NuMI-B-493

Absorber Conceptual Design for the 11/98 DOE Baseline Review

A. Wehmann

April 30, 1999

Shielding calculations for the NuMI Hadron Absorber that were done to develop costs for the November, 1998 Lehman DOE Baseline Review are described.

1 Introduction

Shielding calculations for the NuMI Hadron Absorber have occurred in fits and starts, depending on internal and external reviews and other such diversions. This note will describe the the work that occurred between the time that the Absorber cavern dimensions were specified in Spring, 1998, and the November, 1998, Lehman DOE Baseline Review.

Between March and November, 1998, the requirements for the Target Hall shielding and Decay region shielding were determined. This activity was the major focus of Monte Carlo simulations with the MARS [1] program[1]. The Absorber was represented in those runs simply as a block of steel. During

[1] Cat James was the NuMI person designated to use MARS for this purpose.

that time, consultations[2] with Don Cossairt (ES&H Section) and new considerations regarding the geometry factor (see References [3], [4]) led to an increase in the average star density for the shielding design[3].

In order to have a cost estimate for a realistic design of the Absorber, Gordon Koizumi modified an existing CASIM ([5], [6]) deck (based on previous CASIM runs for the Absorber) so as to have an aluminum core, steel shapes corresponding to the use of Continuous Cast Salvage (CCS) steel[4], and a 3' thick outer wrap of concrete. This Monte Carlo run had 120 GeV beam incident on the Absorber, with Gaussian shape in x and y ($\sigma_x = 12$ cm, $\sigma_y = 12$ cm). The date of the run[5] was 9/3/98; the number of events was 250,000. The geometry was as shown as in Figure 1.

Sam Childress looked through the CASIM output and characterized it as follows. For small radius, large z, (directly downstream of the Absorber) the star density adjacent to the concrete exterior surface is $\approx\ 2 \times 10^{-12} \frac{stars}{cm^3\, p}$. For large radius, small z, (where there is aluminum in the core and at the side wall) the exterior surface star density is $\approx\ 5 \times 10^{-12}$. At large radius, large z, (where there is steel in the core and at the side wall) the exterior surface star density is $\approx\ 3 \times 10^{-11}$. In evaluating the results of Gordon's CASIM run for the Absorber, consideration was given to the new developments mentioned above that had been applied to the shielding in the Target Hall and Decay region.

---

[2]For the outcome of those consultations see Reference [2].

[3]For TM-2009 [3] the maximum star density used was $1.3 \times 10^{-11} \frac{stars}{cm^3\, incident\, proton}$. For the TDR this became 7×10^{-11}. However, there are some ambiguities in this latter number, which are discussed in Appendix E.

[4]Such steel has been used elsewhere at the laboratory. A particular example is the shielding underneath the Booster West tower, where beam is extracted from the Booster and sent to the Main Injector. Purchase Order # 509385 is an example of a purchase of such steel.

[5]The run files have been copied from the RDIV01 disk to FNALU and are available for inspection at location "~ wehmann/numi_studies/Gordons_runs/absorber/abs_tgt_in". They are the files that start out as "abs14A". The numbers in Appendix A, which gives the geometrical details, are taken from one of these files.

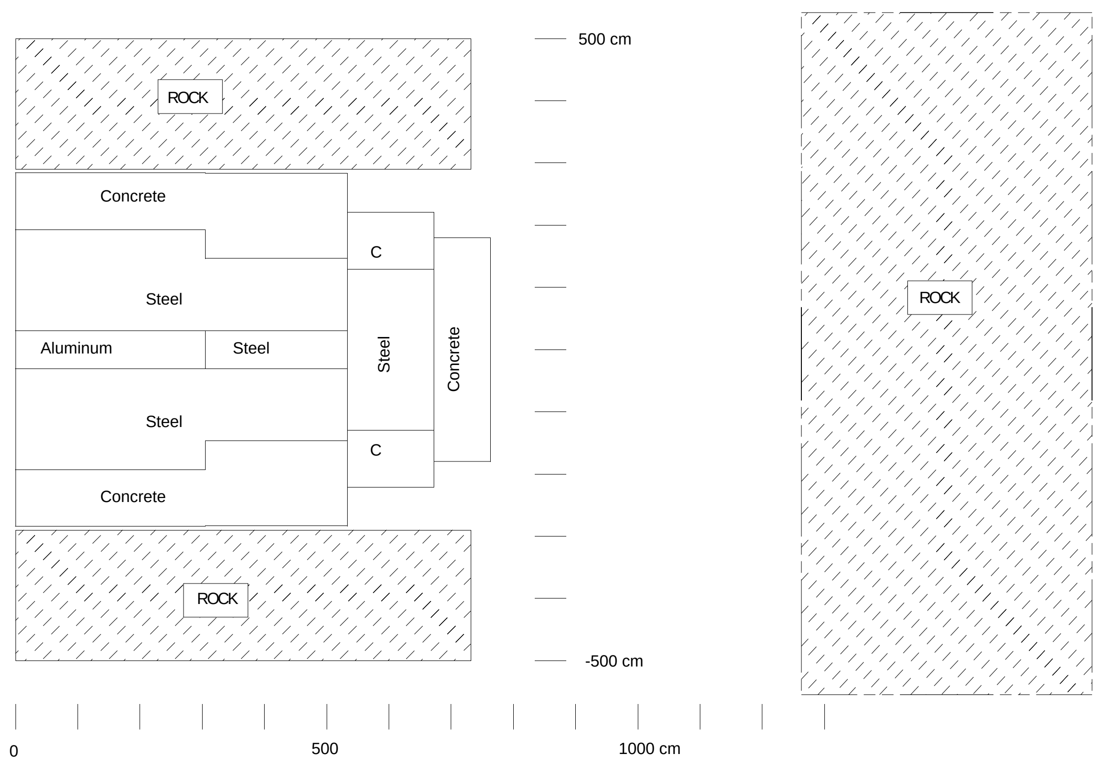

Figure 1: Schematic of Absorber geometry in CASIM run of 9/3/98. Cylindrical symmetry is used.

