Main Injector and Recycler Ring Shielding Assessment

(Revision to MI Note: 0225)

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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)

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 20×10^{31} cm^{-2} sec^{-1}, in order 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 which was in the same enclosure as the Tevatron accelerator. 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 run, an antiproton storage ring (with 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.

Completion of construction and commissioning of the Main Injector/Recycler Ring is broadly classified into three stages:

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 (civil construction of the enclosure of these transfer lines are underway at the time of writing of this report. Hence, in this report we will not discuss shielding assessment of these beamlines).

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]. For purposes of this assessment, location 803 is defined as the point between 803 and 804 where new civil construction began, that is, just downstream of the AP4 dump. 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. Since this beamline consists of old and the new constructions, a multi-faceted approach to the shielding assessment was necessary. The new construction passive shielding was designed and built specifically for the Main Injector operation conditions. The remnant, old structure which includes locations 800 through 803 was originally designed for lower intensity operation. Historically, control of radiation levels in and adjacent to the building due to extraction beam losses has been achieved with a combination of interlocked detectors, radiological postings, and occupancy limitations. During the Main Injector era it will be necessary to follow similar control procedures. However, due to the proximity of the West Booster Tower, the feasibility of placing additional shielding above the remnant enclosure and over the beamline to provide enough radiation shielding, which meet the requirements of the Fermilab Radiological Controls Manual [3], is presently being investigated. Hence, no conclusions will be made regarding the adequacy of shielding for the 800 to 803 location in this assessment.

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 around the MI enclosure and its beamline 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]. 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 commissioning of the Main Injector/Recycler Ring is planned in four steps viz,

i. commissioning of the part of the 8 GeV beamline,

ii. commissioning of the M-10 to MI-40 section of the ring,

iii. establishing low intensity circulating 8-GeV beam and,

iv. establishing 120 GeV circulating beam and beyond.

The first step of commissioning is complete (March 97, see ref.12). The next three steps of commissioning will happen in chronological order in near future.

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's 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 or 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 Dugan's Criteria [Ref. 5, i.e., Attachment -A1 and A2] which applies to all locations along the tunnel. The Dugan's criteria also suggests a consistent way of usage of interlock detectors to limit beam losses at any point in the accelerator or beam where the passive shielding is not enough to meet the shielding criteria suggested by ref. [4]. The radiation shielding drawings included in section V-B indicate that presently the requirement of 24.5 ft soil equivalent shielding is met at all locations in the MI-8 beamline, from MI-100 to MI-517 and MI-612 to MI-641 along the MI berm. From MI-517 to MI-612 there is shielding deficit which will be fixed before the completion of the FMI construction project.

Dugan's 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, in all enclosures considered here, the radial distance between MI 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). The drawings shown in Section VI-B represent the conditions at present and the passive shielding is over 24.5 ft of soil equivalent shielding all along the MI-8 beamline and also from MI-612 to MI-517 in proton direction (i.e., counter clockwise direction). The shielding deficits in the region from MI-517 to MI-612 will be corrected with the addition of shielding and/or necessary precautions in compliance with FRCM [4] will be taken before beam commissioning.

c) Radiation Safety Requirements

The shielding criteria described in Ref. 5 are for accidental beam loss conditions in circulating 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 contents of these tables and present assessment).

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

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. The amount of beam transported through the 8-GeV permanent magnet beamline reaches maximum during NuMI operation.

Table I

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

Operation Mode Batches	**Number of**	**Energy(sec)**	**Cycle (sec)**	**Flattop (Proton/hr)**	**Proton/cycle Booster**
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)

Table II

8 GeV Beam Losses [4]

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

@ Dugan s 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 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. The Dugan criteria adopted here are based upon such a loss at NuMI operating intensity. Other disturbances in the shielding are also evaluated using this conservative accident scenario.

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's criteria demands soil equivalent shielding to be more than that estabilished for MI (i.e., between 24.5 - 27 ft of soil). Hence we suggest that the proton beam in the Recycler Ring during its study should be administratively controlled and beam loss per accident should be less than 1.5E16 p at 8 GeV.

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. 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. Since the steel is almost transparent to low energy neutrons, whenever steel is used as shielding material, precaution is taken to have a minimum of 3 ft of soil/concrete between 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 commissioned [12]. In this report we assess the MI-8 beamline in connection with the commissioning of M-10 to MI-40 part of the Main

Injector.

a) Booster Beam Extraction Region Between Locations 800 and 803

As mentioned earlier, this part of the MI-8 line is to be evaluated under a separate assessment which includes radiation level in the West Booster Tower and radioactive contamination in the ground-water. 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 depth evaluations were carried out 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 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.

