Phyiscal composition of the NuMI and G4NuMI Monte Carlo Hadron Absorber and Muon Monitor Alcoves

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Abstract

An accurate modelling of the physical characteristics of the NuMI Hadron Absorber and Muon Alcoves is essential for understanding muon monitor response. This document details the composition and geometry of the Hadron Absorber and Muon Alcoves as well as noting their representation in the Geant 4 NuMI Monte Carlo, G4NuMI.

1 Introduction

The Neutrinos at Main Injector (NuMI) beam is designed to be mainly composed of muon neutrinos from pion and kaon decays. To limit electron neutrinos that contaminate the NuMI beam there is a Hadron Absorber constructed of steel, aluminum and concrete in the beam line to prevent unwanted hadron decay. Because each pion and kaon decay that produces a muon neutrino is accompanied by a muon, the Hadron Absorber also serves as a beam stop for muons. While this is all superficially mundane there is physics that can be pulled from muons passing through a glob of stuff originally designed to stop hadrons before reaching downstream muon monitors.

Since each parent muon neutrino decay produces a muon, any information that can be gleamed from muon parent hadrons also applies to muon neutrino parent hadrons. There are three Muon Monitors that sit downstream of the NuMI target, Decay Pipe and Hadron Absorber that provide muon data. This data can be used in conjunction with a Monte Carlo simulation, G4NuMI, in order to get a better understanding of the parent hadrons. For any analysis of this kind to bear fruit the Monte Carlo must accurately represent the aspects of the NuMI beam line that may affect muon physics. It is therefore essential to establish the
geometry and composition of the physical elements of NuMI. The specific aspects of the NuMI beam-line that carry a huge importance for muon physics are the Hadron Absorber, Muon Monitors and rock between Muon Monitors.

The basics of the NuMI beam line is that it is located between the Main Injector at FNAL and the MINOS Near Detector. The heavily important Hadron Absorber fits into the equation in that it sits close to the downstream end of the NuMI beam line. The beam line starts with protons from the Main Injector incident on the NuMI target. The ensuing hadrons from the target are focused via two successive downstream parabolic magnetic horns. The most downstream horn is immediately followed by a ~700m long evacuated Decay Pipe. Both ends of the Decay Pipe are capped to provide a vacuum and immediately following the downstream end-cap is the Hadron Absorber Hall, see Fig. 1. The Absorber Hall houses the Pre-Absorber Shielding, Hadron Absorber and first Muon Monitor. Downstream of the Absorber Hall are two excavated Muon Monitor Alcoves separated by ~40' and ~60' of rock respectively, which house the second and third Muon Monitors.

![Figure 1: Overhead view of the Geant4 NuMI Monte Carlo Decay Pipe, Hadron Absorber and Muon Monitors. A - Decay pipe, B - Pre-Absorber Concrete Shielding, C - Hadron Absorber, D - Hadron Absorber Hall, E - Muon Alcove 1, F - Muon Alcove 2 and G - Muon Alcove 3.](image)

The following document serves as a reference guide to the measurements and composition of the NuMI Hadron Absorber and Muon Alcoves. Also included is information containing all physical quantities involved with the Muon Monitors which lie downstream of the Hadron Absorber. This document will serve as a stand alone source of information establishing all physical characteristics between the end of the NuMI Decay Pipe and the beginning of the MINOS Near Detector enclosure that may affect any muon physics. As such it will duplicate much of the information in the Technical Design Handbook[1], but will provide a complete picture of all inputs and geometries included in the Geant4 NuMI Monte Carlo, G4NuMI.
In the Geant4 Monte Carlo every item that is modeled is done so with unrealistically perfect precision. There is no undulation in width, height or depth. Placing an object 3.1416 inches away from another object means that the error in placement is subject only to computer precision. In reality the objects modeled and placed in the G4NuMI Monte Carlo have some variability in dimensions, placement and composition. Approximations are made in the Monte Carlo that accurately reflect the effect of the various variations that accompany inherent differences between a computer constructed NuMI beam line and the what is actually at Fermilab. These approximations are detailed in the following document and their anticipated effect on muon data is small.

2 Hadron Absorber

The Hadron Absorber is a roughly 18’ wide by 18.5’ tall by 28’ long\(^1\), box of assembled steel, concrete and aluminum that lies immediately downstream of the NuMI Decay Pipe in the excavated Absorber Hall\([1]\). The main purpose of the Hadron Absorber is to limit contamination from decays that would occur outside of the Decay Pipe. The Absorber itself is housed in an underground excavated hall 27’ x 20’ x 50’ and is composed of different sections:

- water cooled aluminum/steel core
- steel “BluBlock” core shielding
- concrete shielding
- gaps between blocks

The Core is the center of the Hadron Absorber and is surrounded by a steel (BluBlock) shielding layer. The Core/BluBlock innards are then surrounded with Concrete blocks that form an outer layer of the Hadron Absorber. On top of both concrete layer and BluBlock amalgam there is an additional layer of steel, which constitutes the topmost layer of the Absorber.

