Shielding Assessment Document for the MeV Test Area at the Fermilab Linac Endstation

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Abstract. *An incremental shielding assessment document building on the shielding assessment of the MuCool Test Area. Considerations for passive shielding, shielding penetrations, active controls, residual activation, air activation, ground and surface water activation, muon production, and air-scattered radiation.*

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Contents

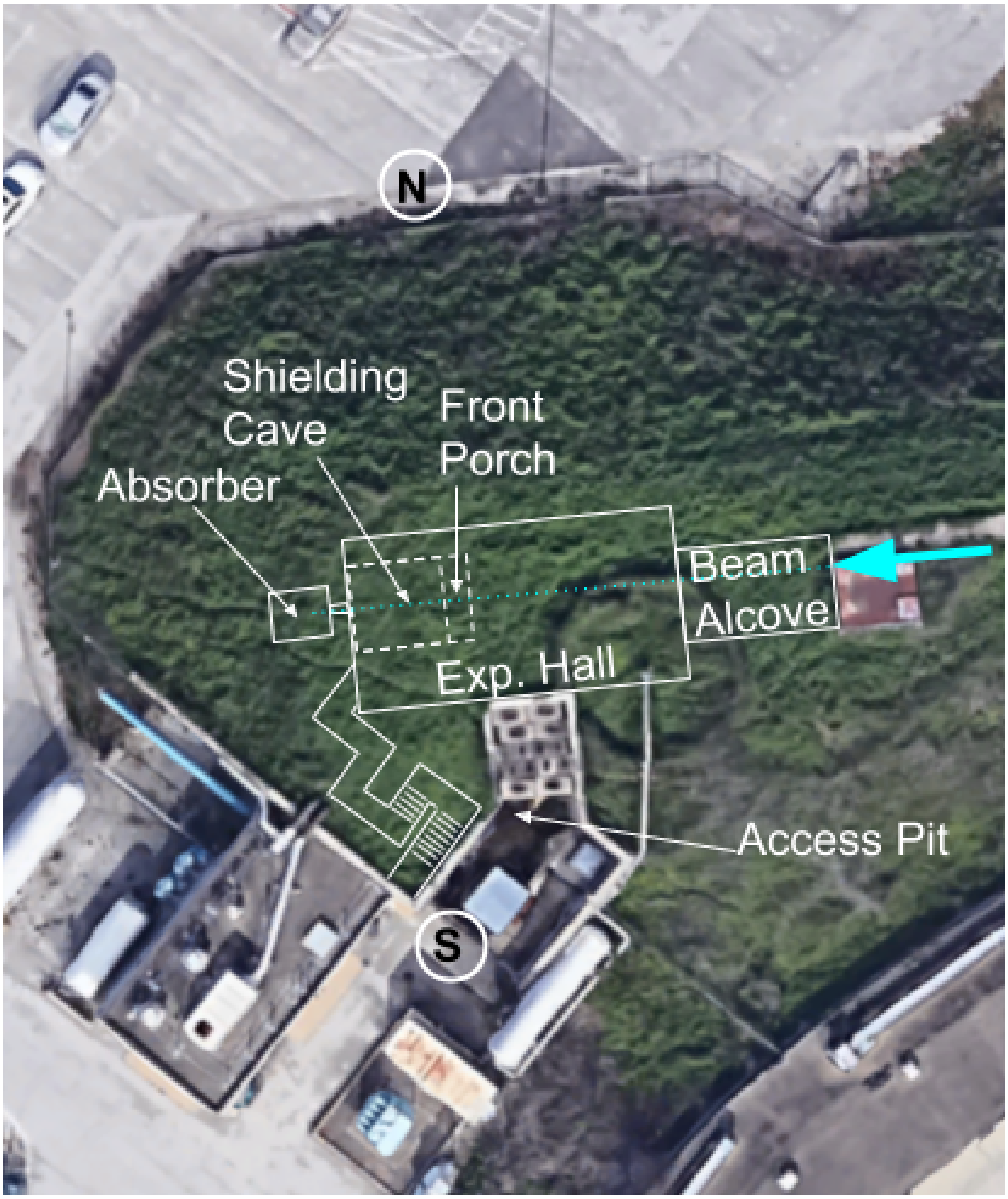

Figure 1. Annotated aerial view showing beam alcove and experiment hall approximately as situated in the grass-covered berm. Beam direction and path are indicated by the cyan arrow and dotted line. Booster Gallery West appears in the lower right corner. The points indicated by Ⓝ and Ⓢ, directly north and south of the Front Porch position, are discussed in Sec. 3.2.2.

1. Description of Facility

The MeV Test Area (MTA) provides a 400 MeV proton beam at high average rate for purposes of irradiation studies on materials and particle detectors. The experiment hall constructed for MuCOOL has been cleaned out and repurposed for these studies. The beam line is that of the MuCOOL Facility with the addition of an electron stripping foil described here. As described below, the passive shielding will be an increase of the shielding of the MuCOOL Facility. Hourly beam intensities (see 1.1) will be less than the emittance-mode rate of MuCOOL [1], the maximum hourly beam rate from that shielding assessment document.

The beam line transports a beam of H^- ions from the Fermilab Linac to the MTA beam alcove which opens onto the experiment hall. See Fig. 2 for a plan view. In the alcove of the experiment hall, a triplet of quadrupole magnets give the beam its final focus. An electron-stripping foil disassociates the electrons from the ions before the final vertical angle correction, from 1.67° upward pitch to flat and level. Any electrons not absorbed by the stripping foil are steered into the grounded beam pipe.

In the study in [6], activation of the stainless steel beam pipe was found to be less than 9.4E-03 mrem/hour following 12 hours of electron irradiation and one second of cool-down time, using conservative assumptions of stripped electron beam intensity and energy.

In the experiment hall, beam emerges at the end of the beam line from a metal vacuum window and continues through air, passing down the center of a Shielding Cave constructed of concrete shielding blocks. See Fig. 2. The cave offers a passage three feet across and three feet high, with at least three feet of shielding block material all around. Target material can be irradiated at the center of this volume. As shown in Fig. 2, the Shielding Cave floor extends an additional three feet toward the vacuum window, making a "Front Porch" area which serves as another position for target material.

1.1. Hourly and Annual Beam Intensities

Hourly beam rate: Unless otherwise noted, the studies in this document assume an hourly average of 7.5E+11 protons per second. This beam intensity gives an average of 4.5E+13 protons per minute and 2.7E+15 protons per hour. For a typical sample exposure of 1E+16 protons, the exposure time would be less than four hours. Nevertheless we take a longer exposure of 12 hours as the nominal, to be safely conservative in our estimates.

Annual beam rate: Significant levels of residual radioactivity are expected inside the MTA experimental enclosure due to the high intensity of irradiation (See Sec. 11), and this motivates the schedule of weekly (rather than daily or constant) operation, allowing appropriate "cooldown" time for samples and for the permanent installations of the MTA experiment hall. Thus for the nominal twelve hours of running once per week for forty weeks each year, this comes to 1.3E+18 protons annually at maximum.

These figures are summarized in Table 1.

proton/ion rate	averaging period
7.5E+11 per second	60.0 s Supercycle
2.7E+15 per hour	60.0 s Supercycle
1.3E+18 per annum	40 wk @ 12 hr/wk

Table 1. MeV Test Area beam flux under planned usage assumptions.

As an example of running conditions meeting the hourly delivered beam flux in Table 1, assuming a supercycle 60 s in length, the accelerator complex might deliver to the MTA 12 pulses per supercycle, with 3.75E+12 protons per pulse.

1.2. Normal Operation Condition and Accident Conditions

The normal operation condition delivers the hourly average beam intensity in Table 1 in pulses on a 15 Hz clock. The pulses sent to MTA may be sent consecutively at this rate or spaced apart, as needed. Linac pulses are adjustable in magnitude from 6 to 40 microseconds (roughly 0.9E+12 to 6.56E+12 depending upon machine conditions) to achieve a given hourly average.

The normal operation condition also includes targets of various materials positioned in the beam path. Targets may be positioned in the Shielding Cave, which surrounds the beam path with 3 ft. of shielding block, or on the Front Porch, which is open on the top and sides. These positions are called out in the elevation view of the Shielding Cave in Fig. 3. A plan view through a plane at the level of the final beam is given in Fig. 4.

In the **beam trajectory accident condition** ("mis-steering the beam"), the nominal beam intensity profile of Table 1 is fully interacted on some material at an arbitrary location along the beamline, increasing prompt radiation around the beam path for one hour before being addressed. The mitigation for this type of scenario is to set an administrative limit on hourly average beam intensity as given in Table 1.

In the **beam intensity accident condition**, the beam trajectory is nominal but we do not take credit for the administratively imposed limit on beam intensity. Instead the beam intensity profile is taken to be unbroken 15 Hz delivery of full Linac pulses of 6.56E+12 protons per pulse. The target is taken to be a highly scattering example: an iron slug 1.6 feet long in the beam direction and 10 cm across, placed on the "Front Porch" position so as to be as unshielded as possible. The mitigation for this scenario is to establish active monitoring of the scattered radiation by at least one interlocked detector outside the shielding, as described in Sec. 5. Thus the beam intensity accident condition analyzed here is a limited-time condition.

1.3. Spreadsheet Implementation of Accident Scenarios

A set of Incremental Shielding Assessment (ISA) spreadsheets was created to partially analyze the accident scenarios described in Sec. 1.2 (Attachment A). MARS [3] simulations were used to analyze the scenarios, and to provide source terms for some of the Labyrinths and Penetration Worksheets.

The nominal beam intensity from Table 1 was the basis for several inputs on the ISA spreadsheets; however, due to the irregular rate at which MTA can receive beam from the Linac (See Sec. 1.2) certain fields required the use of formulae rather than numbers. In order to keep the per-second and per-hour values on the spreadsheet aligned with those in Table 1 no matter what cycle time was chosen, the input for Primary Beam Intensity was set to 7.5E+11 * Cycle_Time. In addition, the Interlocked Detector Beam Pulses Allowed input was set to the following formula:

```
= ROUNDUP(IF(60/Cycle_Time>15, 15, IF(60/Cycle_Time<1, 1, 60/Cycle_Time)), 0).
```

This formula above ensures that the input is a whole number equal to the number of requested MTA pulses per minute when that value is less than or equal to 15, and 15 if the number of pulses per minute is greater than 15. It also sets a lower limit of 1, since it takes at least one pulse to trip an interlocked detector. Note that because it pertains specifically to interlocked detectors, this input is only used when Categories 6 through 10 are invoked.

By utilizing the aforementioned formulae and varying the cycle time while examining the required shielding in the Scaling sheet, the ISA workbook could be used to determine the most conservative case. The value of 0.067 seconds was chosen because the shielding requirements remain at a maximum for any setting of cycle time from 4 seconds (representing 15 MTA pulses per minute) to 0.067 seconds (representing 15 Hz beam).

2. Assessment Boundaries

The upstream boundary of the area covered by this incremental assessment is at extraction from the Linac, which begins in the first pulsed C-magnet (UHB01A) just upstream of the 400-MeV Chopper. The second C-magnet, which is electrically in series with the first and completes the extraction process, is downstream of the Chopper. The stationing coordinate z begins at the upstream face of the first pulsed C-magnet, defining $z = 0$. The endpoint of the beam is the final high-intensity beam absorber at $z = 59$ m, and the assessment includes all the surrounding shielding.

Note that for MARS simulations, the origin $z = 0$ will be at the longitudinal center of the experimental enclosure, and in the beam line.

The geometry and assumptions of the MuCOOL Facility Shielding Assessment document remain valid for the MeV Test Area facility up to the interlocked experimental enclosure. Within the Linac enclosure no changes to the beam line and the shielding are planned. In this reconfigured MTA, the contents of the experiment hall are simplified, prompting this new shielding assessment document and its focus on the experiment enclosure, composed of the final stretch of beam line after the shield wall, the experiment hall, and the immediate environs.

3. Passive Shielding Requirements

Operation of the MeV Test Area beam line was simulated in MARS [3], including the concrete of the experimental enclosure structure, the surrounding and surmounting berm soil, shielding blocks, the high-intensity beam absorber, and a Device Under Test (DUT). Soil density was taken to be 2.24 g/cc and to attenuate radiation with a tenfold attenuation length of 3.38 feet, in keeping with Fermilab TM-2550-ESH [2].