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.

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. 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.

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

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 results of Monte Carlo calculations in combination with results of EXIT2A. The estimated radiation dose under the shielded hatch from CASIM is 3.2 x10-18 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 would be at least 16mrem 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 Location - D Near the elevator - E	0.062 0.042 <0.025	2.1 1.4 <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. In this region the soil shielding is only 22.5 ft with about 2 ft of soil deficit. To improve the shielding, we have added steel. The details of this is shown in reference 16 [Attachment-F].

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. These survey penetrations are potential shielding deficit points. 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.

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. The radiation level is found to be as high as 2.5 mrem/hr from normal operational beam losses and ~100 mrem from accidental beam losses [Ref. 17, Attachment-G]. Hence these penetrations will be filled with a suitable shielding material (steel and concrete, polyethylene beads, or non-silica sand) to reduce the radiation levels to below those which permit unlimited occupancy.

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 49o with 4.5 ft of shielding in between. Over the AP2 beamline tunnel there is only 13 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, we have added 3.75 ft of steel (see drawings 6-6-10 C-3 and 6-6-10 C-5) which provides a soil equivalent shielding of 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 beam is transported through the Transport Enclosure [19]. An interlocked detector has been installed and a set of entry controls has been established and will be maintained to limit this hazard to levels permitted by the FRCM [Ref. 20, Attachment-J].

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 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. For the purpose of this report, the MI accelerator enclosure is assessed in two steps. The first step includes assessment of the regions from MI-100 to MI-517 and MI-612 to MI-641. The second step includes that of MI-517 to MI-612 (which will be done before 3rd and 4th stage of beam commissioning).

Presently, there is a minimum of 24.5 ft of soil equivalent shielding over the enclosure ceiling from locations MI-100 to MI-517 and MI-612 to MI-641. The MI has a total of seven injection and extraction regions (viz., 8 GeV proton injection at MI-10, one 8-GeV antiproton injection at MI-22, one 8-GeV antiproton extraction at MI-32, a 120 GeV slow extraction septum around MI-30, 8-150 GeV beam extraction towards the Beam absorber in the vicinity of MI-40, a 120-150 GeV beam extraction at MI-52 and 150 GeV antiproton extraction at

MI-62). All these extraction or injection regions have enough shielding in accordance with Dugan's Criteria.

b) MI-40 beam abort line and the Beam Absorber

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's criteria requires 25 ft of earth shielding over the beam extraction region. But the drawings 9-6-6-7 C-4 and 9-6-6-7 C-8 show that there is up to about 0.5 ft soil deficit at some location over the enclosure. These locations will be raised to 25 ft before high intensity operation of the MI.

The aborted proton beam will be transported to the MI40 beam absorber using a **270 ft** long beamline. 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's criteria requires 27 ft of soil over the buried beam pipe to protect against accidental beam losses, see ref 5, Attachment A)

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 :

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

The maximum value of the b (lattice) function in the abort line is about 144 m. For a 20p -mm-mr beam the maximum rms beam size in the buried beam pipe is expected to be about 0.31 in 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 (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. The possibility of kicking the beam at different strengths or misfiring of the abort kicker during MI operation/commissioning is also not a problem because our previous experience with Main Ring and other accelerators showed that such probability is very rare (**once in a month of continuous operation**).

The air pressure in the buried beam pipe is expected to be 0.001 Torr. During beam 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 ground water and the soil activation arising from the beam loss is estimated to be much smaller than that would arising from the MI40 beam absorber. Hence, this is not a concern during the operation of the Main Injector/Recycler Ring.

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 in to the beam absorber enclosure will be controlled by a Beams Division entry procedure.

