LBNF Hadron Absorber Final Design Review – Review Introduction & Mechanical Overview

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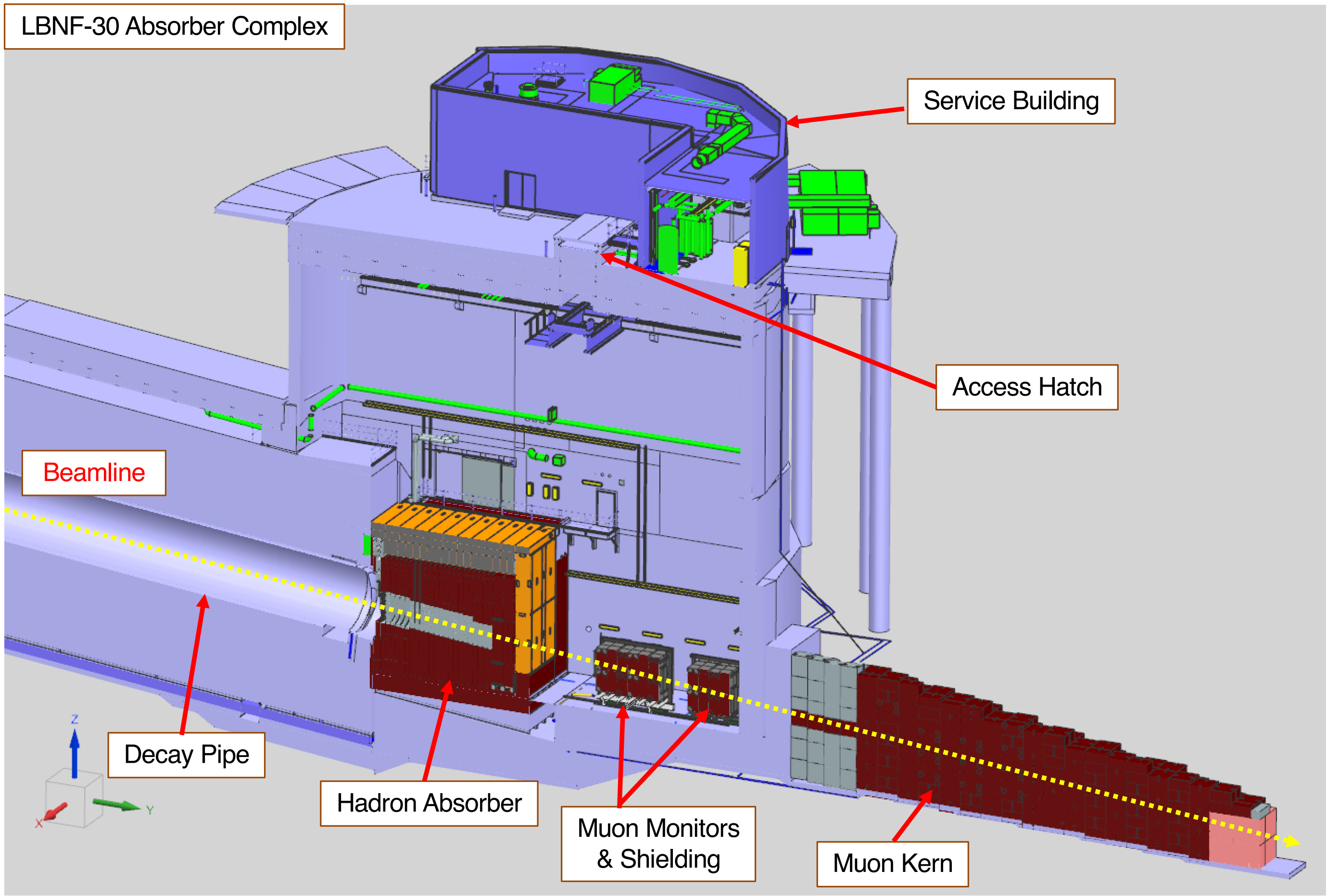
LBNF Absorber Final Design Review

18 December 2024

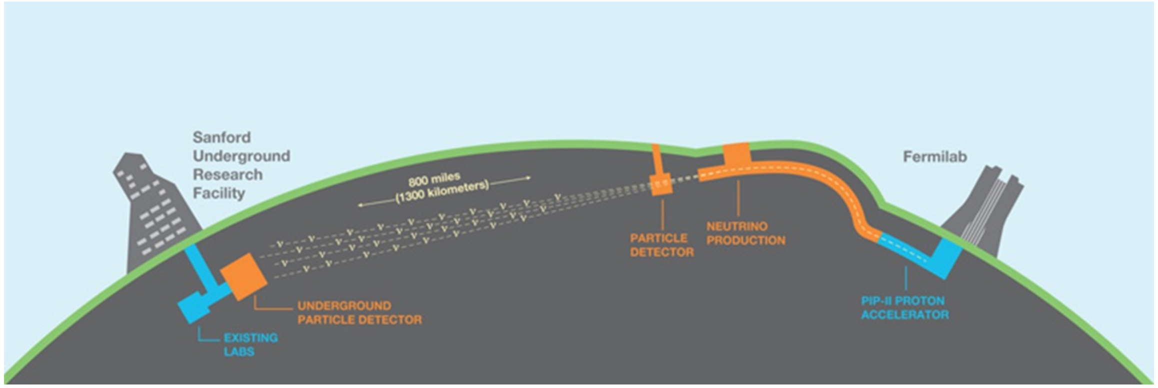
Overview for this talk

- Site & Facility Descriptions
- Mechanical Overview
- Design Analyses
  - Many contributors over the years, see DocDB entries
- Also see draft TDR chapter for Hadron Absorber
  - DUNE-doc-32526
- CAD models available for questions as-needed



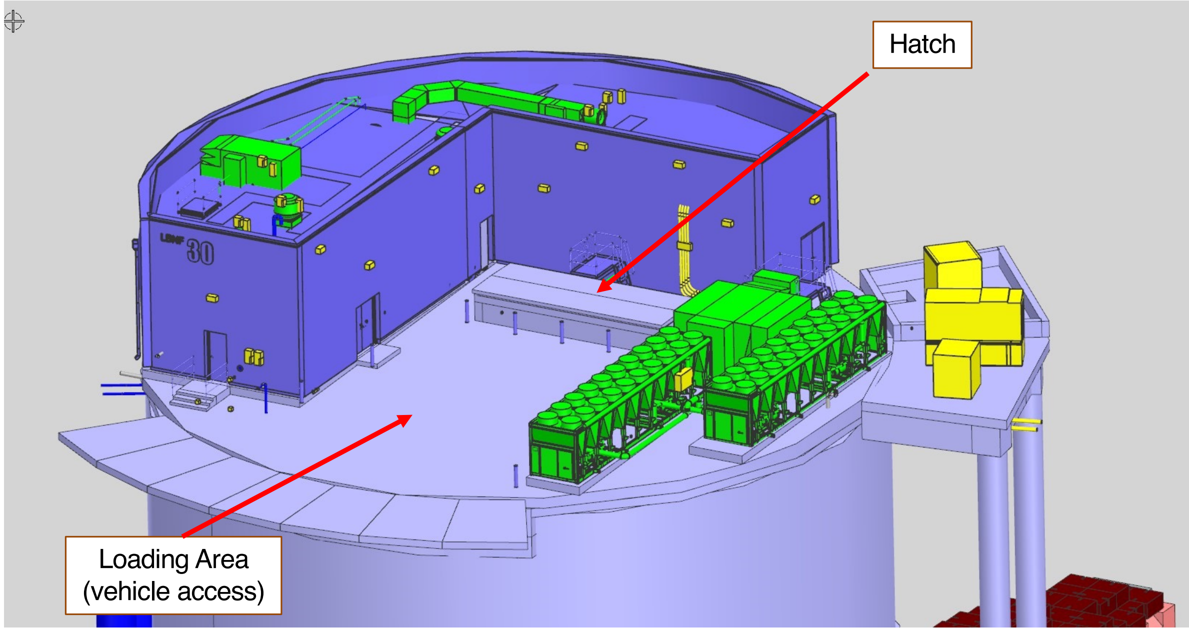
LBNF Site at Fermilab

- Neutrinos produced at Fermilab, fired across 1300 km towards SURF
- Proton beam interacts with a target, residual beam travels through decay region, then is stopped in the Absorber Hall in LBNF-30
- 1.5m graphite target = 3 interaction lengths, ~4% of beam does not interact

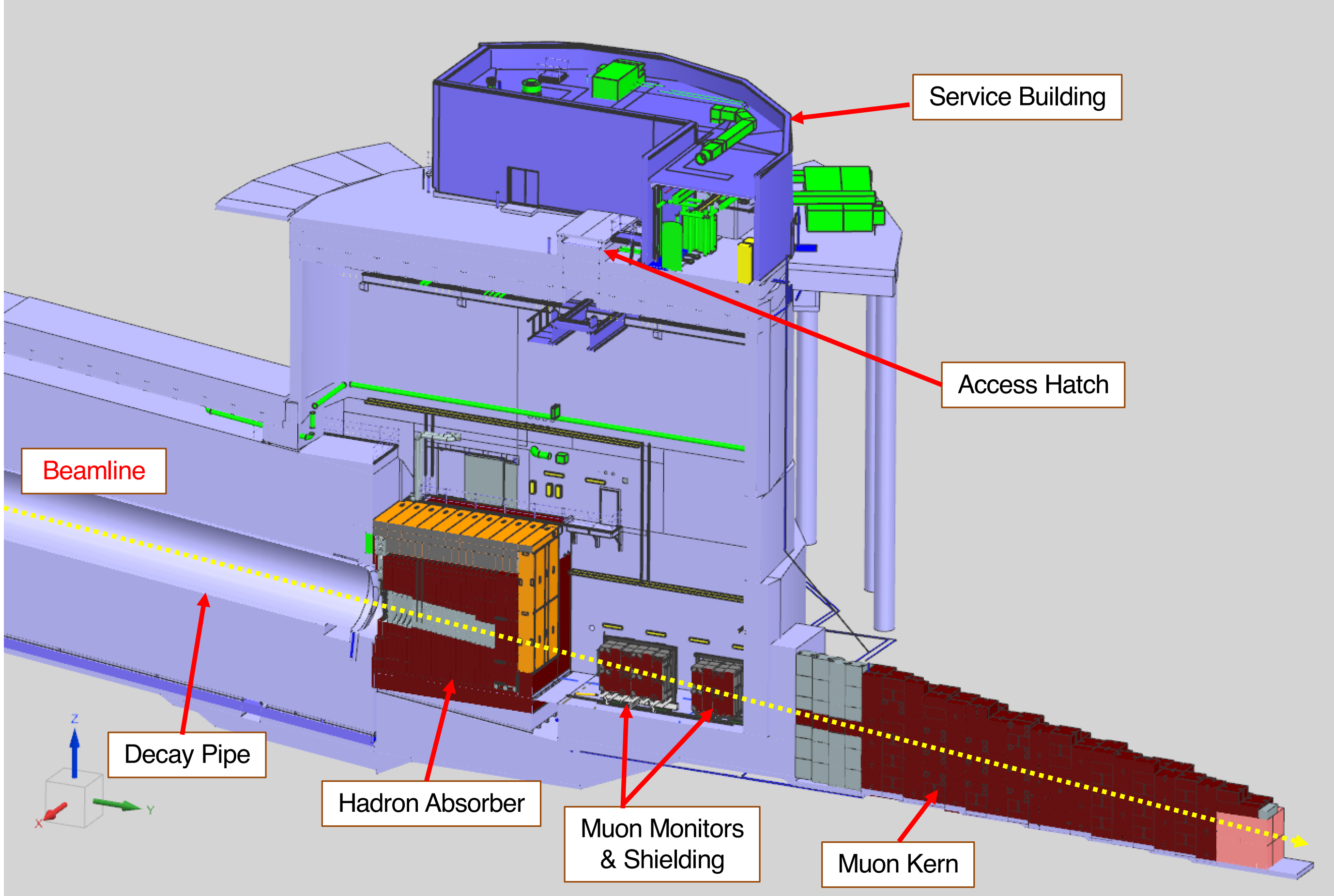


LBNF-30 – Absorber Complex

- LBNF-30 houses the Hadron Absorber and related support systems
  - Provided by CF construction
  - Absorber is installed afterwards into the Bunker

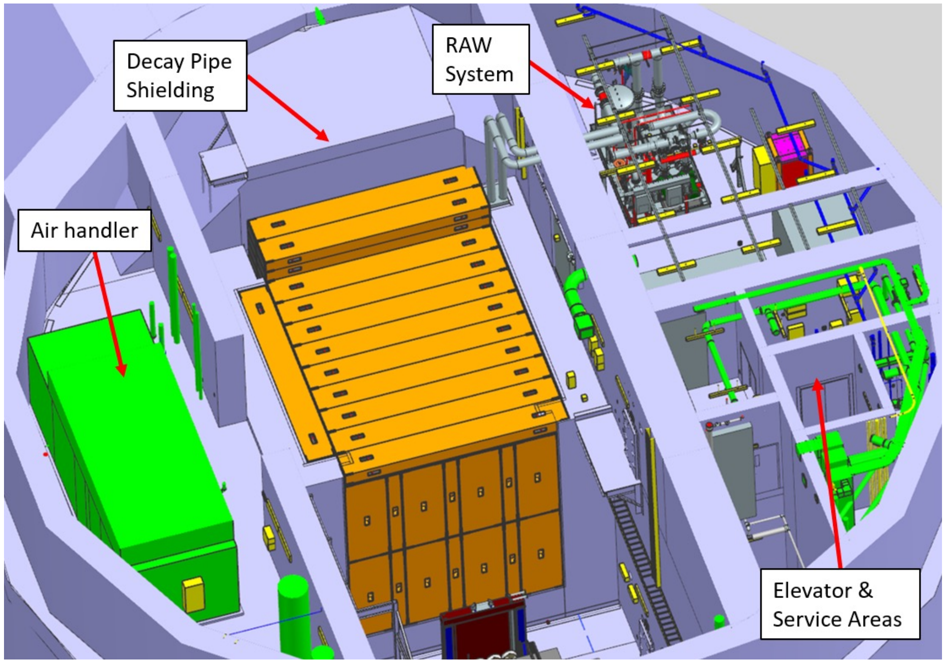


LBNF-30 – Absorber Complex



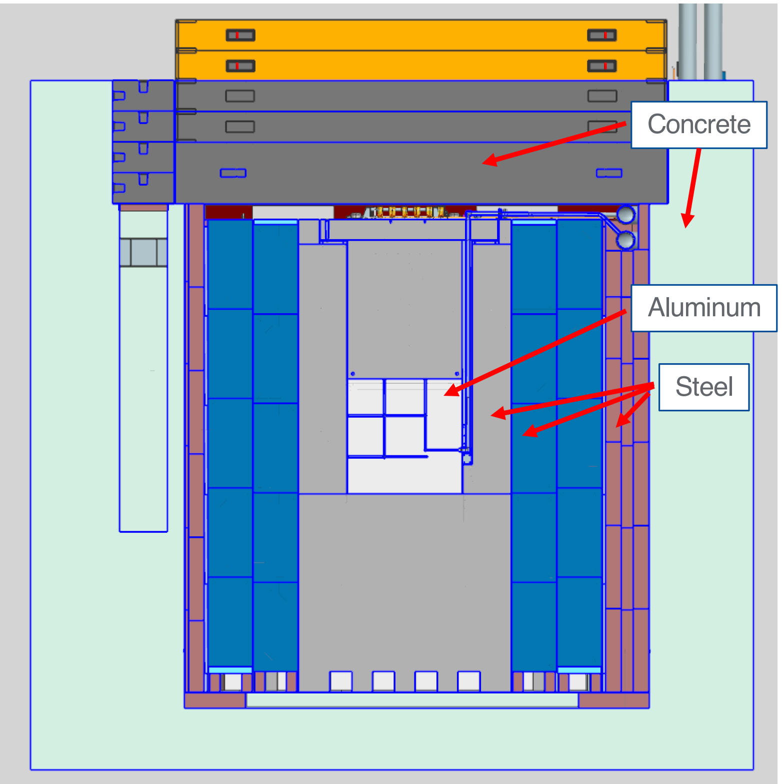
LBNF-30 – Absorber Complex

- CF provides a concrete bunker in the Absorber Hall
  - Beam-left side of the hall has RAW room, Instrumentation Room, elevator and stairwell
  - Beam-right side of the hall has the Absorber and facility air handlers, and related ducting
  - Review scope only includes the Absorber itself, inside the Bunker
    - Under and including the yellow concrete blocks in the figure



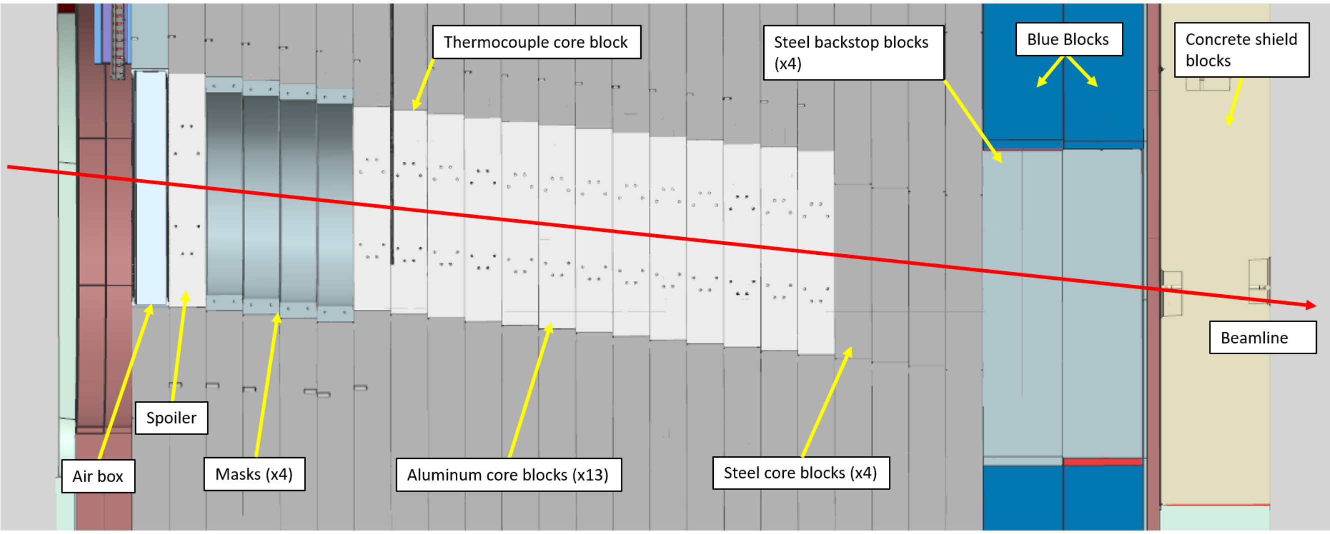
Absorber Pile

- The LBNF Hadron Absorber consists of a water-cooled aluminum core surrounded by air- cooled bulk steel shielding, all assembled inside an outer concrete enclosure.
- The Absorber design is based off the NuMI target chase
  - Outer steel shielding forms a trench along the beamline, into which removable elements are installed underneath T-shaped steel shielding
  - Concrete “bunker” enclosure around the steel
- The core is intended to last the life of the facility
  - To minimize risk, segments of the core can be replaced
  - Storage pit (morgue) provided to store failed components
- The outer steel shielding is permanent



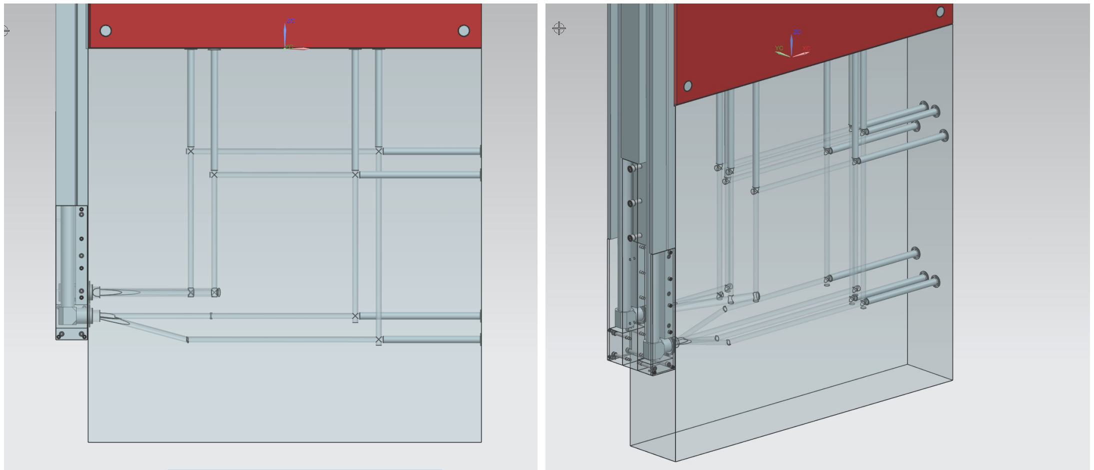
Spoiler, Masks, and Al Core Blocks

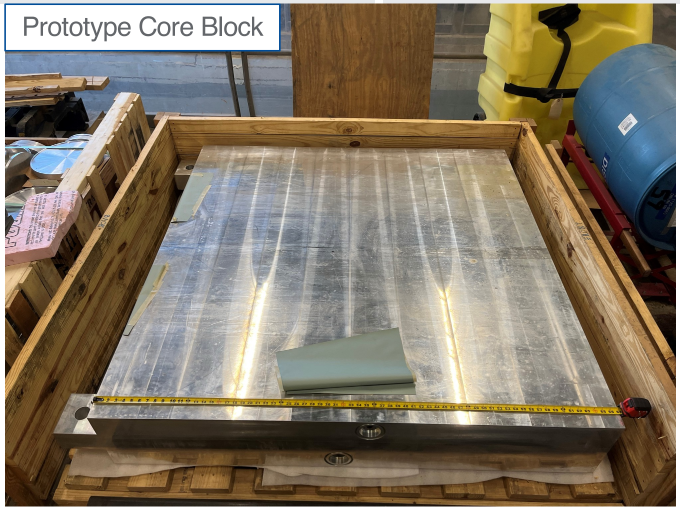
- Spoiler block: interacts with the beam and starts the shower into the rest of the Absorber
- The shower is allowed to grow over a drift space provided by the central hole in 4 Mask blocks, then absorbed in 13 Aluminum Core blocks
- Followed by 4 all-steel core blocks (air cooling only)