The proposed DUT for the initial run was taken as a benchmark: ten thin (1 mm) disks of silicon 10 cm in diameter, axes coincident with the beam axis, longitudinally spaced 1 cm center-to-center. Other DUT options studied were a monolithic silicon slab 4.65 cm thick (10% of a nuclear interaction length), a silicon slab of one full nuclear interaction length, and an iron cylinder 1.6 feet in length. No extensive study was done to find the true worst-case target parameters; instead we take this 1.6 ft. iron target as an approximation to the worst case, and implement active radiation monitoring so as to cover all possible choices of target safely. See Sec. 5.

The berm covering the MTA enclosure is posted as a Radiation Area. In accordance with Fermilab Radiological Control Manual (FRCM) [4] Tables 2-6 and 2-7, the dose rate in this area is not to exceed 100 mrem/hour, not in normal running nor in any accident scenario. The gated area containing the nearby access pit, its elevator, and a

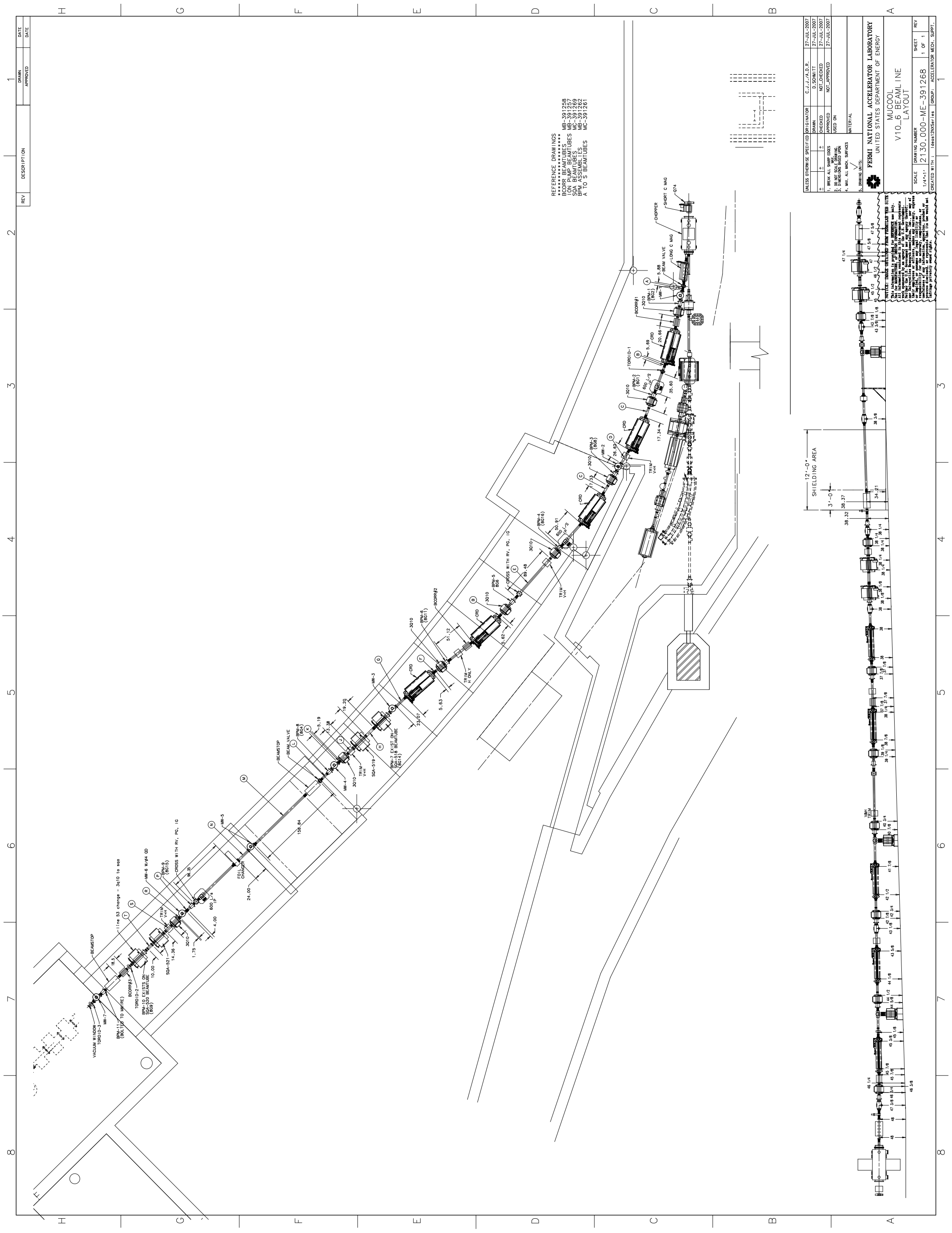

Figure 2. Plan view of beam line from extraction to beam alcove and experiment hall.

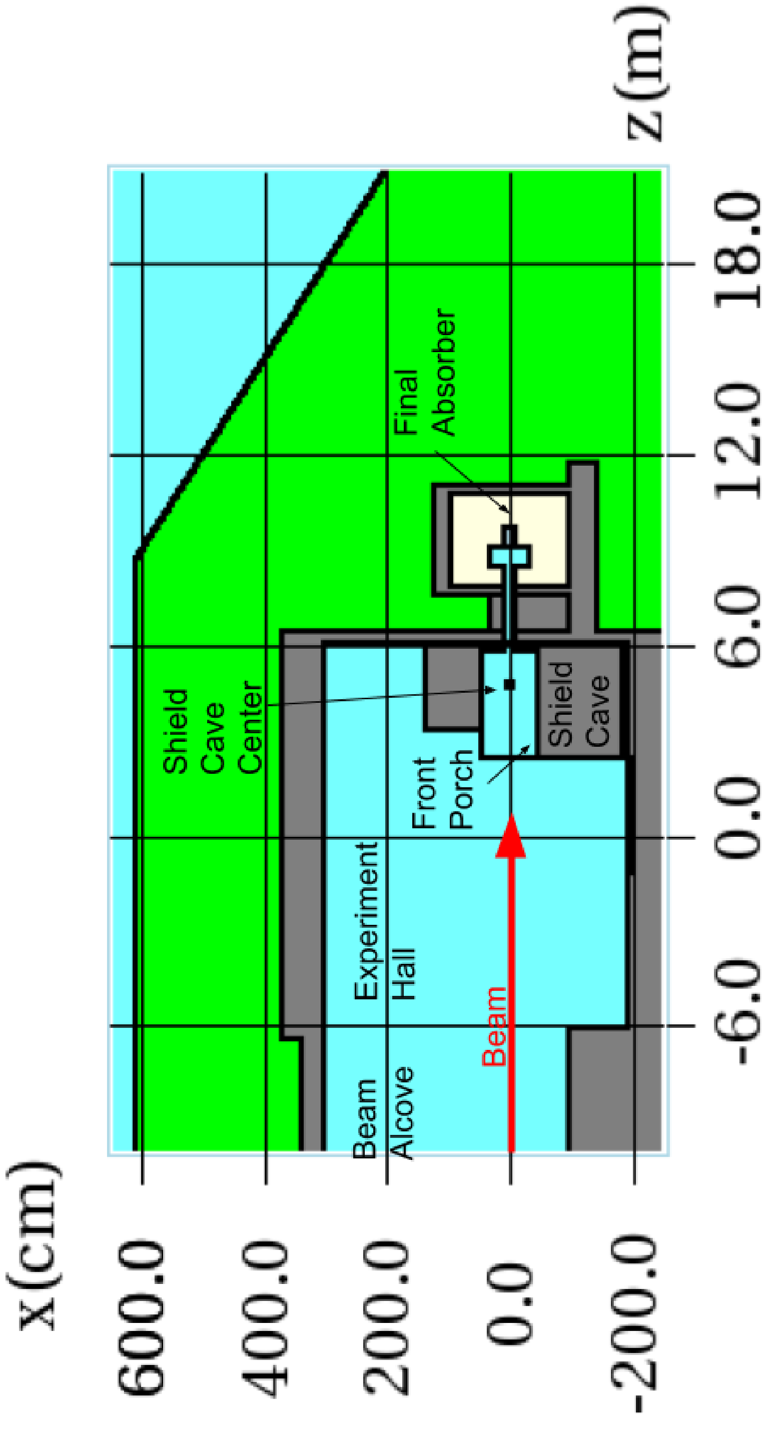

Figure 3. Elevation view through experimental enclosure, with z=0 defined as enclosure longitudinal center. (Note: Not to scale.) Beam enters from negative z along the z-axis, traverses magnets and instruments (not shown), and enters the air of the Shielding Cave. A sample target is shown here inside the cave, although targets may also be placed on the cave's "Front Porch" area, supported from below but out from under the upper shielding of the cave. The pipe to the final absorber, the absorber itself, and the surrounding concrete and berm are all shown.

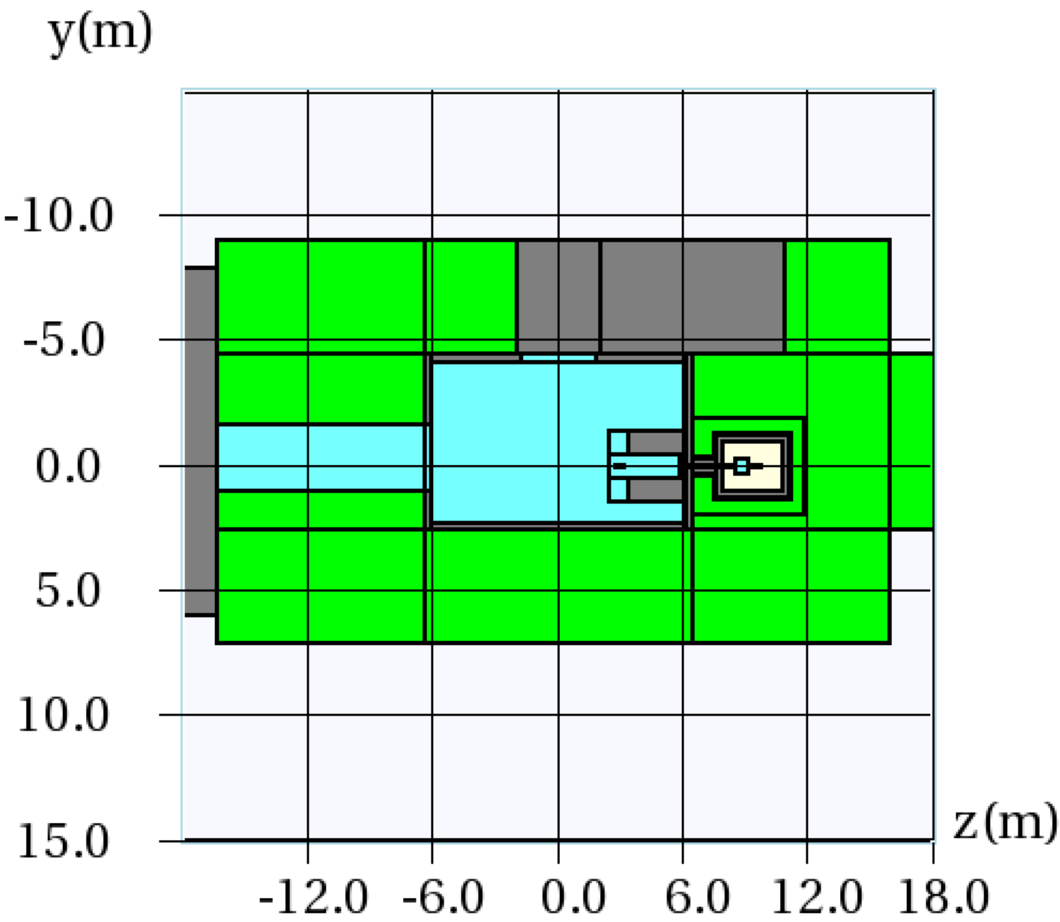

Figure 4. Plan view through experimental enclosure from MARS model. (Note: Not to scale.) Beam enters from negative z along the z-axis, traverses magnets and instruments (not shown), and enters the air of the Shielding Cave. A sample target is shown here on the cave's "Front Porch" area, supported from below but out of the surrounding shielding of the cave. The pipe to the final absorber, the absorber itself, and the surrounding concrete and berm are all shown.

small landing at ground level is posted as a Controlled Area, and so no credible accident condition may cause the hourly dose to exceed 5 mrem in the gated area. A beam-on radiation survey will be performed to confirm adherence to these limits.

3.1. Longitudinal Requirements

We examine the trajectory accident scenario and the intensity accident scenario in this section and in Sec. 3.2.