Since particle energy loss, specifically for muons, is highly dependent on the amount of material a particle travels through, the different gaps, blocks and material that makeup the Hadron Absorber will have different effects on data. In this regard a muon that passes through the aluminum/steel core of the Absorber will lose less energy than if it were to pass through the BluBlock core shielding. Muon Monitor data will therefore be an amalgam of muons passing through the different sections of the Hadron Absorber as well as some muons that pass through a mixture of sections. There is an associative ‘threshold’ for each Absorber section that

\(^1\)All measurements are given in relation to Beam View looking downstream.
denotes the minimum energy a muon must have to reach the different Muon Monitors i.e. a punch through energy. It is therefore necessary to do an exhaustive chase for documents, CAD drawings, design specs etc... because seemingly trivial construction or composition uncertainties could occur in a region of the Absorber that has a significant effect on data. A summary of the following sections 2.1 – 2.3 detailing what is known about the Hadron Absorber and establishing uncertainties for the unknown aspects from a material perspective can be found in section 2.4.

### 2.1 Hadron Absorber Core

The Core is a 51” x 51” x 15.6’ set of aluminum and steel blocks that is transversely centered on the neutrino beam, and partially centered vertically. The reason for the partial vertical centering is that the neutrino beam is angled 58 μrad downward, with respect to gravity, and therefore cuts through the Core at an angle. Since
Figure 3: The Hadron Absorber during installation. Looking upstream the three separate sections of the Absorber are plainly clear. The last steel block of the Absorber Core is the red square with the porcupine-esque water cooling pipes. The blue blocks (Duratek BluBlocks) surrounding the core comprise the steel surrounding Core shielding and lastly in gray are the partially installed concrete blocks. This assortment of blocks and sections comprise the entirety of the Hadron Absorber
the Core is set upon layers of stacked BluBlocks that form a base 52” high, the beam hits the vertical center of Absorber Core ~5’ downstream of its upstream edge.

The upstream edge of the Absorber Core starts 5’ 3” downstream of the middle of the Decay Pipe End-cap. The Core is composed upstream of 8 - 51” x 51” x 12” aluminum blocks, followed immediately downstream by 10 - 51” x 51” x 9.11” steel blocks, where both sets of blocks have water cooling pipes run lengthwise through their respective transverse edges, see Fig. 4 & 5. The cooling pipes are run through the Core in 1.5” diameter holes drilled lengthwise through the aluminum and steel blocks. The holes are drilled in a staggered pattern 5” and 2” in from the both transverse edges of the Core blocks[2]. The specific configuration and G4NuMI representation of the cooling pipes as well as the Core blocks will be dealt with in the following sections.

2.1.1 Aluminum Core Blocks

The aluminum Core Blocks are constructed of 6061-T6 aluminum. This is an industry standard heavy duty aluminum that conforms to the American Society for Testing and Materials (ASTM) specifications[3]. The 6061 alloy is ~98% aluminum by weight with trace elements of Si, Fe, Cu, Mn, Mg, Cr, Zn, Ti and a density of 2.70 g/cm$^3$. The T6 temper is characterized by high tensile strength which is achieved by heat treating and an artificial aging process.

The aluminum Core Blocks have the dimensions and tolerances of $51^\prime\prime$$\pm$$\frac{125}{-0} \times 51^\prime\prime$$\pm$$\frac{125/-0}{x} 12^\prime\prime$$\pm$$\frac{375/-0}{x}$. The fact that all the aluminum Core blocks fit onto the 52” wide carrier plate with enough room for small (5/8”) gaps on both the left and right side between the adjacent BluBlocks suggests that the aluminum block tolerances were cautious. Also, there was 5/8” thick steel slabs that were wedged into the 5/8” gap between the BluBlocks and the whole Absorber Core, which would further limit any significant deviation from 51” x 51” x 12” dimensions, see Fig. 6.

The Core Blocks have an assortment of 1.5” holes drilled lengthwise through the blocks to accommodate water cooling pipes, see Fig. 4. The first and most upstream aluminum block has only 4 holes drilled for 2 water cooling pipes on the left and another 2 on the right, both sets at the bottom of the block[4]. The second downstream aluminum block has an additional 2 cooling pipes on the left and 2 on the right that are situated 5.5” (2 x 2.75”) above the previous pipes. This vertical stagger continues until all 32 cooling lines are through the 8th and most downstream aluminum block.

There were other areas of the blocks where aluminum was also removed. To hoist the blocks there was a 2.25” hole transversely centered 48” from the bottom of the each block. During installation a pin was
Figure 4: The aluminum blocks of the Absorber Core during assembly. Clearly shown are the holes for the cooling pipes, the hole for the hoisting pin (center-top) as well as the removed section to aid threading the cooling pipes.

inserted into the hole and secured to a crane via a cable for lifting. The other cut-out area was removed to ease threading the cooling pipes through their accompanying holes. The two threading sections per block each measured 7.5” x 9.5” x 3.5” and were located at the two downstream transverse edges, centered between the two newly threaded water cooling pipes. The machined areas of absent aluminum are pictured in Fig. 5 and Fig. 4.