2 Residual Radiation Considerations

Sam Childress collected and developed the following information on residual activity. For steel surrounded by three feet of concrete the dose rate at the outside edge is ≈ 30 mr/hr, for $4 \times 10^{-11} \frac{stars}{cm^3\, p}$ and the NuMI beam intensity of 4×10^{13} protons every 1.9 sec. In obtaining this value he used $\omega(\infty, t < 10\text{hrs}) = 7\times10^{-2}\ \frac{mr}{hr} \left\{\frac{star}{cm^3\ sec}\right\}^{-1}$. A reproduction of this calculation is given in Appendix B. Going higher than 30 mr/hr for residual radioactivity was deemed unwise, considering the needs to access the Absorber cavern for servicibility[6].

3 Groundwater Activation Considerations

At the time that Sam Childress was evaluating Gordon Koizumi's CASIM runs, the version number of the NuMI TDR ([4]) was at level 0.8. Sam used Figure 4-10 from that version of the TDR to determine that the limiting star density[7] for groundwater activation was $S_{max} = 7 \times 10^{-11}\ \frac{stars}{cm^3\, p}$.

Figure 4-12 in version 1.0 of the NuMI TDR is equivalent to Figure 4-10 in version 0.8. On Figure 4-12 the averaging factor for the Decay region is marked as either 0.10 or 0.19; what value one should use for the limiting star density is not too clear (see discussion in Appendix E). If one believes Table 4-7, the limiting value for the Decay region should be 7.1×10^{-11}. Table 4-7 indicates that for the Absorber region the limiting star density should be $6.1 \times 10^{-11} \frac{stars}{cm^3\, p}$.

4 Choices Made for Shielding

From the previous discussion we can note that the limit on star density from residual radiation considerations is more severe than the groundwater activation considerations—by about 50%. Changes were made to the shielding thicknesses for the Absorber, starting from the values in the CASIM run

[6]Hadron and muon monitoring equipment is located in the cavern, in addition to the Absorber itself.

[7]Figure 4-10 gives $S_{avg} = 1.4 \times 10^{-11}$. The ratio of $\frac{S_{max}}{S_{avg}}$ is thus 0.20.

described in Section 1. The rule-of-thumb that Sam Childress used is given in the following section[8]. This was done to determine approximate shield dimensions (in advance of additional Monte Carlo runs).

4.1 Rule-of-Thumb

A reduction of transverse thickness by one plate of CCS steel ($9\ \frac{1}{8}$ inches) increases the star density by a factor[9] of ≈ 6. A reduction of longitudinal thickness by two plates of steel ($18\ \frac{1}{4}$ inches) increases the star density by a factor[10] of ≈ 6.

4.2 Changes Made

Table 1 shows the change in star density that results from the change in values of shielding thicknesses. The trial change was to remove one $9\ \frac{1}{8}$ inch layer of steel on the sides, decrease the length of the aluminum portion of the core from ten feet to eight feet, increase the length of the steel portion of the core from 7.5 feet to 9.5 feet, and remove four layers of CCS steel at the downstream end of the Absorber.

	as in CASIM run $\left(\frac{stars}{cm^3\,p}\right)$	after trial change $\left(\frac{stars}{cm^3\,p}\right)$
small radius, large z	2×10^{-12}	1.6×10^{-11}
large radius, small z	5×10^{-12}	3×10^{-11}
large radius, large z	3×10^{-11}	1.8×10^{-10}

Table 1: Results of making trial changes in the thickness of steel shielding, as well as reducing the length of the aluminum in the core region by two feet.

Based upon the numbers in Table 1, and the criteria discussed in Sections 2 and 3, it was decided that it was okay to change from 6 to 2 layers of steel at

[8]This rule-of-thumb is discussed further in Appendix C.

[9]Starting with a factor of ten change in star density corresponding to a foot of steel, $9\ \frac{1}{8}$ inches of steel gives a change of $10^{(.76)} = 5.76$.

[10]Starting with a factor of ten change in star density corresponding to 23.7 inches of steel (see Table 3 in Appendix C), $18\ \frac{1}{4}$ inches of steel gives a change of $10^{\left(\frac{18.25}{23.7}\right)} = 5.9$.

the downstream end of the Absorber[11]. However, for the transverse shielding it was decided that for the top and one side of the Absorber we should not remove one layer of steel, based on residual radioactivity considerations. For the bottom, and for the side of the Absorber not serving as a passageway, it was decided that a reduction in cost could be achieved by removing one layer of steel. Figures 2 and 3 are two views of the resulting shielding configuration that was costed for the Lehman Review.

It is to be noted that roughly 20% of the energy of the beam reaches the absorber when the production target is in place and the proton beam is properly positioned on the target[12]. Since this is expected to be the case for most beam delivered on the NuMI target, groundwater shielding can assume this factor. Residual radioactivity calculations can do the same. Prompt radiation calculations cannot automatically use this factor. This factor has not been explicitly included in the determination of shielding thicknesses that was done for the costing study for the 11/98 Lehman DOE baseline review; this means that the shielding thicknesses can probably be reduced further—dependent on further studies with MARS and a more detailed design of the Absorber core.

[11] The length of aluminum in the core region had been reduced by two feet as well, so the net change in the length of steel equivalent in the core region was $24\left(1-\frac{2.7}{7.87}\right)-4\times 9.25=-21.2$ inches.

