LBNF HADRON ABSORBER: MECHANICAL DESIGN AND ANALYSIS FOR 2.4 MW OPERATION*

B. Hartsell†, K. Anderson, J. Hylen, V. Sidorov, S. Tariq, FNAL, Batavia, IL 60510, USA

Abstract

Fermilab's Long-Baseline Neutrino Facility (LBNF) requires an absorber, essentially a large beam dump consisting of actively cooled aluminum and steel blocks, at the end of the decay pipe to stop leftover beam particles and provide radiation protection to people and groundwater. At LBNF's final beam power of 2.4 MW and assuming the worst case condition of a 204 m long helium filled decay pipe, the absorber is required to handle a heat load of about 750 kW. This results in significant thermal management challenges which have been mitigated by the addition of an aluminum 'spoiler' and 'sculpting' the central portion of the aluminum core blocks. These thermal effects induce structural stresses which can lead to fatigue and creep considerations. Various accident conditions are considered and safety systems are planned to monitor operation and any accident pulses. Results from these thermal and structural analyses will be presented as well as the mechanical design of the absorber. The design allows each of the core blocks to be remotely removed and replaced if necessary. A shielded remote handling structure is incorporated to hold the hadron monitor when it is removed from the beam.

DESIGN OVERVIEW

The absorber consists of two major sections, as shown in the left image of Figure 1. The core, a section consisting of replaceable water-cooled blocks, is shown inside the green box. It is enlarged in the right image of Figure 1. The core consists of an aluminum spoiler block to initiate the particle shower, five aluminum mask blocks with air space in the center to allow the shower to spread, nine sculpted aluminum blocks of reduced central density to further distribute the heat load, four solid aluminum blocks, and four solid A36 steel blocks. All aluminum in the core is 6061-T6. The beam power deposited into the core during 2.4 MW operation is approximately 520 kW, which is the majority of the incoming beam power into the absorber. Outside of the core is forced-air cooled steel and concrete shielding.

ANALYSIS

Using MARS15 [1] energy deposition results as a basis for heat load on the absorber and its core blocks, many iterative simulations between MARS and ANSYS have been carried out to determine the final configuration of the absorber. The main driver of this optimization is reduction of temperature and stress to acceptable levels for the materials during both normal operation and accident scenarios. Creep and fatigue effects have been considered when applicable.

Aluminum core blocks are all water cooled via four 1 inch diameter gun-drilled channels in the aluminum with 20 gallons per minute (gpm) volumetric flow rate through each channel. The water will be cooled to 10°C to help reduce steady state temperatures. Steel blocks are cooled via two 1 inch diameter stainless steel lines along the perimeter of the block with 20 gpm flow rate each.

Steady State Operation

Steady state temperatures and stresses were evaluated at the locations shown in Table 1 for both 120 GeV and 60 GeV operation. 120 GeV operation is by far the worst case due to the lower amount of beam scattering and higher overall beam power compared to 60 GeV operation. Further analysis shown will focus only on 120 GeV operation.

Table 1: Maximum Temperature and Von-Mises Stress for Steady State Operation

Location	Temperature (°C)	Von-Mises Stress (MPa)
Spoiler	60	34
Mask Block 1	25	-
Sculpt Al 3, Ctr	88	103
Sculpt Al 3, WL	25	74
Solid Al 2	84	48
Steel 1	225	199

Creep must be considered since the aluminum is being held at an elevated temperature under stress – 103 MPa at 88°C in the worst case. Creep data for 6061-T6 aluminum bus conductors [2] shows an average stress required to produce 1% creep at 100°C for 10 years to be 172 MPa. Other data [3] indicates the stress values are well below the 250 MPa needed to produce even 0.1% creep at 100°C, although this data only extends to 1000 hours.

A possible concern is losing the T6 temper of the aluminum due to elevated temperature for an extended period of time. After 100,000 hours (11.2 years) at 100°C, there is no change to tensile strength, yield strength, elastic modulus, or elongation [3].