Core Blocks

- The aluminum core is broken up into 12” (~30 cm) thick core blocks
- Blocks are staggered in a wide-narrow pattern longitudinally to provide labyrinthing along with the support shielding
- Each block has gundrilled passages for cooling water, and welded elbows that connect to the water circuit

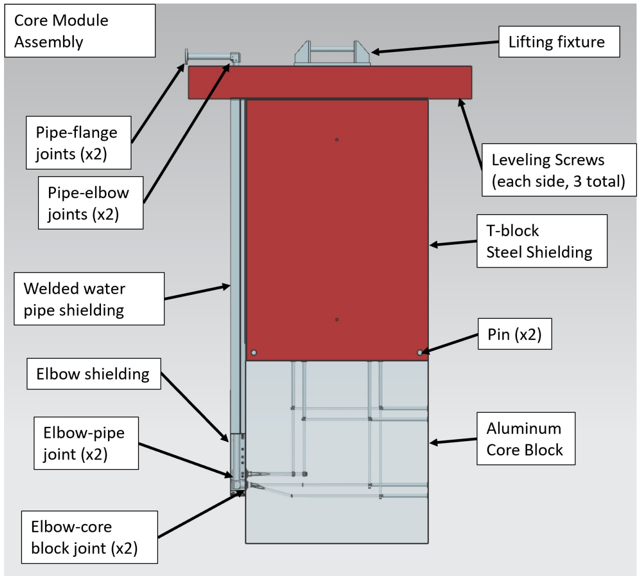


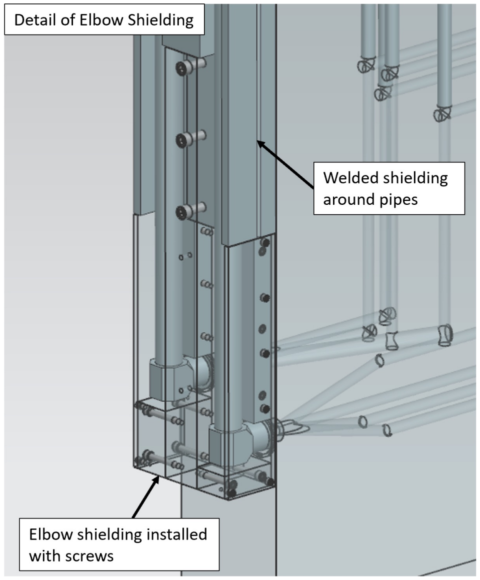


Prototype Core Block

Core Modules

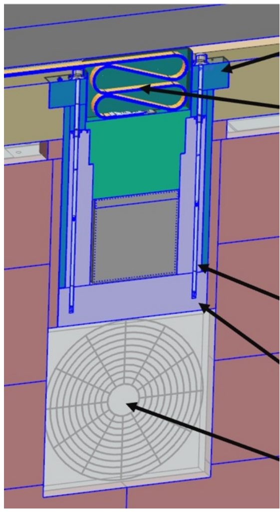
- Each core block is suspended from a steel T-block shielding piece
- The assembly of a T-block and a core block is termed a Core Module
- The Core Module is a removable, replaceable (but not repairable below the shielding) unit
- Positions the core blocks in the correct position on the beamline



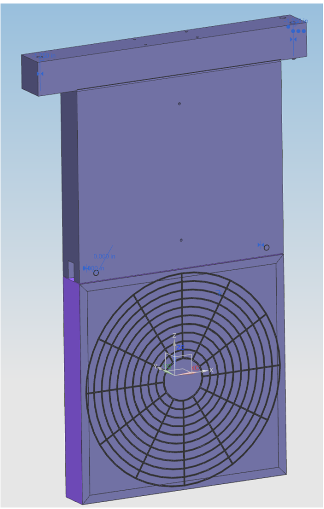


- All modules are unique:
  - T-blocks get taller further into the Absorber to follow the beam path
  - Longitudinal labyrinthing means there are two versions of masks, solid Al, and solid steel core blocks

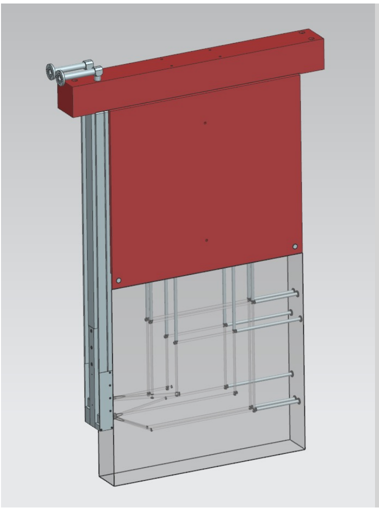
HADeS



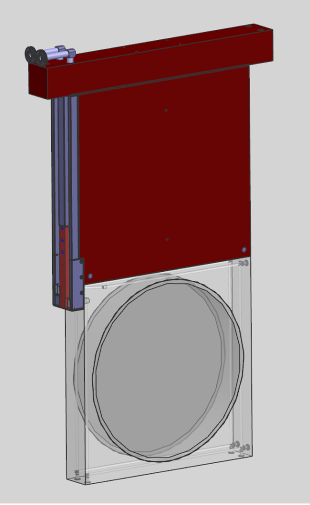
Air box



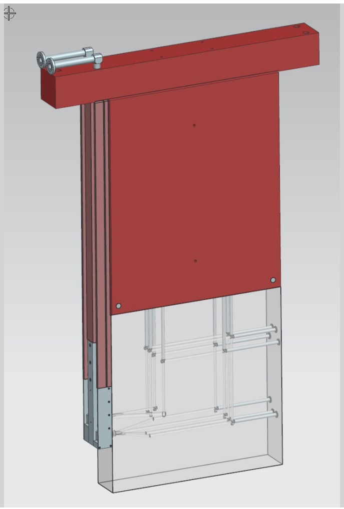
Spoiler



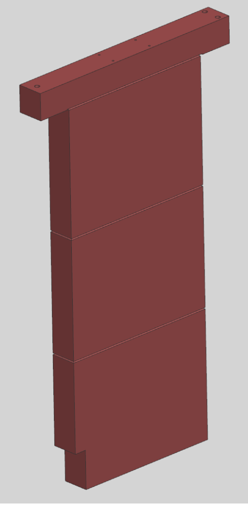
Mask



Al Core

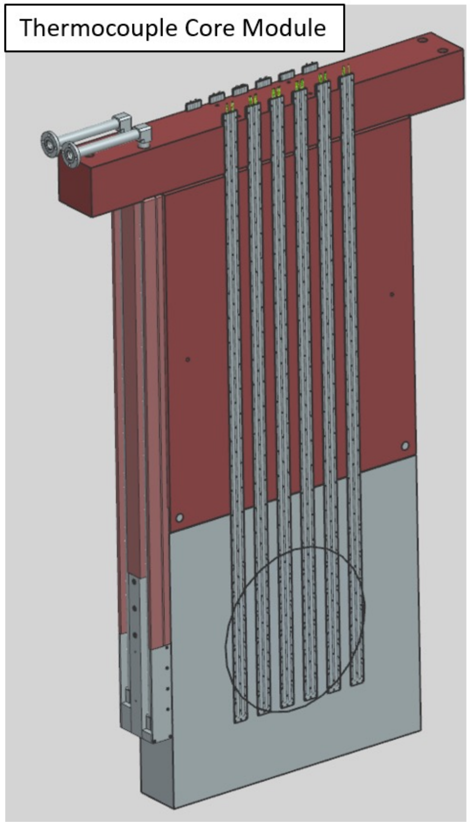


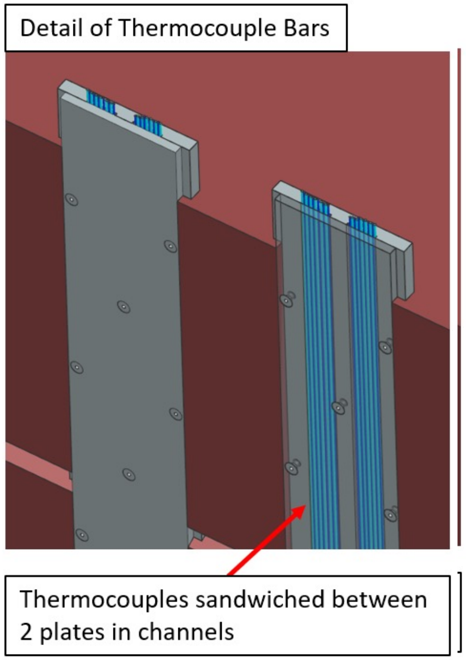
Steel Core



Thermocouple Core Block

- The highest energy deposition and temperature occurs in the second solid aluminum core block
- An array of 228 thermocouples is installed into this block to monitor the beam
    - See DUNE-doc-32078
    - An absolute temperature limit and pulse-to-pulse temperature limit can withdraw beam permit
- Thermocouple bars are replaceable in the event thermocouples fail
    - Original NuMI absorber thermocouples are still operational (DUNE-doc-23991)

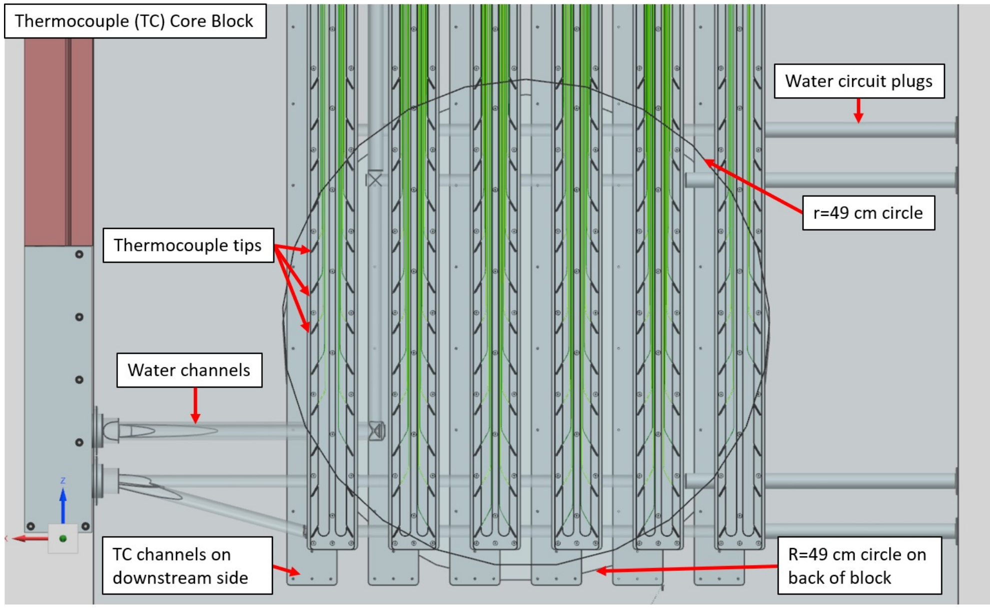

Thermocouple Core Module


Detail of Thermocouple Bars

Thermocouples sandwiched between 2 plates in channels

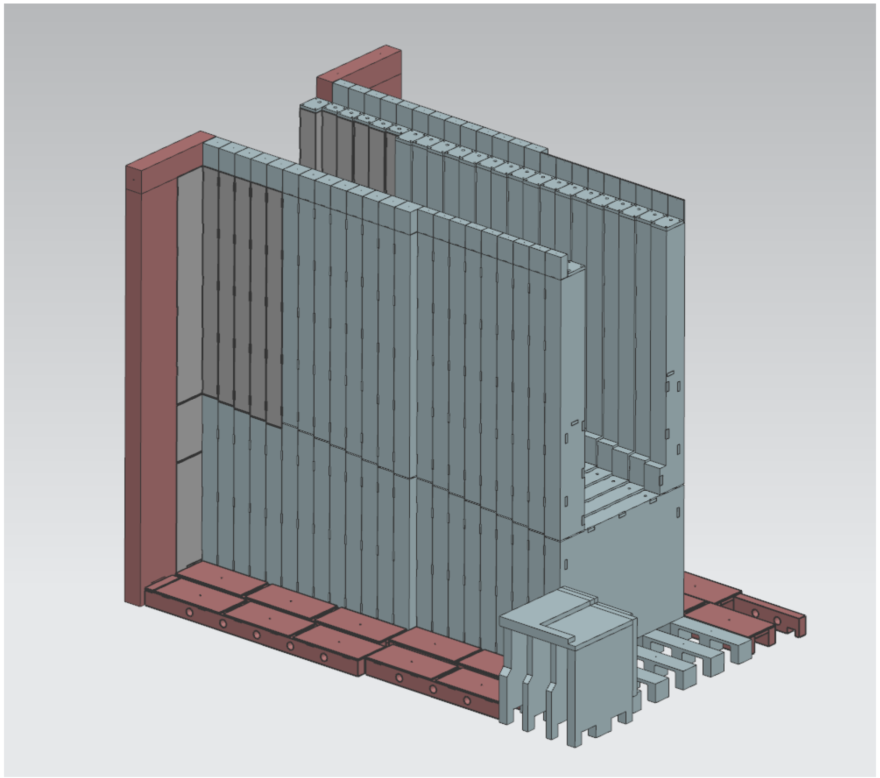
Thermocouple Core Block

- The thermocouple (TC) sensing tips are staggered within a r=49 cm circle so that the beam center is never more than 4 cm from a TC tip (DUNE-doc-23948)
  - Circle encloses the maximum geometrically-possible displacement of a mis-steered beam based on the last magnet aperture before the target, the aperture of the baffle, and the downstream position of components
  - Note that this circle includes the water lines inside the blocks
    - A beam strike on a water passage was examined to see if the pressure pulse damaged the core block. It did not.
    - See DUNE-doc-32369



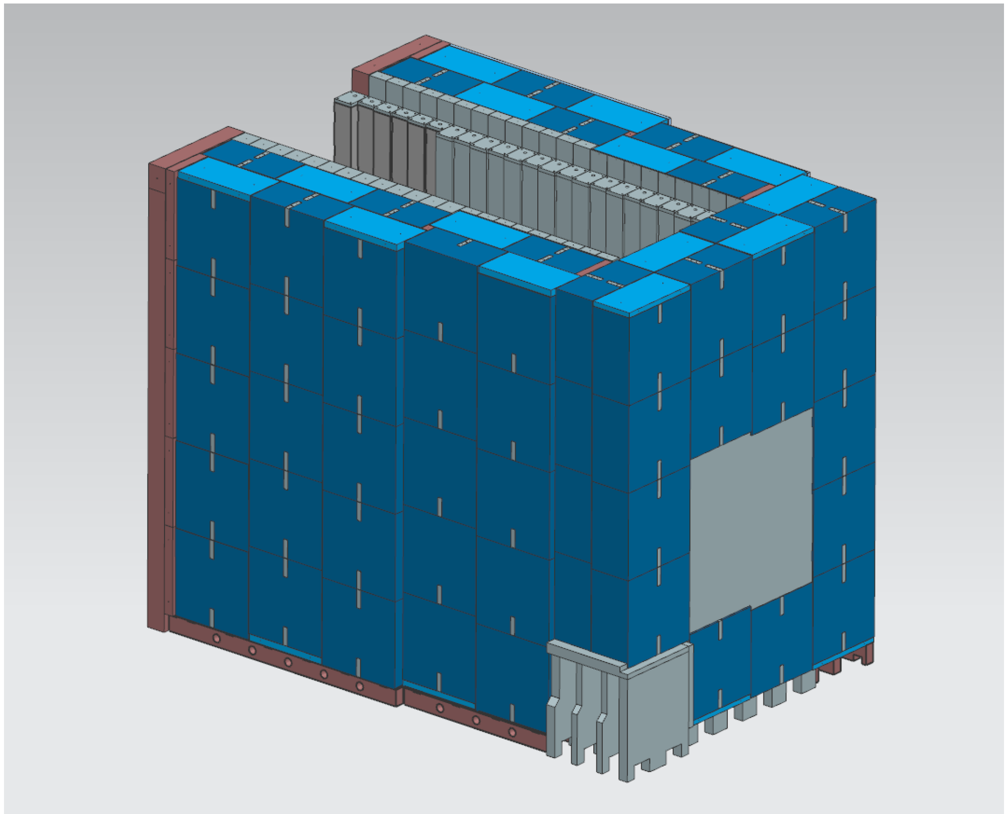
Core Module Chase and U-Supports

- The core modules are installed in the Pile on a set of U-shaped steel supports that collectively form the Module or Absorber Chase.
- These supports set the spacing of the modules
  - Air gap between modules and supports is set with welded spacer plates
  - U-supports act as the first layer of outer steel shielding
- 1-2 base pieces plus the uprights of the “U” shape
  - Largest part size limited by 30-ton Absorber Hall crane capacity



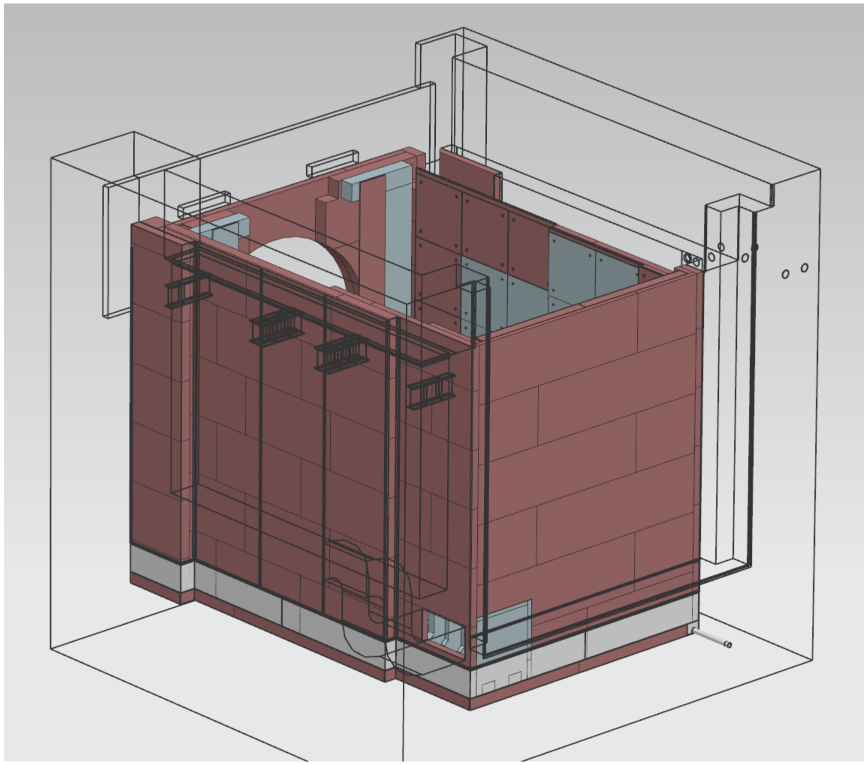
Blue Block Shielding

- Energy Solutions/Duratek S2 Shield Blocks
  - “Blue Blocks” due to blue paint job
  - Stenciled with weight and average density
- 130 used for bulk steel shielding
- Cooled by forced air, like the core module steel and supports
  - See “Analyses” talk



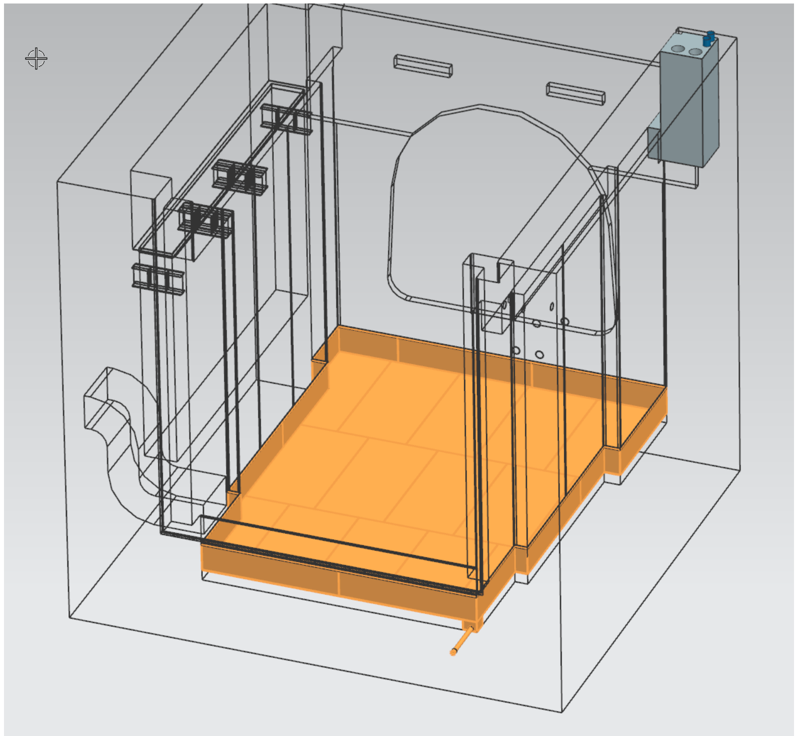
Outer Steel Shielding

- Outer layers of 9.11” steel slab shielding
  - Continuous cast salvage steel (CCSS)
  - Welded in position, tied back to embeds in Bunker wall
  - Plates have threaded holes to accept hoist rings
- Filler plates between Blue block stacks and outer steel
  - 2” thick, used if needed to fill gaps
  - Outer steel plates and Blue Blocks have loose tolerances, could leave a gap
- Bottom steel layers are located underneath RAW Pan (see next slide)