3.1.1. Beam trajectory accident scenario

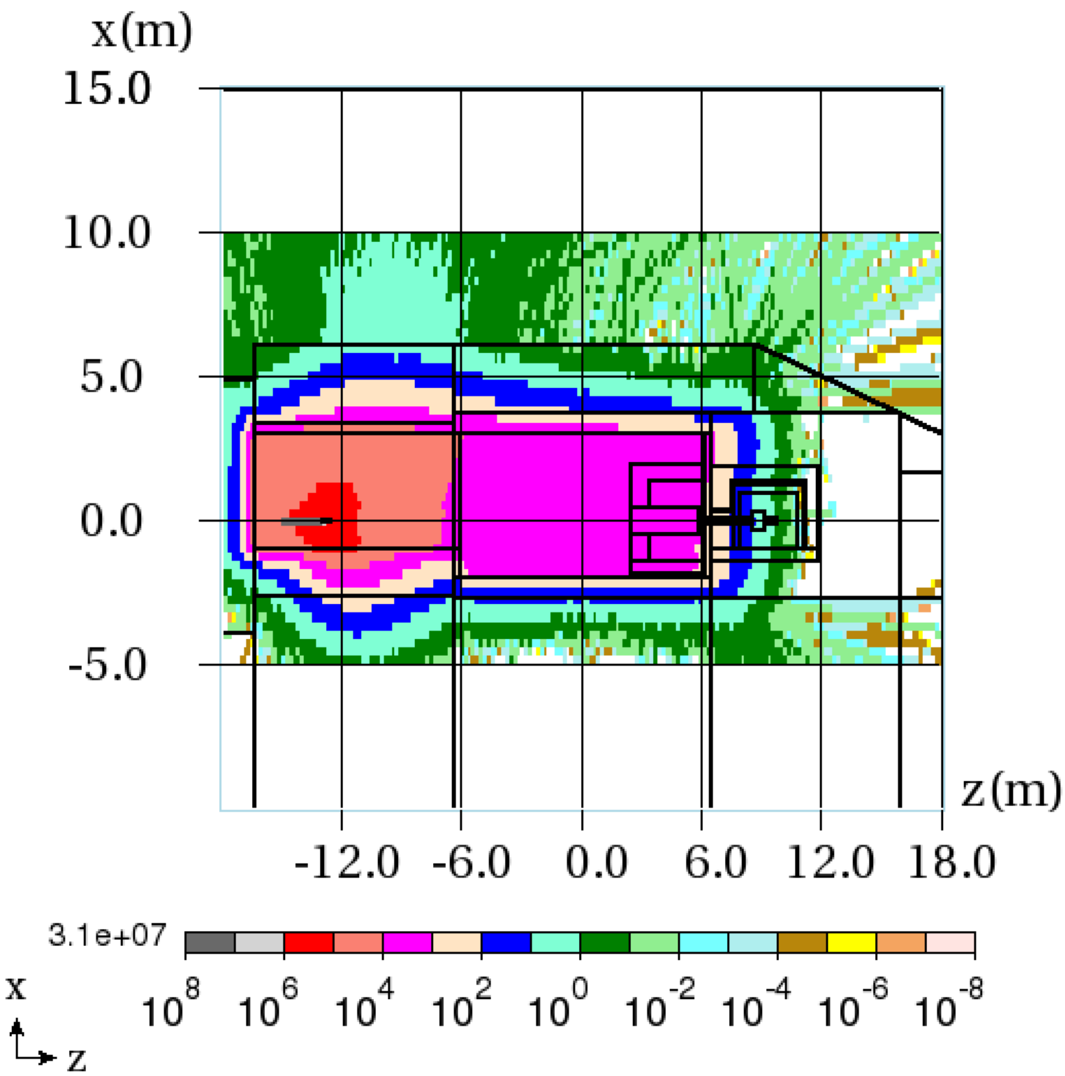

Figure 5. Elevation view of experimental enclosure for trajectory accident scenario of severe beam loss in the beam alcove, such as beam steered into iron magnet yoke. Color axis is in mrem/hour. Maximal radiation dose rate outside of the shielding is approximately from z=-1200 to -750 cm, at less than 100 mrem/hour.

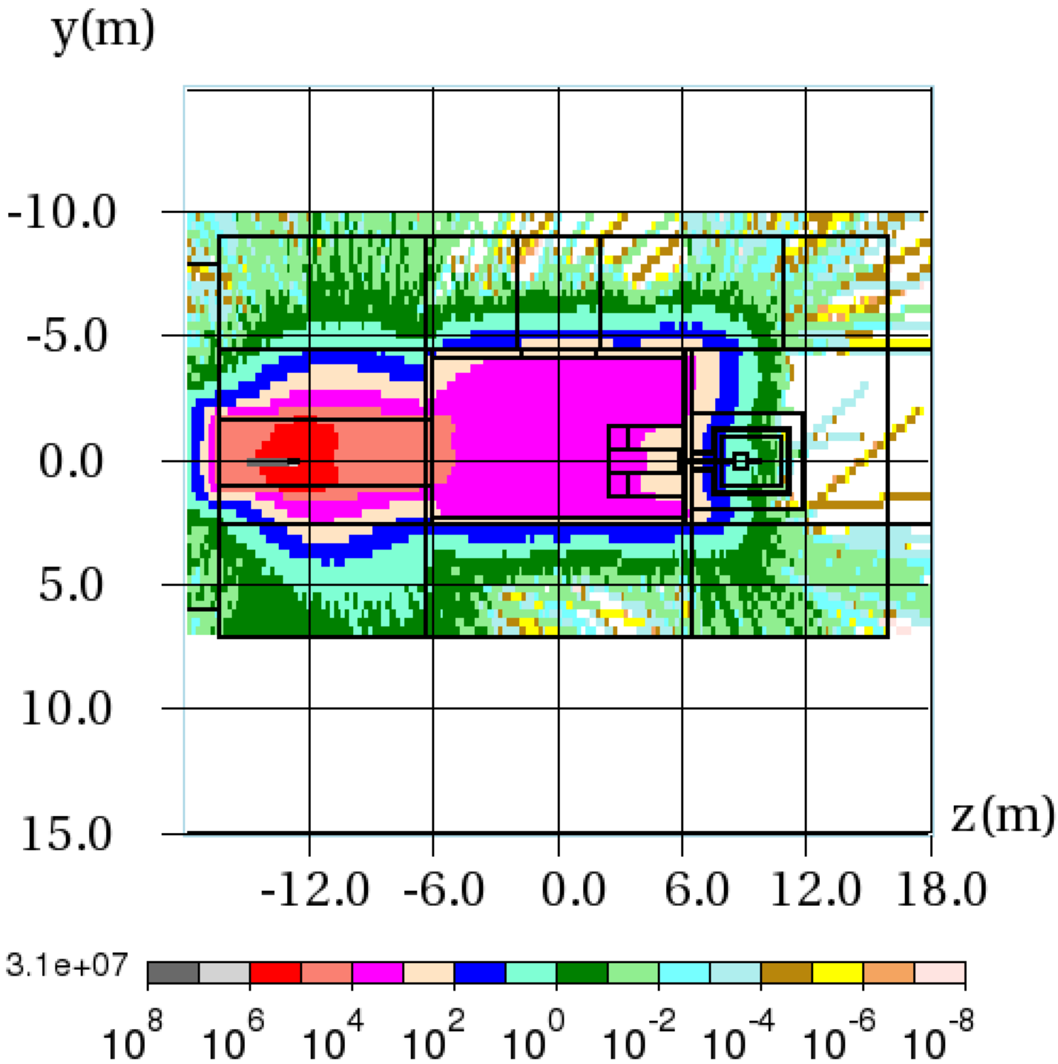

Figure 6. Plan view of experimental enclosure for trajectory accident scenario of severe beam loss in the beam alcove, such as beam steered into iron magnet yoke. Color axis is in mrem/hour. Containment in this plane is better than in the vertical plane of Fig. 5.

Both the Longitudinal Shielding Spreadsheet (See Attachment A) and MARS [3] simulations independently show that a beam steering accident at 7.5E+11 protons per second for one hour would not violate the FRCM limit of 100 mrem for the posted Radiation Area.

A MARS study was done in the beam alcove, where the shielding (enclosure ceiling and berm soil) is thinnest, and with the same 1.6 ft. iron slug used elsewhere in this assessment as a highly scattering target. See Fig. 5 and Fig. 6. The greatest dose rates outside of shielding were found on top of the berm, located in the modeled geometry from z=-1200 cm to z=-750 cm, discussed in Sec. 3.2. This study also concludes that a beam steering accident at 7.5E+11 protons per second for one hour would not violate the FRCM limit of 100 mrem for the posted Radiation Area.

3.1.2. Beam intensity accident scenario

For the iron slug on the maximally unshielded Front Porch position as shown in Fig. 7 and Fig. 8, the greatest dose rate outside of shielding is again found on the berm surface, and not in the horizontal plane of the beam. MARS [3] simulation predicts a maximal berm-surface dose rate of 10.0$\pm$0.8 mrem/hour for the normal operation condition of 7.5E+11 proton per second. In the beam intensity scenario of 6.56E+12 protons per pulse at 15 Hz described in Sec. 1.2, this berm surface dose rate scales to 1310 mrem/hour. We turn to active shielding measures using interlocked detectors on the berm surface.

Assuming one second for an interlocked detector to switch off beam, and assuming the intensity accident scenario during that one second interval, the dose during this time would be 0.36 mrem. Active controls with at least one interlocked detector can limit the dose delivered outside of the shielding.

Together, the longitudinal shielding and the active shielding controls described in Sec. 5 are sufficient to prevent a violation of the 100 mrem limit in one hour in the posted Radiation Area along the top of the berm.

3.2. Transverse Shielding Requirements

Transverse sections through the enclosure are shown in Fig. 10 (through a beam obstruction in the beam alcove) and Fig. 9 (through a target on the Front Porch). These figures are included to help interpret dose rate histograms found in Sec. 3.2.1 and Sec. 3.2.2.

3.2.1. Beam trajectory accident scenario

The Transverse shielding spreadsheet in Attachment A shows that all transverse stations pass at their assigned categories for the trajectory accident scenario.

MARS results are presented in Fig. 11 for nominal-intensity beam impinging upon the same 1.6 ft. iron slug used elsewhere in this assessment as a highly scattering target, and for the longitudinal location of greatest dose rate outside of shielding, from z=-1200 to -750 cm. Dose rates in the posted Radiation Area do not violate the FRCM limit of 100 mrem.