Another consideration is the effect of a failed water line. In the case of the 3rd sculpted aluminum block, the downstream end of the block has a larger energy deposition than the upstream side. For this analysis, convection in the downstream inner water line is removed and the analysis is re-run. Maximum temperature and Von-Mises stress reach 109°C and 174 MPa respectively. At this temperature and stress level, the block would be at least temporarily operable while

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† hartsell@fnal.gov

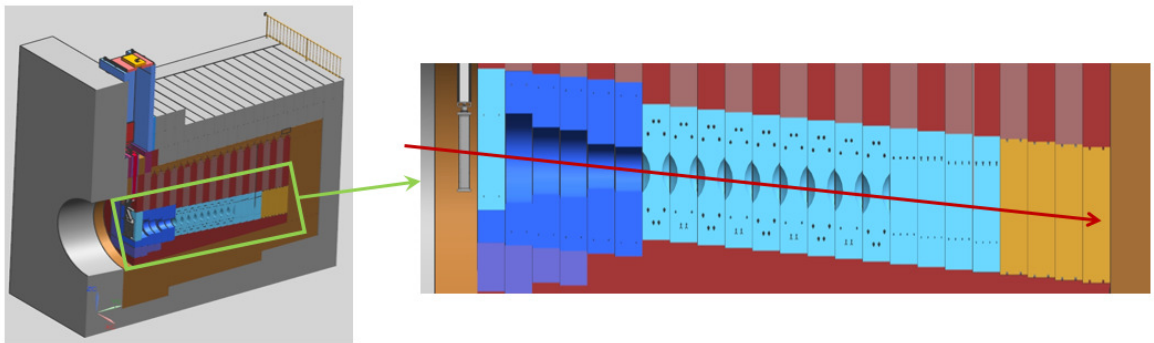

Figure 1: Left, cross section of absorber through beam axis and the core shown in the green box. Right, cross section of absorber core with red arrow indicating the central axis of the beam.

a replacement is fabricated, and could possibly be run longer if necessary.

To assess temperatures of the steel shielding surrounding the core, a simplified model of the absorber shielding was constructed using 34 steel blocks at 9.11 inch thick each, with dimensions of 6 m wide and 6 m tall. The blocks are spaced 5 mm apart, and 11.8 m^3/sec (25,000 cfm) of air passes through these gaps. With these parameters, the pressure drop through the 5 mm gaps is approximately 2490 Pa gauge. To model temperatures, an axisymmetric version of this model is implemented in ANSYS with convective cooling and MARS generated loads are applied. After accounting for temperature rise of the air, the maximum steel temperature is about 130°C.

Accident Conditions

The absorber must be able to handle, without loss of function or damage, an accident condition where two pulses of the full proton beam do not hit the baffle or target and travels down the decay pipe. Two accident scenarios were considered, shown in Figure 2. First, an on-axis accident, in which the beam travels down the center of the absorber and strikes the region that already has the highest temperature and largest stress from normal operation. Second, an off-axis accident where the beam strikes the absorber offset from the on-axis accident and passes directly through the water lines, where the water-line geometry might induce stress-risers and where one does not have the shower-spreading advantage of the central sculpting region.

In the on-axis accident case, temperatures and stresses were simulated for the spoiler, 2nd sculpted Al block, 2nd solid Al block, and 1st steel block. Results from these simulations are summarized in Table 2. For a point of reference, the yield strength of 6061-T6 aluminum at 150°C is 190 MPa. All of the aluminum stress values are below this. The thermal portion of the model was also run out to 10 pulses to determine if any melting would occur. Maximum temperature after 10 pulses occurred in the spoiler. It reaches about 270°C, which is well below the melting point of 660°C.

The off-axis accident case was modeled for sculpted Al block 2, where the peak energy deposition occurs. Water in the line and the energy deposition into it are included in

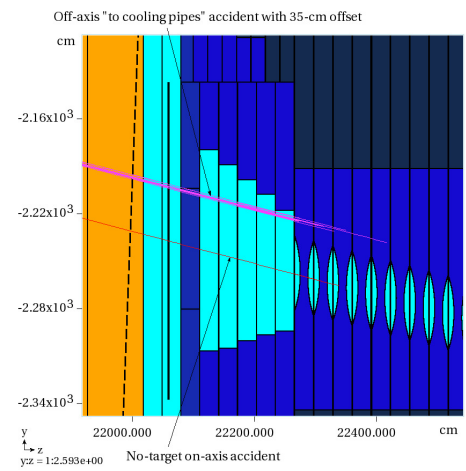

Figure 2: Locations for accident conditions.

Table 2: Maximum Temperature and Stress After Two On-axis Accident Pulses

Location	Temperature (°C)	Von-Mises Stress (MPa)
Spoiler	146	121
Sculpt Al 2	140	148
2nd Full Al	120	63
1st Steel	242	199

this model. After two pulses, the maximum temperature reaches 170°C as shown in Figure 3. At this temperature, a possible concern is a localized loss of the T6 temper. Tensile data at elevated temperature [3] shows no change in 6061-T6 mechanical properties after 0.5 hours at 177°C.