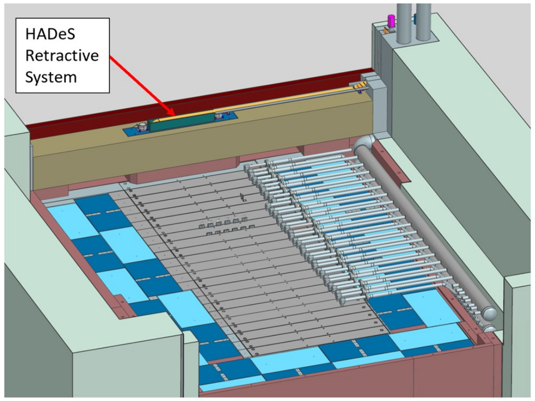
RAW Pan and Bottom Steel

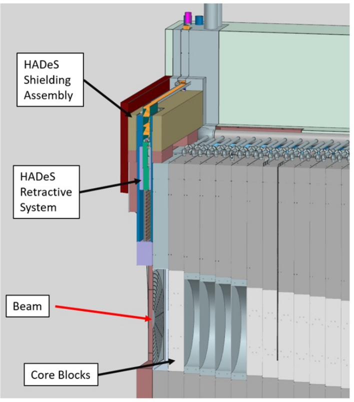
- Stainless steel sheet bathtub to catch any water leaks
  - Pan seals at upper edge, welded to an embed in the bunker wall
- Outer layer of 9.11” slab steel underneath
- Bottom layer of outer steel is grouted underneath (to prevent deformation under load)
- Grouted again on top surface, beneath the RAW Pan
  - Ensures a flat surface for building the shielding pile



HaDES Shielding

- Steel shielding stack around upstream top corner of Pile
- HADeS module seats into this shielding element
- Interface with HADeS


HADeS Retractive System


HADeS Shielding Assembly

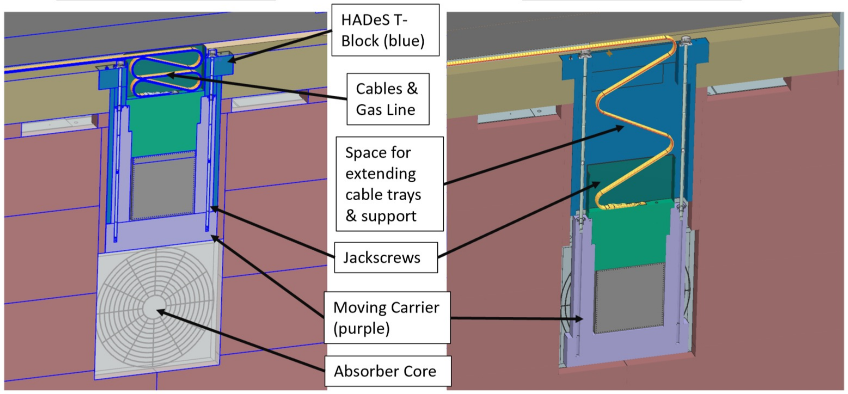
HADeS Retractive System

Beam

Core Blocks

HADeS in retracted position (normal beam operation)

HADeS in extended position (during beam calibration)


HADeS T-Block (blue)

Cables & Gas Line

Space for extending cable trays & support

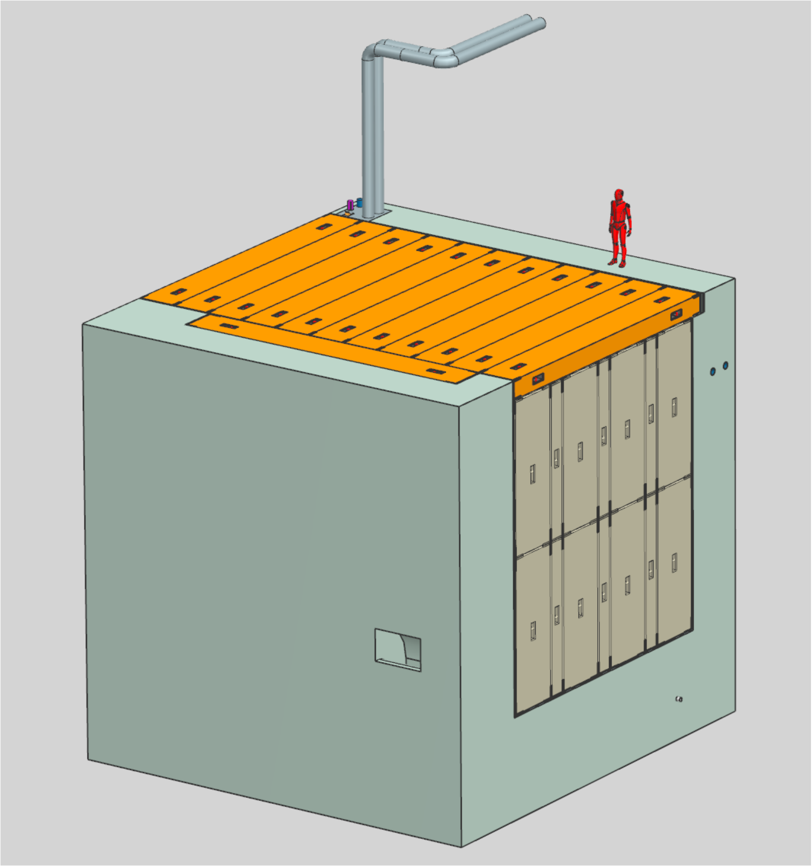
Jackscrews

Moving Carrier (purple)

Absorber Core

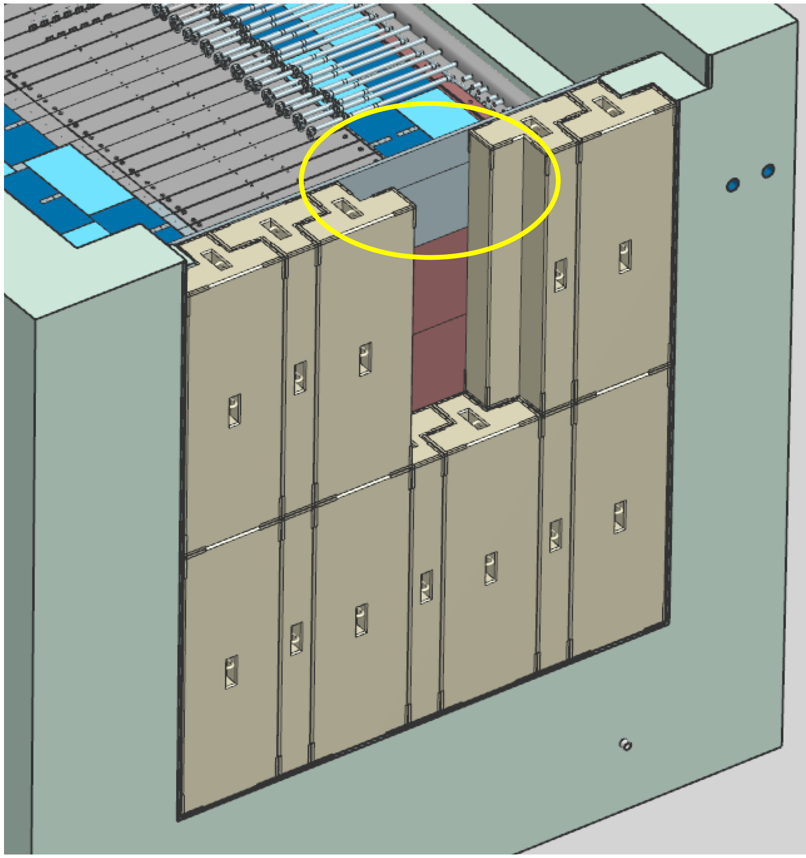
Concrete Shielding blocks

- G-size concrete blocks (18' x 3' x 1.5') cover the top of the Absorber bunker
  - 10 blocks at the upstream end (bottom layer) are a heavier borated concrete mix for neutron reduction
  - ISD examined the G-block cover for load bearing capacity
    - DI casks from the RAW room and equipment will be positioned on top of the blocks during operations
- T12 blocks (12' x 1.5' x 4.5') form the downstream wall of concrete around the Pile
  - Allows easier access to the Pile during construction



Concrete Shielding Blocks

- T-12 blocks not designed for significant sideload
  - ex. from air pressure transients in Absorber cooling circuit
  - Nominal air pressure ~30 inches water column
- Downstream air seal
  - See gray piece above red downstream steel wall
  - Steel wall welded on seams to be air-tight
  - Leakage path over top of wall blocked by the gray piece
    - Ex., for concrete plates, add corner angles to weld across, or weld steel plate joints



Questions on Mechanical Layout?

Up Next: Design Analyses

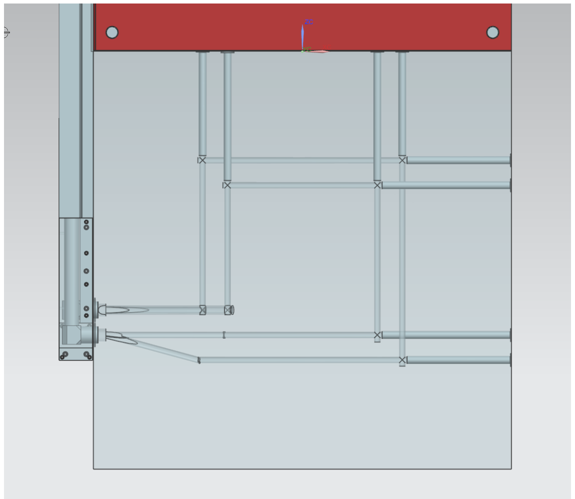
Design Analyses Overview

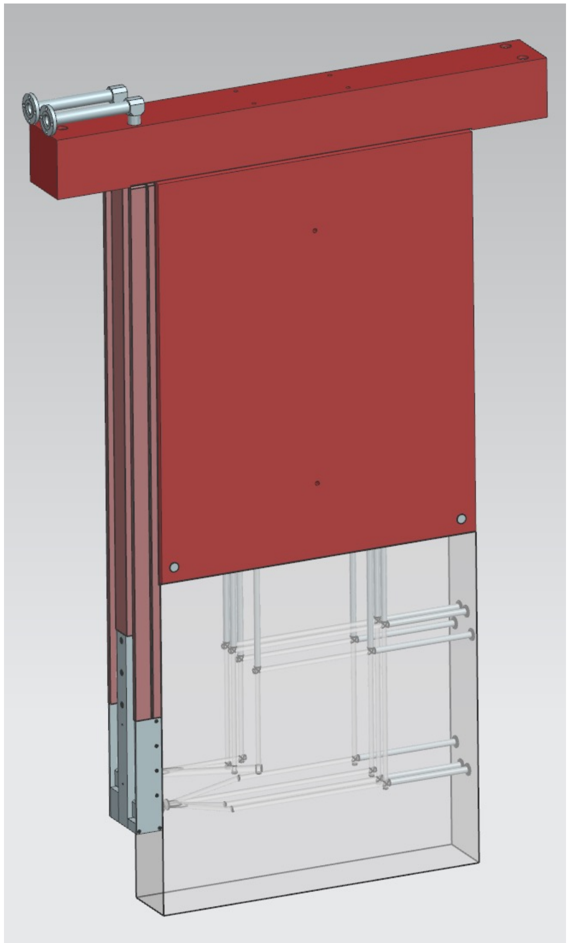
- Core Water Cooling
- Shield Pile Air Cooling
- Air Cooled Steel Core Modules
- Radiation Modeling
- Stability Analyses

Core Water Cooling

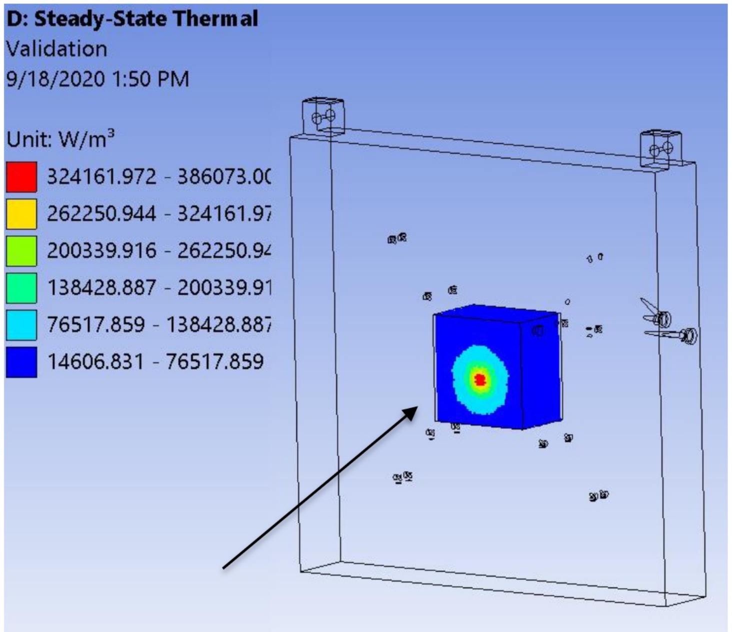
Core Water Cooling

- DUNE-doc-20651
- MARS calculation provided energy deposition in upstream core blocks
- Assumed heat transfer coefficient of 7000 W/m-K in channels at 25 C coolant temp





Core Water Cooling – MARS Binning

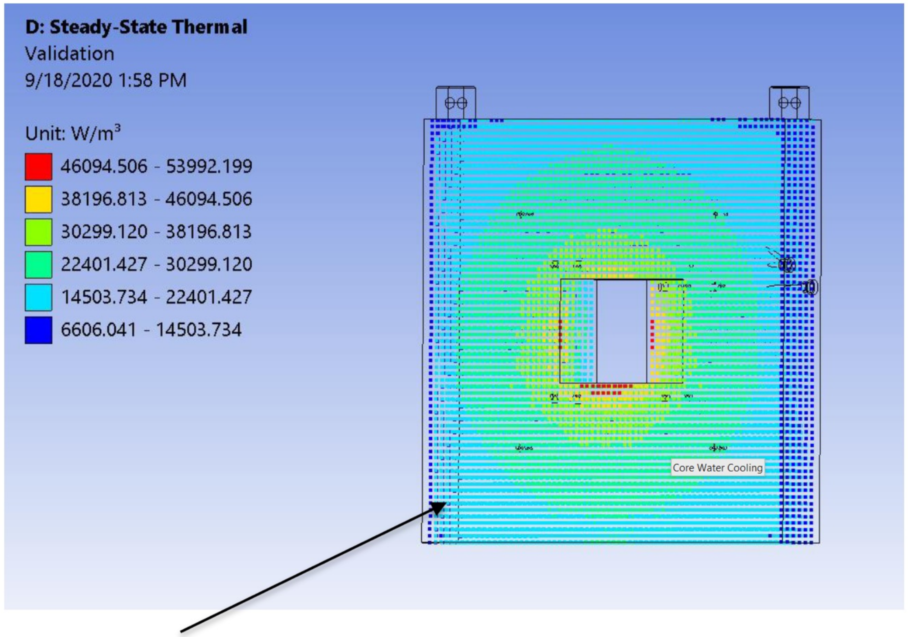


D: Steady-State Thermal
Validation
9/18/2020 1:50 PM

Unit: W/m^3

🟥	324161.972 - 386073.0
🟨	262250.944 - 324161.97
🟩	200339.916 - 262250.94
🟩	138428.887 - 200339.91
🟦	76517.859 - 138428.887
🟦	14606.831 - 76517.859

1 cm MARS bin in the center
48 cm x 48 cm x 30 cm



D: Steady-State Thermal
Validation
9/18/2020 1:58 PM

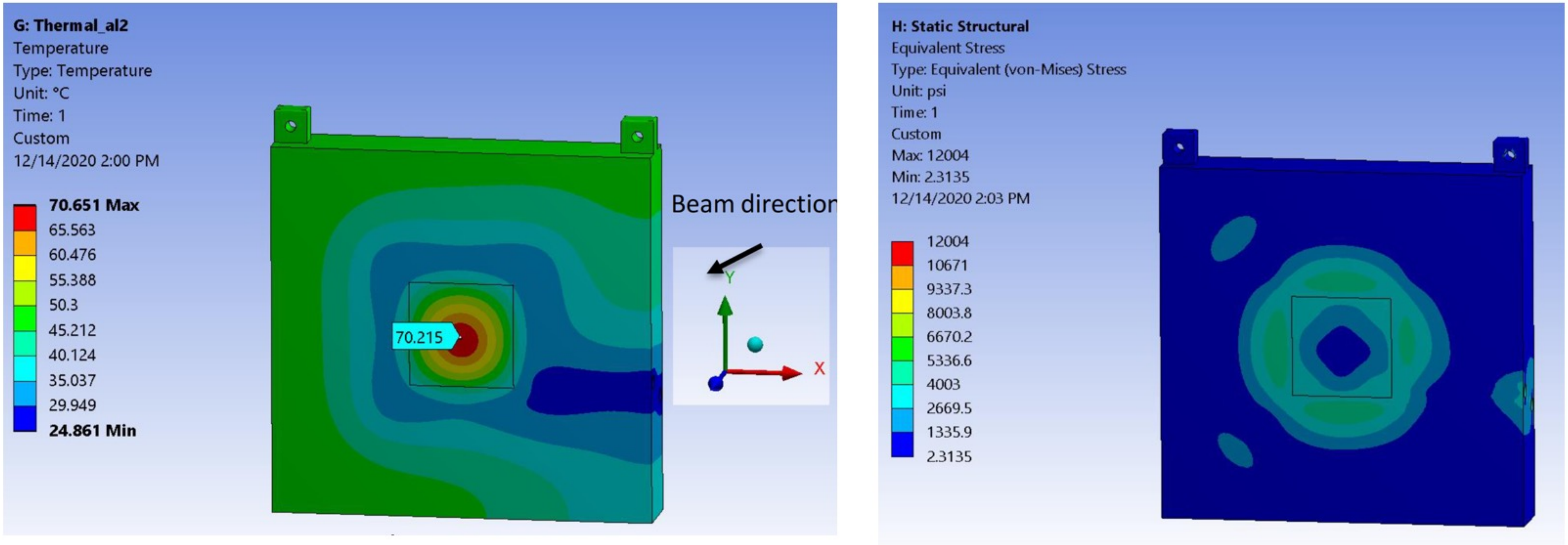
Unit: W/m^3

🟥	46094.506 - 53992.199
🟨	38196.813 - 46094.506
🟩	30299.120 - 38196.813
🟩	22401.427 - 30299.120
🟦	14503.734 - 22401.427
🟦	6606.041 - 14503.734

3 cm MARS bin surrounding

Aluminum Core 2 Temperature and Stress

Al Core 2 Steady-State Temperature and Stress



G: Thermal_al2
Temperature
Type: Temperature
Unit: °C
Time: 1
Custom
12/14/2020 2:00 PM

H: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 1
Custom
Max: 12004
Min: 2.3135
12/14/2020 2:03 PM

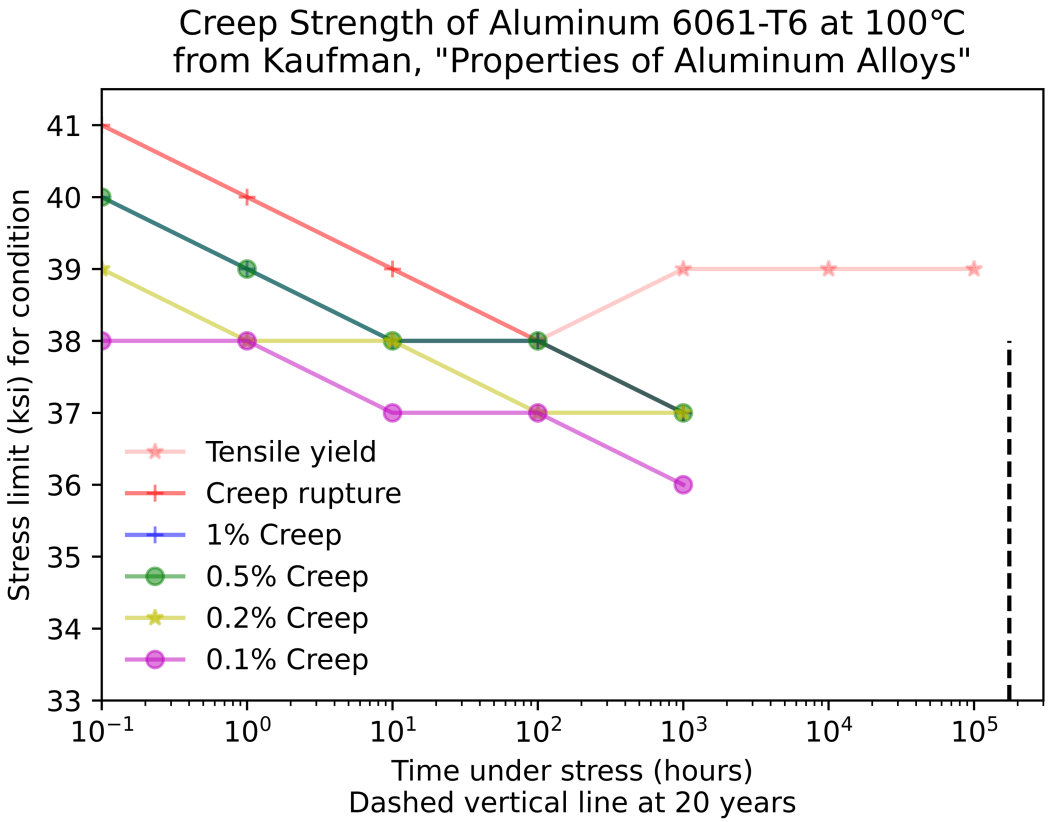
Core Water Cooling Data Summary

- DUNE-doc-20651
- MARS calculation provided energy deposition in upstream core blocks
- ANSYS thermal analysis of water cooling

	Rectangular Cooling Circuit					
	Maximum temperature (C)	FEA heat reaction (KW)	MARS data	Ratio	Stress (psi)	Total deflection (mm)
Spoiler	58.28	27.05	27.32	99.01%	14234	1.28
Aluminum_1	59.245	28.549	29.27	97.54%	13991	1.1572
Aluminum_2	70.678	31.691	32.18	98.48%	11301	1.1417
Aluminum_3	69.138	28.092	28.67	97.98%	9946.1	1.0983