[12] The distribution of where energy is deposited under these conditions has been studied with separate Geant [7], CASIM, and MARS runs. The results shown in Figures 4 and 5 come from Geant runs (see the discussion in Section 5). A MARS run made by Cat James in Fall, 1998 gave an energy deposition of 30 GeV in the steel blocks that represented the central part of the Absorber (incident proton energy was 120 GeV). The concrete surrounding the steel received only 0.002 GeV. This MARS run used the medium energy parabolic horn configuration.

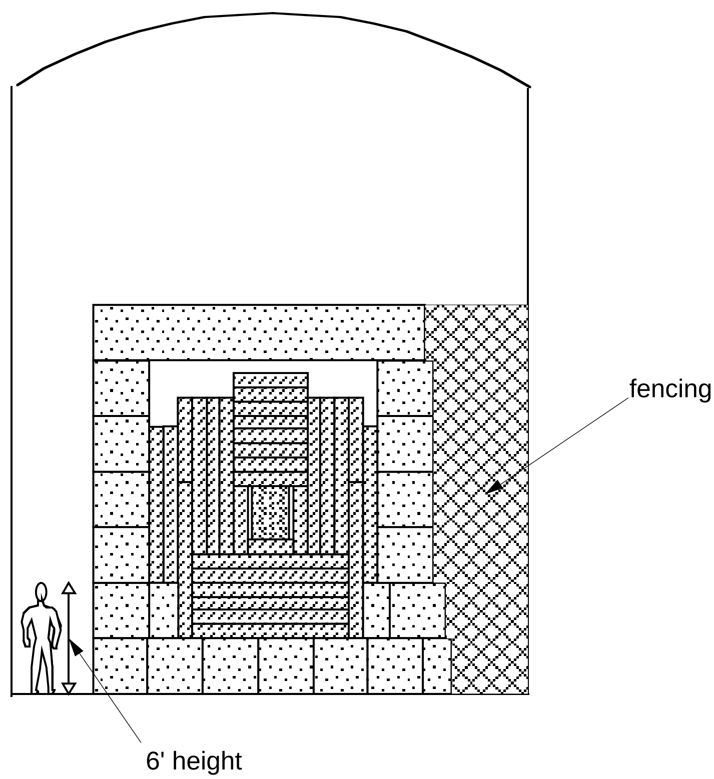

Figure 2: View of front of Absorber (in the Absorber Cavern), based on the costing design for the 11/98 Lehman Baseline DOE Review. Fencing is shown on the side of the Absorber where one layer of steel (present in the CASIM run) was removed. This fencing is meant to restrict access on that side—due to residual radioactivity considerations. The steel plates directly above the core of the Absorber were configured to allow easy vertical access to the core, for servicibility.

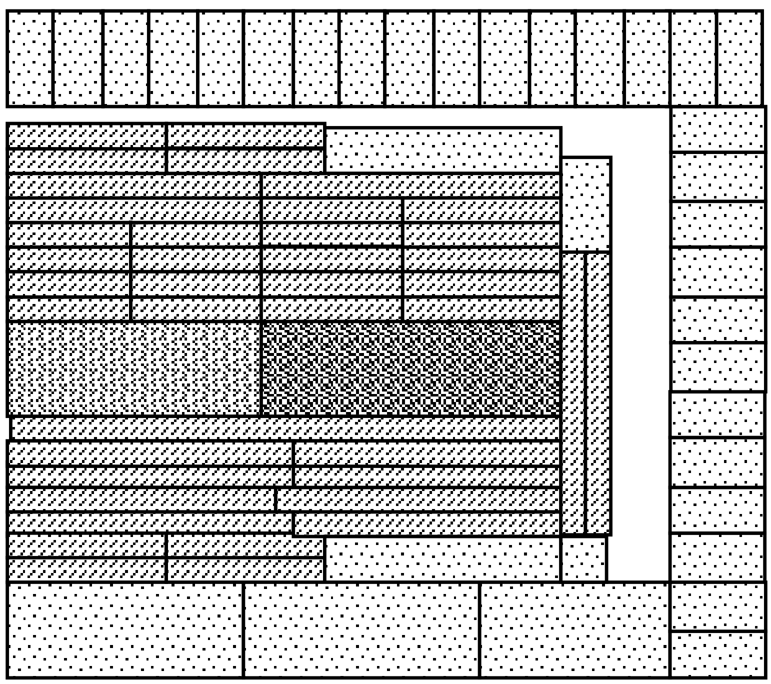

Figure 3: Elevation view of Absorber, sliced through center of the core, based on the costing design for the 11/98 Lehman Baseline DOE Review. The beam enters from the left. The core material that it first hits is envisaged to be water-cooled aluminum.

5 Absorber Core

The water cooled core of the Absorber in the conceptual design is sized to contain most of the beam energy that impinges on it. Figures 4 and 5 are taken from just one study[13] of the beam distribution at the face of the Absorber. Based upon these distributions (and others like them made in earlier studies) the core size for the conceptual design was chosen as $\pm$ 30 cm horizontally, $\pm$ 45 cm vertically[14]

From Figure 4 it can be noted that twenty percent of the incident beam energy[15] strikes the face of the absorber, for the case of the low energy beam horn configuration. Figure 5 indicates that less beam energy (14%) impinges the Absorber for the case of the medium energy beam horn configuration.

[13] This study was done during the Summer of 1998. Appendix D gives details for the target and beam parameters that were used.

[14] The added amount in the vertical direction was chosen to allow for putting the Absorber level, with the beam elevation dropping with a 58.3 mr slope. For a travel distance of 17.5 feet, this is a drop of 31.1 cm.

[15] This means incident on the primary target.