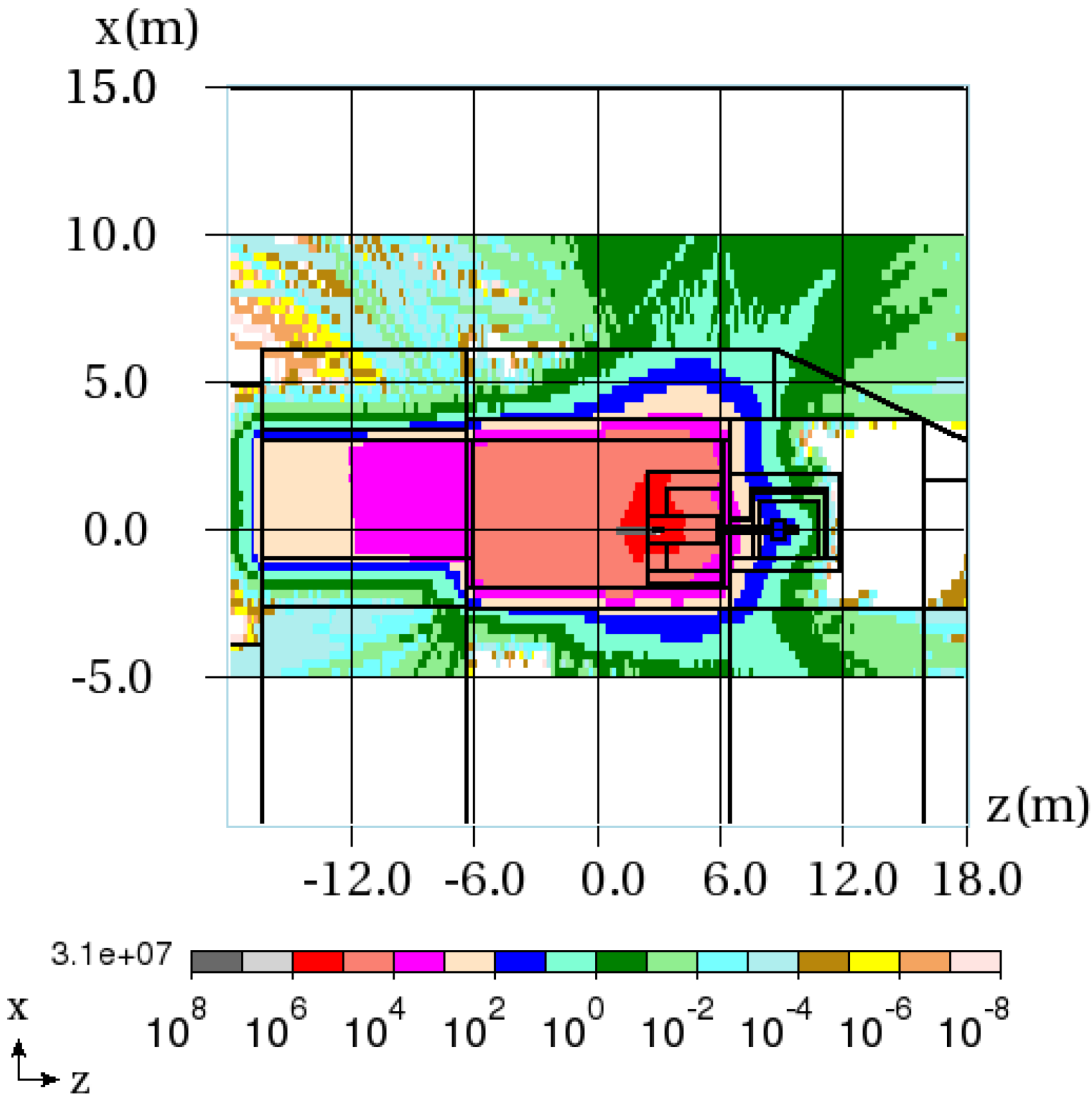

Figure 7. Elevation view through experimental enclosure showing target on the Front Porch. Color axis is in mrem/hour and beam rate is the nominal 7.5E+11 protons per second. In the beam intensity accident scenario (See Sec. 3.1.2) the instantaneous dose rates indicated here scale up by a factor of 131.

3.2.2. Beam intensity accident scenario

Here we build on the MARS [3] calculation for normal operation condition discussed in Sec. 6 **Normal Operation Condition**, scaling up to the beam intensity accident scenario of 6.56E+12 protons per pulse at 15 Hz, and comparing to the relevant dose limits. For reference, this rate is 9.84E+13 protons per second, 131 times higher than the nominal rate of 7.5E+11 protons per second. A histogram showing the pattern of dose rate in the transverse plane is given in Fig. 12, becoming statistics-limited at seven or eight orders of magnitude down from the peak dose rate. Active shielding is needed, as discussed in Sec. 5.

Under the intensity accident scenario the dose rate nearest the target in the access

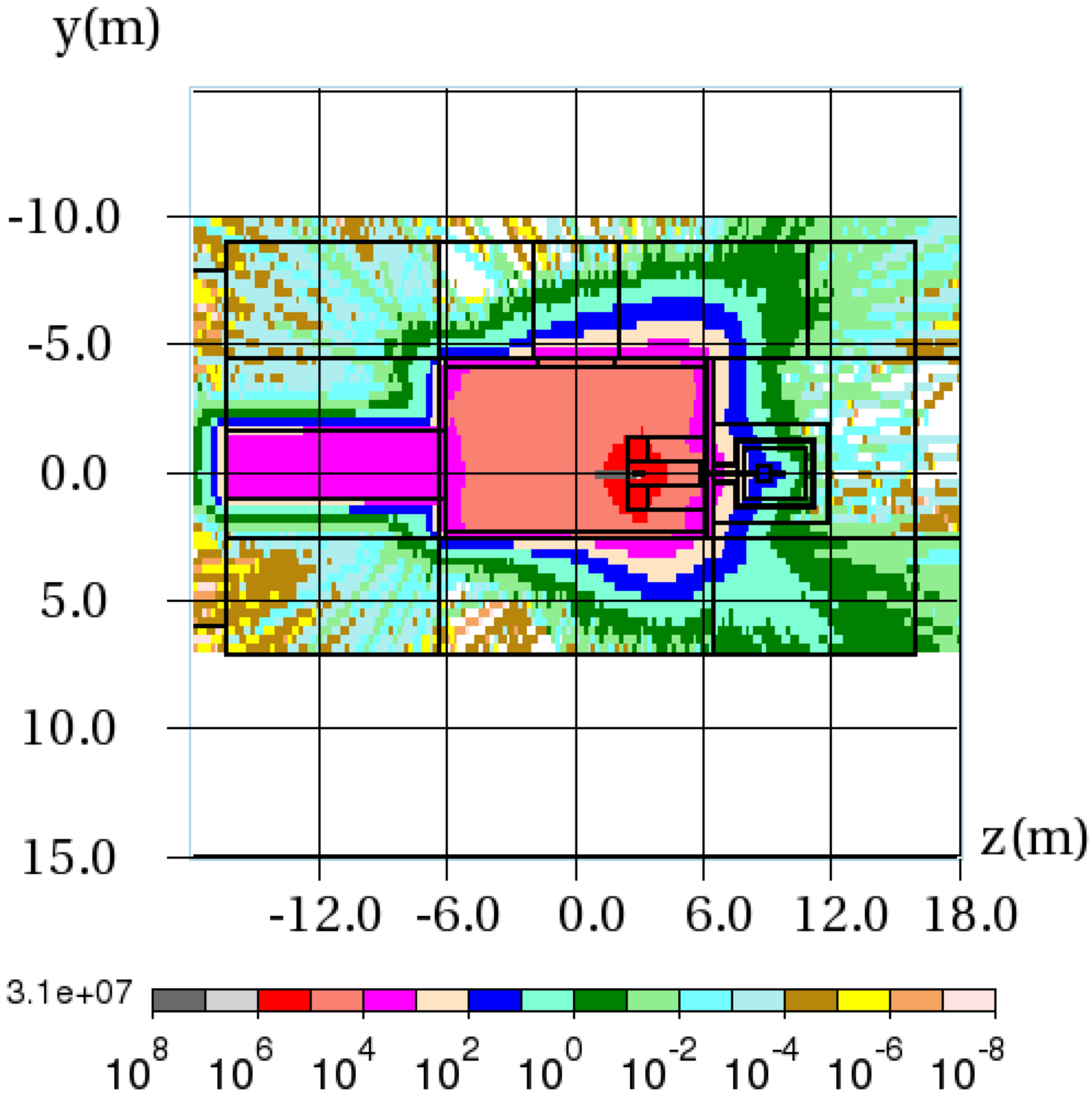

Figure 8. Plan view through experimental enclosure showing target on the Front Porch. Color axis is in mrem/hour and beam rate is the nominal 7.5E+11 protons per second. In the beam intensity accident scenario (See Sec. 3.1.2) the instantaneous dose rates indicated here scale up by a factor of 131.

pit (posted as a Controlled Area) is expected to be 0.76 mrem/hour until the interlocked detector shuts off the beam. Thus the posted Controlled Area will not exceed the required dose limit of 5 mrem in this intensity accident scenario because the beam will be shut off in less than one hour, by an interlocked detector on the berm-top surface.

The point in the parking lot outside the posted Controlled Area and closest to the target is more than 50 feet from the target. This point is approximately due south of the Front Porch position, indicated by Ⓢ on Fig. 1. In the access pit the closest approach to the target is 30 feet. (See Attachment E, drawing SC-5, for scale drawings.) The distance factor $(30/50)^2$ alone reduces the maximum expected dose at Ⓢ to 36% of the access pit dose rate, or 0.27 mrem/hour, before the interlocked detector on the berm has had one second to interrupt beam. The dose limit in an unposted area with unlimited occupancy

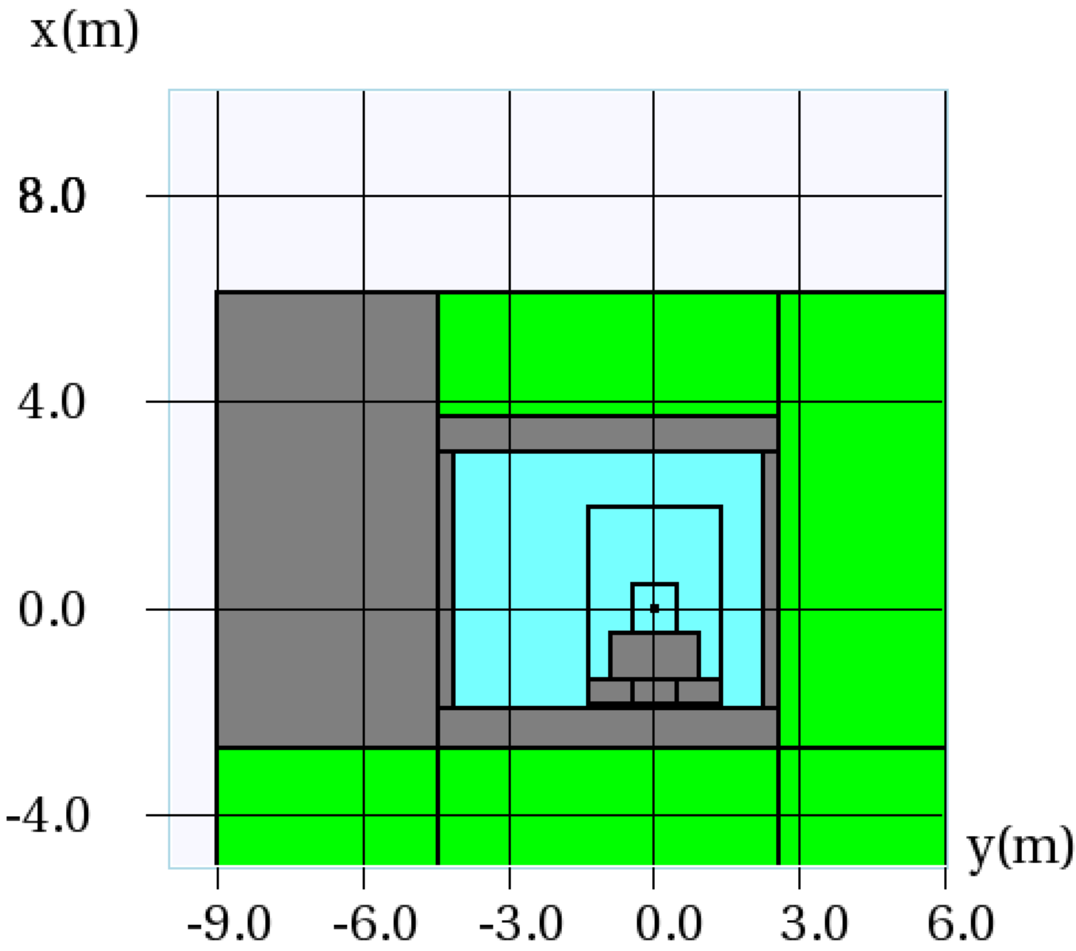

Figure 9. Transverse elevation view through experimental enclosure at the longitudinal location of a target on the Front Porch. The beam path coincides with the z-axis, into the page. Black lines above and around the target indicate the outline of the Shielding Cave and the square opening through its center, just behind the Front Porch.