Aluminum Stress and Temperature Limits

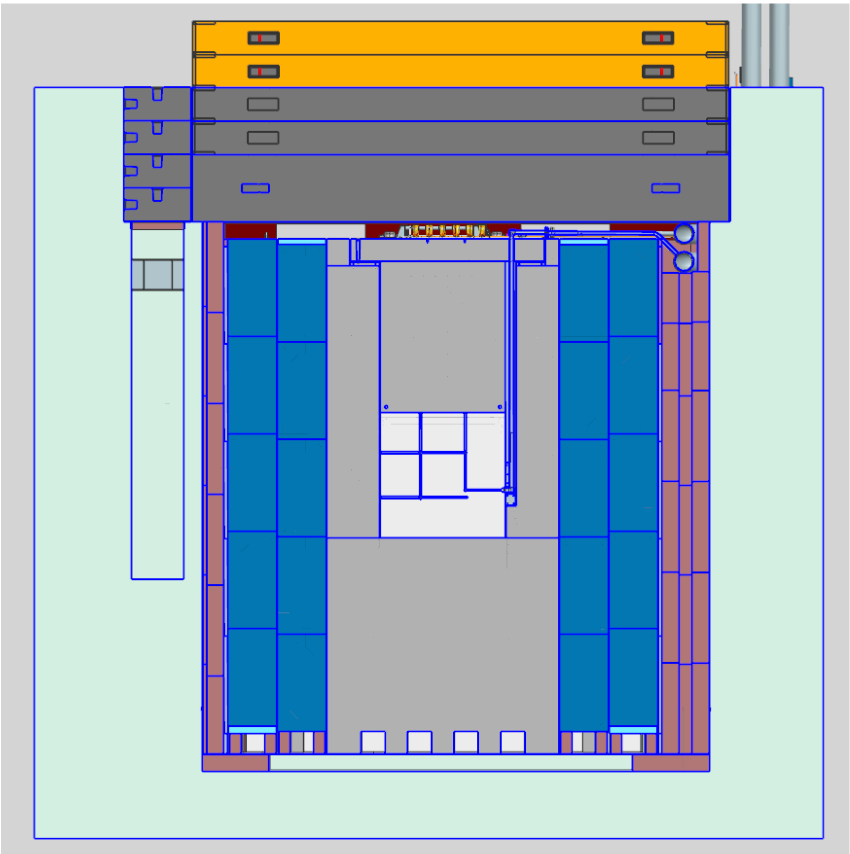
- 100 C temp limit imposed to avoid most creep
  - Rough extrapolation from Kaufman data gives 100,000 hour creep rupture at ~35 ksi
    - *Very* rough number, no real data exists at this time frame
  - Actual stress values far below even 0.1% creep limit
  - Actual block held well below 100 C
- 40 ksi nominal yield strength
  - ~14.23 ksi maximum (mostly from thermal stress)



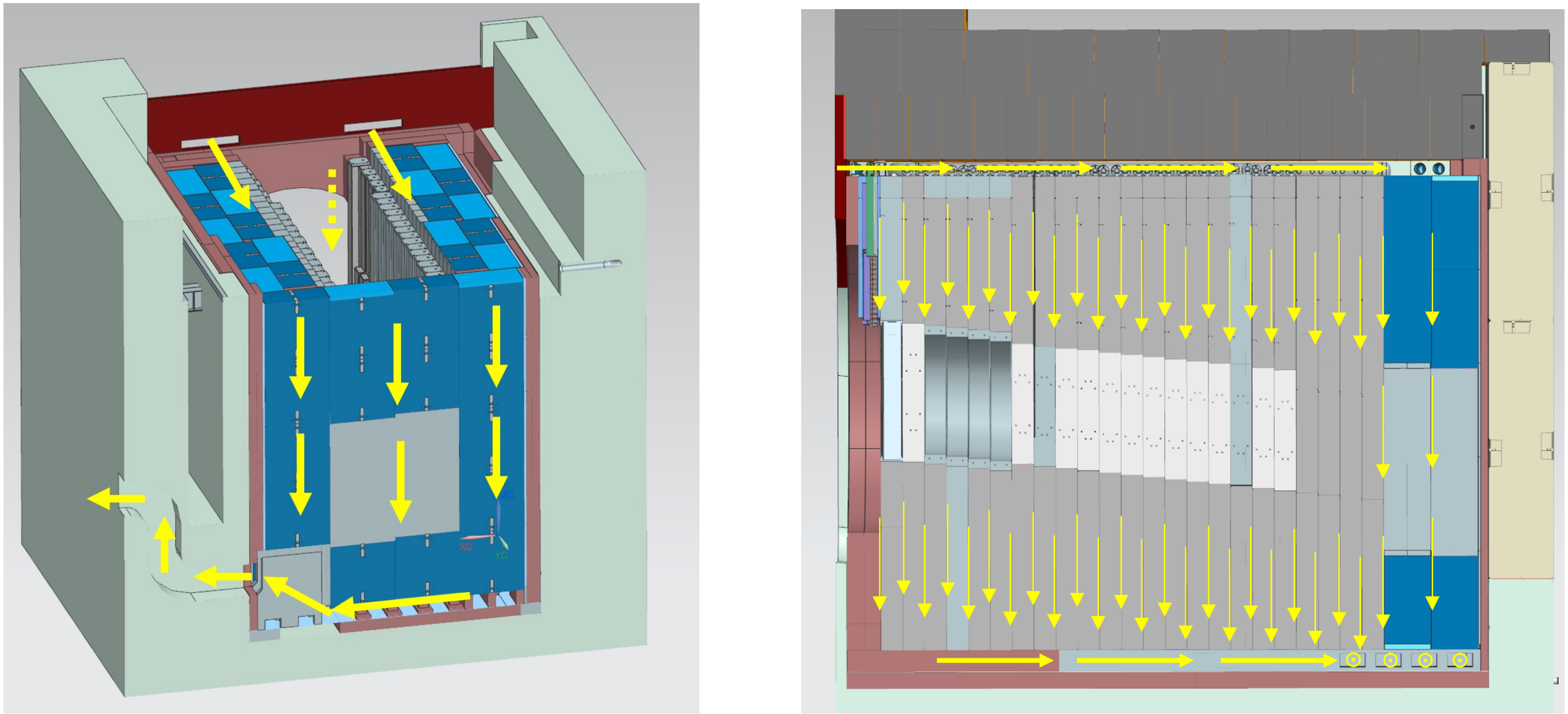
Shield Pile Air Cooling

Shield Pile Air Cooling

- DUNE-doc-20831
- Bulk steel radiation shielding surrounds the core
  - 20831 is the analysis to show blue blocks work with the air cooling scheme
- Inner steel is cooled by forced air
  - Outer steel layers and bunker are uncooled
    - Technically, the inside face of the outer steel is air-cooled, but this is not considered

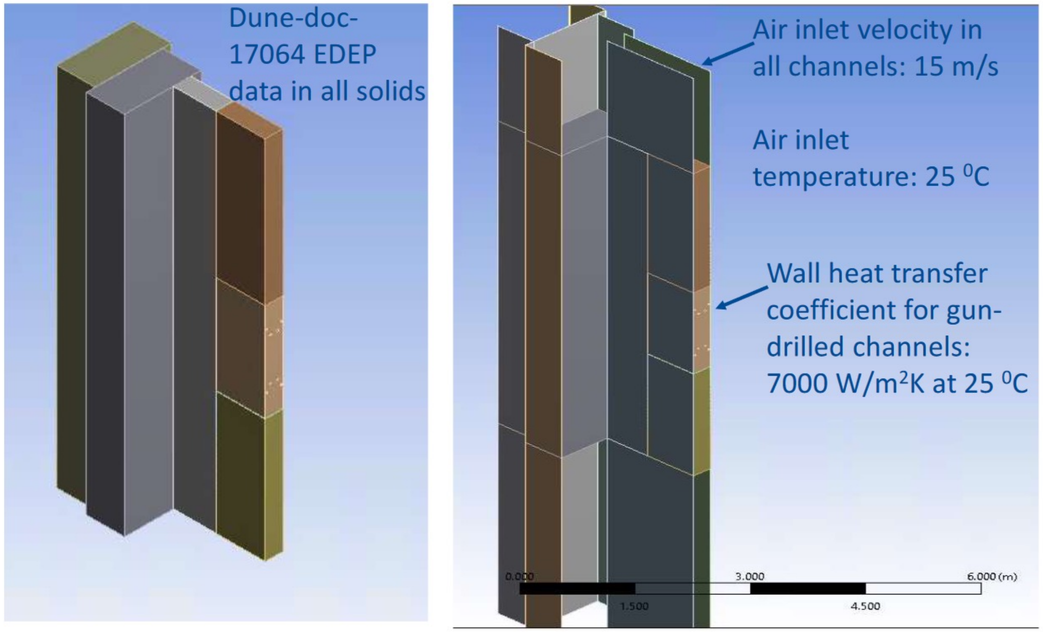


Shield Pile Air Cooling



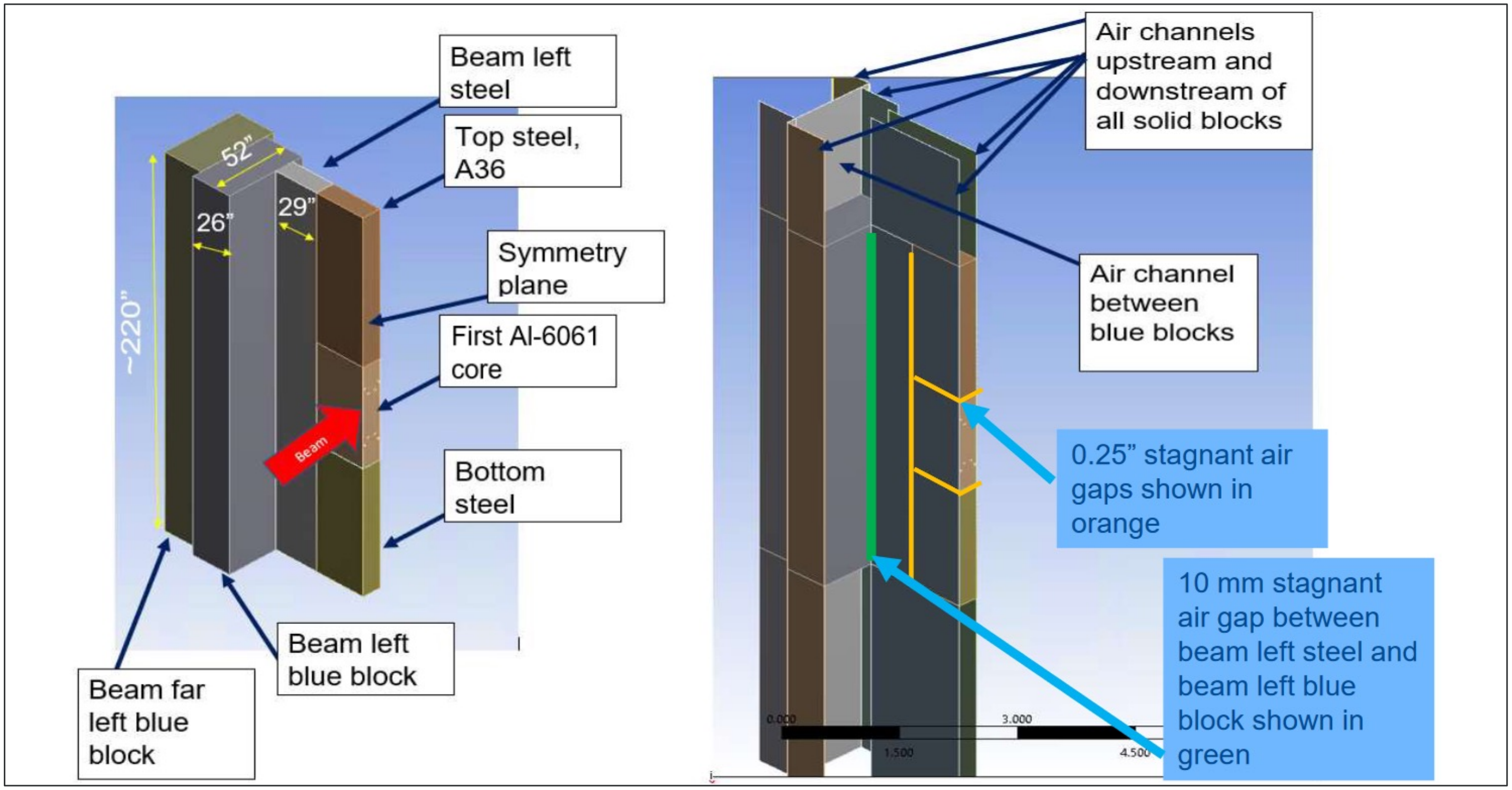
Shield Pile Air Cooling

- Modeled a symmetric region of inner steel shielding and blue blocks
- Air channels 5 mm thick
- Inlet temp 25 C, 15 m/s
  - (velocity calculated from separate air flow models, see DUNE-doc-431, DUNE-doc-6005 and their references)
  - Blue Blocks modeled as stacks of blocks (assuming stagnant air in flat vertical gaps without convection)



- EDEP for 2.4 MW beam operations with a 1.5-m RAL target.

Shield Pile Air Cooling



Beam left steel

Top steel, A36

Symmetry plane

First Al-6061 core

Bottom steel

Beam far left blue block

Beam left blue block

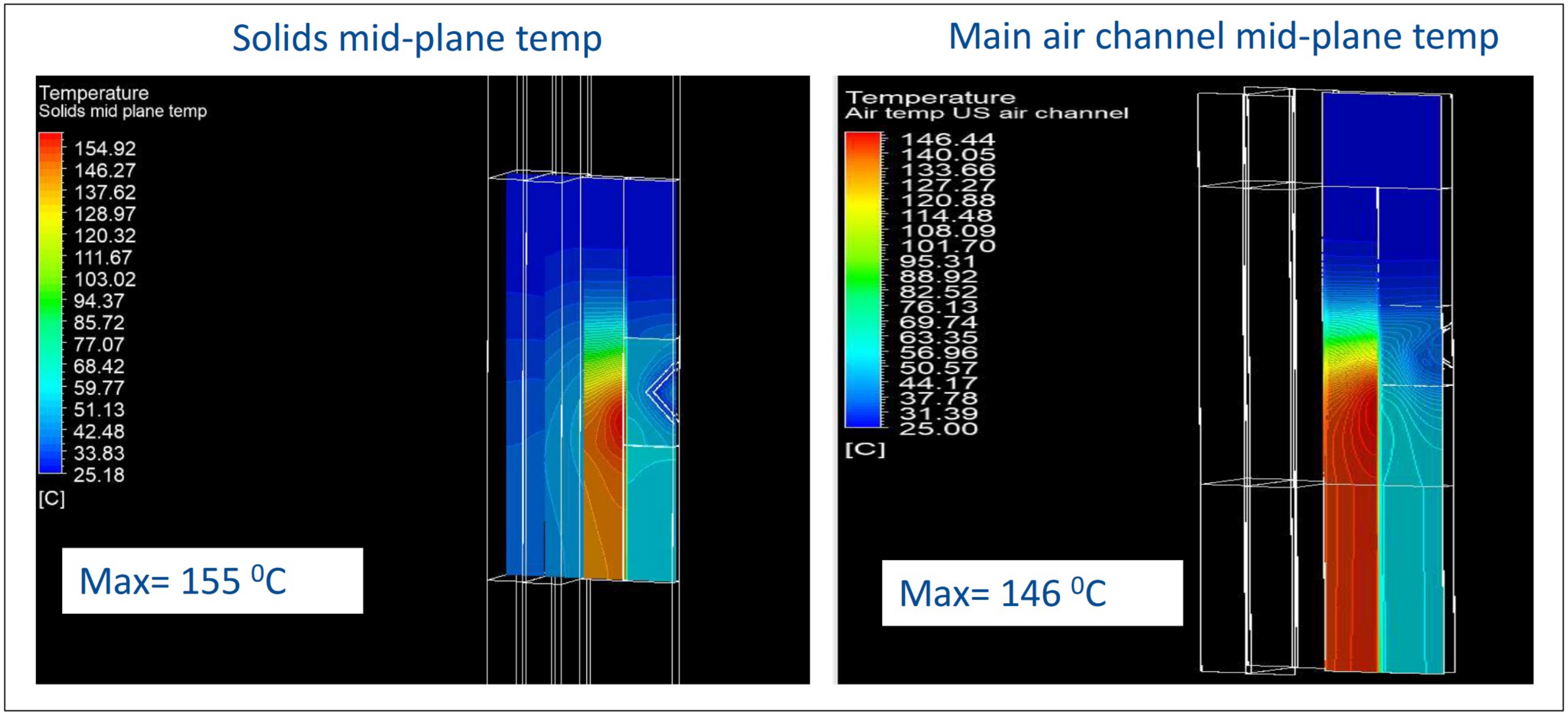
Air channels upstream and downstream of all solid blocks

Air channel between blue blocks

0.25” stagnant air gaps shown in orange

10 mm stagnant air gap between beam left steel and beam left blue block shown in green

Shield Pile Air Cooling



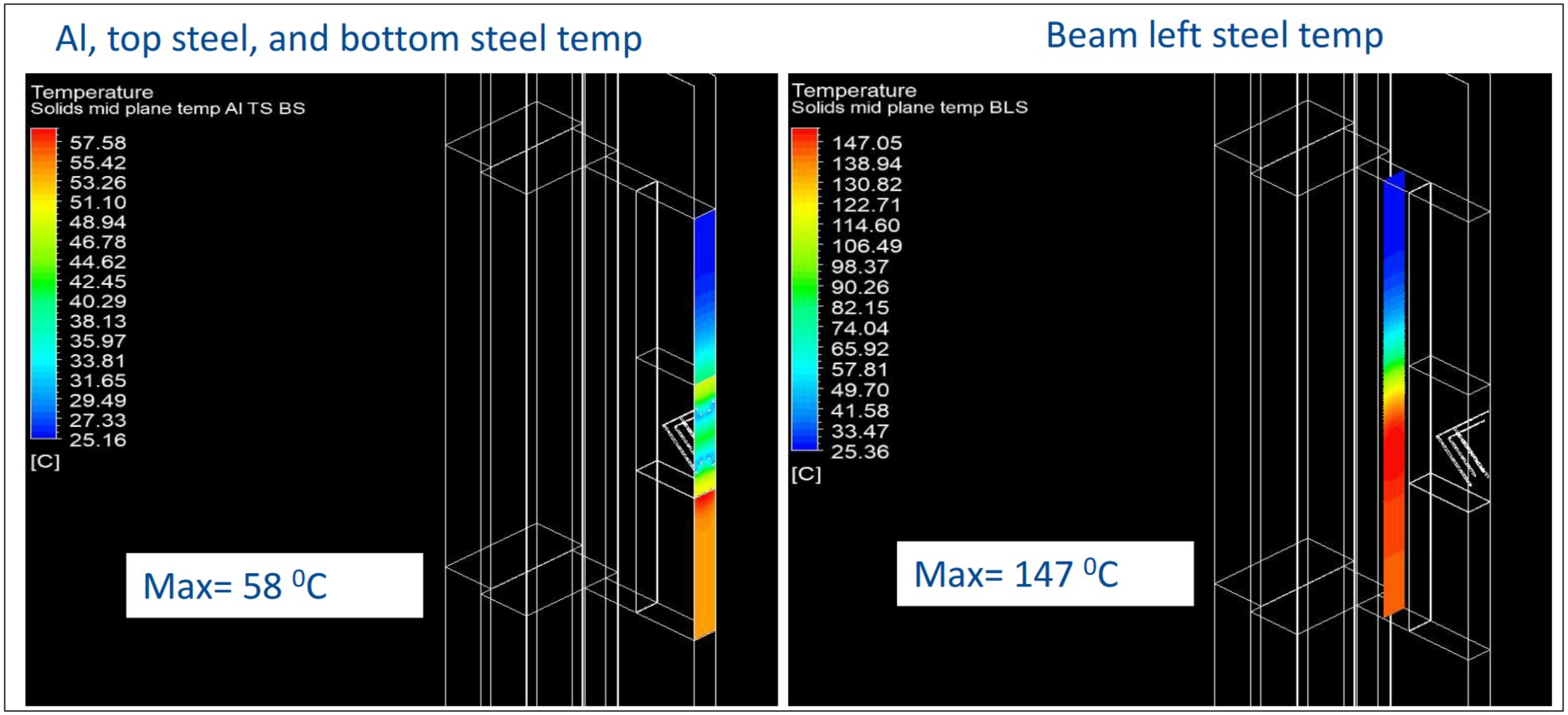
Solids mid-plane temp

Main air channel mid-plane temp

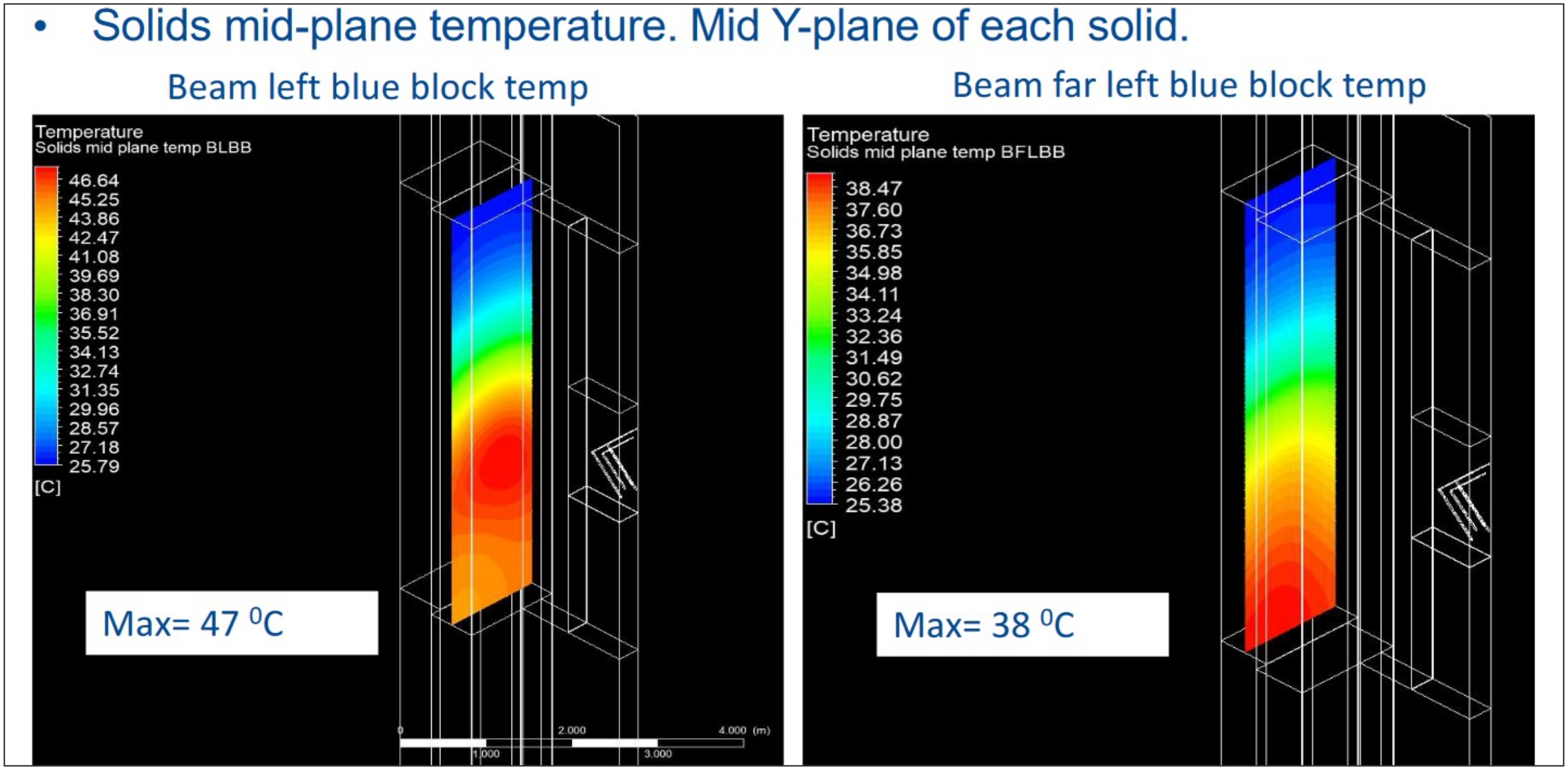
Max= 155 ^{0}C

Max= 146 ^{0}C

Shield Pile Air Cooling



Shield Pile Air Cooling



- Solids mid-plane temperature. Mid Y-plane of each solid.