We have investigated the ground and surface water activation [21] 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 both during MI commissioning and operation phases in compliance with FRCM.

c) MI60 region of Main Injector and F0 of Tevatron for commissioning of MI-10 to MI-40 Region of MI

In this report we do not undertake the shielding assessment of MI60 region of the enclosure because of the civil construction is yet to be completed. During MI-10 to MI-40 beam commissioning, we will establish administrative controls to prohibit any accelerator/ construction personnel entry the MI enclosure. The entire MI enclosure with its beamlines will be searched and secured and the RSS and ESS interlock system will prevent beam operation in the event of entry is made into the enclosure..

d) 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 the MI berm. First five of the six service buildings have similar structure. MI-60 service building serves a special purpose. The low-level and high-level RF controls for the MI are situated in this building and this is the only service building at the MI enclosure which is provided with an indoor equipment drop hatch. At the enclosure level there are two labyrinths : a 4' ft (w) x 7.5 ft (h) labyrinth and a 10 ft (w) x 8 ft (h). The radiation level at the far end of the labyrinth of first type is estimated to be less than the unlimited occupancy limit for both normal as well as accidental beam loss conditions [22, Attachment K1].

Typical view of service buildings and kicker buildings 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 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].

e) MI60 Service Building

The MI60 service building is situated 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 unlimitted 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

f) Penetrations

Each of the service building is provided with three groups of 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 penetrations [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 bus. The results of estimated radiation levels due to these penetrations are well below unlimited occupancy limit and are also listed in ref. [22] (.Attachment K2).

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 levels at the surface level near the exhaust are found to be well below FRCM limits [22, Attachment K2]. The exhaust ventilation in the MI40 beam absorber enclosure is also assessed in similar way and found to be fully shielded (see 22, Attachment K2).

g) 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, 626, 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 stair stairs is shown in figure 6-6-7 SC-33. We find that the radiation level at the exit doors near the surface [22] is well below the unlimited occupancy limit . The exit stairs near locations MI-527 and MI-614, and near MI-601 and MI-609 have similar structure. In the present report we do not give detailed assessment of these exit stairs because of on-going civil construction. They will be assessed in a future assessment.

h) Sight Risers (survey points)

There are ten sight riser along the MI enclosure, viz., at locations 116, 128, 207, 301, 332, 416, 507, 532, 609, and 633. All of them have similar structure as explained in section II.A.g. These sight risers will be filled up with suitable material in similar way as is done for MI-8 beamline sight risers to keep radiation levels at the surface well below unlimited occupancy limit.

i) Culverts

There are a total of 11 culverts along the MI enclosure. Pipes of three different size, viz., 4 ft, 3 ft and 2ft dia, are used to build them. Some of these culverts have more than one pipes placed side by side. The length of each culvert vary. The 4 ft dia culverts are in the vicinity of locations MI-110, MI-123 and MI-423 and a 3 ft culvert is at MI-332. Seven 2 ft dia culverts are at MI-117, MI-228, MI-315, MI-402, MI-502, MI-617 and MI-634 locations. Some of these culverts intersect at an angle other than 90o. Ends of the culverts are potential locations of high radiation level.

We have estimated [23] the radiation level at the end of each type of culvert using CASIM (CASPEN). The table below summarizes the results of our estimation of the radiation level at the end of each culverts.

Accident = Continuous loss of 5.7E16 p@8 GeV or 8.5E15 p@120 GeV.

Location of the Culvert	Size (dia)	Length (L) Thickness (T) (ft)	Angle (deg)	Comments
MI-110	4 ft, 7 pipes are spread in 60 ft region	136(L) 12.5 (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) 18.5 (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-107	2 ft	44(L) 18.5 (T)	90	<1mr/acc No steel
MI-117	2 ft	56(L) 16.5 (T)	90	<1mr/acc No steel
MI-228	2 ft	48(L) 16.5 (T)	90	<1mr/acc No steel
MI-315	2 ft	55(L) 14 (T)	90	<1mr/acc No steel
MI-402	2 ft	63(L) 11.0 (T)	90	1mr/accN No steel
MI-502	2 ft	55(L) 17.5 (T)	90	<1mr/acc No steel
MI-617	2 ft	45(L) 19.5 (T)	90	<1mr/acc No steel
MI-634	2 ft	45 (L) 18.5 (T)	90	<1mr/acc No steel

* With steel included

and and a culvert is at . Seven dia culverts are at , , , , and locations.

Suggestions were made prior to the civil constructions of these regions of the MI enclosure and precautions were taken by either adding steel under them or by extending the culverts or combination of both, so that the radiation level is well below the acceptable limit at all locations.

j) Beam stop at MI409 for MI10-40 commissioning

During MI10-40 beam commissioning a temporary **3 ft thick steel** beam stop will be inserted at MI409 location to inhibit accidental beam transfer downstream of the MI40 section of the MI ring. During commissioning beam will be sent to the beam MI40 beam absorber. In the scenario of misfiring of the MI40 kickers, the beam could be directed towards the temporary beam stop. We have estimated the radiation level assuming one misfire per hour. Since the MI52 location is about 2000 ft from this location and is not in direct line of site with this location, prompt radiation is not a problem (Also, the MI enclosure is searched and secured during commissioning). Removal of the iron block will be done in compliance with the FRCM upon completion of MI10-40 commissioning.