2.1.2 Steel Core Blocks

The steel that makes up the Absorber Core blocks is Continuous Cast Salvage (CCS) from US Steel - Gary Works. This is a grade of steel from the areas of the batches, or heats, where the steel does not conform to ASTM standards. This generally occurs at the beginning and end of the heat when the mixture is not properly uniform. The non-ASTM conforming steel is cut off and sold as CCS. The CCS steel in the Hadron Absorber is a less pure variant of ASTM-836 steel, but for all intensive purposes has the properties of ASTM-836 grade.
The composition of the steel is mainly iron (~98%+) with trace elements of Ni, Cu, $^{12}$C, Si and Mn.

Figure 5: The assembly of the Absorber Core is clearly seen in this picture. The entirety of the aluminum blocks is in place upstream, and the steel blocks are being threaded onto the cooling pipes and slid upstream to abut the downstream edge of the aluminum section.

Unlike the machined aluminum Core blocks the steel Core blocks were flame cut from ~10 slabs of CCS. The slabs were chosen for compositional consistency from nearly 88 heats, that all exhibited astonishingly similar densities of $7.8416 \text{ g/cm}^3 \pm .0004$. The flame cutting procedure resulted in slabs of 9.11” thick steel being cut into 10 blocks measuring 51”±.25 x 51”±.25 x 9.11”±.01. All 10 blocks have the full contingent of 32 water cooling lines and can be seen in the familiar staggered pattern in Fig. 5. It also has the exact same hole configuration for the hoisting pin as the aluminum blocks.

On top of the steel blocks is a plate of CCS steel that was not part of the original design. The extra steel reduces the amount of air that can be activated in the Absorber, which was a major source of concern during installation. It also helps reduce gaps that would allow unimpeded muon travel though the Absorber. The exact specifications of the plate are unknown, but close-ups of pictures(such as Fig. 6) and an installation newsletter published during installation suggest that the plate had dimensions 51”±.25 x 2”±.5 x 91.1”±1,
which exactly match the length of the steel Absorber Core blocks.

### 2.1.3 Gaps

In the construction of the Hadron Absorber there was a 5/8” gap between each side of the Absorber Core and the surrounding Steel Shielding BluBlocks. There is also an estimated 3” gap between the top of the aluminum blocks of the Absorber Core and the bottom of the steel plate above the Core. To mitigate the release of activated air and water, steel slabs were wedged into the side gaps from the downstream end to "plug" the hole, see Fig. 6.

No records were taken to place a limit on how far upstream these slabs were wedged, i.e. the length of the slabs. A picture taken during installation has shown that the minimum length upstream is 104”, and an upper bound can be established because the wedged steel cannot stick out of the 208” long Hadron Absorber. So all told this gives dimensions of the two wedged steel slabs as .625” x 51”±.125 x 108”±.125, which is exactly what is in the G4NuMI MC.

### 2.1.4 G4NuMI Absorber Core

In the G4NuMI Monte Carlo all 18 of the Absorber Core blocks are modeled individually. They are constructed and placed in the simulation according to the prescription in the previous paragraphs. To cut down on runtime but still maintain a physics accurate MC, the cooling pipes are modeled as rectangular boxes of decreased density aluminum/steel in each Absorber Core block. The left and right boxes in the steel Absorber blocks measure 4.5” x 42.75” x 9.11” which effectively outlines the cooling pipes and threading recesses. The steel Absorber Core blocks have the full contingent of cooling pipes which corresponds to ~ 14.7% of the Core block rectangular volume containing water. The change in density for the steel rectangular boxes, assuming the density of water is 1.0 g/cm$^3$, within each individual Core block is

$$7.8416 \text{ g/cm}^3 \times 0.853 + 1.0 \text{ g/cm}^3 \times 0.147 = 6.836 \text{g/cm}^3$$

The boxes, used as to approximate the effect of the machined aluminum areas, for the aluminum Core blocks measure 7.5” x 42.75” x 12” to include the volume covering cooling pipes and the threading recesses. The density decrease because of the recess is averaged across the box. Because the aluminum blocks only have half the full contingent of 32 water pipes in any average block, there is only ~ 4.4% water by volume.

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$^2$The similar 'gap' over the steel Absorber Core blocks is filled with a CCS slab of steel. See 2.1.2
in the rectangular boxes. The void space constitutes 6.5% of the box volume. The density for the aluminum recess boxes is then:

\[ 2.70 \text{ g/cm}^3 \times (1 - 0.044) + 1.0 \text{ g/cm}^3 \times 0.044 + 0.012 \text{ g/cm}^3 \times 0.065 = 2.45 \text{ g/cm}^3 \] (2)

Another approximation concerns the MINOS Absorber Helium box. The box is constructed of a \( \frac{1}{16} \)" thick aluminum skin filled with helium that sits between Hadron Monitor and the upstream edge of the Absorber Core. The purpose of the box is to reduce the amount of air that can get activated by the beam, but since it contains such a tiny amount of material this feature has not been included in the G4NuMI Monte Carlo.
2.2 Steel Shielding and Support

The Absorber Core is surrounded on the sides, above and below by 88 steel Duratek BluBlocks. All blocks provide containment for excess hadrons and the bottom BluBlocks also provide a base that doubles as a support to elevate the Absorber Core into the beam path. The upstream edge of every BluBlock layer is 1’ .75” upstream of the first aluminum block of the Absorber Core.