Beam left blue block temp

Max= 47 ^{0}C

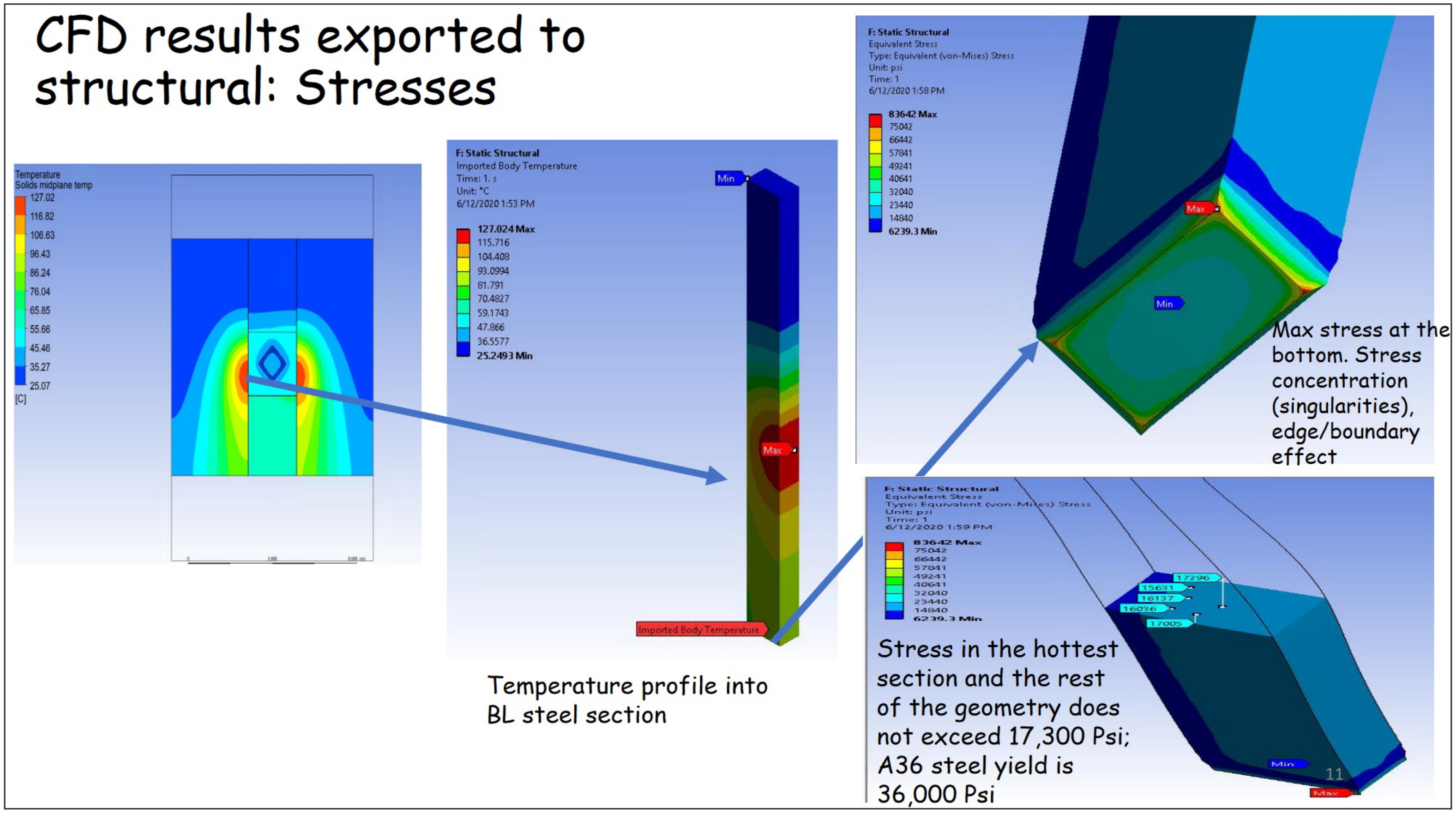
Beam far left blue block temp

Max= 38 ^{0}C

Shield Pile Air Cooling

- DUNE-doc-20831
- Temperature limit for NuMI-style paint is 260 C (also referenced in DUNE-doc-24749)
- Maximum steady-state steel temperature is 155 C, blue block stacks are less than 50 C
- Also note that exhaust air at center is ~146 C, according to the air temperature simulation
  - Cooler Blue block exhaust mixes in downstream
  - Average exhaust temp rise is 17 C
    - (240 kW in steel at 2.4 MW, 25,000 CFM airflow)
- Thermal mass of pile will keep heating air after an abort triggered by a water leak
  - Helps mitigate leaks and prevent puddling
- DUNE-doc-19797 examines stresses and deflections in U-supports with load and temperature
  - See next 2 slides

U-Support Stresses



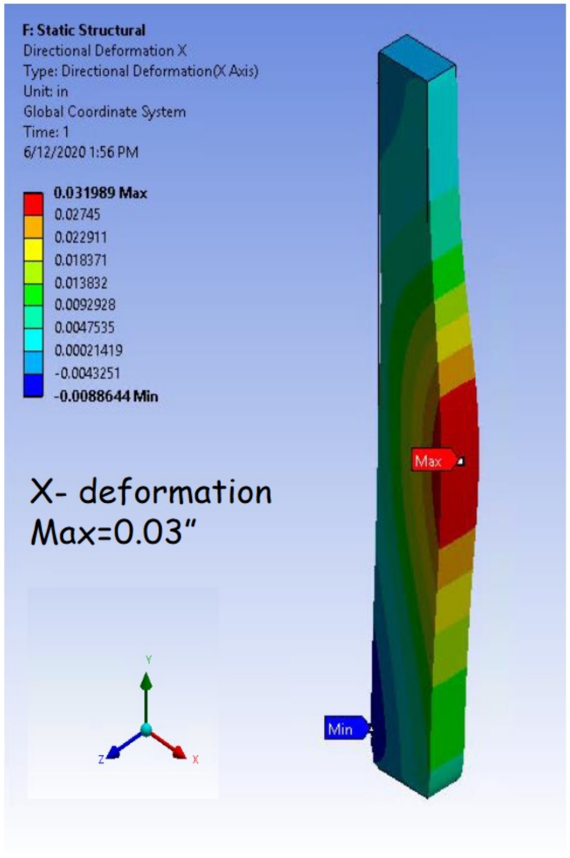
CFD results exported to structural: Stresses

Temperature profile into BL steel section

Max stress at the bottom. Stress concentration (singularities), edge/boundary effect

Stress in the hottest section and the rest of the geometry does not exceed 17,300 Psi; A36 steel yield is 36,000 Psi

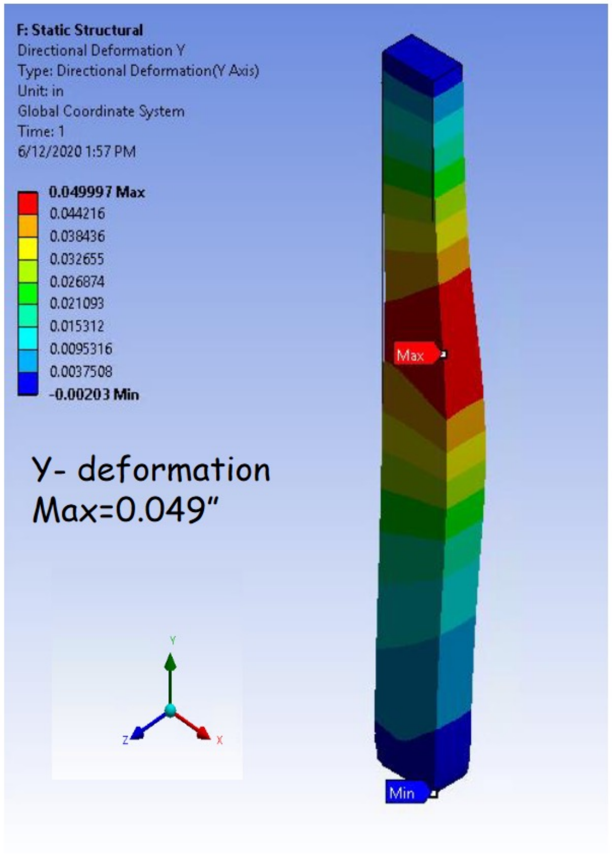
U-Support Deformation



F: Static Structural
Directional Deformation X
Type: Directional Deformation(X Axis)
Unit: in
Global Coordinate System
Time: 1
6/12/2020 1:56 PM

🟥 **0.031989 Max**
0.02745
0.022911
0.018371
0.013832
0.0092928
0.0047535
0.00021419
-0.0043251
🟦 **-0.0088644 Min**

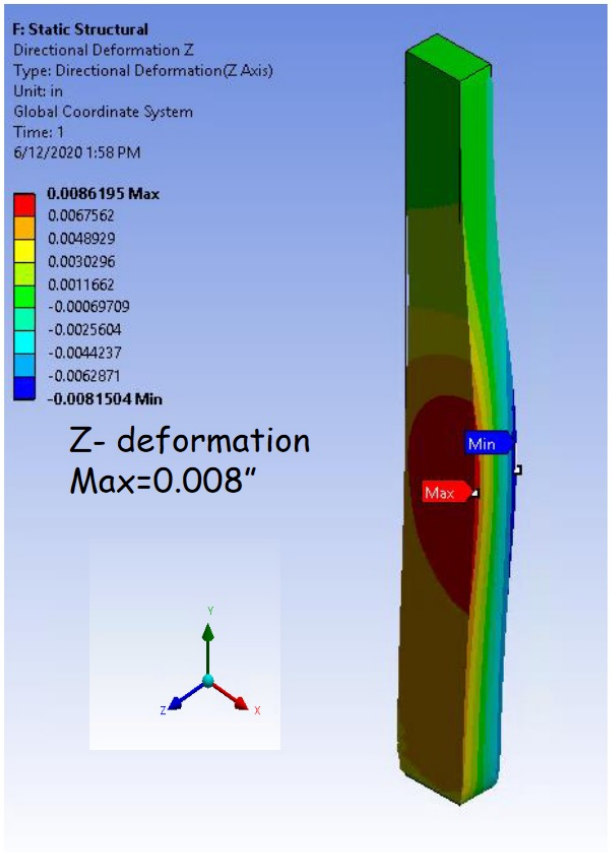
X- deformation
Max=0.03"



F: Static Structural
Directional Deformation Y
Type: Directional Deformation(Y Axis)
Unit: in
Global Coordinate System
Time: 1
6/12/2020 1:57 PM

🟥 **0.049997 Max**
0.044216
0.038436
0.032655
0.026874
0.021093
0.015312
0.0095316
0.0037508
🟦 **-0.00203 Min**

Y- deformation
Max=0.049"



F: Static Structural
Directional Deformation Z
Type: Directional Deformation(Z Axis)
Unit: in
Global Coordinate System
Time: 1
6/12/2020 1:58 PM

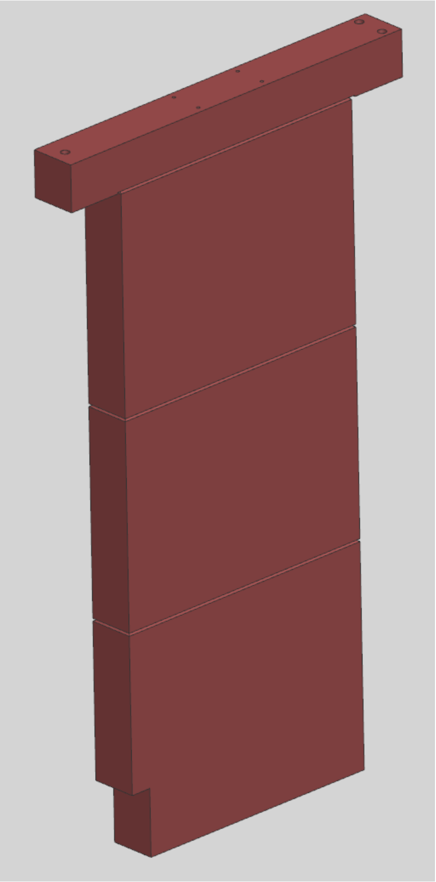
🟥 **0.0086195 Max**
0.0067562
0.0048929
0.0030296
0.0011662
-0.00069709
-0.0025604
-0.0044237
-0.0062871
🟦 **-0.0081504 Min**

Z- deformation
Max=0.008"

Air Cooled Steel Core Modules

Air-Cooled Steel Core Modules

- A previous design iteration had the final 4 steel core modules fitted with water cooling loops
  - These have been removed in favor of air cooling
  - See DUNE-doc-24749
- 4 kW of heat total in last four steel core blocks
  - Conservatively assume all 4 kW in first block, and cool with 10 m/s of air in 5mm gap (instead of 15 m/s)
  - Assume 2 kW out front and back face
- Center temperature of 44.6 C (below 260 C limit for Aeroglaze paint)
  - Water cooling is unnecessary, air cooling is sufficient
- Removes 4 water loops, and reduces cost of all-steel modules



Radiation Modeling

Radiation Modeling

- The MARS group has a 3D model of the Absorber (built from the version-controlled CAD assembly in Teamcenter) to use for dose and particle flux calculations
  - See DUNE-doc-27243 for initial residual dose calculations (2022)
  - See DUNE-doc-27733 for LBNF Preliminary Shielding Assessment
    - Shielding thickness details
    - Irradiated air paths through complex
  - See DUNE-doc 31590 for HaDES Shielding discussion (2024)
  - See DUNE-doc 32390 for maintenance scenario and updated residual dose (2024)

Residual Dose Modeling

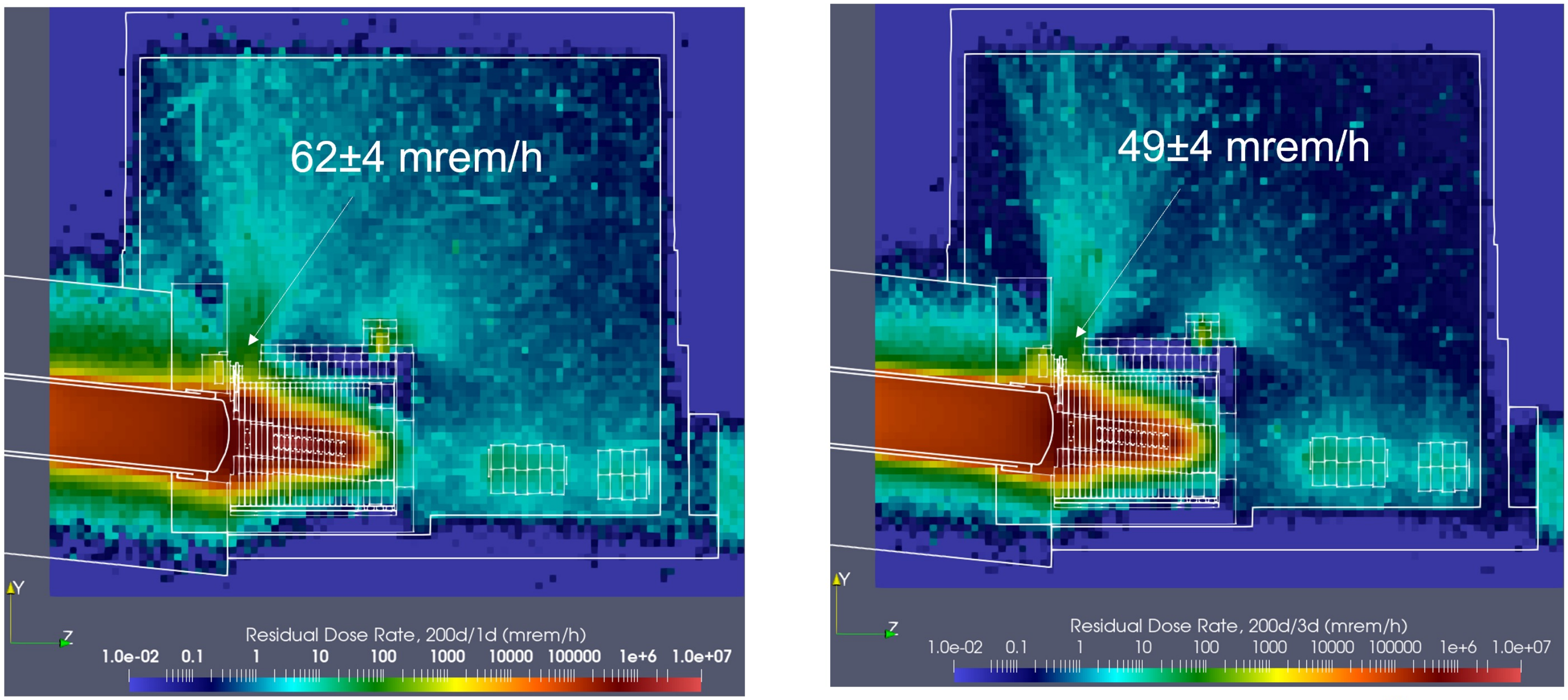
- DUNE-doc-32390
- Assume 200-day irradiation, followed by a maintenance access at the upstream end of the pile
  - 1, 3, 7, 14-day cooling periods
- G-blocks removed to access top of steel
  - E.g., to attach a lifting fixture, access a thermocouple connection, or diagnose a water connection
- Hotspot at upstream end by HADeS
  - Motivation for new steel shielding structure at this location
- Downstream and off-center areas have much lower dose rates

Residual Dose Modeling

Elevation view (slice 33 cm along X axis)

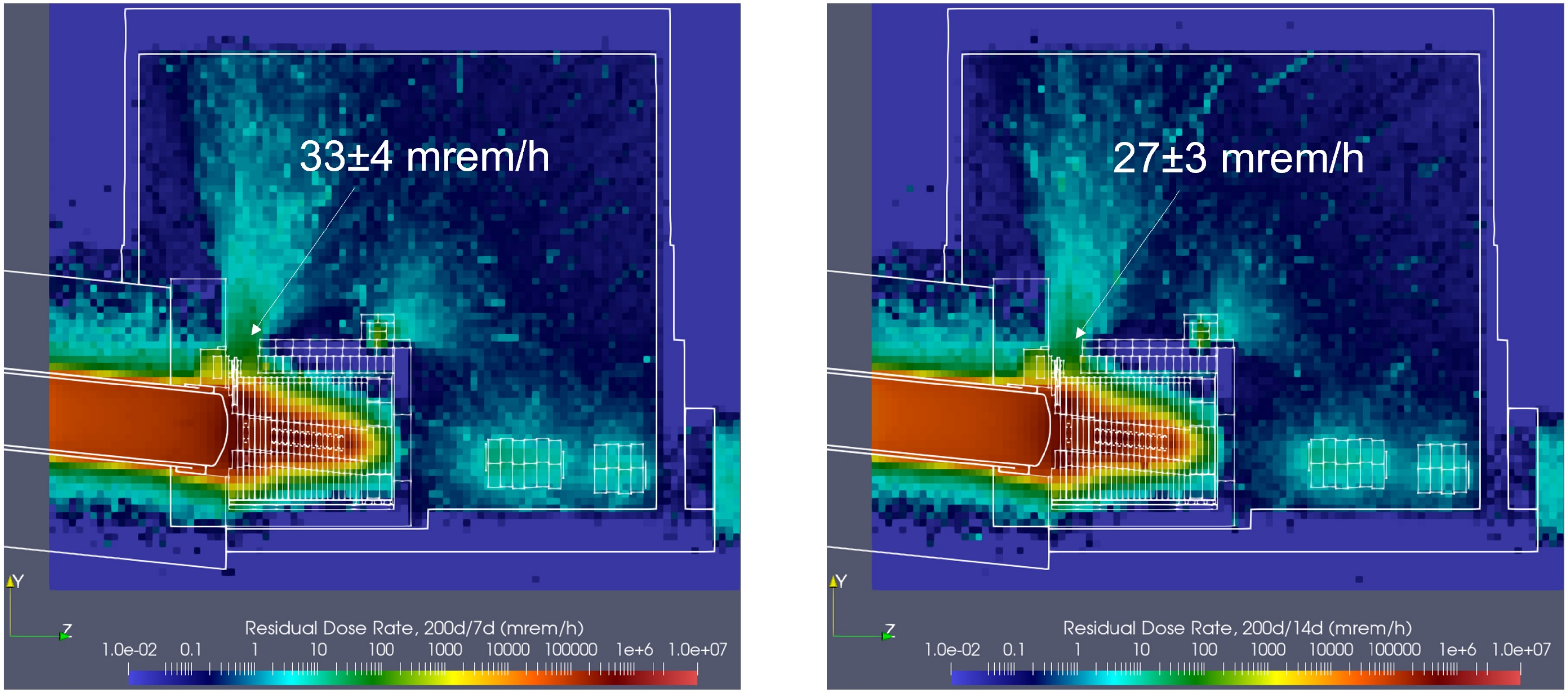
1 day cooling

3 days cooling



Residual Dose Modeling

Elevation view (slice 33 cm along X axis)