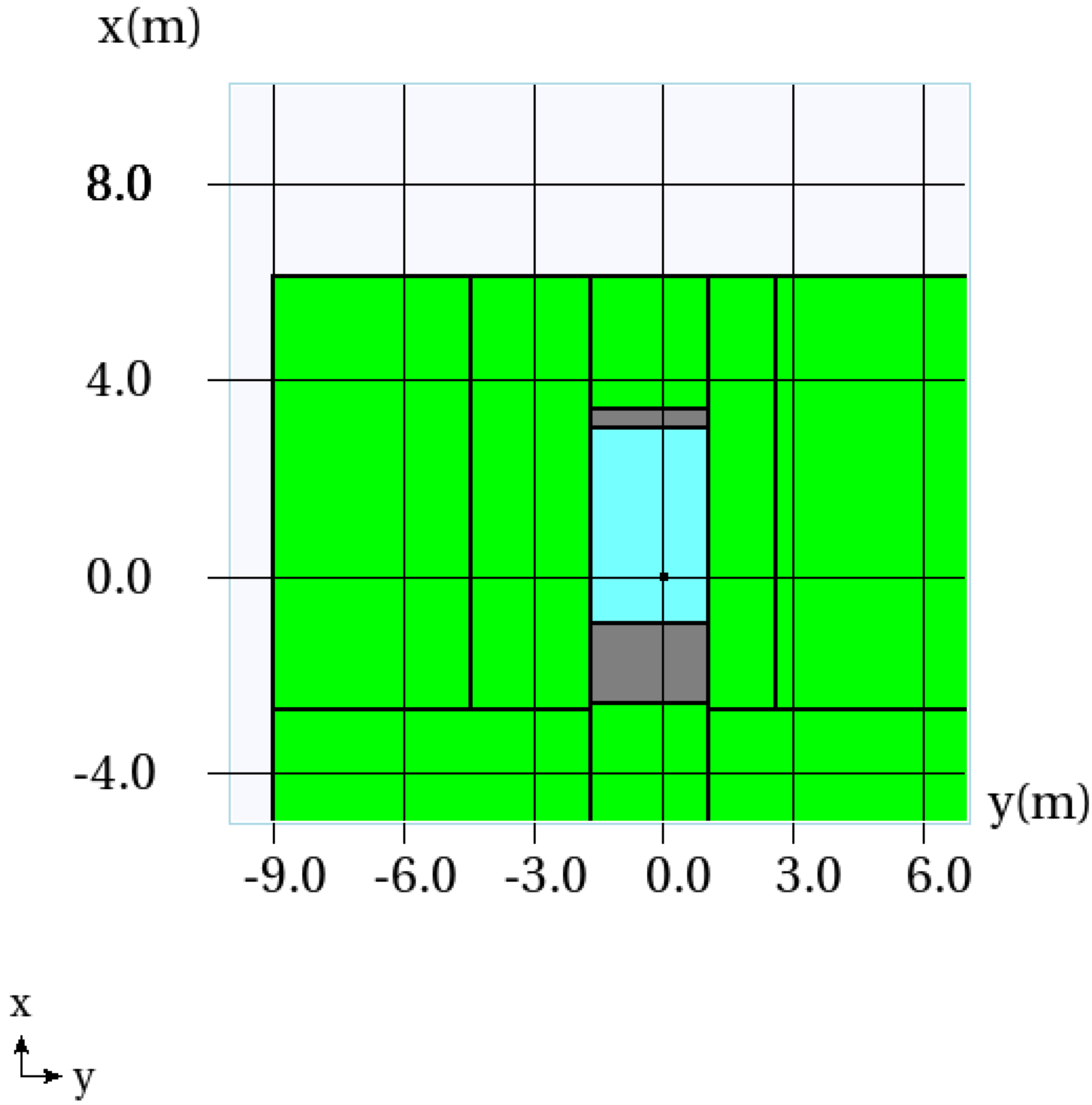

Figure 10. Transverse elevation view through the Beam Alcove. The beam path coincides with the z-axis, into the page.

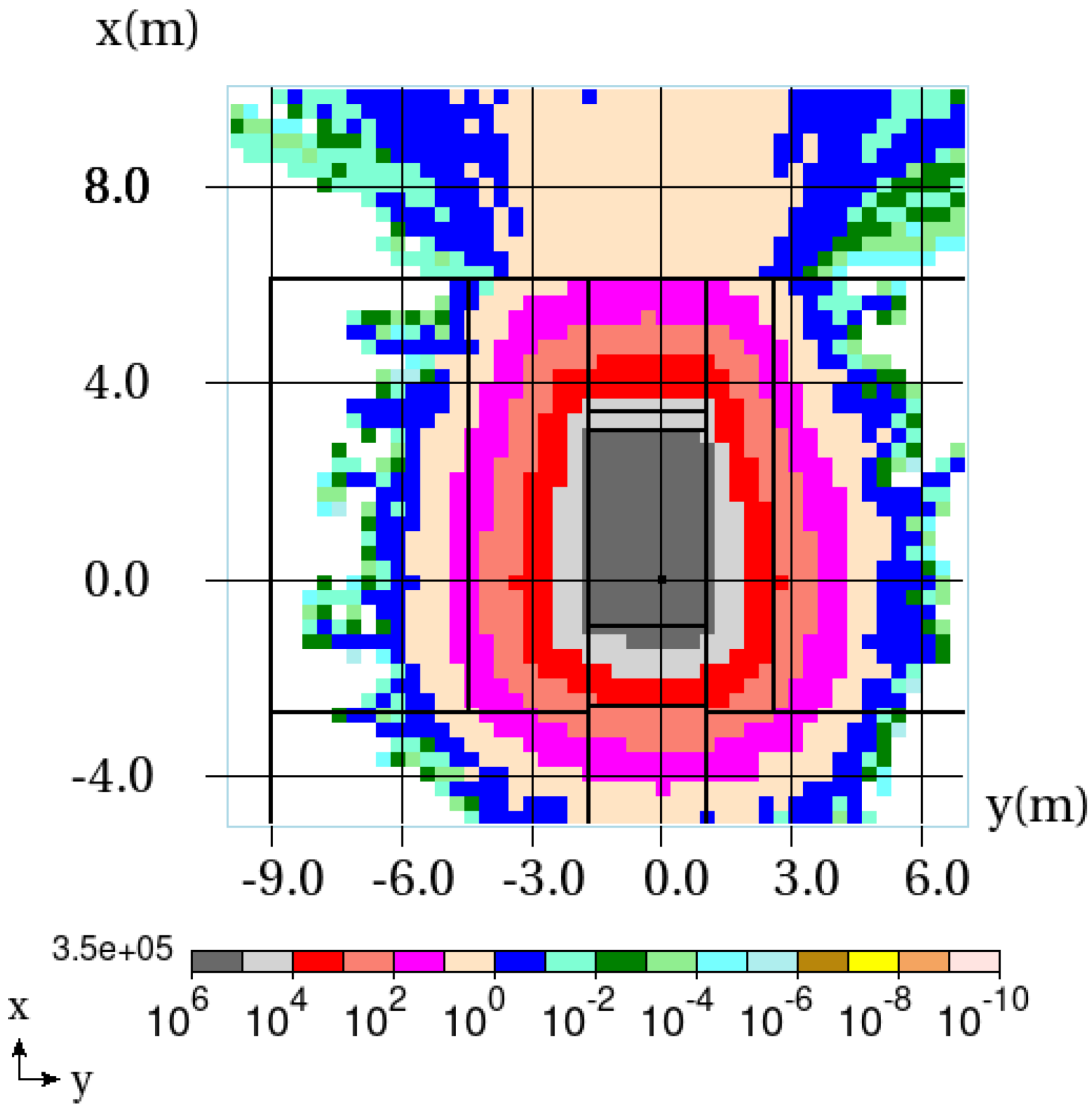

Figure 11. Transverse view through the Beam Alcove for the longitudinal location of greatest dose rate outside of shielding under the trajectory accident scenario. The beam path coincides with the z-axis, into the page. Dose rate is binned transversely in a 50 x 50 grid, and integrated longitudinally from z=-1200 to -750 cm. Color axis is in mrem/hour and beam rate is the nominal 7.5E+11 protons per second. Statistical power drops off rapidly below the 10 mrem/hour contour.

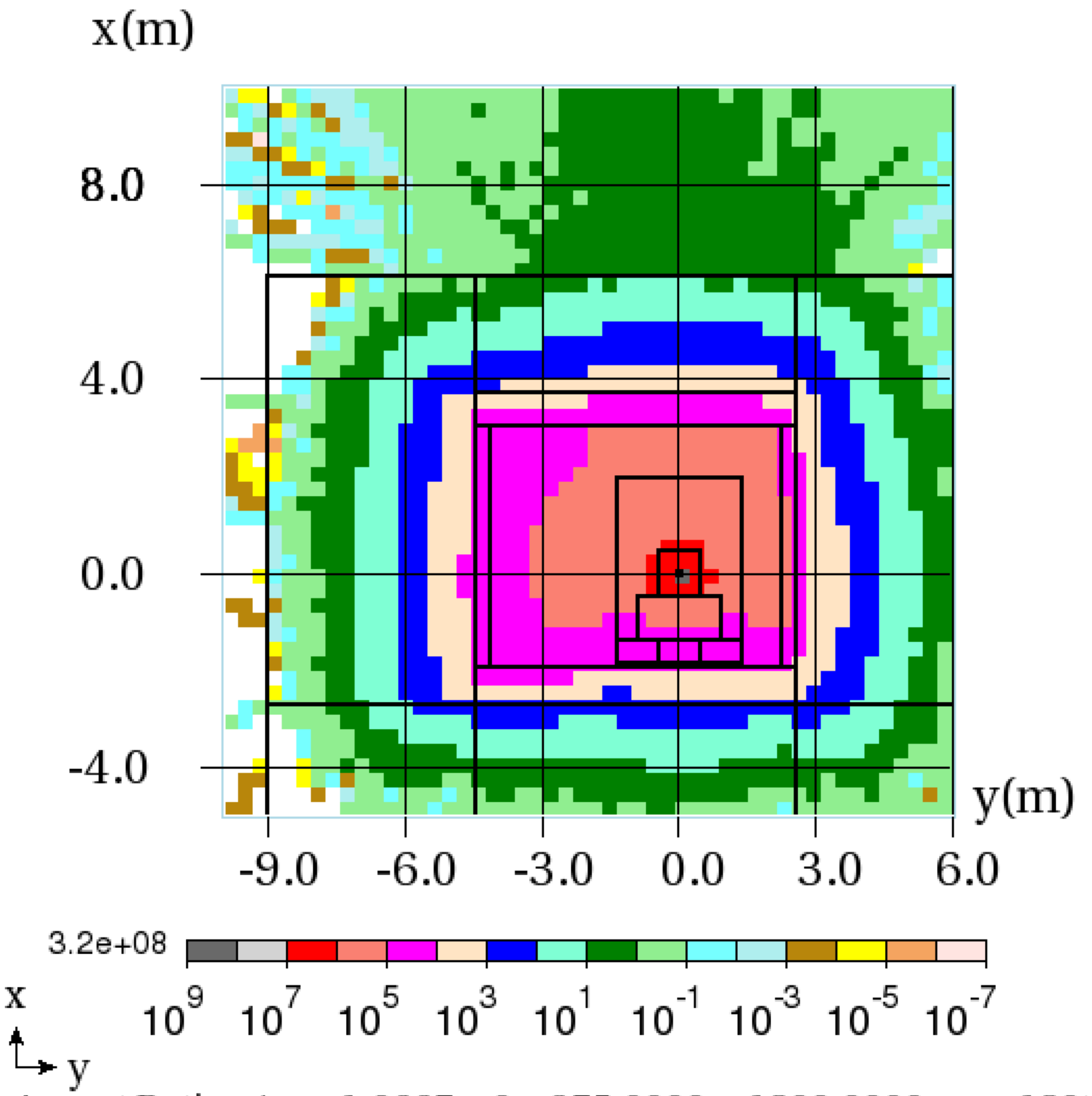

Figure 12. Transverse view through experimental enclosure at the longitudinal center of the simulated iron target on Front Porch. The beam path coincides with the z-axis, into the page. Dose rate is binned transversely in a 50 x 50 grid, and integrated longitudinally from z=200 to 600 cm, the longitudinal location of greatest dose rate outside of shielding. Color axis is in mrem/hour and beam rate is the nominal 7.5E+11 protons per second. Multiply by 131 to arrive at dose rates for the beam intensity accident scenario. Statistical power here drops off rapidly below the 10 mrem/hour contour.

from an accident is 1 mrem.

On the other side of the enclosure, the distance to the posted Radiation Area fence at the toe of the berm is also more than 50 feet. This point is approximately due north of the Front Porch position, indicated by Ⓝ on Fig. 1. (See Attachment E, drawing C-8, for scale drawing.) Soil attenuates any dose all along this path, reducing the dose in an accident further below the dose found at this distance above. The dose limit in an unposted area with unlimited occupancy from an accident is 1 mrem.

4. Labyrinths and Penetration Summary and Calculations

The Labyrinths and Penetrations Shielding Spreadsheet in Attachment A shows that the labyrinths and all penetrations pass analysis following the implementation of the mitigation measures described in Sec. 4.3.

4.1. Beam trajectory accident scenario

Twelve Labyrinths and Penetration Worksheets analyzed the various MTA penetrations for worst-case beam trajectory accidents; these are included in Attachment A (PWKS-ALP001A through PWKS-ALP012A) and are summarized in the ISA Labyrinths and Penetrations Summary Sheet (Normal Operating/Beam Trajectory Accident).