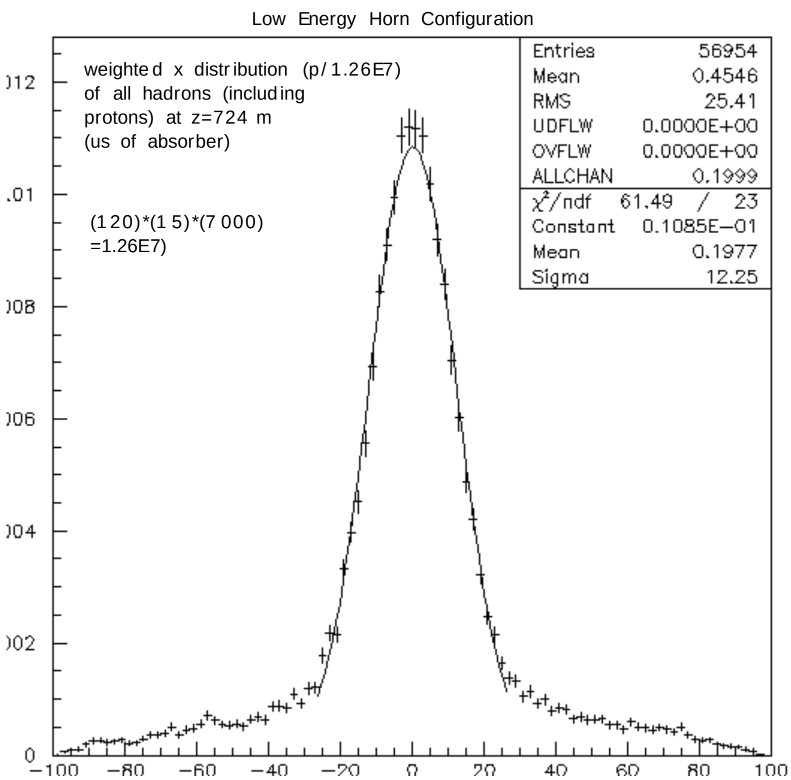

Figure 4: Shown in the figure is the energy-weighted x distribution of all hadrons incident on the Absorber as determined using Geant, for the low energy horn configuration. The weighting is the expression (hadron momentum)/(120 GeV * number of protons on target for the calculation). The standard deviation (sigma) of a Gaussian fit to the x distribution is 12.25 cm.

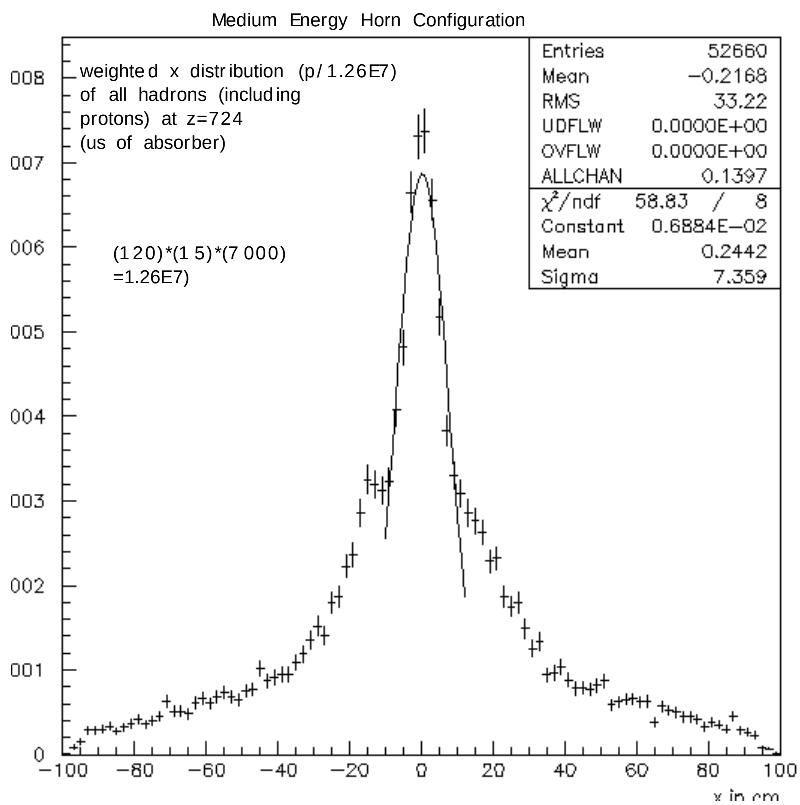

Figure 5: Shown in the figure is the energy-weighted x distribution of all hadrons incident on the Absorber as determined using Geant, for the medium energy horn configuration. The weighting is the expression (hadron momentum)/(120 GeV * number of protons on target for the calculation). The distribution is less well fit by a Gaussian distribution, in comparison with Figure 4. It has a central peak between -10 cm and 10 cm which has a Gaussian sigma of 8 cm.

References

[1] N.V. Mokhov, *The Mars Code System User's Guide*, Fermilab-FN-628 (1995). O.E. Krivosheev and N.V. Mokhov, *A New MARS and its Applications*, Fermilab-Conf-98/43 (1998)

[2] V. Cupps and J.D. Cossairt, *Parameters for NuMI Groundwater Protection*, draft report, September, 1998

[3] A. Wehmann, W. Smart, S. Menary, J. Hylen, and S. Childress, *Groundwater Protection for the NuMI Project*, Fermilab TM-2009 (also NuMI-B-279), Oct. 11, 1997

[4] K. Anderson, et. al. , *The NuMI Facility, Technical Design Report, Version 1.0*, Fermilab, October, 1998

[5] A. Van Ginneken, *CASIM: Program to Simulate Transport of Hadronic Cascades in Bulk Matter*, Fermilab-FN-272 January, 1975

[6] A. Van Ginneken and M. Awschalom, *Hadronic Cascades, Shielding, Energy Deposition*, High Energy Particle Interactions in Large Targets, Fermi National Accelerator Laboratory, Batavia, IL., 1975

[7] See WWW URL"http://wwwcn.cern.ch/asdoc/geant_html3/geantall.html"