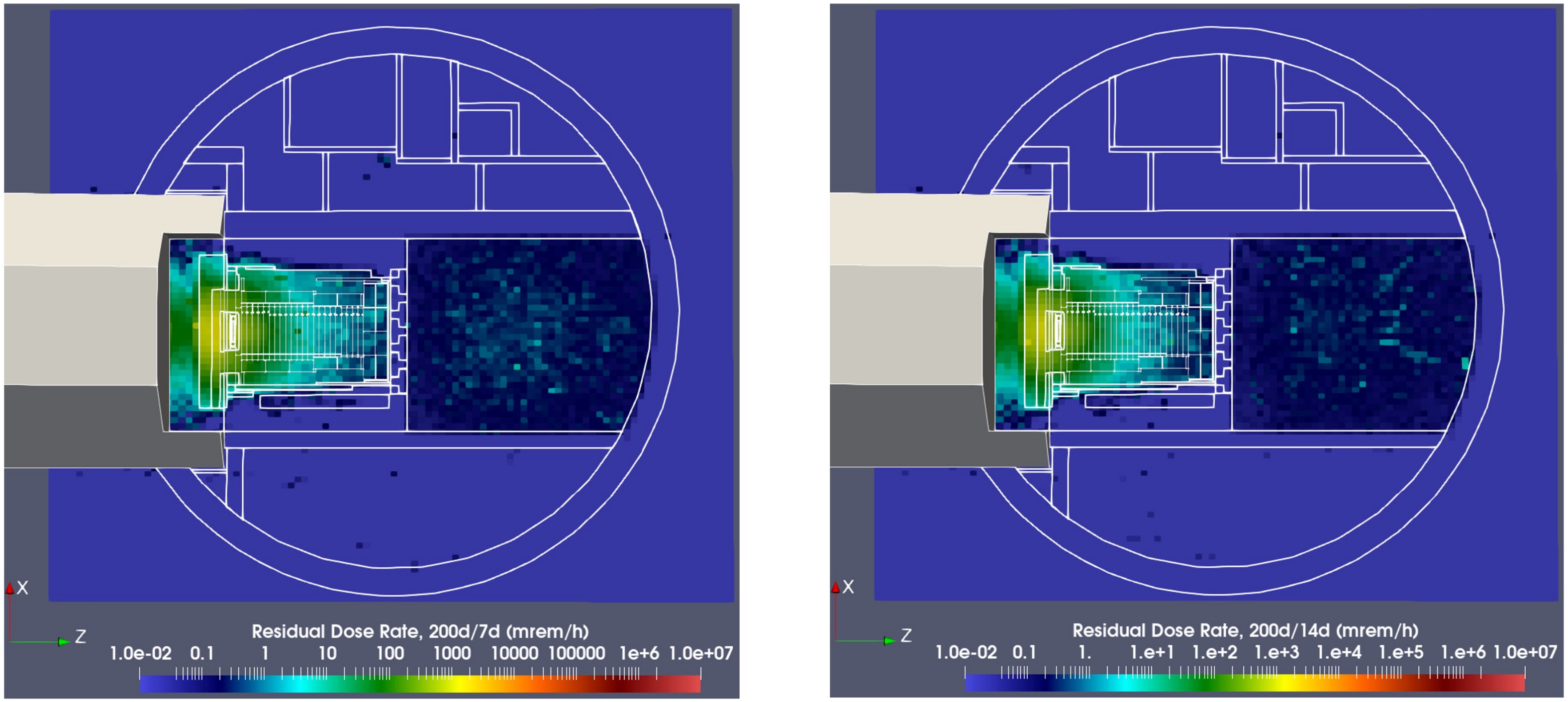


7 days cooling

14 days cooling

Residual Dose Modeling

Plan view through air gap between steel and concrete (slice 39 cm along Y axi



7 days cooling

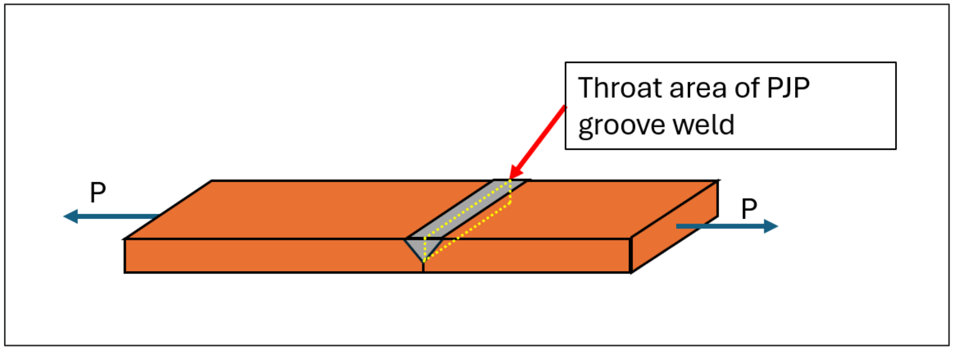
14 days cooling

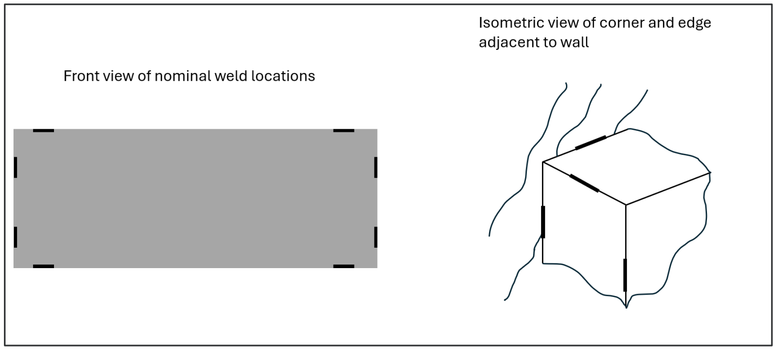
Installation Stability and Structural Analysis

Outer Steel Weld Sizing

- DUNE-doc-30781
- AISC Spec. for Structural Steel Buildings used to size welds
  - Base and weld metal checks, tension and shear, throat requirement based on thickness
- Partial joint penetration (PJP) groove welds, 6” effective length
  - preparation bevel may be made longer for less sensitivity to alignment

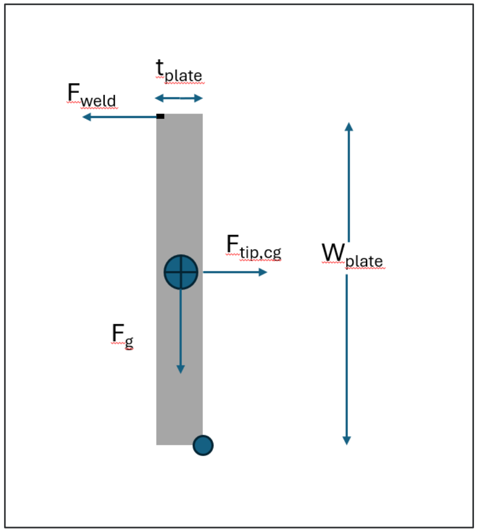
Weld throat size	½”	5/8”
Tension strength	67 kips	83.8 kips
Shear strength	52.2 kips	54 kips

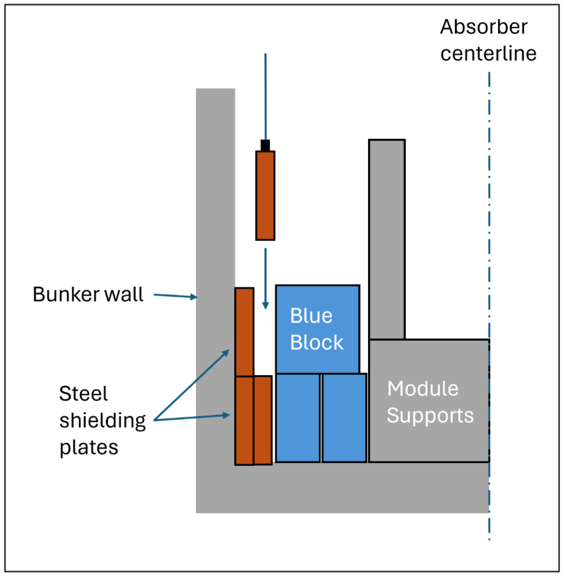




Outer Steel Installation

- Assume a 9.11” plate experiences a 5% sideload applied at c.g.
  - 1.4 kips on a single weld. Multiple welds are still used for stability
- Blue Blocks will be used to brace steel plates in position to eliminate the possibility of a plate tipping onto workers

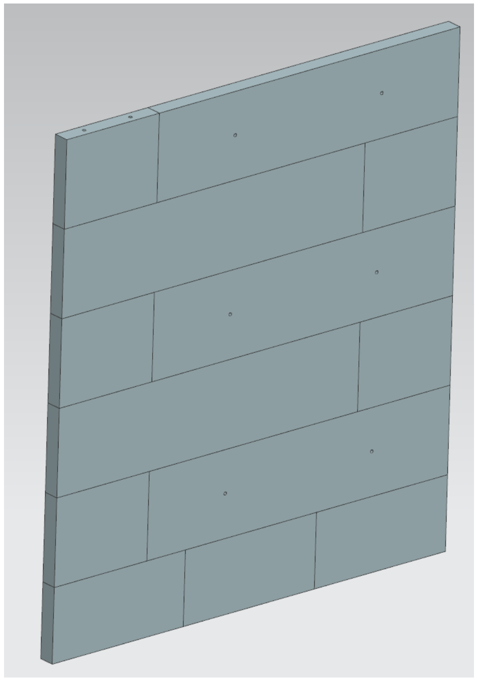


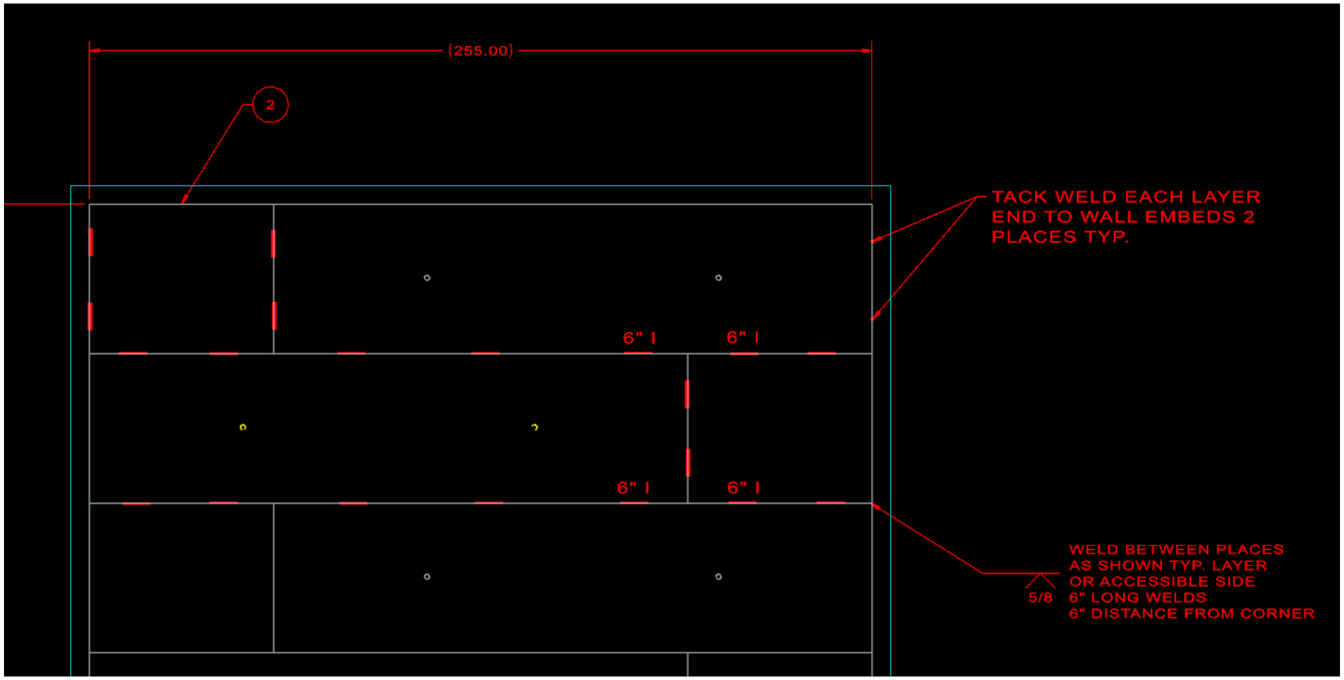


Weld throat size	½”	5/8”
Tension strength	67 kips	83.8 kips
Shear strength	52.2 kips	54 kips

Outer Steel Weld Plan

- Representative weld plan for beam right side 9.11” steel layer





Backup

LBNF Beamline

- The LBNF primary beamline includes the extraction and transfer line from the Main Injector enclosure, the target station building (LBNF-20), the Decay Region/Decay Pipe, and the Absorber Complex.
  - Protons hit a graphite target in LBNF-20 to create pions, which are selectively captured by 3 pulsed focusing horns
  - Focused pions fly into the Decay Pipe, a large steel pipe filled with helium inside which they decay into muons (or antimuons), then neutrinos (or antineutrinos)
    - Neutrino/antineutrino mode depends on the sign of pion selected by the focusing horns
- 1.5m graphite target = 3 interaction lengths, ~4% of beam does not interact
  - Undecayed hadrons (pions, etc.) also remain further downstream
  - Remaining hadrons are filtered out by the Hadron Absorber, located at the end of the Decay Region
  - High-energy muons (leptons) penetrate through the Absorber and proceed into stacked steel muon shielding further downstream

Design Beam Condition

- 2.4 MW operation:1.5E14 protons per pulse at 120 GeV energy and 1.2 seconds repetition rate
  - This is the maximum upgraded beam power envisioned for LBNF
  - The Absorber is designed and built to this condition from the beginning. No upgrades are required.

Accident Conditions

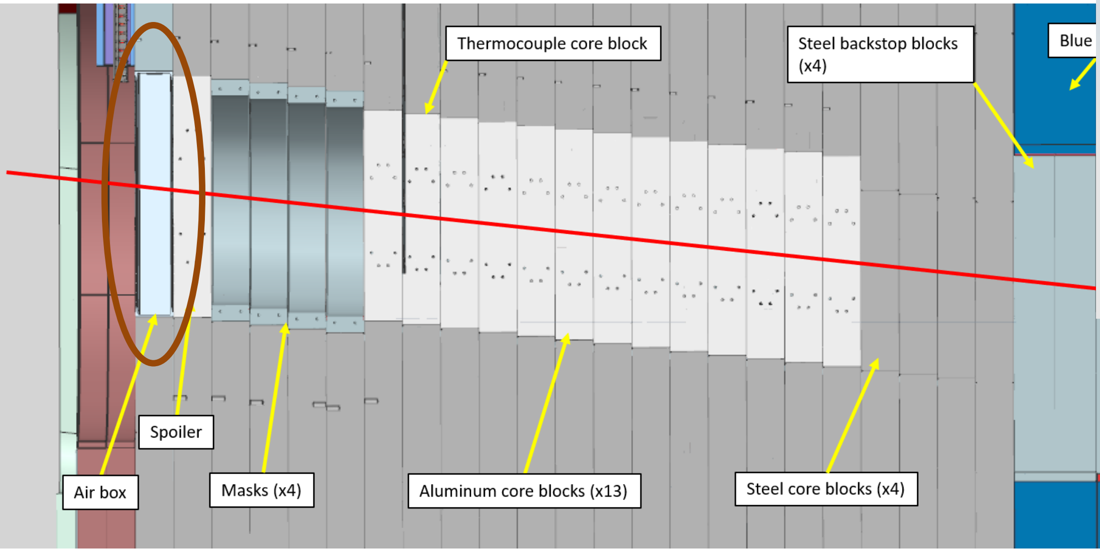
- Accident Pulse: assumes no target upstream, uninhibited beam, maximum energy and intensity on front face of Absorber
  - Both on-axis and mis-steered (hitting water passage) cases examined
- Requirement to limit to 2 accident pulses – Absorber is designed to survive 2 accident pulses
  - Keep materials within prescribed temperature limits – administrative limits set well below melting point
    - 100 C for Aluminum blocks (to avoid creep) and 260 C for steel (temperature limit of paint)
- Multiple independent aborts to withdraw beam permit in time to prevent a third accident pulse
  - In LBNF-30: Thermocouple array (absolute and relative limits, x228 channels) and MuMS count aborts can withdraw permit

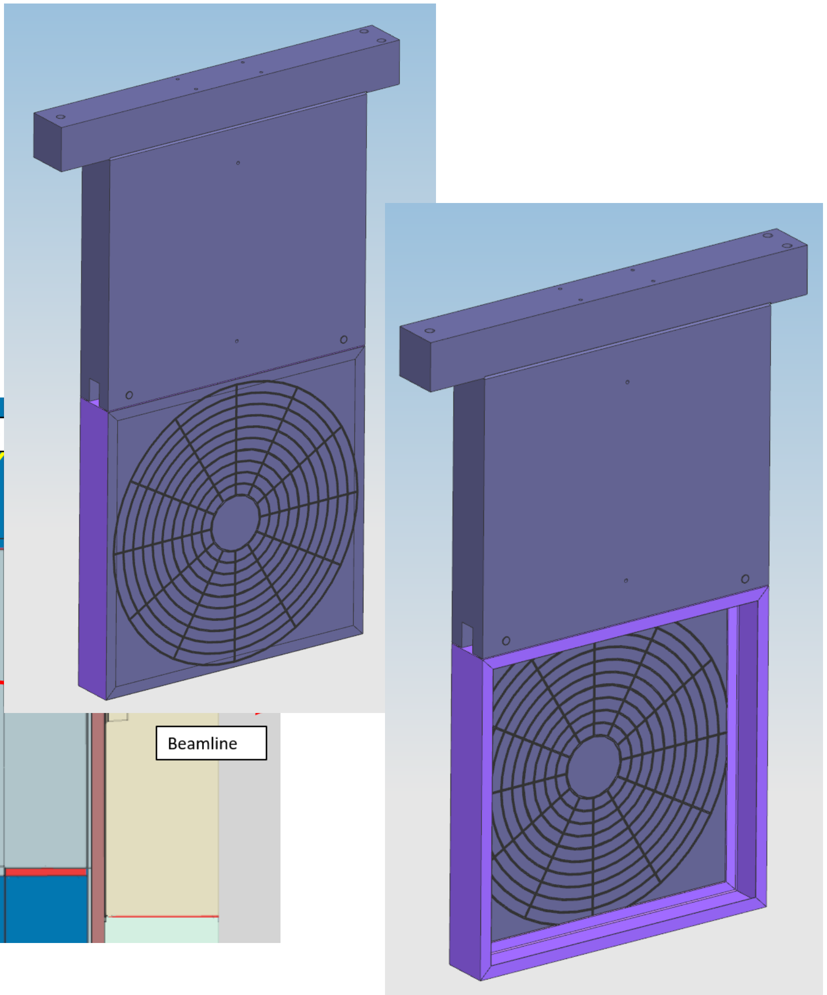
Data Management

- Relevant review documentation is included in (or linked from) DUNE-doc-30121
- Engineering Notes are generally hosted on Teamcenter
  - Notes have been included in the DocDB entries as dated copies for easier reference
- The CAD model for the Absorber (and integration model for the LBNF-30 Absorber Complex) are maintained on Teamcenter
  - F10156700 – Absorber model
  - F10151229 – LBNF-30 Integration model
- Individual part drawings are complete consistent with 90% design completion
  - installation/assembly prints of outer shielding (specific in-process weldments)
  - Assembly step-by-step prints (This will occur after FDR – plan exists, but not in official drawings yet. See later talks)