Five failures appear on this Labyrinths and Penetrations Summary Sheet, four of which pertain to the single-leg penetrations in the former Refrigerator Building, and one of which is for the 20-inch-diameter ceiling vent. Mitigation strategies for these are described below in Sec. 4.3 and are summarized in Phase II sheets in Attachment A. As shown on the Labyrinths and Penetrations Summary Sheet, the planned mitigations will adequately address the failures.

4.2. Beam intensity accident scenario

The same twelve labyrinths and penetrations of Sec. 4.1 were separately analyzed for the beam intensity accident scenario, where the maximum Linac intensity of 6.56E+12 protons per pulse is delivered to a hypothetical worst-case target on the front porch at 15 Hz for one hour. The Labyrinths and Penetration Worksheets for these are included in Attachment A (PWKS-ALP001B through PWKS-ALP012B) and are summarized in the ISA Labyrinths and Penetrations Summary Sheet (Full-Linac Accident at Target/Beam Intensity Accident). Source terms for some of these worksheets were obtained from MARS [3] calculations, while others used the standard worksheet method.

Five failures appear on this Labyrinths and Penetration Summary Sheet, all of which occur at the same locations as in the other accident case. As shown on the Labyrinths and Penetrations Summary Sheet, the planned mitigations will also adequately address these failures.

4.3. Mitigation strategies

Six single-leg penetrations, all greater than 30 feet long, connect the experiment hall to the Fridge Room at parking lot level. Listed in Table 2, they are known as the Cooldown Line, the Transfer Line, and the four Single-Leg Utility Penetrations, and these run through berm soil except where they pass through concrete walls. All will be sealed off from within the experiment hall and filled with sand bags except for the three feet closest to the Fridge Room, which will be filled with bags of polyethylene beads.

The 20-inch-diameter Ceiling Vent vertical penetration in the south corner of the experiment hall ceiling rises to the berm surface. It will be sealed off from inside the experiment hall with an appropriately load-rated plate, then filled to the height of the berm surface. The fill material will be loose sand except for the final three feet, which will be bags of polyethylene beads.

5. Active Shielding Controls and Monitoring

At least one interlocked radiation detector will be placed on the berm above the target area as determined by the assigned RSO. This arrangement effectively monitors for the beam over-intensity accident scenario for either target placement (inside Shielding Cave or on Front Porch) and for any choice of target, however strongly scattering.

Additionally, as discussed in [1], an interlocked radiation detector in the downstream Linac labyrinth ensures that for the upstream portion of the MTA beam line, accident dose rates are within FRCM limits.

6. Normal Operation Condition

During normal operation, losses along the beam line are expected to be negligible. However beam will be incident on targets placed either in the Shielding Cave or on its Front Porch. Targets of various makeup and geometry are expected to occupy either of these positions, scattering radiation which becomes the source term for dose rates outside the enclosure.

MARS [3] calculations show that dose rates along the top of the beam line will be kept under the limit of the posted Radiation Area. For example the berm surface dose rate will be 10.0 mrem/hour $\pm 8\%$ from normal operation in the case of the 1.6 ft iron cylinder on the maximally unshielding Front Porch, a worst case for normal operation. See Sec. 3.1.2. At least one interlocked detector will be placed on the berm and will prevent dose rate anywhere inside this posted Radiation Area from exceeding the normal operation limit of 100 mrem/hour.

Looking transverse to the beam, the rollup door to the access pit is the closest approach to the target material undergoing irradiation. A calculation was done with MARS [3] for the rollup door under the normal operation scenario. We estimate the maximum dose rate at the rollup door to be 1.0E+04 mrem/hour ($\pm 3\%$) at the nominal beam intensity (see Fig. 8) with the 1.6 foot iron cylinder target positioned on the Front Porch. This dose rate is attenuated by a stack of shielding blocks just outside the rollup door. The stack is 15 feet thick and rises to the height of the berm surface. The five layers of 3-foot-deep shielding blocks are offset to occlude cracks between blocks. Standard concrete attenuates dose rate by a factor of ten every 2.86 feet, thus the shortest path through these shielding blocks attenuates the dose rate 5.24 orders of magnitude to 0.058 mrem/hour, less than the normal operation limit of 0.250 mrem/hour in the access pit, which is posted with signs reading "CAUTION – Controlled Area" and no occupancy limit is imposed.

Just outside the fencing of the access pit is an unposted area adjacent to the parking lot. The closest point to a scattering target is more than 50 feet away, indicated by Ⓢ

on Fig. 1. Inside the access pit the closest straight-light distance to the target is 30 feet, straight through the shielding. Normal operation dose rate here will be attenuated by a distance factor smaller than than 0.36, the square of 30 ft/50 ft, to less than 0.02 mrem/hour. The maximum permitted dose rate in an unposted area of unlimited occupancy is 0.05 mrem/hour. A beam-on survey will be conducted to ensure that this area will remain under its normal operation dose rate limit.

On the north side of the beam opposite the access pit, the shortest path connecting the target area to a point in the unposted parking lot traverses more than 45 feet of soil, to a point indicated by Ⓝ on Fig. 1. Here, too, the expected dose rate from normal operation is substantially less than the required limit of 0.02 mrem/hour, and will be checked in a beam-on survey.

To estimate dose rates delivered by the labyrinths and penetrations during normal operating conditions, the exit dose rates calculated for the intensity accident scenario in Attachment A can be scaled down to normal operational intensity. As shown in Table 2, following the planned mitigation (See Sec. 4.3), their exit dose rates will be within FRCM limits for normal operation. The normal condition mitigations (penetration filling plans) are a subset of the accident condition mitigations.

Description	Generic Shielding Criteria Category	Exit Eff. Dose Rate Before Mitigations, Scaled from Beam Intensity Accident [mrem/hour]	FRCM Table 2-6 Limit [mrem/hour]	Failure?	Exit Eff. Dose Rate After Mitigations [mrem/hour]	OK After Mitigations?
Hatch Coaxial	3	1.41E-01	1.00E+02	OK		
Hatch Waveguide	3	7.40E-02	1.00E+02	OK		
Ceiling Vent	3	6.57E+00	1.00E+02	OK	2.12E-01	OK
Gas Manifold Room Pen.	3	4.70E-01	1.00E+02	OK		
Ref. Bldg. Cooldown Line	1	2.72E-01	5.00E-02	X	4.82E-07	OK
Ref. Bldg. Transfer Line	1	4.53E-01	5.00E-02	X	8.03E-07	OK
Ref. Bldg. Single-Leg Util. Pen. (Group of Four)	1	3.26E-01	5.00E-02	X	5.78E-07	OK
Sum of Ref. Bldg. Pens	1	1.05E+00	5.00E-02	X	1.86E-06	OK
Stairway Lab. Pit Door	3	2.04E-03	1.00E+02	OK		
MTA Labyrinth Top Door	2	5.76E-07	2.50E-01	OK		
Ref. Bldg. Four-Leg Util. Pen.	1	3.54E-16	5.00E-02	OK		
Ventilation Supply	2	1.38E-09	2.50E-01	OK		
Ventilation Return	2	2.46E-09	2.50E-01	OK		

Table 2. Labyrinths & Penetration normal operating dose rates in mrem/hour. Normal condition mitigations are a subset of the accident condition mitigations. Locations of all penetrations are described and depicted in Labyrinth and Penetration Worksheets in Attachment A. Dose rate estimates on this normal-conditions table are obtained by scaling intensity accident scenario dose rates down to normal operational intensity.

7. Air Activation Calculations, Estimate of Annual Release, and Air Release Point

Both the 1.6 ft. iron slug target and the target of ten 1 mm silicon slabs were evaluated for the generation of airborne radionuclides. We present here the results from the worse of the two, the silicon slabs.

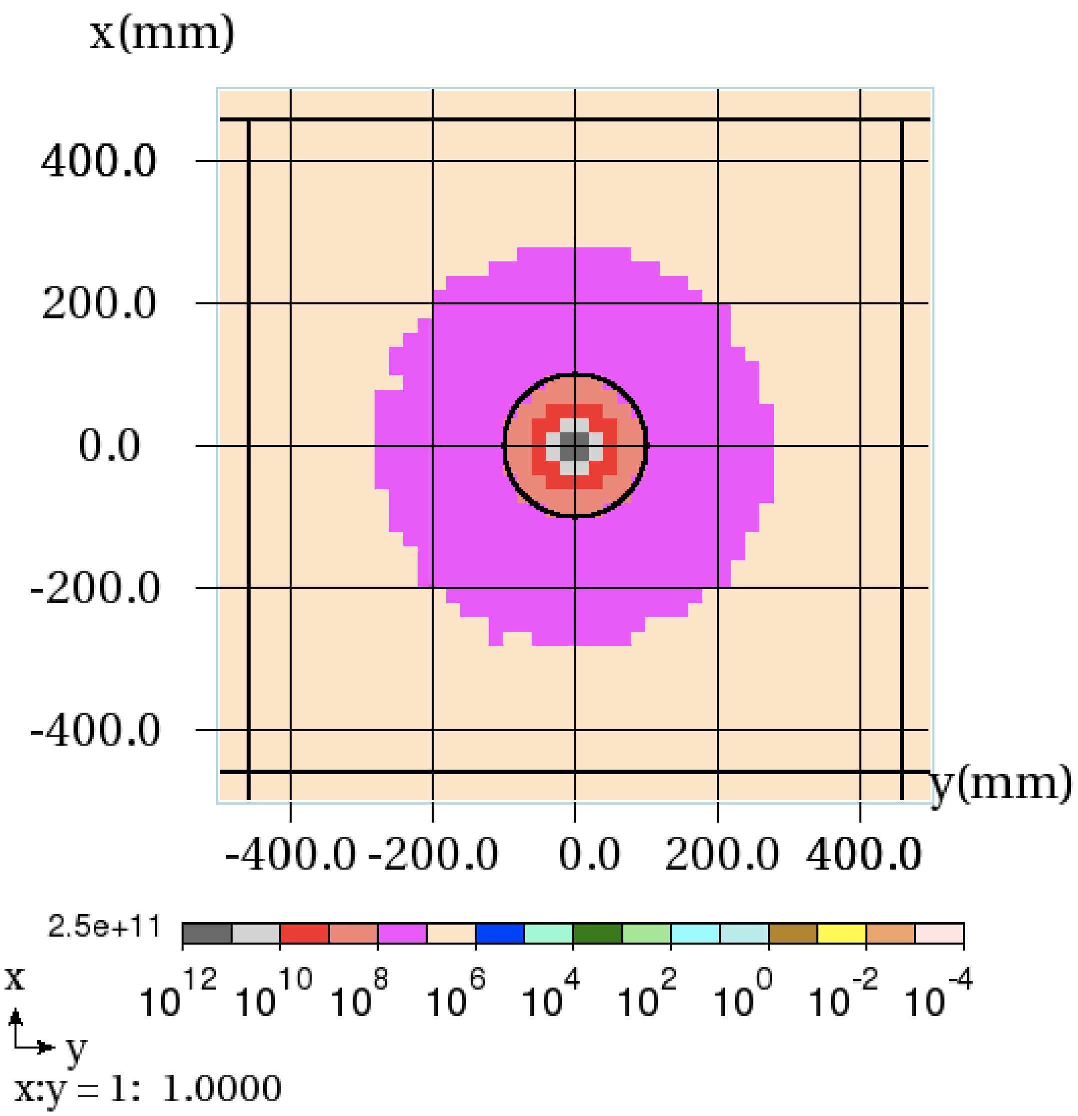

Figure 13. Flux (counts per square cm per second) of charged hadrons > 30 MeV averaged over beam path from vacuum window through the target to rear wall of experiment enclosure. Color scale is arbitrary, showing size of decadal containment contours. The target used here is ten one-millimeter slabs of silicon.

MARS [3] calculations found the 1.4 liter volume containing 99.9% of the beam-induced hadron flux >30 MeV per hadron and the average of this hadron flux within that volume (1.19E-04 hadrons per proton on target per square centimeter). See Fig. 13 for the contours of flux along the z axis.

The room volume is 13,500 cubic feet or 3.82E+08 cm^3. (See Attachment E.) To account for mixing, the effective volume of this room is used for calculation of the transport of the 99.9% volume to the exhaust point. Assuming continuous operation of the 200 cfm air handling fan, annual release is estimated at 0.99 Ci/year. See Attached B, Air Activation spreadsheet. This is an acceptable addition to Fermilab's annual nuclide release inventory.