The induced stress exceeds the yield point of 6061-T6 aluminum after a single pulse, and a temperature dependent bilinear kinematic plasticity model was introduced to determine plastic strain. The maximum plastic strain achieved after two pulses is 0.7% while the plastic strain to failure for 6061-T6 aluminum is 16%. The volume of material with permanent deformation is very small.

When beam strikes a water line, the induced water pressure spike from the thermal expansion of water must be

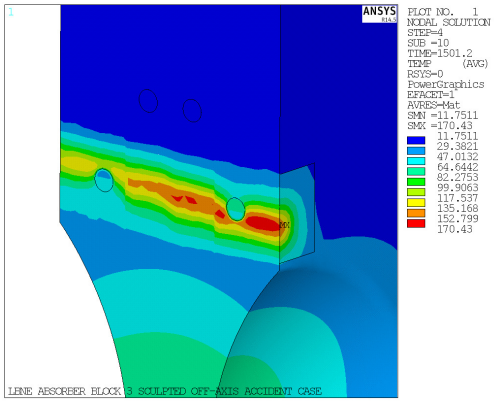

Figure 3: Temperature (°C) after two off-axis accident pulses.

considered. A simplified model was constructed to examine this effect. The maximum pressure achieved is 1.7 MPa. This pressure spike would most likely be attenuated by any gas in the system and the 90 degree bends formed by the gun drilled cooling channels, but still must be considered when constructing the water piping system and its joints.

MECHANICAL DESIGN

The mechanical design of the absorber is based off the proven design of the NuMI target hall, utilizing remotely handled T-blocks to support the core. These T-blocks are supported by the steel shielding, and are fully encapsulated by steel and concrete shielding for radiation protection. The T-Blocks are removable via an overhead crane with a lifting fixture attached. Components that have failed can be stored in morgues integrated into the absorber design.

Water cooling of the aluminum core blocks is achieved by gun-drilling intersecting holes for water to flow through and plugging the remainder of the hole that is not needed, as shown in Figure 4. Aluminum pipes are then welded to the entry and exit ports of the gun-drilled water channel and routed up the T-Block to make connections with a manifold, which is then connected to a header leading to the radioactive water (RAW) room. There are 23 core blocks that require water cooling, with each of the aluminum blocks requiring 80 gpm of total flow. The steel core blocks require 40 gpm each. With the addition of 80 gpm for filtration purposes, the water system flow rate is estimated to be 1760 gpm with a total volume of 1810 gallons. Additional optimizations to the core are planned to reduce this required system flow rate.

Active temperature monitoring of select core blocks will be necessary to determine if any accident pulses arrive at the absorber and to aid in beam and target diagnostics. A design for a thermocouple array in a solid Al block is designed with thermocouples spaced to allow the detection of an accident pulse. These thermocouples fit in removable bars that slide in T-slots on the T-block and core block to allow easy access for replacement as necessary. Jack screws are implemented on both sides of the bar to facilitate removal.

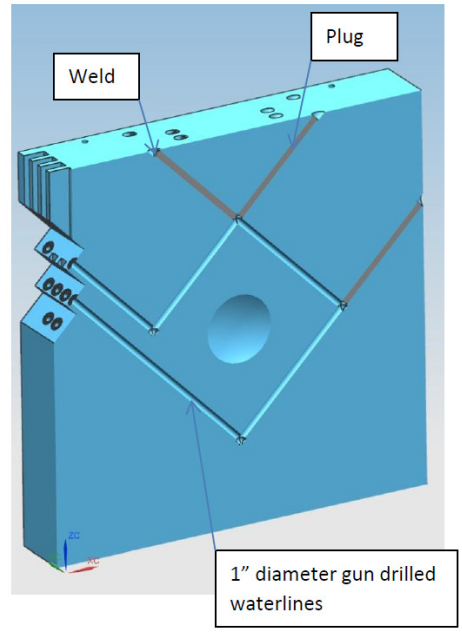

Figure 4: Gun-drilled water channels for cooling in an aluminum core block.

The absorber design incorporates three different sized morgues to accommodate failed radioactive core blocks and hadron monitors. The most upstream is the mask morgue and can accept a total of two mask or spoiler blocks. Next is the core block morgue and it can accept a total of two sculpted Al blocks, full Al blocks, or steel blocks. The hadron monitor morgue is sized for three hadron monitors. All morgues are covered with concrete shielding blocks.

An integrated remote handling facility for the hadron monitor is also included in the design. The facility is shown as the blue tower in the left image of Figure 1. The hadron monitor can be remotely inserted and removed from the beam and stored in the tower while not in use. The facility also aids in the replacement of the hadron monitor.

ACKNOWLEDGMENTS

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