The blocks were cast by Duratek Inc. at the Oak Ridge National Laboratory in Tennessee from reclaimed steel and iron. The BluBlocks are nominally identified as being 52” x 52” x 26”, with 3 hoist mounts situated in each block which each measure 3”±.06 x 11.25”±.06 x 11.25”±.06[5]. The variable manufacturing procedure and non-uniformity of the ingredients resulted in BluBlocks with dimensions 52.27”±.17 x 25.97”±.11 x 52.34”±.24. The actual dimensions and a density of 7.25 g/cm$^3$±.16 were the average values and uncertainties from Oak Ridge Quality Control Checklists on 21 BluBlocks.

The inherent unevenness in every BluBlock is because the process of form casting the blocks is imprecise. While the average dimensional deviation is <0.25” there can be a .5” change in any single dimension from one end of the block to the opposite end. This undulation causes gaps at the vertical and horizontal abutment of stacked BluBlocks. Horizontal gaps were filled in with grout to maintain an even stacking surface for the next layer of BluBlocks. The vertical gaps were left open except at the outermost edges of the Absorber where they were filled with a small amount of Portland type III concrete to trap the activated air. The unevenness creates conduits for a muon to travel through, but the random nature of the unevenness as well as other geometrical effects reduce the impact of the conduits. The affect of horizontal planes is almost completely reduced and the vertical planes are largely minimized.

The horizontal gaps do not significantly affect any muon monitor data because of the downward beam angle. A muon would have to scatter off the front edge of the Absorber at exactly 58 µrad up at one of three horizontal planes to have an affect Muon Monitor data. Both horizontal and vertical planes will be minimized because the unevenness of the blocks is random and undulating. When the BluBlocks are stacked there is no clear conduit for a muon to travel through that completely lacks material, there are only paths that offer less material. In the event where there are maximally unrealistic .5” wide vertical gaps from uneven BluBlocks through the entire Absorber, the conduits affect <.005% of the muons that reach the ~2.2m x 2.2m Muon Monitors.

\[3\]The density takes into account the recesses of the BluBlocks where the hoist mounts are located.
2.2.1 Base

The Base section of the Hadron Absorber is constructed of a drip pan, 2 steel shims, 1 Absorber Core carrier plate and 48 BluBlocks arranged in 4 vertical layers of 12 BluBlock sections (3 blocks transverse to the beam and 4 longitudinal). To provide an even and non-undulating surface for the Absorber Core there are 5 steel plates welded into a 52”±.25 x 195.38”±.56 x 2”±.25 steel Absorber Core carrier plate that sits on top of the the 4th layer, middle row of blocks, right under the Core. To collect potentially activated runoff water, there is a small pan sandwiched between the second and third layer of the Base that spans the whole 12 BluBlock layer. Inside the pan and immediately under the left and right BluBlock sections of the base there are two slabs of CCS steel 52” x 208” x 3” that act as shims to match shielding block heights above the Core. All of these features, excluding the drip pan, are constructed and located in the G4NuMI MC with no approximations.

2.2.2 Sides

The shielding immediately adjacent to the Core is constructed of 16 BluBlocks that are rotated 90° so that the blocks are now stacked on the Base in such a way that their dimensions are 26” wide x 52” tall x 52” long. There are two, essentially tipped up, BluBlocks stacked side by side adjacent to the Absorber Core in real life as well as the G4NuMI. To complete the shielding coverage there are 3 more downstream sections on each side that in total run the full length of the Hadron Absorber (see fig.3).

2.2.3 Top

So as not to cause serious warping of the Absorber Core aluminum and steel blocks there is a 156” x 208” x 1” section of steel that constitutes the first layer above the Absorber Core. The 1” steel layer rests on the BluBlocks that are adjacent to the Core, i.e. the ‘Sides’. The 1” steel layer creates a 3” gap between the top of the aluminum blocks in the Core and the bottom of the steel sheet. The steel layer eliminates any major weight bearing, and therefore warping, on the Absorber Core, while allowing for another BluBlock layer to be stacked above the Core. The top section of the BluBlock shielding is then two more 3 x 4 layers (3 blocks transverse to the beam and 4 longitudinal) that rest upon the 1” steel plate. This arrangement of BluBlocks will be found in the actual Hadron Absorber as well as the G4NuMI simulated Hadron Absorber.

4It is best to think of the Hadron Absorber from the Core moving radially outward, instead of being built from the floor up. The Decay Pipe has a ~2m diameter and as such most of the physics processes occur radially out from the Core. Thinking from the beam center out lends itself better to visualization and physics intuition.

5The original design called for 3 layers above the Core, but due to the size of the Absorber Hall there was no vertical space available for another BluBlock layer.
2.2.4 G4NuMI BluBlocks

For the G4NuMI MC the entirety of the BluBlock shielding is modeled on a block by block basis i.e. there are no approximations that join 4 BluBlocks into 1 large mega-BluBlock. They are arranged and located according the prescription in the Base, Top and Sides sections.