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 will be used 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 to antiproton production and, c) 120 GeV proton beam from MI towards Fixed Target Switchyard areas using the Main Ring remnant as 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 about Q516 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 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 1025 ft. The beamline enclosure is built with a minimum of 24.5 ft soil equilant shielding, as per the requriements from Dugan's criteria[ref]. The construction drawing for this beamline is shown in Figure (**???**).

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

This beamline will be used to transfer the 150 GeV antiproton beam from the Main Injector to the Tevatron during the collider runs. This beamline is a mirror reflection of P150. The beamline enclosure is built with a minimum of 24.5 ft soil equilant shielding, as per the requriements from Dugan's criteria [ref].. The construction drawing for this beamline is shown in Figure (**???**).

c) F0 straight section

Tunnel Radiation Shielding Evaluation:

The P150 beam line and A150 beam line have symmetry around TeV F0 location. The P150 beam line is intended for transfer of 150 GeV protons from the Main Injector to the Tevatron. This beam line is also used to transfer 120 GeV beam from MI to F17 for pbar production, S witchyard, 8 GeV antiproton transfer from Accumulator to the MI and 150 GeV antiprotons from the Tevatron. The 120-150 GeV proton beam extraction takes place at MI52. The beam line elevates from 715.85 ft (at MI extraction point) to about 723.5 at F0 location and to about 725.5 at F11 location and, has a length of about 575 ft. After the completion of the MI project, the soil equivalent shielding over the MI52 extraction region will be about 26 ft and over the P150 GeV beam line enclosure it will be about 24.5 ft. Hence, the beam line is in compliance with the shielding requirements of Ref. 9 for unlimited occupancy [**and REF.1**] during MI operation.

The A150 beam line, on the other hand, is intended for the transfer of 150 GeV antiprotons from the Main Injector to the Tevatron. The total amount of beam extracted at MI62 and transported is about 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. 9 for unlimited occupancy [**and REF.1**] during MI operation.

The Tevatron enclosure from E48 to F10 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[10] thus meeting the requirement for unlimited occupancy.

From F10 to F23 locations along the Tevatron enclosure which includes the remnant of the Main Ring, the soil equivalent shielding over the tunnel is <19.3 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. The fenced F10 to F23 location is required to be posted as a Radiation Area. The permitted normal and accident dose rates for a posted Radiation Area are <10 mrem/hr and <100 mrem/hr respectively. 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.

e. MI and Tevatron RF Cavity Regions

The Tevatron and MI - RF cavities are installed in the Tevatron F0 sector and the MI-60 sector, respectively. Access to the MI60 region of the MI with MI RF cavities operating is permitted since x-ray exposure rates are relatively low (on order of 1 to 2 mrad/hr). Access to the FØ straight section during Tevatron RF cavity operation is prohibited due to very high x-ray exposure rates (on order of 1 rad/hr). The Tevatron Electrical Safety System permit is required in order for the Tevatron RF supplies to be energized. The Tevatron ESS permit requires that all Tevatron enclosure keys are in the respective key tree and the Tevatron enclosure is seached and secured. The Tevatron Electrical Safety System and sector gates at the boundaries of the FØ straight section (gates at E35, F47, and Tevatron enclosure access doors between them) provide the necessary protection to prevent significant personnel exposure due to x-rays.

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 or interlocked detectors 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 three gates: 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 gates 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 gates 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.

A temporary gate may be installed in each of the P150 and A150 beam transfer line enclosures as part of the MI Electrical Safety System to permit electrical testing of MI. These gates would 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 the 16 foot thick shield walls are installed in each of these 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 will be 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 16 foot shield walls contained within the A150 and P150 beam transport lines is adequate for this mode of access.

Personal access into the FØ region of the Tevatron during the operation of the Recycler Ring, will be permitted. The entire Tevatron enclosure including the FØ region will be 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 16 foot shield walls contained within the A150 and P150 beam transport lines is adequate for this mode of access.