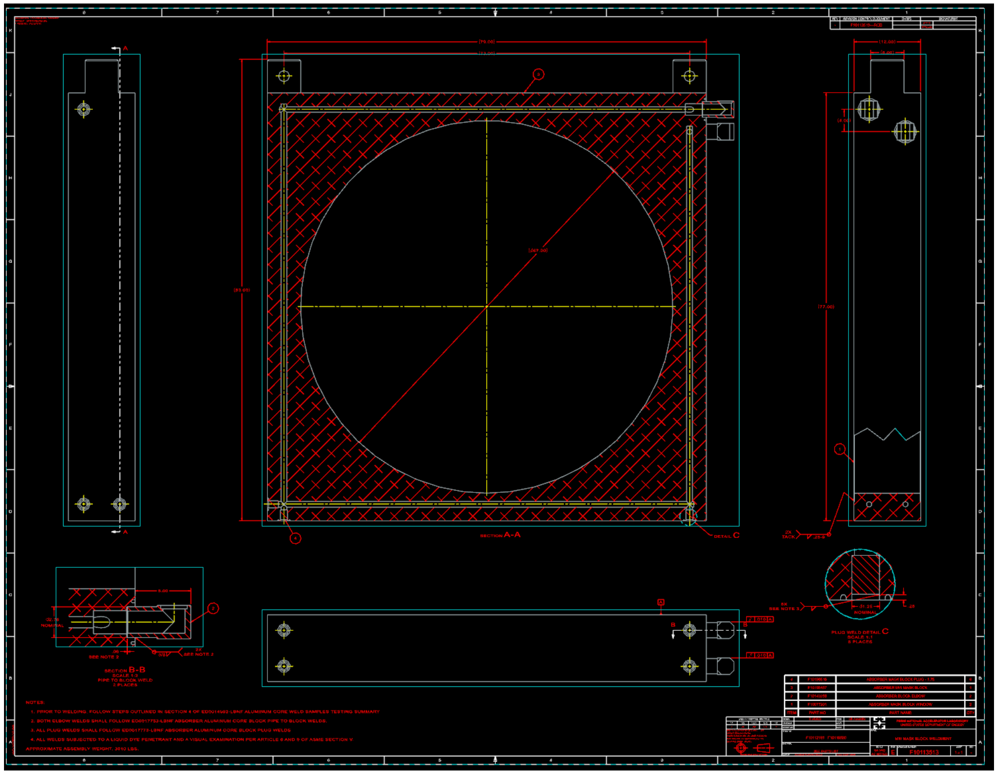
Spoiler, Masks, and Al Core Blocks

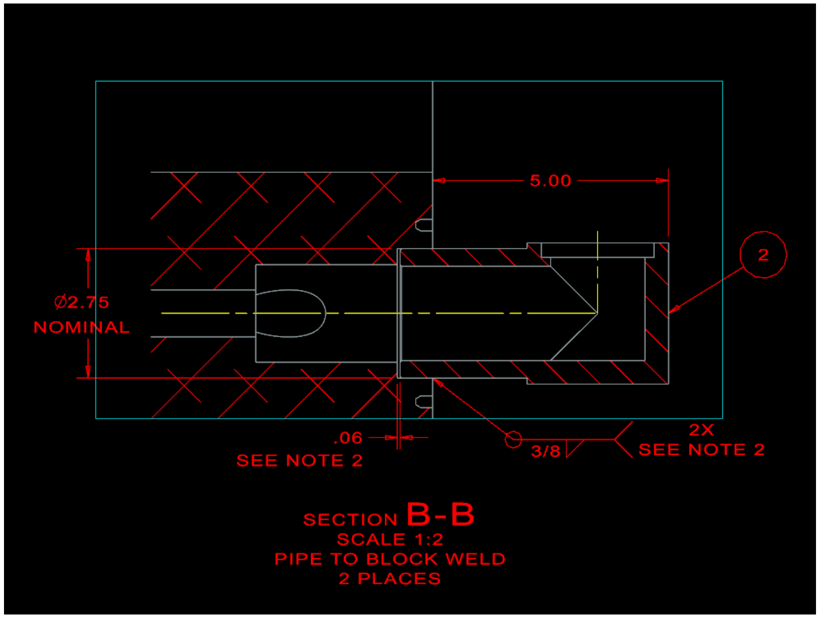
- Upstream of the Spoiler is the Air Box
  - Hollow aluminum box that keeps the air channel sizing in front of the spoiler without a solid core block



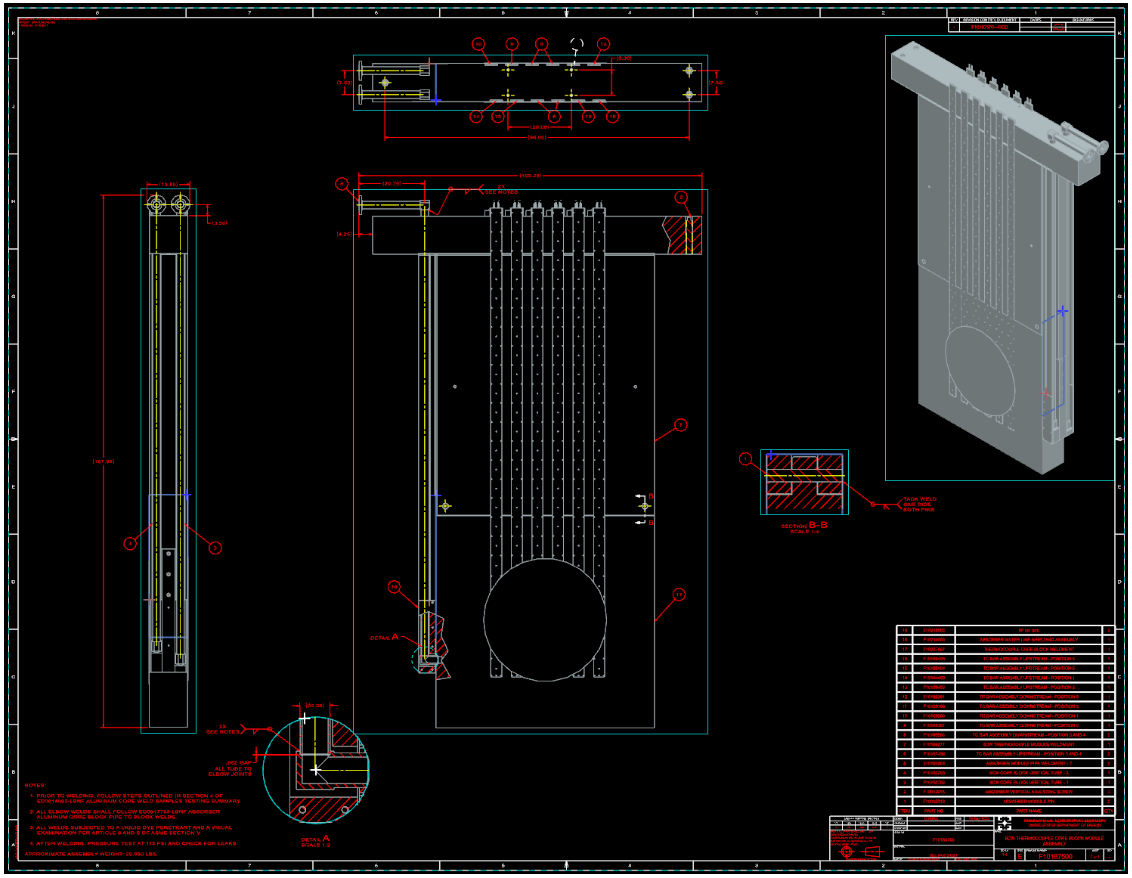


Mask Block (Wide) Weldment Drawing - F10113513





Thermocouple Core Module Drawing – F10167500



NOTES:

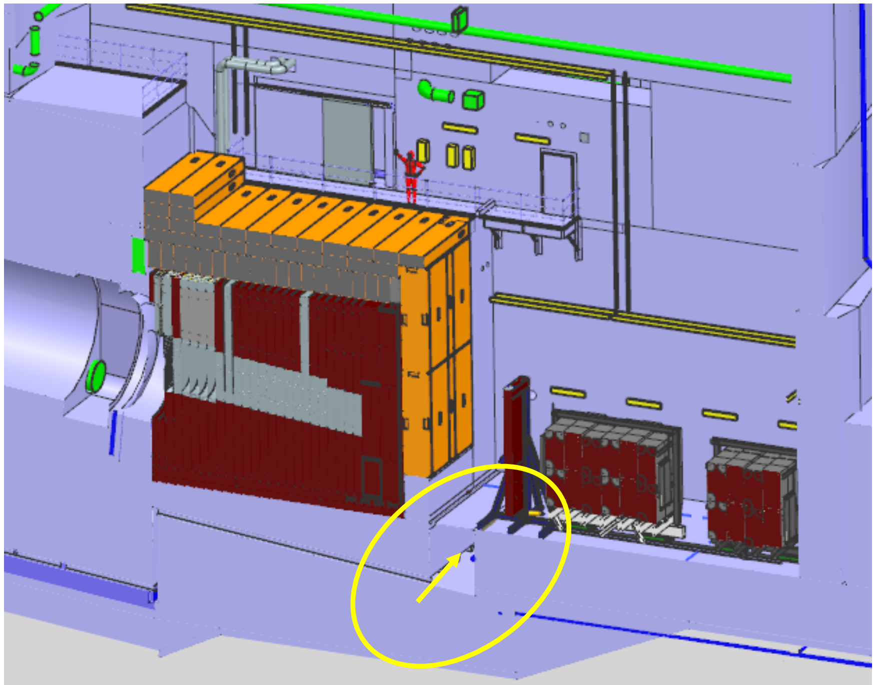
1. PRIOR TO WELDING, FOLLOW STEPS OUTLINED IN SECTION 4 OF ED0014692-LBNF ALUMINUM CORE WELD SAMPLES TESTING SUMMARY
2. ALL ELBOW WELDS SHALL FOLLOW ED0017753-LBNF ABSORBER ALUMINUM CORE BLOCK PIPE TO BLOCK WELDS.
3. ALL WELDS SUBJECTED TO A LIQUID DYE PENETRANT AND A VISUAL EXAMINATION PER ARTICLE 6 AND 9 OF ASME SECTION V.
4. AFTER WELDING, PRESSURE TEST AT 115 PSI AND CHECK FOR LEAKS.

APPROXIMATE ASSEMBLY WEIGHT: 29,630 LBS.

ITEM	PART NO	PART NAME	QTY
19	[illegible]	[illegible]	2
18	[illegible]	ABSORBER WATER LINE SHIELDING ASSEMBLY	1
17	[illegible]	THERMOCOUPLE CORE BLOCK WELDMENT	1
16	[illegible]	TC BAR ASSEMBLY UPSTREAM - POSITION 6	1
15	[illegible]	TC BAR ASSEMBLY UPSTREAM - POSITION 5	1
14	[illegible]	TC BAR ASSEMBLY UPSTREAM - POSITION 1	1
13	[illegible]	TC BAR ASSEMBLY UPSTREAM - POSITION 2	1
12	[illegible]	TC BAR ASSEMBLY DOWNSTREAM - POSITION 6	1
11	[illegible]	TC BAR ASSEMBLY DOWNSTREAM - POSITION 5	1
10	[illegible]	TC BAR ASSEMBLY DOWNSTREAM - POSITION 1	1
9	[illegible]	TC BAR ASSEMBLY DOWNSTREAM - POSITION 2	1
8	[illegible]	TC BAR ASSEMBLY DOWNSTREAM - POSITION 3 AND 4	2
7	[illegible]	BCW THERMOCOUPLE MODULE WELDMENT	1
6	[illegible]	TC BAR ASSEMBLY UPSTREAM - POSITION 3 AND 4	2
5	[illegible]	ABSORBER MODULE PIPE WELDMENT - 2	2
4	[illegible]	BCW CORE BLOCK VERTICAL TUBE - 2	1
3	[illegible]	BCW CORE BLOCK VERTICAL TUBE - 1	1
2	[illegible]	ABSORBER VERTICAL ADJUSTING SCREW	3
1	[illegible]	ABSORBER MODULE PIN	2

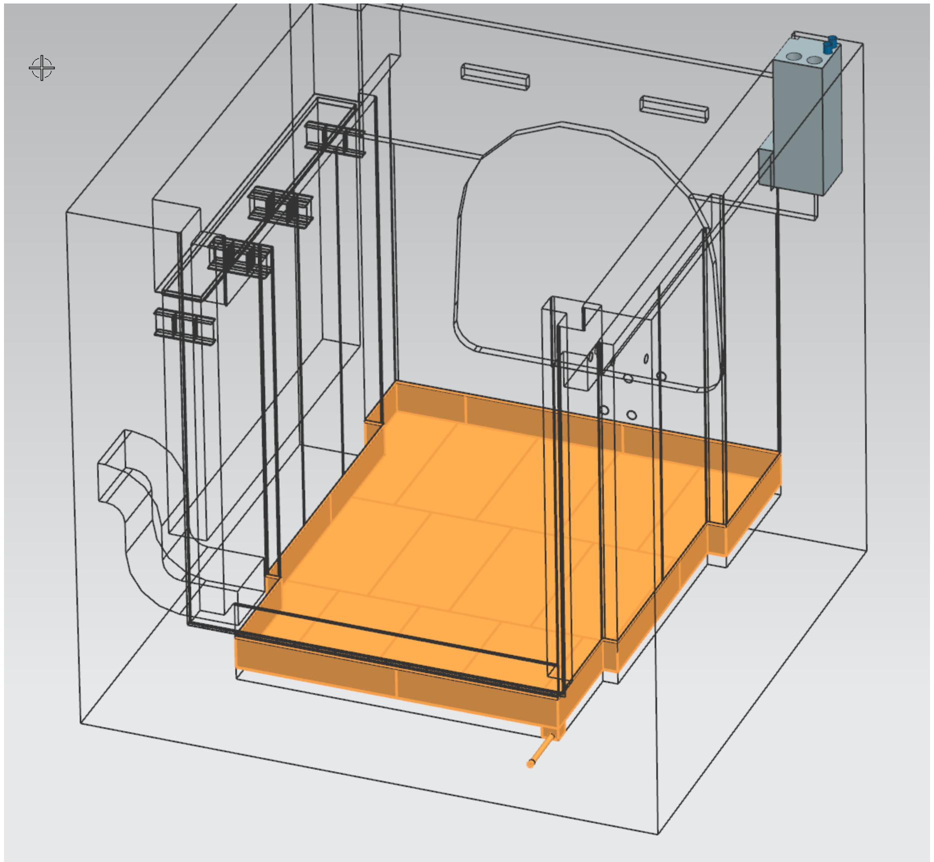
RAW Pan Drainage

- Drains to instrumented sump tanks in lower beam-left level of LBNF-30
    - Drain positioned at downstream beam-left corner of bunker, in a socket in the shielding
    - Drain pipe exits into the grating-covered trench just downstream of the bunker, upstream of the crane landing area
        - Piping continues to sump towards beam-left
    - Top edge of pan welds to stainless steel strip embeds in bunker wall to seal against the wall



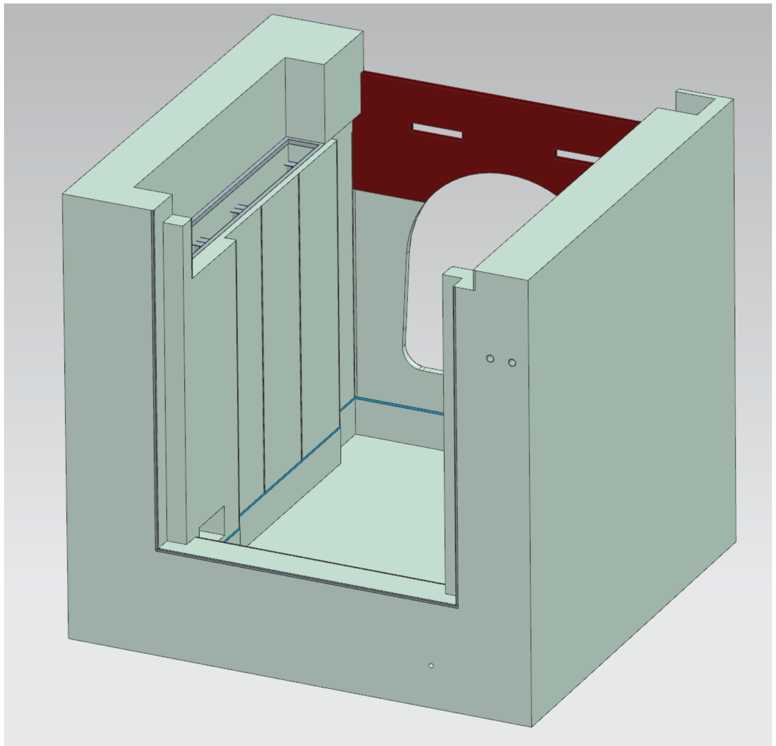
RAW Pan Drainage

- An instantaneous, catastrophic loss of all coolant water would fill the pan to a depth of several inches (<1 ft with steel shielding in place)
- That much water will self-level
  - Pan does not need to be slanted – return air channels guide any massive spills to the downstream end of the Bunker
  - Small leak - drips and evaporates
  - Medium leak, pools and evaporates
  - Catastrophic leak – fills pan and flows towards low point (drain)



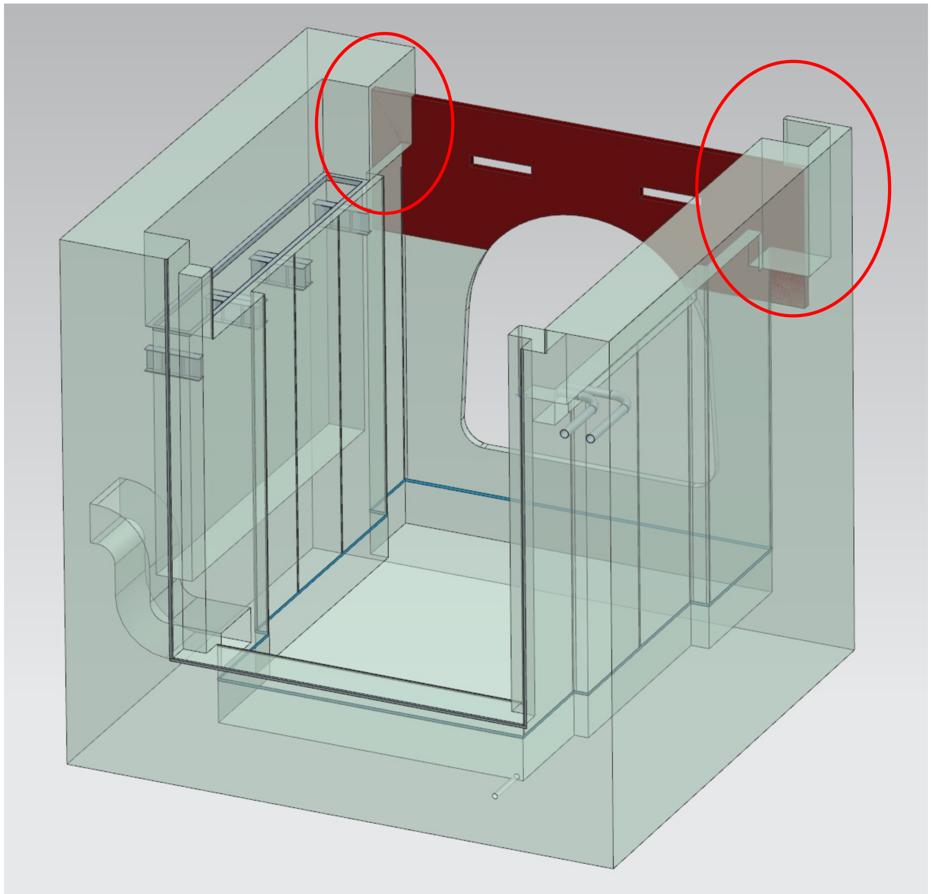
Bunker

- Concrete enclosure in LBNF-30 built by Near Site CF
  - Structurally part of the Decay Pipe Shielding
- Slides on “rails” (HSS beams) within Absorber Hall
  - 6” gap provided by CF between end of Decay Pipe Shielding and Absorber Hall foundation
  - ~2” travel expected during operation
  - Expansion joints/gaps provided for air ducting, water pipes, and walkways around the bunker
  - See Volume 3 of NSCF drawing package (DUNE-doc-29403)



Bunker Upstream Concrete Pours

- 2 in-situ concrete pours to finish bunker around parts
  - Upstream top beam-right – space above outermost side steel shielding layer
    - This space could be filled with a custom concrete block or steel instead of a pour
  - Upstream top beam-left – Absorber water pipes and HaDES retraction system mechanism encased in concrete inside channel provided by CF
    - HaDES retraction mechanism elements may route through here depending on final design of shielding castle. Space is reserved.

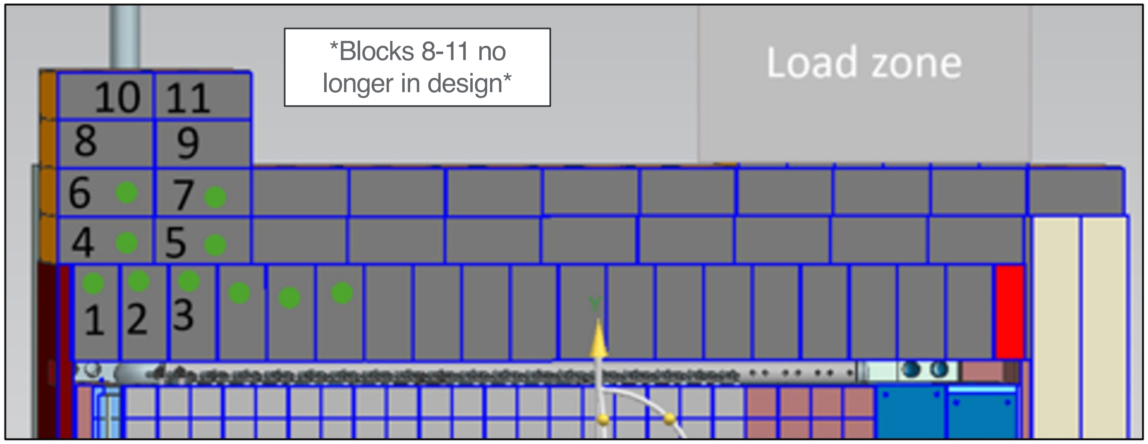


G-Block Cover Load Capacity

G-Block Cover Load Capacity (from ISD)

- See DUNE-doc-32420
- During installation activities, RAW Room shield door pieces need to be moved into position
  - Current plan is a piece-by-piece door install. Initial plans were a monolithic install
- During operational maintenance, water deionizer bottles are removed at intervals into shielding casks
  - These casks are made of thick steel and very heavy (26,740 lbs for a fully-loaded cask)

Blocks with green mark are heavy borated concrete



Blocks 8-11 no longer in design

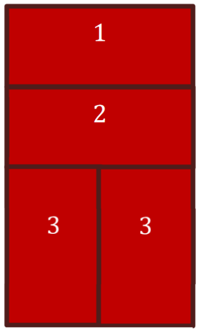


Figure 2. Analysis Section

G-Block Cover Load Capacity (cont.)