The BluBlocks themselves are modeled as perfect 52’’ x 52’’ x 26’’ boxes, when in actuality there are small recesses for hoist mounts, which a careful examination of Fig. 3 will reveal\(^6\). The muon interaction in the BluBlocks hoist mount region is limited since the blocks were stacked to minimize recess overlap from the Beam View. The recesses measure 11.25’’ x 11.25’’ x 3’’. Worst case scenario has a straight non-scattering muon traveling lengthwise through 4 recesses (2 lined up in the Beam View per block) or 22.5’’ out of 208’’ total(\(\sim 11\%\)). Since the muon monitors are \(\sim 2.2m \times 2.2m\) in area, the \(\sim 11\%\) change in density affects \(<.005\%\) of the data. The overall effect is \(<.0001\%\) for the total number of muons seen in the muon monitors, making this a negligible effect.

2.3 Concrete Shielding

The Concrete Shielding was designed for radioactive shielding and not hadron absorption. Even so, the concrete contributes, however trivially, to the energy loss of muons as they move downstream, and is therefore modeled in the G4NuMI Monte Carlo. The shielding is made up of a two different sections: the Pre-Absorber shielding surrounding the Decay Pipe End-Cap and its extension to surround the BluBlock Shielding of the Absorber Core.

2.3.1 Pre-Absorber Concrete Shielding

The End-Cap Concrete Shielding (see Fig.7) is similar to the Hadron Absorber BluBlock assembly in that it can be thought of as 3 different sections; a base, adjacent sides and a top section. Each section consists of and is modeled as a number of interlocking blocks. The base section measures 16.5’ wide x 3’ tall x 6’ long which is centered horizontally on the NuMI beam and rests on the floor of the cavern[6]. The two side concrete shielding sections sit at the transverse edges of the base and measure 4.5’ x 7.5’ x 6’. The top section is also horizontally centered on the beam spans the gap above the Decay Pipe End Cap while resting being supported by the two side concrete shielding sections. The top section measures 12’ x 3’ x 6’ \(^7\). On the very top of the

\(^6\)Exclusion of the 3 hoist mounts is accompanied by a shift in the G4NuMI density of the BluBlocks. This decreases the overall density by an insignificant \(0.0038\%\).

\(^7\)The whole End Cap Concrete Shielding downstream edge sits flush against the upstream edge of the BluBlock assembly of the Hadron Absorber. Therefore the upstream edge of the BluBlock assembly matches the upstream edge of the Absorber Concrete Shielding.
concrete shielding sits steel shielding layer, measuring 12’ x 3’ x 18.22”. The pre-absorber concrete shielding is modeled as the individual blocks surrounding the Decay Pipe. This section has little to no physics relevance to muons but was still modeled as accurately as possible.

2.3.2 Hadron Absorber Concrete Shielding

The Concrete Shielding that surrounds the Absorber Core and the BluBlock assembly is composed of 3’±.125” x 7.5’±.25” x 3”±.125” concrete blocks laced with type 8 rebar reinforcements \[7\]. In order for the tensile strength of the blocks to hold under stress a rebar cage was produced into which concrete was poured to construct the blocks. The concrete is 4000 psi grade and around the edges of the blocks there is another layer of steel to prevent chipping and bulging during stacking. The concrete combined with the rebar gives a density of 2.61 g/cm\(^3\)±.013\[8\]. There are two small hoist mounts 5”±.125 x 15”±.125 x 7”±.125 located in the center of one of the sides and end that are used for the crane.

The concrete blocks are stacked two high and the upstream most column of blocks sit flush against both the downstream edge of the End-Cap Concrete Shielding and the upstream edge of the BluBlock assembly. The two high concrete blocks are then set in a row, 3” away from the outside edges of the BluBlock assembly to the tune of 7 columns of blocks on the right edge looking downstream and 6 on the left edge (see Fig.3). The
cause for a difference between right and left is because the water cooling pipes that run through the Absorber Core exit through a gap at the left downstream edge of the Concrete Shielding. There is another row of twin concrete block towers that span the back edge of the BluBlock assembly that begin 226” downstream of the upstream edge of the BluBlock assembly[6].

There is a gap of 18” between the downstream edge of the BluBlock assembly and the upstream edge of the back plane of concrete blocks and this allows room for the water cooling pipes to exit the Core and bend left to get to the recycler. There is a plywood box filled with polystyrene beads that occupies the space where the ‘missing’ 7th concrete block tower on the downstream left edge would be situated. The gap allows the cooling pipes to pass through the wooden box to the cooling recycler, but also blocks the escape of activated air.

The G4NuMI representation of the concrete shielding blocks surrounding the Hadron Absorber are large composite blocks of concrete. Instead of 14 (2 x 7) blocks on the downstream right side of the Absorber there is one large 3’ x 15’ x 21’ block. The hoist mounts provide no sizeable change in material that a muon may pass through and are therefore not included in the composite blocks. The low density and reduced material vs. aluminum or steel make the concrete sections insignificant from a muon energy loss perspective and makes any approximation within reason valid.