[8] J.D. Cossairt, *Radiation Physics for Personnel and Environmental Protection*, Fermilab TM-1834, Revision 4, February, 1999

[9] *Fermilab Radiological Control Manual*, available at URL "http://www-esh.fnal.gov/FRCM/", exists in printed form as a controlled document, Fermilab ES&H Section

[10] A. Wehmann, "A Study of Muons Downstream of the Hadron Absorber", NuMI Note B-369, May 28, 1998

[11] See WWW URL "http://wwwinfo.cern.ch/asd/paw/index.html"

[12] See WWW URL "http://www1.cern.ch/Adamo/ADAMO_ENTRY.html"

[13] A. Malensek, A.A. Wehmann, A. J. Elwyn, K. J. Moss, and P. M. Kesich, "Groundwater Migration of Radionuclides at Fermilab", Fermilab TM-1851 (1993)

Appendix A Fortan Geometry, CASIM run

This Appendix contains an extract of the geometry specified in the Fortran deck for the CASIM run described in Section 1. The geometry is illustrated in Figure 1. The steel dimensions correspond to multiples of a plate thickness of 9.125 inches, since that is the thickness of plates of the CCS steel that we plan on using. The number of such plates next to the aluminum core in the upstream part of the Absorber is seven (transverse shielding). Further downstream the number drops to five such plates. At the downstream end there is longitudinal shielding consisting of six such plates (followed by $\approx$36 inches of concrete).

In the CASIM geometry the length of aluminum in the upstream part of the core was ten feet. The aluminum was followed by a steel core that was 7.5 feet in length[16]. Considerations for the core design were cooling and handling for servicibility. In the following extract the units are centimeters.

```
C       GEOMETRY
C       1=TEST DOLOMITE,2=FE,3=CONCRETE,4=DOLOMITE,5=TEST AL,6=AL,7=AIR,
C         8=TEST MATERIAL 3 CU, 9=CU
C
      IF(Z .GE. 0. .AND. Z .LT. 304.8)THEN
        IF(R .LT. 30.5) N=1     !ALUMINUM
        IF(R .GE. 30.5 .AND. R .LT. 192.7425) N=2       !STEEL
        IF(R .GE. 192.7425 .AND. R .LT. 284.1825) N=3   !CONCRETE
        IF(R .GE. 284.1825 .AND. R .LT. 290.) N=7       !air
        IF(R .GE. 290. .AND. R .LT. 500.) N=4   !DOLOMITE
      ENDIF
C
      IF(Z .GE. 304.8 .AND. Z .LT. 396.24)THEN
        IF(R .LT. 30.5) N=9     !STEEL
```

[16] For the conceptual design of the Absorber costed at the time of the November, 1998 Lehman DOE Review, the length of the aluminum in the core was reduced to eight feet (correspondingly, the length of steel in the core was increased by two feet). The number of 9 $\frac{1}{8}$ inch thick, steel plates on the sides and rear of the Absorber was adjusted to match residual radiation criteria and groundwater shielding criteria, using a rule-of-thumb formula for scaling star density according to set changes in steel thickness.

```
        IF(R .GE. 30.5 .AND. R .LT. 146.3875) N=2       !STEEL
        IF(R .GE. 146.3875 .AND. R .LT. 283.5475) N=3   !CONCRETE
        IF(R .GE. 283.5475 .AND. R .LT. 290.) N=7   !air
        IF(R .GE. 290. .AND. R .LT. 500.) N=4   !DOLOMITE
      ENDIF
      IF(Z .GE. 396.24 .AND. Z .LT. 533.4)THEN
        IF(R .LT. 30.5) N=9     !STEEL
        IF(R .GE. 30.5 .AND. R .LT. 146.3875) N=2       !STEEL
        IF(R .GE. 146.3875 .AND. R .LT. 283.5475) N=3   !CONCRETE
        IF(R .GE. 283.5475 .AND. R .LT. 290.) N=7   !air
        IF(R .GE. 290. .AND. R .LT. 500.) N=4   !DOLOMITE
      ENDIF
C
      IF(Z .GE. 533.4 .AND. Z .LT. 672.465)THEN
        IF(R .LT. 129.54) N=2   !STEEL
        IF(R .GE. 129.54 .AND. R .LT. 220.98) N=3       !CONCRETE
        IF(R .GE. 220.98 .AND. R .LT. 290.) N=7 !AIR
        IF(R .GE. 290. .AND. R .LT. 500.) N=4   !DOLOMITE
      ENDIF
C
      IF(Z .GE. 672.465 .AND. Z .LT. 762.825)THEN
        IF(R .LT. 180.) N=3     !CONCRETE
        IF(R .GE. 180. .AND. R .LT. 284.1825) N=7       !AIR
        IF(R .GE. 284.1825 .AND. R .LT. 500.) N=4       !DOLOMITE
      ENDIF
C
      IF(Z .GE. 762.825 .AND. Z .LT. 1262.825) N=7      !AIR
      IF(Z .GE. 1262.825 .AND. Z .LT. 1500.0) N=4       !DOLOMITE
```

Appendix B Residual Radiation Calculation

TM-1834, Revision 4 ([8]) has the following expression[17] for calculating residual activity:

$$\frac{dD}{dt} = \frac{\Omega}{4\pi}\frac{dS}{dt}\omega\left(t_i, t_c\right)) \tag{1}$$

Equation 5.32 a in reference [8] gives $\omega(\infty, 0) = 9 \times 10^{-6}\ \frac{rad}{hr}\left\{\frac{star}{cm^3\ sec}\right\}^{-1}$ for iron. The methodology for obtaining a value for $\omega(\infty, t_c)$ for concrete with 1% sodium content is discussed next.