7.1. Absorber Air Considerations

The six-foot, ten-inch-long volume of air contained in the final beam absorber is expected to mix completely with the room air only on a time scale much longer than the lifetime of the longest-lived isotopes of interest. Thus these radionuclides may be assumed to be substantially decayed away before they enter the room air for exchange. Relaxing this assumption, the air in the absorber could be taken to extend the volume containing 99.9% of the hadron flux above 30 MeV by an additional 47%, and thus the annual release estimate could be conservatively taken to be 2.4 Ci/year. This figure is also an acceptable addition to Fermilab's annual nuclide release inventory.

8. Skyshine (Air-Scattered Radiation)

Taking the normal operation intensity MARS [3] was used to calculate the source term for skyshine, or air-scattered radiation. For this study the highly scattering iron slug 1.6 feet long was positioned on the Front Porch of the cave (and so unshielded from above or on the sides). The source term is the contour containing 90% of the total radiation on the surface of the berm. While irregular in shape, it is contained within a rectangle 13.6 m by 16.4 m and contains an average dose rate of 12 mrem/hour during operation. Using the NCRP-51 methodology (National Council on Radiation Protection & Measurements) and the beamline operation schedule of Table 1, the calculation gives an operational dose rate within a 20 m radius of 4 microrem/hour during operation (1.8 mrem/yr). This radius includes the parking lot, which is considered a low-occupancy area.

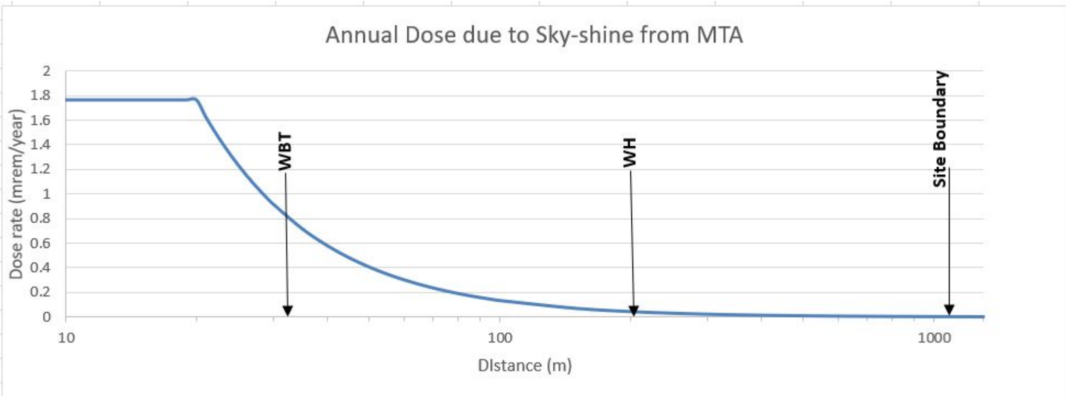

Figure 14. Annual dose due to skyshine as a function of distance from location of peak dose rate on the MTA berm surface, calculated using the NCRP51 methodology. The radii of locations discussed in the Sec. 8 are highlighted for West Booster Tower (WBT) and Wilson Hall (WH).

The dose rate due to skyshine radiation was also calculated for several points of interest at greater distances. The nearest offices are those in the West Booster Tower (WBT), 34 m away, where the calculation suggests an additional 0.8 mrem/yr. Radiological safety training requirements apply to this Gallery. The nearest point within publicly accessible Wilson Hall (WH), 200 m distant, might receive an additional 0.04 mrem/yr. The nearest off-site location is due west, across Kirk Rd, where the additional dose rate is 0.002 mrem/yr.

9. Muon production

At 400 MeV kinetic energy the primary beam will not produce very many muons proportional to primary beam flux. At a mass of 105.7 MeV/c^2 those muons cannot have kinetic energy even as high as 300 MeV. A simple MARS [3] calculation shows that a beam of pure 300 MeV μ^+ incident on soil ranges out completely in less than a meter of soil (much less than 10^{-9} survival fraction). See Fig. 15. This is much less than the effective thickness of passive shielding already in place on all sides and on top of the enclosure.

In Fig. 16 and Fig. 17 we attempt to plot the muon flux from our MARS model in the longitudinal and transverse elevation views for the normal operation condition and the 1.6 foot iron slug target on the Front Porch. With 1.0E+08 simulated protons on target, the contours showing muon penetration into the shielding are not smoothly resolved. Significantly improving the statistics of this job does not seem presently feasible.

10. Ground and Surface Water Activation Calculations

Beam scattering through the target material will take on an angular spread due to multiple Coulomb interactions with the material [5]. There will also be some secondary and knock-on radiation produced in this process, with its own nontrivial angular spread. These effects widen the angular spread of the (heterogeneous) particle beam leaving the downstream face of the target material and heading toward the upstream end of the six-inch-diameter iron pipe connecting the experiment hall to the high-intensity absorber. See drawings in Attachment E. As shown in cross section by Fig. 18, this absorber pipe is embedded in a relatively narrow concrete support whose top and sides are specified to be one foot from the common axis of beam and tube. Outside the concrete support's watertight outer membrane is the soil of the berm. Water in this berm soil eventually percolates down to an aquifer below the lab. Thus the absorber pipe represents the point of least shielding for groundwater concerns.

MARS [3] calculated the density of nuclear interactions in the 1 cm of soil surrounding the absorber pipe's concrete support ("star density"). No credit was taken for the waterproof membrane other than implicitly assuming soil and concrete are not interpenetrated. The same calculation was done for the 1 cm of soil immediately surrounding the concrete case of the absorber itself. The higher star density of the two was conservatively taken to represent the average star density throughout the soil of the berm. This density was found to be 7.26E-05 star/cc ($\pm$25%), and is used as the input to the calculation in the Groundwater spreadsheet. (See Attachment D.)

Groundwater activation must be kept under the "limit of detectability" (1 pCi/mL and 0.04 pCi/mL for tritium and ^{22}Na) as per FRCM [4]. Assuming operation as specified in Table 1, the fraction of this limiting concentration reached starts at about 5.23E-06 times the limit after one year of operation (and groundwater percolation) and after one decade of such use, has risen to 5.23E-05 times the limit.

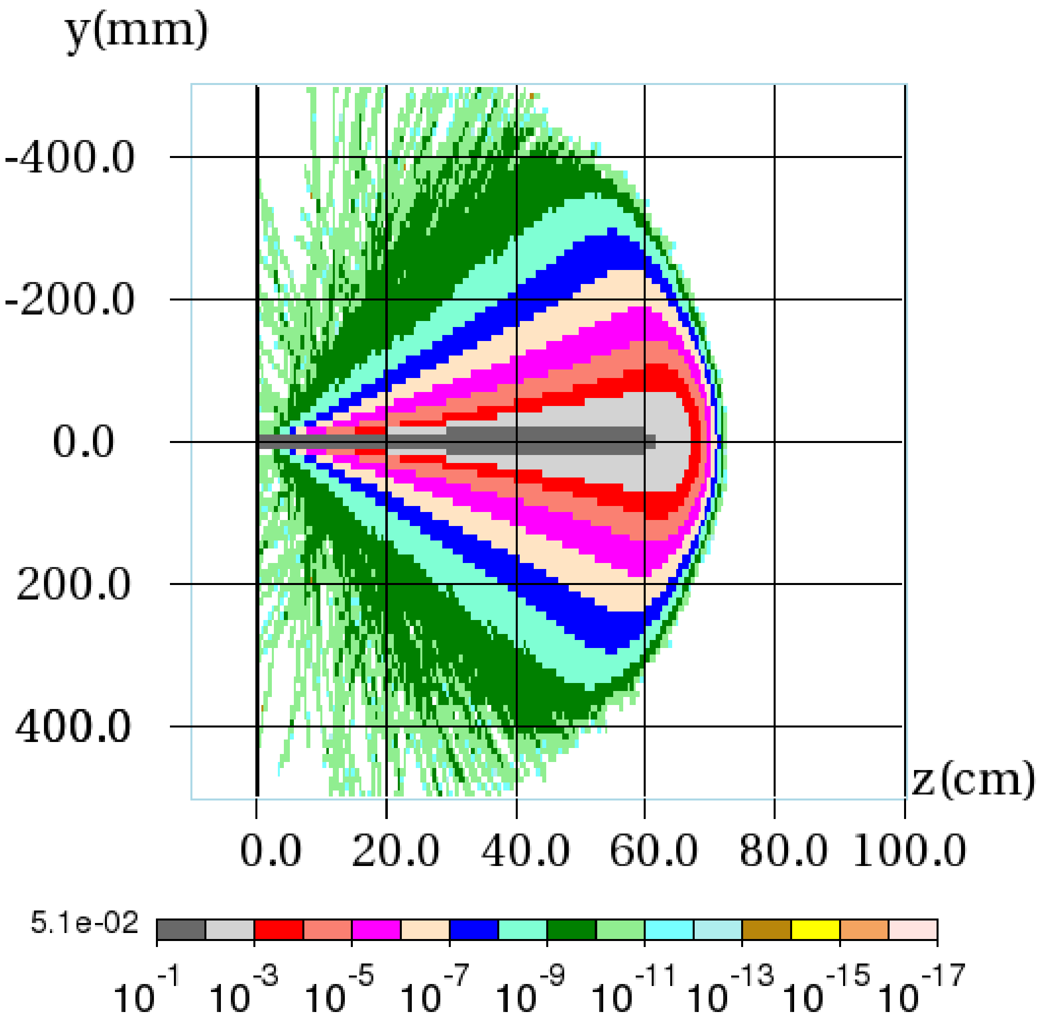

Figure 15. Survival fraction of a 300 MeV muon beam incident from the left into a thick cylinder of soil. Note the different units on the axes here.

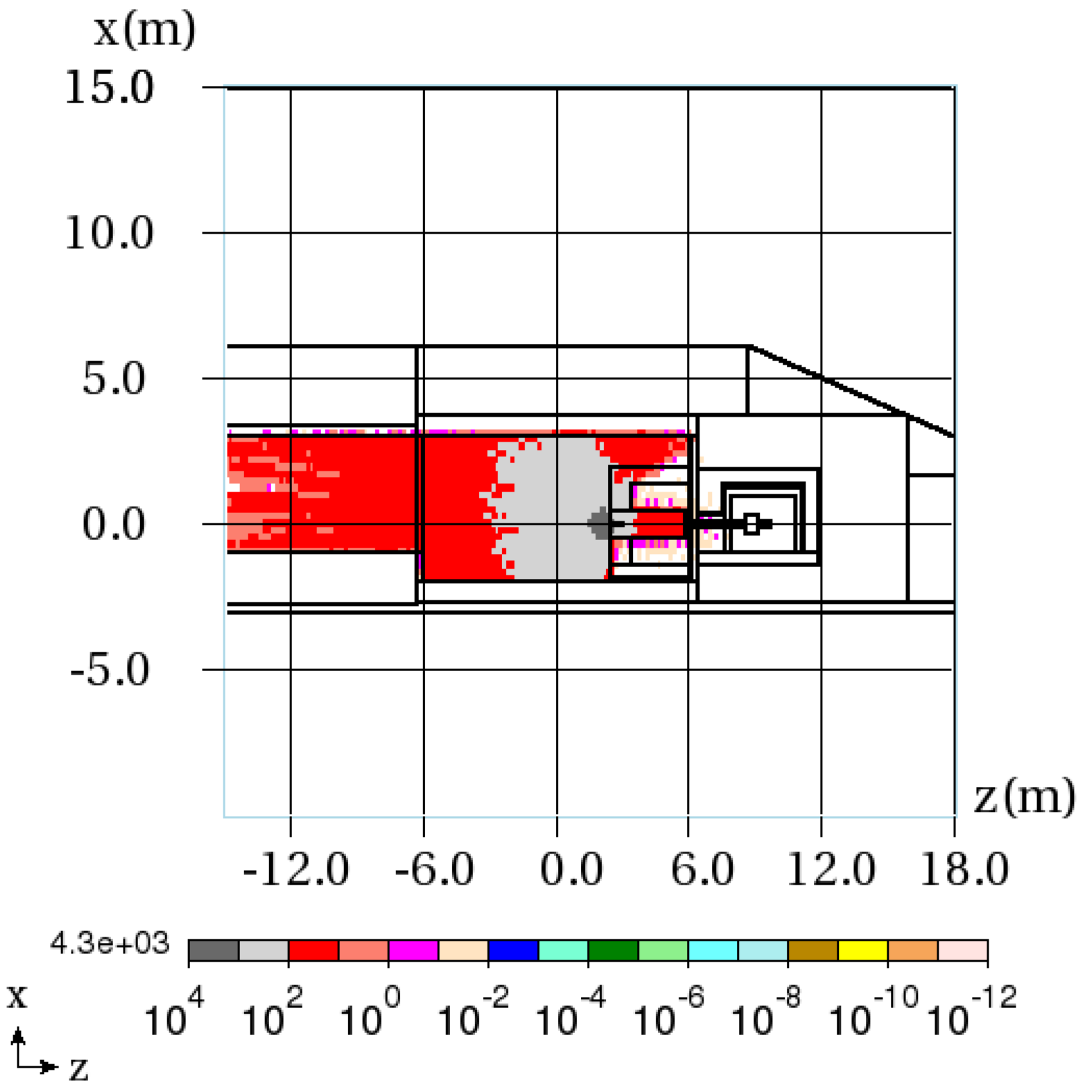

Figure 16. Longitudinal elevation view showing muon flux in muons/cm^2/s for normal beam operation and the iron slug target on the front porch.

