron RF region with boundaries at E35 though F47 will be entry prohibited during MI operation due to the combination of relatively high beam intensity of the MI and the relatively thin shielding available between the MI and Tevatron enclosures.

The minimum transverse soil shielding thickness between the Tevatron and the MI enclosures is just over 6 ft at the MI/Tevatron Crossover locations. The floor elevations are respectively, at 722.5 ft and 713.5 ft. Elsewhere in this region. the nominal shielding thickness is approximately 12 feet or more. Additional shielding will be needed at the Crossover locations to provide adequate protection to personnel in the MI RF section against losses from a Tevatron store.

The Crossovers at 531/532 and at 609/610 are interconnecting labyrinths between the FØ region of the Tevatron and MI60 region of the MI. Each of the Crossovers has doors: one as an exit from the MI, one as an exit from the Tevatron. and one as an emergency exit to the surface. Personnel access within either of the Crossovers is prohibited by the Radiation Safety System during any type of beam operation in either the Tevatron or the MI enclosures. The doors at the entrances to either the Tevatron or the MI are equipped with crash bars so that personnel may escape from either enclosure to the surface in the event of an emergency. If any of the three doors in either of the Crossovers is opened during beam operation in either the Tevatron or MI enclosure, the beam operation will be immediately terminated by the Radiation Safety System.

Temporary gates have been installed in the P150 and A150 beam transfer line enclosures as part of the MI Electrical Safety System to permit electrical testing of MI. These gates prevent personnel access from the Tevatron enclosure to the MI enclosure. They will not be useful for any MI Radiation Safety System and will not be necessary after shield walls are installed in each of A150 and P150 transfer lines.

Personal access into the MI60 RF region during the operation of the Tevatron will be permitted. The entire MI enclosure including the MI60 RF region is posted "Caution Radiation Area". This posting requires that normal and accident condition dose rates be less than 10 and less than 100 mrem/hr respectively. The shielding between the MI60 RF region and the Tevatron and the shielded walls contained within the A150 and P150 beam transport lines is adequate for this mode of access [see attachment K4].

Personal access into the FØ region of the Tevatron during the operation of the Recycler Ring, is permitted. The entire Tevatron enclosure including the FØ region is posted Caution Radiation Area. This posting requires that normal and accident condition dose rates be less than 10 and less than 100 mrem/hr respectively. The shielding between the MI60 RF region and the Tevatron and the shielded walls contained within the A150 and P150 beam transport lines is adequate for this mode of access [see attachment K4].

The Tevatron RF region with boundaries at E35 though F47 will be an exclusion area during MI operation due to the relatively thin shielding available between the MI and Tevatron enclosures. Interlocked gates are installed at E35 and F47 locations [28].

e) Main Ring Remnant from F13 to F23

The enclosure from F13 to F23 locations along the Tevatron is also part of the present assessment. This enclosure includes the remnant of the Main Ring as a beam transfer line connecting to the AP1 beamline. The 120 GeV beam from the Tevatron enclosure will be transported through the Main Ring remnant to F17 where the beam is transferred to the pbar production target station via the AP1 beam line. The soil equivalent shielding over this region is <19.3 ft except near the F1 refrigerator building. The building itself is protected by an interlocked detector. However, very near to it, the shielding is slightly less than 19 ft. A locked fence around the berm from F10 to F23 is required in order to control personnel access in accordance with the FRCM and Beams Division entry control procedures. To reach the MI operational goal, one needs to add fences as mentioned above and radiation area postings. Also, interlocked doors at F1, F2, F3 and F4 service builidngs along with an interlocked gate at F47 are provided to inhibit personnel entrance to the F17 location during commissioning and pbar production.

III. Radiation Dose from the Muons

The on-site and off-site radiation level due to the muons produced as a result of 8-150 GeV proton beam loss in the MI/MI-8 enclosure or that due to the beam on the MI-40 absorber have been considered. The produced muons will attenuate to an acceptable limit in about 600 ft of soil in longitudinal direction and in about 15 ft in radial direction [see for example ref. 21] .Since the MI is in a plane and the tunnel is at about 24.5 ft below the surface level, the muons produced will not be a problem from the radiation point of view either on-site or off-site locations. However, the beam gets a vertical kick of about 24mradian at the extraction locations (MI52 and MI62). Hence, the direction of the produced muons at these locations will be upwards by about 24 mradian. We have estimated that the longitudinal soil shielding at these two locations are in excess of 700 ft. Hence, these locations are fully protected from muon radiation.

IV. Summary

We have performed a detailed shielding assessment of the 8 GeV beamline and Main Injector / Recycler Ring enclosures to ensure that the shielding is in compliance with the FRCM. To meet the criteria of 24.5 ft soil equivalent shielding over 8 GeV the beamline, we have added steel shielding wherever necessary. A separate assessment will be made for the Booster extraction region and for the locations 800 to 803. The configuration of the Radiation Safety System precludes personnel access to the AP2 tunnel at the crossover region when beam may be transported through the 8 GeV line.

In the case of MI/RR enclosure, there is 24.5 ft of earth equivalent shielding everywhere. Over the P150 and A150 beam lines, there is 24.5 ft of earth equivalent shielding. There is adequate shielding in the vicinity of the extraction regions MI52 and MI62. Necessary steel is added to meet the criteria of 24.5 ft of soil equivalent shielding over the MI60 straight section (under the passage way connecting the MI60 and F0 service buildings) and F0 straight sections. The soil shielding over the MR remnant in the region from F13 to F23 is >19 ft except near the F1 refregerator building. The shielding is added to be in compliance with FRCM.

In the case of Recycler Ring, the beam intensity should be administratively controlled and kept below 1.5E16/hour @ 8 GeV.

We also have to control administratively, the amount of pbar transfer through the AP2 beamline over the MI8 enclosure when MI8 beamline is not used for beam transfer.

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VI. Drawings

A. Construction Drawings for MI-8 Beamline

B. Radiation Shielding Drawings for MI-8 Beamline

C. Construction Drawings for MI/RR Enclosure

D. Radiation Shielding Drawings for MI/RR Enclosure

E. Radiation Shielding Drawings for P150, A150 and F0-F23 Region