The following is taken[18] from an e-mail message from Sam Childress, dated 9/8/1998:

> I have not been able to find much information on an appropriate conversion factor for concrete. The quantitative data I currently have is from Don's very useful[19] TM-1834, Fig. 5-10 (taken from 1969 paper by Armstrong and Barish). This shows the photon dose rate both for Fe in a tunnel and for surrounding concrete walls. For this example, where the concrete contains 1% sodium by weight (relatively low %?) the dose rate from the concrete is about three times higher[20] than that from Fe for the first ten hours, then falls rapidly to match the Fe dose after about 30 hours[21]. To obtain a concrete conversion factor from stars to dose rate using this data (where the same particle flux is seen by both Fe and concrete) I would first multiply the conversion factor for Fe by 2.6 (the ratio[22] of absorption lengths for concrete/Fe), and then multiply that by the ratio of concrete/Fe photon dose rate

[17] Equation 5.31 in Reference [8].

[18] I've taken the liberty of making a few changes for the sake of clarity.

[19] Revision 3 of TM-1834 is what Sam was using at the time. Revision 4 of this TM has been issued since then; it has this figure renumbered as Figure 5.7. The vertical axis has been changed and the general appearance of the figure has been improved.

[20] If I use Figure 5.10 in TM-1834, Revision 3 and a ruler marked in tenths of an inch, I get the factor as $10^{\left[\left(\frac{.5}{2.88}\right)3\right]} = 3.3$. Repeating this with Figure 5.7 in TM-1834, Revision 4 I get the factor as $10^{\left[\left(\frac{.64}{2.5}\right)2\right]} = 3.25$.

[21] The ^{24}Na half-life is 15 hrs.

[22] This number is used to convert from star density in iron to star density in concrete.

from the plot. As an example, for $<$ 10 hrs after shutdown, the conversion factor from star density to dose rate for concrete[23] is

$$\left(9 \times 10^{-3}\right) \times 2.6 \times 3 \;=\; 7 \times 10^{-2} \, \frac{mr}{hr} \left\{ \frac{star}{cm^3 \; sec} \right\}^{-1} .$$

Discounting the possibility of a significant ^{56}Mn contribution to Fe (which is not seen on this plot[24]), the concrete conversion factor would decrease more rapidly than for Fe, becoming $2.3 \times 10^{-2} \, \frac{mr}{hr} \left\{ \frac{star}{cm^3 \; sec} \right\}^{-1}$ at 30 hrs. after shutdown.

Substituting $\frac{\Omega}{4\pi} = \frac{1}{2}$,

$$\frac{dS}{dt} = \left(\frac{4 \times 10^{13}}{1.9} \right) \left(4 \times 10^{-11}\right) ,$$

and $\omega = 7 \times 10^{-2}$ into Equation 1 gives the result of 29.5 mr/hr as the dose rate due to residual radioactivity at the outer surface of the concrete layer (see Section 2 of the paper for further discussion).

Appendix C Effect of Shielding Thickness Change

C.1 Rule of Thumb

I explore in this Appendix the rule-of-thumb that is used by some of us; it is that for a thick transverse shield a change of one foot of steel changes the star density by a factor of 10. It is often said as a corollary that a change of three feet of concrete also produces a factor of 10 change in the star density. Perhaps more correctly stated, the Fermilab Radiological Control Manual ([9]) says[25] "Roughly, 1 meter of concrete $\simeq$ 40 cm of iron. (Since the ratio of absorption lengths $= \dfrac{17.3 \text{ (iron)}}{44.6 \text{ (concrete)}} = 0.39$.)".

[23] The value of 9×10^{-3} comes from Equation 5.32a of Reference [8].

[24] ^{56}Mn has a half-life of 2.6 hours.

[25] I find this in Appendix 8B, "Brief Summary Of General Methods Of Estimating Shielding, 1. Hadron And Muon Shielding, C. Design of Efficient Transverse Shielding". The closest URL reference point is "http://www-esh.fnal.gov/FRCM/Ch08/CH08.html#Heading5".

One way to justify this rule-of-thumb for transverse shielding scaling is to consult Reference [6]. In Figure VIII it gives star density curves for 30, 100, 300, 1000 GeV/c protons incident on a solid iron cylinder[26]. Using a ruler (e.g. conveniently marked off in tenths of an inch) one can measure the transverse amount of iron between the contours shown there, using the locations where the contours are parallel to the x axis of the graph. The results of doing this are shown in Table 2.

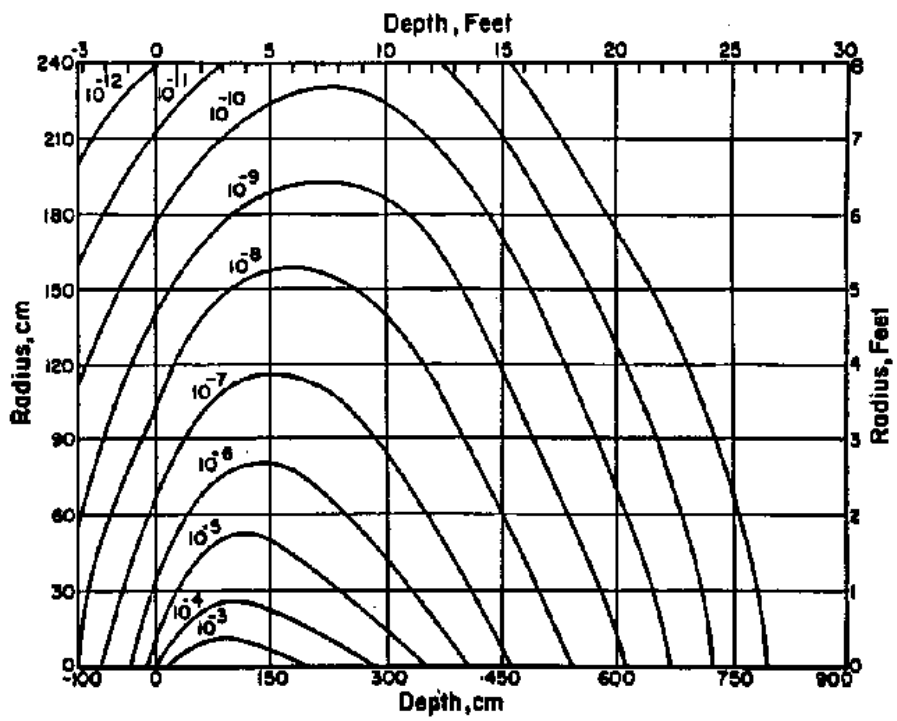

Figure 6: Figure 8-1 extracted from the Fermilab Radiological Control Manual ([9]). This figure is the same as Figure VIII.3 in Reference [6]. It represents 300 GeV/c protons incident on a solid iron cylinder.