2.3.3 18.22” Steel Shielding

In the initial design of the Hadron Absorber there was a 3’ layer of concrete that was to be layered on top of the Hadron Absorber to satisfy groundwater shielding requirements. The intended concrete layer on top of the BluBlocks had to be replaced in the design with ~18” of steel because of height restrictions of the Absorber Hall. The swap of steel for concrete manifests itself as a 18.22” layer of the ASTM 836 CCS variant steel situated on the top most BluBlock layer. This steel layer of the Absorber was constructed of various sized plates of steel each with a height of 9.11”. These plates were stacked two high for a total assembled dimension of 156”±1.22 x 18.22”±.014 x 208”±1.41, which covers the whole top BluBlock layer[9][10].

There is another 18.22” layer of twin stacked steel plates that wraps around the Absorber and rests on the stacked concrete columns (sec 2.3.2). The individual steel plates on these side layers are 9.11” tall and 30” wide, with various lengths in order to stack neatly next to the Absorber to the tune of 208”. The layer on both transverse sides of the Absorber has a total dimension of 30”±.70 x 18.22”±.014 x 208”. The 18.22” layer of steel along the back of the Absorber is slightly different than the side layers.

In order to have the rear layer abut the downstream edge of the BluBlock layer a small ledge was welded
onto the BluBlocks to support the 30” long steel plates over the ~18” air gap that exists between the downstream edge of the Absorber and upstream edge of the concrete shielding layer. The layer is constructed of individual plates stacked two in length (2 x 30”) and two in height (2 x 9.11”) with varying width to match the 156” width of the Absorber. In total the back steel layer of the Absorber constitutes a dimension of 156”±1.21 x 18.22”±.014 x 60”±.50. The length of 60” sticking of the back of the Absorber causes a 10” ledge to extend off the downstream edge of the twin stacked concrete blocks.

While the 18.22” steel layer is made of smaller sized steel plates, the G4NuMI Monte Carlo has the layer as large and uniform steel solids. The top layer measures 156” x 18.22” x 208”, each side layer measures 30” x 18.22” x 208” and the rear layer measures 156” x 18.22” x 60”.

2.3.4 30” Steel Shielding

To provide coverage over cracks surrounding the 18.22” layer(sec 2.3.3) as well as extra shielding, there were 30” tall by twin stacked 9.11” wide plates incorporated into the shielding on top of the Absorber. The 30” steel section wrapped around the BluBlock inner section of Absorber and was situated above the twin stacked concrete blocks, resting on the side 18.22” sections. This occurred down the 208’ length of both sides of the Absorber as well as the 192.44” (156” + 2 x 18.22”) width at the downstream end. In contrast, the upstream edge of Absorber was devoid of any additional steel cradling the BluBlock innards, because there was already a layer of steel on top of the Pre-Absorber Concrete Shielding (sec 2.3.1) that fit snug against the topmost BluBlock layer.

The G4NuMI representation of the amalgam of blocks that constitute the 30” layer is similar to that of the 18.22” steel layer. The side blocks that sit on the 18.22” layer measure 18.22” x 30” x 208” while the back layer measures 192.44” x 30” x 18.22”.

2.4 Hadron Absorber Uncertainties

The previous sections detailing the intricate makeup of the Hadron Absorber all produce dimensions, densities and their corresponding uncertainties. These values can be compiled into a table that offer the salient contributions to muon energy loss through the Absorber. Length and density are the most important values because a muon’s path, and hence energy loss, is mostly affected by the material parallel (length) to the muon’s direction, and not perpendicular (width, height), i.e. a muon’s path is seldom affected by material it does not encounter.

Convolving all the uncertainties in dimensions and density from the separate pieces that comprise the
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<tr>
<td>Steel slab in gap (2)</td>
<td>7.8416</td>
<td>.0004</td>
<td>108</td>
<td>.25</td>
</tr>
<tr>
<td>Concrete Shielding</td>
<td>2.61</td>
<td>.013</td>
<td>36</td>
<td>.125</td>
</tr>
<tr>
<td>18.22” steel layer (sides)</td>
<td>7.8416</td>
<td>.0004</td>
<td>208</td>
<td>.5</td>
</tr>
<tr>
<td>18.22” steel layer (downstream)</td>
<td>7.8416</td>
<td>.0004</td>
<td>60</td>
<td>.18</td>
</tr>
<tr>
<td>30” steel layer (sides)</td>
<td>7.8416</td>
<td>.0004</td>
<td>208</td>
<td>.5</td>
</tr>
<tr>
<td>30” steel layer (downstream)</td>
<td>7.8416</td>
<td>.0004</td>
<td>18.22</td>
<td>.014</td>
</tr>
</tbody>
</table>

Table 1: Table of dimensions, densities and uncertainties for the constituent pieces of the Hadron Absorber. The 18.22” and 30” Steel Layers are considered in their entirety, not piecewise, in the previous table because many pieces in the layer are unique in dimensions in order to stack neatly.