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.

d) Main Ring Remnant from F10 to F23

At about QF12 the nominal elevation of the MR remnant is reached. In the following pages, the three sections are described briefly and a compilation of beamline components and their status are provideded.

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 (including NuMi extraction location).

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 in the vicinity of 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 over the MI-100 to MI-517 and MI-613 to MI-641 part of the Main Injector enclosure. From MI-527 to MI-613 there is shielding deficit which will be fixed before the completion of the FMI construction project. The shielding for the region will be assessed in a later assessment.

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

Also, during the MI10-MI40 commissioning, the entire MI enclosure will be protected by a RSS and ESS and, it will be searched and secured before sending the beam to MI40 beam absorber.

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V. References (* Implies these references are included as attachments)

[1] Fermilab Main Injector Technical Design Handbook (1994). "The Fermilab Recycler Ring Technical Design Report", Gerry Jackson, FERMILAB-TM-1991, (1996).

[2] Fermilab III Design Handbook (1995).

[3] Fermilab Radiological Control Manual (Jan. 1997, Nov. 1997).

[4] "Fermilab Main Injector Preliminary Safety Analysis Report"-(1992).

[5]* Dugan Criteria " Radiation Shielding Calculations for Booster Operations with Main Injector", Memo to Vinod Bharadwaj, July 29, 1991. * Dugan Criteria " Shielding Requirements for the Main Injector Era ", (1997).

[6] Ginneken, A. Van, "CASIM: Program To Simulate Transport of Hadronic Cascades in Bulk Matter", 272 1100.050.

[7] Ginneken, A. Van, "High Energy Particle Interactions in large Targets" page 83, VOL. 1

[8]* "Study of Attenuation of Radiation Level in Free Space in a Beamline Enclosure" C. M. Bhat, April 1997.

[9]* "Radiation Shielding of the Main Injector" , Bhat, C. & Martin, P. Proceedings of the 1995 Particle Accelerator Conference and International Conference on High Energy Accelerators. May 1-3, (1995) Dallas, TX. pg. 2105.

- EXCEL program by P. Martin
- 3D FORTRAN program by C. Bhat

[10] "Labyrinth and Penetration Methodology" Version 1.3 by Regina Rameika February 28, 1991 (private communication), "Computer Code EXIT2A", Regina Rameika and C. Moore, (private Communication 1996) and "A Study of Neutron Attenuation in the E-99 Labyrinth", Paul Ruffin and Craig Moore, Radiation Physics Note #9.

[11] "Procedures for Application of Don Cossairt's CASIM Calculations in TM-1140 to Bulk Shielding", P. Garbincius, FERMILAB-TM-1719.

[12] "Fermilab Main Injector (8 GeV Beamline Commissioning Phase) Safety Assessment Document/Accelerator readiness Review " Prepared by S. D. Holmes, FMI Project Manager and FMI Project Staff, January 1997.

[13]* 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).

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

[14] "Calculations of Shielding Steel Requirements for the 8 GeV Line", by P. S. Martin and C. M. Bhat (1996).

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

[16]* "8 GeV shielded Hatch", Memo by C. M. Bhat to Tom Pawlak, Feb. 13, 1996.

[17]* "Radiation Dose on the 8 GeV Beam-line Berm due to Sight Riser", C. M. Bhat. September 20, 1995.

[18]* "Shielding Requirements Around the Intersection of AP2 and 8 GeV Beamlines", by C.M. Bhat (April 7, 1994).

[19]* "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).

[20]* "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.

[21] "GROUND WATER , AIR-BORNE AND SOIL ACTIVATION FROM THE OPERATION OF THE MI-40 BEAM ABSORBER DURING THE **FMI** ERA" C.M. Bhat , MI Note 219 (Dec. 1997).

"A Design Study of MI40 Beam-Abort Dump" C.M. Bhat, MI Note 86, 1993,

Ground-water Activation from the upcoming operation of MI40 Beam Absorber, C. M. Bhat and L. Read, Fermilab TM-1985 (1996).

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

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

[23] "Radiation Shielding for MI Culverts", C.M. Bhat, MI Note MI-87 (1993).

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

List of Selected References Included as Attachments

Attachment A1 Dugan Criteria " Radiation Shielding Calculations for Booster Operations with Main Injector", Memo to Vinod Bharadwaj, July 29, 1991.

A2 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. Proceedings of the 1995 Particle Accelerator Conference and International Conference on High Energy Accelerators. 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)

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