[26]Two of these figures are given in Reference [9], in an electronic form. I've included the 300 GeV/c one here, as Figure 6.

Momentum GeV/c	Contours 10^{-9} - 10^{-10} Units (inches)	Contours 10^{-10} - 10^{-11} Units (inches)
300	14.6	
100	11.4	9.0
30	12.9	8.4

Table 2: Amount of transverse steel thickness between contours on plots in Figures VIII.1-4 of Reference [6] (Figure 6 in this paper is one of those plots), based on measuring contours at the point where the contours are parallel to the x-axis of the figure. An analogous number can be extracted from Figure VIII.34 of Reference [6] (300 GeV, iron cave, 10^{-9} - 10^{-10} contours); it is 10.7 inches.

A similar exercise can be made for changes in thickness of steel in the longitudinal direction, at small radius. The results of doing so are shown in Table 3.

Momentum GeV/c	Contours 10^{-9} - 10^{-10} Units (inches)	Contours 10^{-10} - 10^{-11} Units (inches)	Contours 10^{-11} - 10^{-12} Units (inches)
300	22	21.1	27.3
100	24.7	24.7	22
30	22	22	24.7

Table 3: Amount of longitudinal steel thickness between contours on plots in Figures VIII.1-4 of Reference [6], based on measuring contours at the point where the contours intersect the r=0 line on the figure. An analogous number can be extracted from Figure VIII.34 of Reference [6] (300 GeV, iron cave, 10^{-9} - 10^{-10} contours); it is 26.9 inches.

Reference [9] gives values for the absorption length in iron and concrete; they are 17.3 cm (7.86 inches) and 44.7 cm (24 inches). That for iron would correspond to an attenuation by a factor of 10 in 15.7 inches[27].

[27] This factor does not include the geometrical effect of the hadron flux diverging from a narrow source point, which further reduces the star density (compared to simple attenuation).

Appendix D Target and Beam Parameters in Geant Runs

The energy weighted charged particle distributions in Figures 5 and 4 in Section 5 were obtained from Geant runs done in the Summer of 1998, for the purpose of studying muon distributions behind the Absorber[28]. These Geant runs had in them the low energy and medium energy configurations of the NuMI parabolic focusing horns (see the NuMI TDR, Reference [4]). The parameters of the beam and target for these runs were specified by Jorge Morfin. Energy weighted distributions of charged particles at the face of the Absorber could be made from the PAW [11] files produced by these runs.

Given below is the beam and target information extracted from the Adamo [12] GAF file for the medium energy horn configuration. The units are meters, GeV/c, and g/cm^3.

```
TI> tab/print all Beam
tab/print all Beam
 |-----------------------------------------------------------------------|
 | Table: Beam                                                 ADAMO/TAP |
 | Count:  1                                                             |
 | Page (   1,   1)                                                      |
 | Printed along:  ID [MINC,MAXC]                                        |
 |-----------------------------------------------------------------------|
 |ID  |x0          |y0          |z0          |sigx        |sigy        |
 |----|------------|------------|------------|------------|------------|
 |   1|0.000000E+00|0.000000E+00|-1.01000    |0.630000E-03|0.820000E-03|
 |-----------------------------------------------------------------------|
 |-----------------------------------------------------------------------|
 | Table: Beam                                                           |
 | Page (   2,   1)                                                      |
 |-----------------------------------------------------------------------|
 |ID  |maxx        |maxy        |dx          |dy          |sigdx       |
 |----|------------|------------|------------|------------|------------|
 |   1|0.200000E-02|0.225000E-02|0.000000E+00|0.000000E+00|0.480000E-04|
 |-----------------------------------------------------------------------|
```

[28] An earlier study of muons behind the Absorber was described in Reference [10].

```
|--------------------------------------------------------------|
| Table: Beam                                                  |
| Page (  3,  1)                                               |
|--------------------------------------------------------------|
|ID  |sigdy       |maxdx       |maxdy       |P           |
|----|------------|------------|------------|------------|
|   1|0.400000E-04|0.660000E-04|0.130000E-03| 120.000    |
|--------------------------------------------------------------|
```

The distributions are Gaussian in x,y,x angle, y angle, with cut-offs imposed on maximum x, maximum y, maximum x angle, and maximum y angle.

```
TI> tab/print all Target
tab/print all Target
 |-----------------------------------------------------------------------------|
 | Table: Target                                                     ADAMO/TAP |
 | Count:  1                                                                   |
 | Page (  1,  1)                                                              |
 | Printed along:  ID [MINC,MAXC]                                              |
 |-----------------------------------------------------------------------------|
 |ID  |x0          |y0          |z0          |dxdz        |dydz        |
 |----|------------|------------|------------|------------|------------|
 |   1|0.000000E+00|0.000000E+00|-1.00000    |0.000000E+00|0.000000E+00|
 |-----------------------------------------------------------------------------|
 |-----------------------------------------------------------------------------|
 | Table: Target                                                               |
 | Page (  2,  1)                                                              |
 |-----------------------------------------------------------------------------|
 |ID  |length      |radius      |A           |Z           |density     |
 |----|------------|------------|------------|------------|------------|
 |   1|0.940000    |0.200000E-02| 12.0100    | 6.00000    | 1.81000    |
 |-----------------------------------------------------------------------------|
 |-------------------------------------------|
 | Table: Target                             |
 | Page (  3,  1)                            |
 |-------------------------------------------|
 |ID  |RL          |GE|                       |
```

```
|----|------------|--|                       |
|   1| 23.5912    |18|                       |
|------------------------------------------|
```

This is a graphite target, with length 0.94 meters (1.97 interaction lengths, 4 radiation lengths).