Hadron Absorber can be done with an annuli approximation. The concept of a three dimensional Hadron Absorber is now reduced to a two dimensional representation, which aids in establishing the effect of the different densities, dimensions and uncertainties of the Hadron Absorber. From the Beam View the Hadron Absorber can be broken down into 4 separate areas:

- Cooling Pipe annuli: Water cooling pipe sections of the Absorber Core(averaged over size and density of aluminum and steel rectangular boxes)
- Core annuli: Absorber Core (excluding the cooling pipes)
- Gap annuli: Gaps between the Absorber Core and BluBlock shielding, steel slab resting on steel Absorber blocks and Carrier Plate
- BluBlock annuli: BluBlock shielding and 1” steel resting plate above Absorber Core

The move from a three dimensional Hadron Absorber to a two dimensional representation neatly parameterizes the contributions of separate areas. The amount of material, and corresponding uncertainty, in the Absorber is now a product of area. Also to explore the effects of uncertainty in the width and height of the various blocks, it is now sufficient to either expand or contract the size of the Gaps annuli. The laborious alternative is to increase/decrease the surface area of each block.

The annuli representation allows for a new spread of values that inclusively gives the amount of material in the Hadron Absorber. Table 2 is useful in illustrating that the amount of material in the Hadron Absorber is known to $<3\%$.

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$^8$These 4 sections apply to the ‘cross-section’ or area that is covered by the Muon Monitors. The muons that interact with monitors are never directly affected by the 18.22” or 30” steel layers, and are therefore dutifully neglected in the Annuli approach

$^9$This takes into consideration the uncertainty stemming from the single concrete layer of concrete blocks at the downstream end of the Absorber which cover 100% of the muon monitor area
Figure 8: A qualitative representation of the four different ‘annuli’ that make up the Hadron Absorber. The outline is defined by the 2.2m x 2.2m surface area of the muon monitors. This gives an idea of the material between the end of the Decay Pipe and the downstream muon monitors. The light grey represents the BluBlock shielding. The solid black represents the Gaps Area. The hatched area denotes Core area (both steel and aluminum blocks). The circle area represents the cooling pipes.

<table>
<thead>
<tr>
<th>Annuli</th>
<th>Material (g/cm²)</th>
<th>uncertainty (g/cm²)</th>
<th>% of Muon Monitor Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td>2466</td>
<td>10.43</td>
<td>27.83</td>
</tr>
<tr>
<td>Water pipes</td>
<td>2175</td>
<td>9.68</td>
<td>6.84</td>
</tr>
<tr>
<td>Gaps</td>
<td>2676</td>
<td>415</td>
<td>3.45</td>
</tr>
<tr>
<td>BluBlock</td>
<td>3858</td>
<td>94.17</td>
<td>61.88</td>
</tr>
</tbody>
</table>

Table 2: This table represent the amount of material for each annuli in g/cm². The uncertainty is a linear combination of both the density and length uncertainty. The last column provides the percentage of the muon monitors area that the different annuli cover. In other words this the percentage of muon monitor data that will be affected by the Absorber annuli.

3 Muon Alcoves and the Rock

There are 3 muon alcoves downstream of the Hadron Absorber, see Fig. 1. Each serve as an excavated area for the construction of the muon monitors, which rest in the middle of each alcove, each centered to within ~1 cm of the beam center[11]. The first muon alcove is situated at the end of the Absorber Hall where there is no rock between the Alcove and the Hadron Absorber. The two other Alcoves sit further downstream where there is rock between alcoves 1 & 2 as well alcoves 2 & 3. As well as rock there is also a civil construction and reinforcing ‘lining’ of sprayed concrete, known as shotcrete, that was applied to the walls and ceiling post rock excavation. To further understand physics affects on muons that interact with the Muon Monitors, the detailed work of establishing all material between the Alcoves hinged on a thorough knowledge of five topics:
- Survey points establishing Alcove wall location
- Rock Composition
- Rock Density
- Shotcrete Composition
- Shotcrete Density

Round numbers put ~40’ of rock between alcoves 1 & 2 and a further ~60’ between alcoves 2 & 3 and a large uncertainty or variation in the rock density over such a large region would spell disaster for using the muon monitors for any physics analysis.

### 3.1 Alcoves

The dimensions of the Muon Alcoves were established from survey points taken of the walls, floors and ceilings of the Alcoves. This was a necessary procedure because the walls of all the caverns are undulating due to the excavation process of blasting, drilling and then layering with with Shotcrete, which introduces a void space uncertainty. Thankfully, the width and height of the alcoves are relatively unimportant for the Monte Carlo because these dimensions wholly encompass the beam while it passes through the rock. The location of the upstream/downstream walls on the other hand determines how much rock is located between each monitor.

Muon Alcoves 2 and 3 are nominally 12’ x 12’ x 9’10” while the first Muon Alcove is 12’ x 14’8” x 9’9”. In reality every excavated area was contracted to be ‘void space’ compliant i.e. drill, dynamite, chisel, bite etc... past the required dimensions and then fill in with cement material to within some distance of a ‘neat line’. Muon alcove 1 was over-excavated in length and had to be ‘backfilled’ with 4000 psi concrete, instead of the customary 3-5” layer of Shotcrete. This produced a void space length of 9.75’±.05 for Muon Alcove 1, 9.95’±.45 for Muon Alcove 2 and 10.18’±.34 for Muon Alcove 3. From these numbers the amount of rock between the Alcoves can be derived.