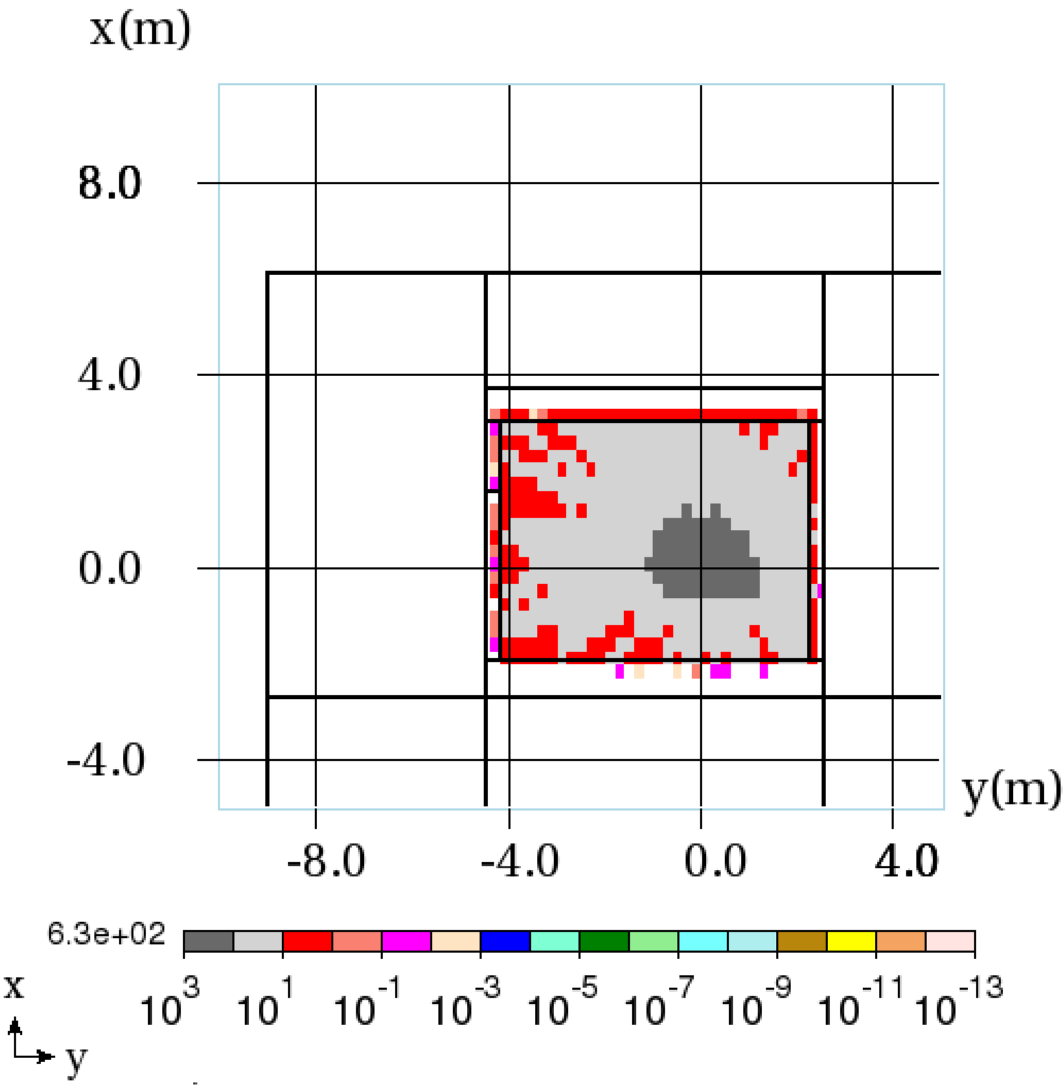

Figure 17. Trasverse elevation view showing muon flux in muons/cm^2/s for normal beam operation and the iron slug target on the front porch.

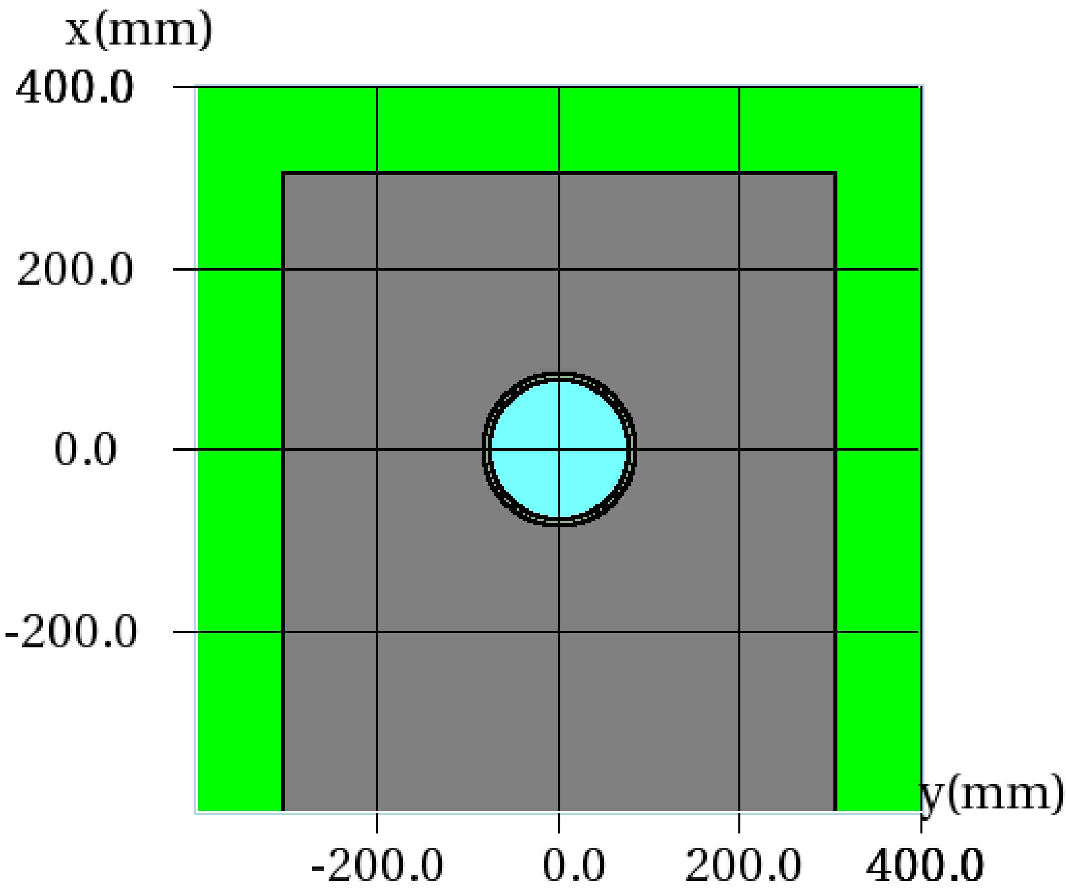

Figure 18. Cross section of the pipe leading to the final absorber, showing the pipe material, the concrete encasing it (gray), and the surrounding soil (green).

There are no drains in the vicinity of the absorber, and so no contributions to mobile surface water.

11. Residual Dose Rate Estimates

Simulation with MARS [3] shows that the Shielding Cave's internal and external surfaces (one centimeter thickness) will be activated by use of the beam line. We simulated the Shielding Cave material and geometry to arrive at estimates of the residual radiation in the inner and outer faces of the Shielding Cave, as well as the permanently installed downstream wall of the radiation enclosure, induced by normal operation of the beam line and a range of possible targets. An iron 'back splash' one foot thick protects the downstream wall of the enclosure, and a six-inch diameter through-hole allows beam into the absorber pipe.

The simuation was also used to calculate the residual activity of the floor of the experiment hall in the case of the target material being placed at the upstream edge of the cave.

The results are presented in table 3 for various cool-down times following a steady 12-hour irradiation at normal operation beam rates and two choices of target. (See Table 1.)

Location and Cooldown Time	Target Choice	
	10% X_0 (0.9 cm) Si	45 cm Fe
Inner surfaces - 1 hour	5.4E+02	2.4E+03
Inner surfaces - 1 week	1.8E+00	4.6E+00
Outer surfaces - 1 hour	6.1E+00	3.2E+01
Outer surfaces - 1 day	9.6E-01	5.0E+00

Table 3. Calculated residual activity in mrem/hour after 12 hours of irradiation at 5E+12 protons/second, and various cooldown times. The highest residual activity of all surfaces (upstream, downstream, wall, etc.) is reported.

Placing a target of multiple thin silicon slabs on the Front Porch of the cave can be expected to increase the residual activation of the nearby floor, so a study was done in MARS [3]. In this configuration 12 hours of normal operation even at an elevated beam intensity of 5E+12 protons per second, the top 10 cm of the concrete floor does not exceed an activation on contact of 1.256E-02 mrem/hour.

12. Absorber Integrity Analysis

The final absorber was previously analyzed and found to be structurally sound at a much higher beam intensity than proposed here. The copper core, tightly embedded in steel for good thermal contact, reaches thermal equilibrium well below melting temperature at 3.5E+17 protons per hour. (See [7] and [8]). This is more than one hundred times the nominal rate here of 2.7E+15 protons per hour.

13. Summary

We have here presented the results of analysis of the MeV Test Area shielding through MARS calculations and spreadsheets under the operational intensities given in

Table 1, both in normal operation and in accident scenarios. During normal operation, the shielding meets or exceeds FRCM requirements, as will all the penetrations once the unused penetrations are filled as described in Sec. 4.3. The analyses for air activation, skyshine, muon production, and water activation also meet requirements.

Under accident scenarios of beam trajectory or beam intensity, passive shielding meets or exceeds requirements in both the longitudinal and transverse, when coupled with the planned active shielding measure described in Sec. 5.

Residual activation has been predicted and allowing cooldown time for this activation drives a credible operational frequency of the facility. Dose to personnel will be kept as low as reasonably achievable (ALARA) via standard radiological work controls, such as ALARA work plans and Radiological Work Permits.

References

[1] C. Johnstone, I. Rakhno, N. Mokhov, W. Higgins, ed. M. Gerardi, “MuCOOL Facility Shielding Assessment” Fermilab, Nov. 1, 2010.

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[3] N.V. Mokhov and C.C. James, “The Mars Code System User’s Guide, Version 15 (2016)”, Fermilab-FN-1058-APC (2017). https://mars.fnal.gov.

[4] Fermilab Radiological Control Manual. `http://eshq.fnal.gov/manuals/frcm`.

[5] J. A. Johnstone, “H^- Electron-Loss Collisions & Mulitiple Scattering in Thin Neutralizing Foils”, Fermilab Colloquium, 1990.

[6] J. M. St. John, “Ion Stripping at the Irradiation Physics Area”, Fermilab 2018. https://beamdocs.fnal.gov/AD-private/DocDB/ShowDocument?docid=8025

[7] N. Mokhov, C. Johnstone, I. Rahkno, M. Foley, K. O’Brien, “MTA Absorber”, Fermilab 2003. MuCOOL Shielding Assessment Document, Attachment 12.

[8] A. Lee, “The Temperature Study for the Beam Dump Used in Muon Cooling”, Fermilab 2003. MuCOOL Shielding Assessment Document, Attachment 12a.

Attachments

Attachment A - MTA Incremental Spreadsheets
Attachment B - Air Activation Spreadsheet
Attachment C - Air Scattered Radiation (Skyshine) Spreadsheet
Attachment D - Groundwater Spreadsheet
Attachment E - MTA Complete Drawing Package