Next I give the extract from the Adamo GAF file for the low-energy horn configuration.

```
TI> tab/print all Beam
tab/print all Beam
|-----------------------------------------------------------------------|
| Table: Beam                                                  ADAMO/TAP |
| Count:  1                                                              |
| Page (  1,  1)                                                         |
| Printed along:  ID [MINC,MAXC]                                         |
|-----------------------------------------------------------------------|
|ID  |x0          |y0          |z0          |sigx        |sigy        |
|----|------------|------------|------------|------------|------------|
|   1|0.000000E+00|0.000000E+00|-.100000E-01|0.630000E-03|0.820000E-03|
|-----------------------------------------------------------------------|
|-----------------------------------------------------------------------|
| Table: Beam                                                            |
| Page (  2,  1)                                                         |
|-----------------------------------------------------------------------|
|ID  |maxx        |maxy        |dx          |dy          |sigdx       |
|----|------------|------------|------------|------------|------------|
|   1|0.200000E-02|0.225000E-02|0.000000E+00|0.000000E+00|0.480000E-04|
|-----------------------------------------------------------------------|
|----------------------------------------------------------|
| Table: Beam                                               |
| Page (  3,  1)                                            |
|----------------------------------------------------------|
|ID  |sigdy       |maxdx       |maxdy       |P           |
|----|------------|------------|------------|------------|
|   1|0.400000E-04|0.420000E-04|0.840000E-04| 120.000    |
```

```
 |----------------------------------------------------------|


TI> tab/print all Target
tab/print all Target
 |-------------------------------------------------------------------------|
 | Table: Target                                                  ADAMO/TAP |
 | Count:  1                                                               |
 | Page (  1,  1)                                                          |
 | Printed along:  ID [MINC,MAXC]                                          |
 |-------------------------------------------------------------------------|
 |ID  |x0          |y0          |z0          |dxdz        |dydz        |
 |----|------------|------------|------------|------------|------------|
 |   1|0.000000E+00|0.000000E+00|0.000000E+00|0.000000E+00|0.000000E+00|
 |-------------------------------------------------------------------------|
 |-------------------------------------------------------------------------|
 | Table: Target                                                           |
 | Page (  2,  1)                                                          |
 |-------------------------------------------------------------------------|
 |ID  |length      |radius      |A           |Z           |density     |
 |----|------------|------------|------------|------------|------------|
 |   1|0.600000    |0.320000E-02| 9.01000    | 4.00000    | 1.85000    |
 |-------------------------------------------------------------------------|
 |---------------------------------------------|
 | Table: Target                               |
 | Page (  3,  1)                              |
 |---------------------------------------------|
 |ID  |RL          |GE|                        |
 |----|------------|--|                        |
 |   1| 35.2432    |18|                        |
 |---------------------------------------------|
```

This is a beryllium target of length 0.6 meters (1.48 interaction lengths, 1.7 radiation lengths).

Appendix E Ambiguities in the NuMI TDR

This appendix mentions some ambiguities seen while examining the Radiation Safety Chapter in version 1.0 of the NuMI Technical Design Report [4]. Values for average Star Density and Geometry Factor are found in Table 4-7 in the NuMI TDR; these are shown in the first three rows of local Table 4. The values shown for maximum Star Density in these first three rows were obtained by the formula $\frac{S_{avg}}{G}$. Four figures from the NuMI TDR have values for S_{avg} or S_{max}; these values are shown in the next four rows in local Table 4. The last row in the table is taken from Reference [3]. It isn't obvious how to reconcile the various values for S_{avg} or S_{max} shown in local Table 4.

Location in TDR	Region	S_{avg} $\left(\frac{stars}{cm^{-3}\, p^{-1}}\right)$	S_{max} $\left(\frac{stars}{cm^{-3}\, p^{-1}}\right)$	Commentary
Table 4-7	Target Hall	4.3×10^{-12}	6.1×10^{-11}	Geometry Factor 0.07
Table 4-7	Decay Region	7.1×10^{-12}	7.1×10^{-11}	Geometry Factor 0.10
Table 4-7	Beam Absorber	9.7×10^{-12}	6.1×10^{-11}	Geometry Factor 0.16
Fig. 4-6		$< 1.2 \times 10^{-11}$		
Fig. 4-9	Target Hall		1.8×10^{-10}	ME beam
Fig. 4-12	Decay Region	1.2×10^{-11}	9×10^{-11} (labeled Design Goal)	ME beam
Fig. 4-15	"	"	"	LE beam
TM-2009	Decay Region	2.5×10^{-12}	1.3×10^{-11}	from TM-2009

Table 4: Various values for Star Density from the NuMI TDR. The last row is taken from TM-2009, for comparison.

Table 4-7 in the NuMI TDR has a value for the Geometry Factor for the Beam Absorber that is greater than that for the Decay Region; this is hard to understand when one considers the arguments in TM-1851 [13] as to how the Geometry Factor should behave.

The caption of Figure 4-8 in the NuMI TDR refers to a factor of 3, but what is being compared?

Why are the axes of Figure 4-13 both linear, the axes of Figure 4.4 logarithmic in the ordinate and linear in the abscissa, yet a straight line fit is applied in both cases?