<table>
<thead>
<tr>
<th>Location</th>
<th>Length (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alcove 1 - Alcove 2</td>
<td>39.45±.09</td>
</tr>
<tr>
<td>Alcove 2 - Alcove 3</td>
<td>59.24±.54</td>
</tr>
</tbody>
</table>

Table 3: This table represents the length of rock and Shotcrete that exists between the Muon Alcoves.

Because the Muon Alcoves were designed to be situated in the middle of the NuMI beam they do not all sit at the same horizontal depth. The floors of Alcoves 1 and 2 are level with the Absorber Hall while the Muon Alcove 3 floor is 4’ deeper. Since the beam passes through the middle of the alcoves the relative depth...
is generally unimportant because a vertical offset of 1’ would not change the amount of material in the beam line.

The size of the three separate Muon Alcoves are all modeled as perfect boxes in the G4NuMI Monte Carlo. The first Muon Alcove is 12’ x 14’8” x 9.75’, Alcove two is 12’ x 12’ x 9.95’ and Alcove three measures 8” x 10.18’. The muon monitors that reside in the Muon Alcoves are modeled as 2.2m x 2.2m perfectly active detector elements. From survey points and data analysis the monitors are centered on the beam to within 2cm, and so they are perfectly centered on the beam in the MC.

3.2 Rock Composition

The rock between Muon Alcove 1 and the downstream Muon Alcoves 2 & 3 is all in the Maquoketa group - Brainerd Formation geological strata. The Brainerd Formation is a 100’ vertical formation of mainly Shale, Dolomite and Siltstone. It is situated ~450’-550’ above sea level or ~190’-290’ below the surface at the location of the Muon Alcoves. From top to bottom the formation has the approximate compositional breakdown:[12]

- 0 - 5’ Dolomite
- 5’ - 22’ Dolomite : with small amounts of Chert( ~5%)
- 22’ - 52’ Dolomite and Shale : Argillaceous, Calcite, Pyrite(<5%)
- 52’ - 72’ Sandy Dolomite
- 72’ - 87’ Mudstone/Siltstone
- 87’ - 100’ Sandy Dolomite : Argillaceous, Calcite (<5%)

The chemical formulas for the differing rock types are:[12]

- Dolomite - CaMg(CO₃)₂
- Chert - SiO₂
- Maquoketa Shale - K₀.₆(H₂O)₀.₄Al₁₃Mg₀.₃Fe²⁺₀.₁Si₅.₅O₁₀(OH)₂₋·(H₂O) [13]
- Calcite - CaCO₃
- Pyrite - FeS₂
- Sandy - Dolomite with ~ 5% SiO₂
3.3 Rock Density

The density of the rock between the Muon Alcoves will have a direct effect on the energy loss of muons as they travel downstream from the Hadron Absorber. Thankfully the vertical drop from Alcove 1 to Alcove 3 is 10.34’ and therefore all 3 muon alcoves sit in the vertical range of 280’-290’. This specific section of the Brainerd Formation is fairly uniform, and has a dry density of 2.79 g/cm$^3$ ± .04. The density measurements come from 6 rock samples from a core sample that was drilled ~ 150’ from the NuMI beam-line that were sent to a geological testing lab for results. The samples were evenly distributed throughout the 280’-290’ range, see Fig. 9.

![Figure 9: Overhead view of a variety of bore-hole sites at FNAL. The core samples used to determine the density of the 10’ vertical region in which the muon alcoves reside is S1271.](image)

There were other sources available for establishing the density in the Brainerd Formation; the NuMI Geotechnical Baseline Report[14], Fermilab Geotechnical reviews for the SSC[15] and a geophysical log using a density probe dropped down the S-1215 bore-hole[16]. The two GeoTechnical reviews were inadequate because the requisite density precision is greater than .1 g/cm$^3$ and neither review had density values with greater precision than .1 g/cm$^3$. The geophysical log while initially promising because of greater precision succumbed to the problem of an undocumented testing procedure, i.e. there are two different kinds of probes.
that could have been used. One probe has a continuous calibrating process that provides accurate density, whereas the other probe provides data which must be calibrated off-line.

Even though the data from the density probe was unreliable for establishing an absolute value it was very useful for categorizing the relative density changes. The probe made continuous measurements of density, resistivity, temperature etc... which can all be used to finely monitor the vertical changes in rock type and density. All the data remain very consistent over the 280’-290’ vertical region of the muon monitors. The density fluctuates mildly $0.05-0.1 \text{ g/cm}^3$ in a random noise fashion around an uncalibrated mean of $\sim 2.4 \text{ g/cm}^3$. This is strong support that absolute density measurements from a nearby bore hole will provide an accurate representation of the rock characteristics between the muon alcoves.

4 Summary

The first step towards using MINOS/NuMI data for a comparison to Monte Carlo data is a physically accurate simulation. The need for a high level of precision for the Hadron Absorber and the Muon Alcoves stems from their particularly large effect on muon momentum. To this effect scouring vendor quotes, engineering drafts, data from lab samples sent for testing etc... has provided the necessary information for a functionally accurate Monte Carlo.

References