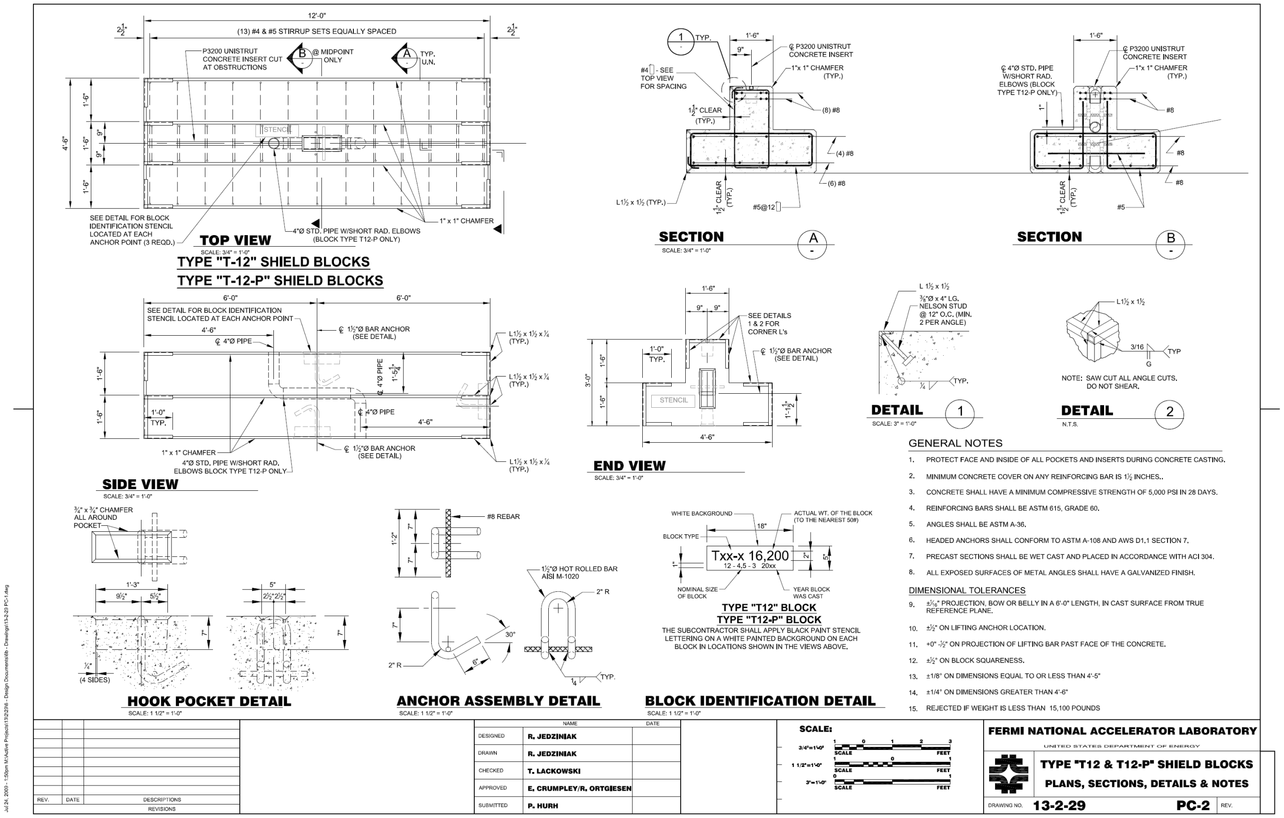
- ISD analyzed the G-block cover to establish load-bearing capacity
  - Max service level live point loading is 21,000 lbs on G- block cover
  - DI cask distributes load across multiple blocks, so it’s ok
- ISD recommends that areas with heavy concrete blocks underneath should not have additional weight placed on them, or that more-heavily-reinforced blocks be designed and used.
- The plan is to redesign the heavy blocks with more reinforcement to avoid this concern
  - Heavy blocks have not been procured yet
  - All standard-weight G blocks and T-12 blocks are already on-site

“G” Concrete Shielding Blocks

“T-12” Concrete Shielding Blocks

T-12 Block Drawing

- All T-12 blocks in the Absorber are T-12, not T-12P
  - T-12P blocks have a labyrinth pipe



THE SUBCONTRACTOR SHALL APPLY BLACK PAINT STENCIL LETTERING ON A WHITE PAINTED BACKGROUND ON EACH BLOCK IN LOCATIONS SHOWN IN THE VIEWS ABOVE.

GENERAL NOTES

1. PROTECT FACE AND INSIDE OF ALL POCKETS AND INSERTS DURING CONCRETE CASTING.
2. MINIMUM CONCRETE COVER ON ANY REINFORCING BAR IS 1½ INCHES..
3. CONCRETE SHALL HAVE A MINIMUM COMPRESSIVE STRENGTH OF 5,000 PSI IN 28 DAYS.
4. REINFORCING BARS SHALL BE ASTM 615, GRADE 60.
5. ANGLES SHALL BE ASTM A-36.
6. HEADED ANCHORS SHALL CONFORM TO ASTM A-108 AND AWS D1.1 SECTION 7.
7. PRECAST SECTIONS SHALL BE WET CAST AND PLACED IN ACCORDANCE WITH ACI 304.
8. ALL EXPOSED SURFACES OF METAL ANGLES SHALL HAVE A GALVANIZED FINISH.

DIMENSIONAL TOLERANCES

9. ±1⁄16" PROJECTION, BOW OR BELLY IN A 6'-0" LENGTH, IN CAST SURFACE FROM TRUE REFERENCE PLANE.
10. ±½" ON LIFTING ANCHOR LOCATION.
11. +0" -½" ON PROJECTION OF LIFTING BAR PAST FACE OF THE CONCRETE.
12. ±½° ON BLOCK SQUARENESS.
13. ±1/8° ON DIMENSIONS EQUAL TO OR LESS THAN 4'-5"
14. ±1/4° ON DIMENSIONS GREATER THAN 4'-6"
15. REJECTED IF WEIGHT IS LESS THAN 15,100 POUNDS

	NAME	DATE
DESIGNED	R. JEDZINIAK	
DRAWN	R. JEDZINIAK	
CHECKED	T. LACKOWSKI	
APPROVED	E. CRUMPLEY/R. ORTGIESEN	
SUBMITTED	P. HURH	

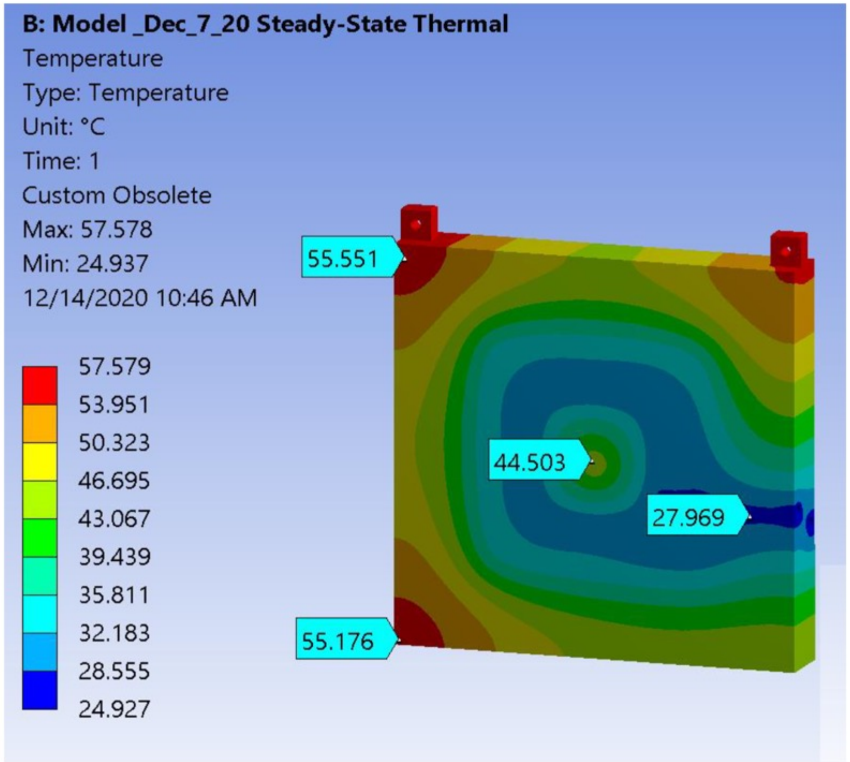
SCALE: 3/4"=1'-0" 1 1/2"=1'-0" 3"=1'-0"

FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY
TYPE "T12 & T12-P" SHIELD BLOCKS
PLANS, SECTIONS, DETAILS & NOTES
DRAWING NO. **13-2-29** **PC-2** REV.

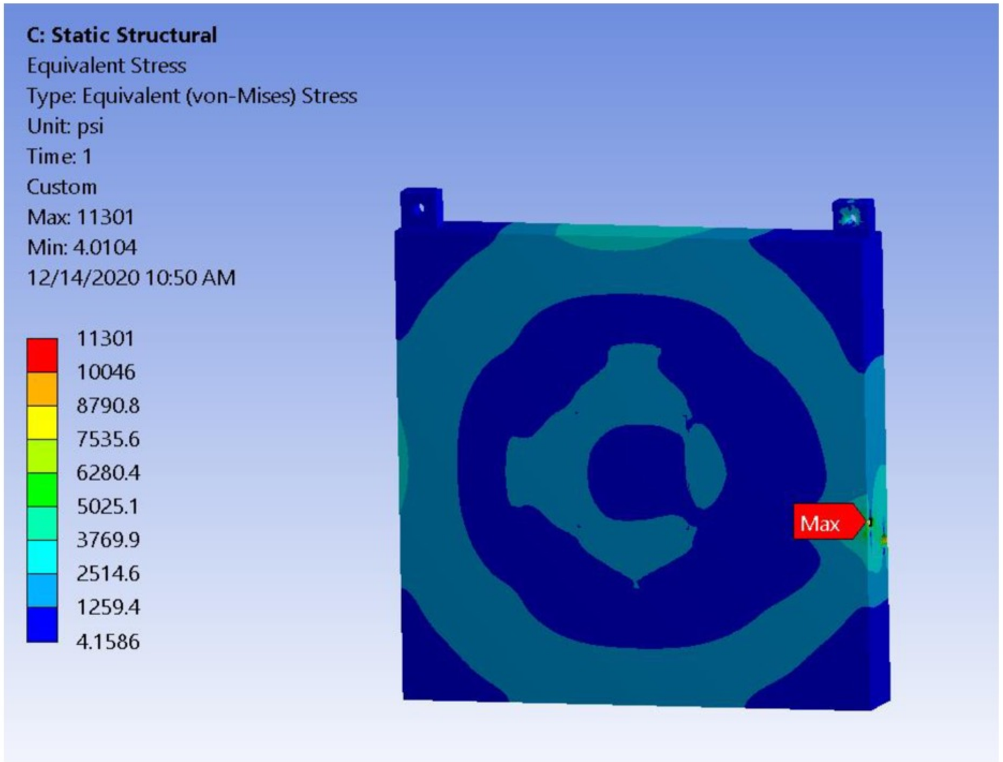
Backup

Spoiler Temperature and Stress

Spoiler Steady-State Temperature and Stress



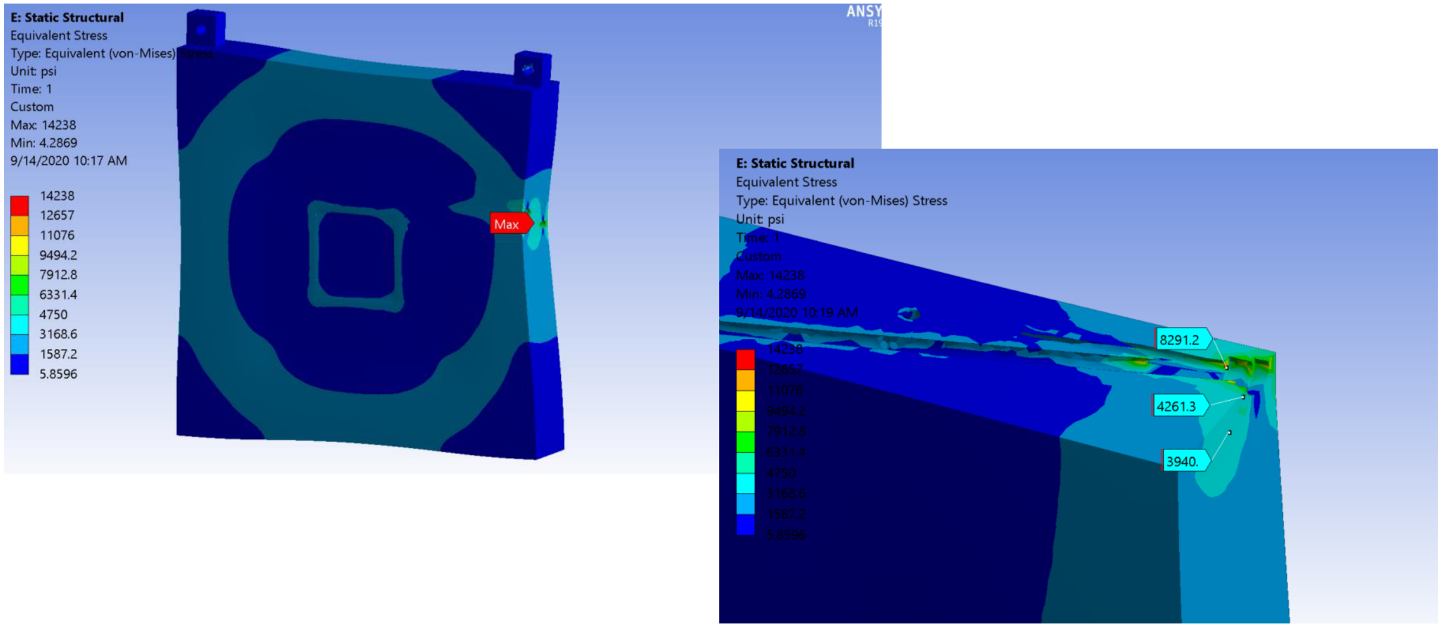
B: Model _Dec_7_20 Steady-State Thermal
Temperature
Type: Temperature
Unit: °C
Time: 1
Custom Obsolete
Max: 57.578
Min: 24.937
12/14/2020 10:46 AM



C: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 1
Custom
Max: 11301
Min: 4.0104
12/14/2020 10:50 AM

Spoiler Stress Detail

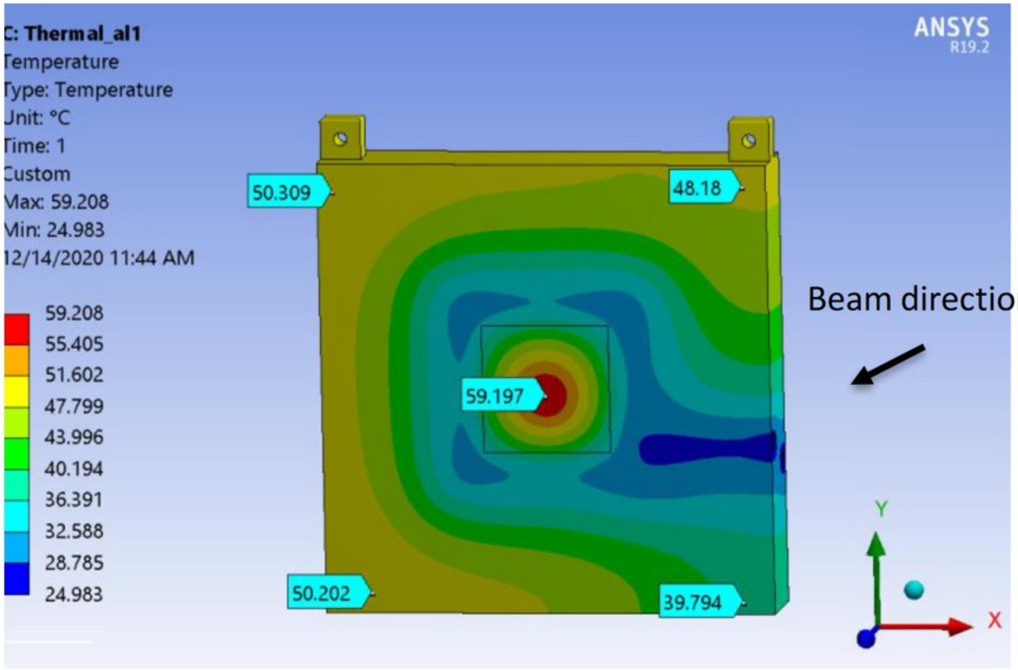
- Stress concentrations at sharp corners where gundrilled holes intersect



Rectangular cooling circuit stress (psi)

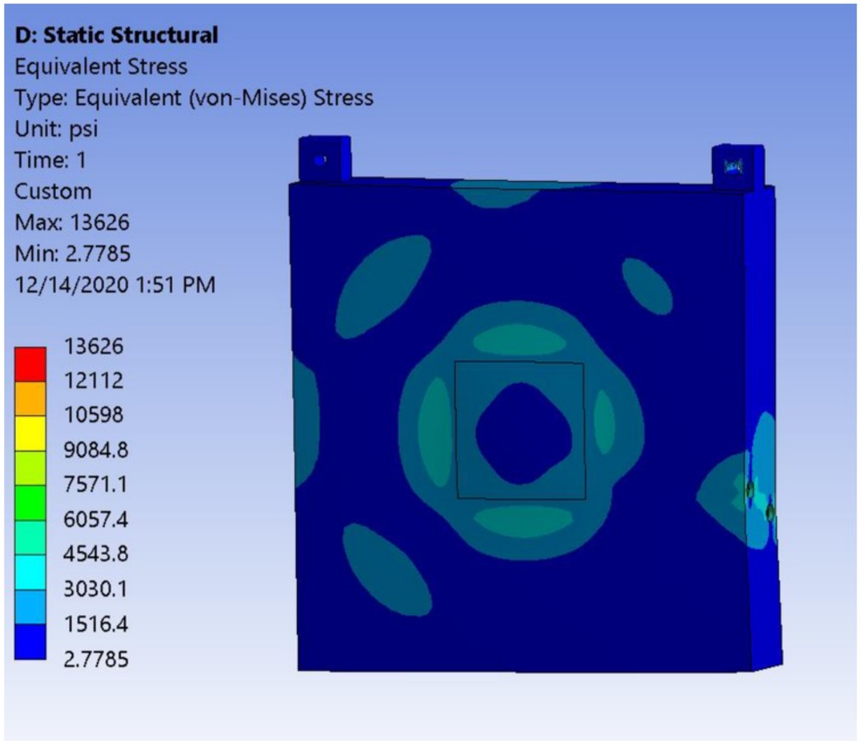
Aluminum Core 1 Temperature and Stress

Al Core 1 Steady-State Temperature and Stress



C: Thermal_al1
Temperature
Type: Temperature
Unit: °C
Time: 1
Custom
Max: 59.208
Min: 24.983
12/14/2020 11:44 AM

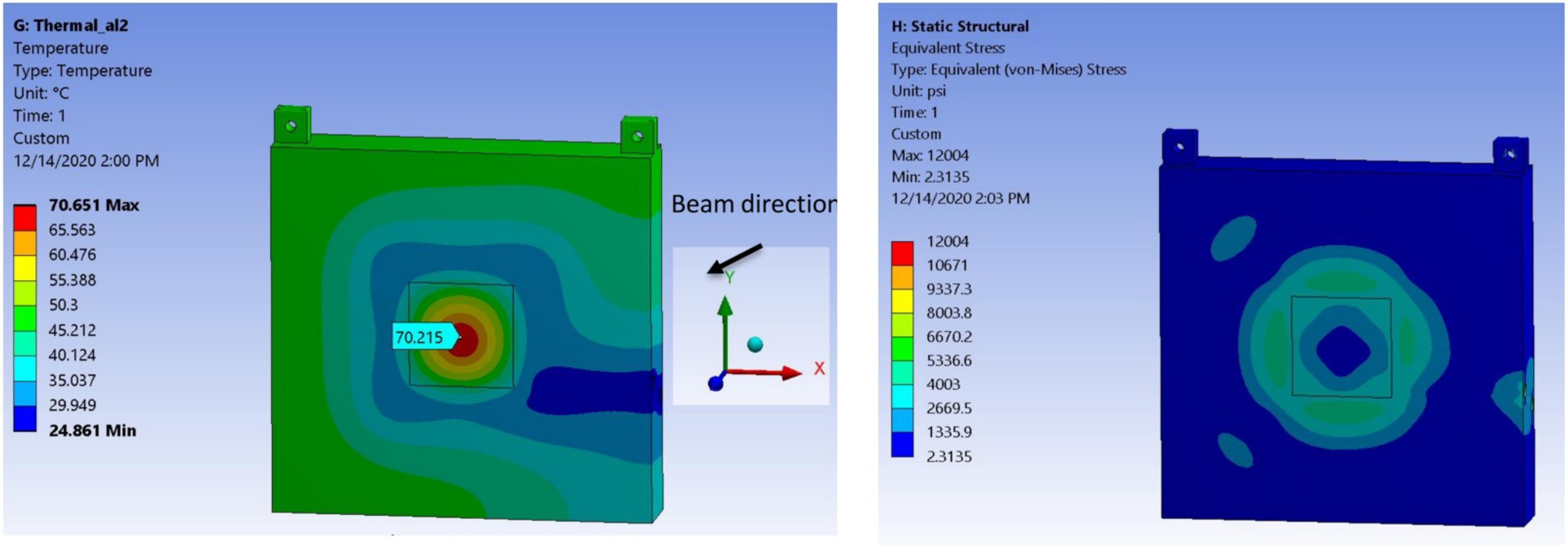
Beam direction +Z



D: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 1
Custom
Max: 13626
Min: 2.7785
12/14/2020 1:51 PM

Aluminum Core 2 Temperature and Stress

Al Core 2 Steady-State Temperature and Stress

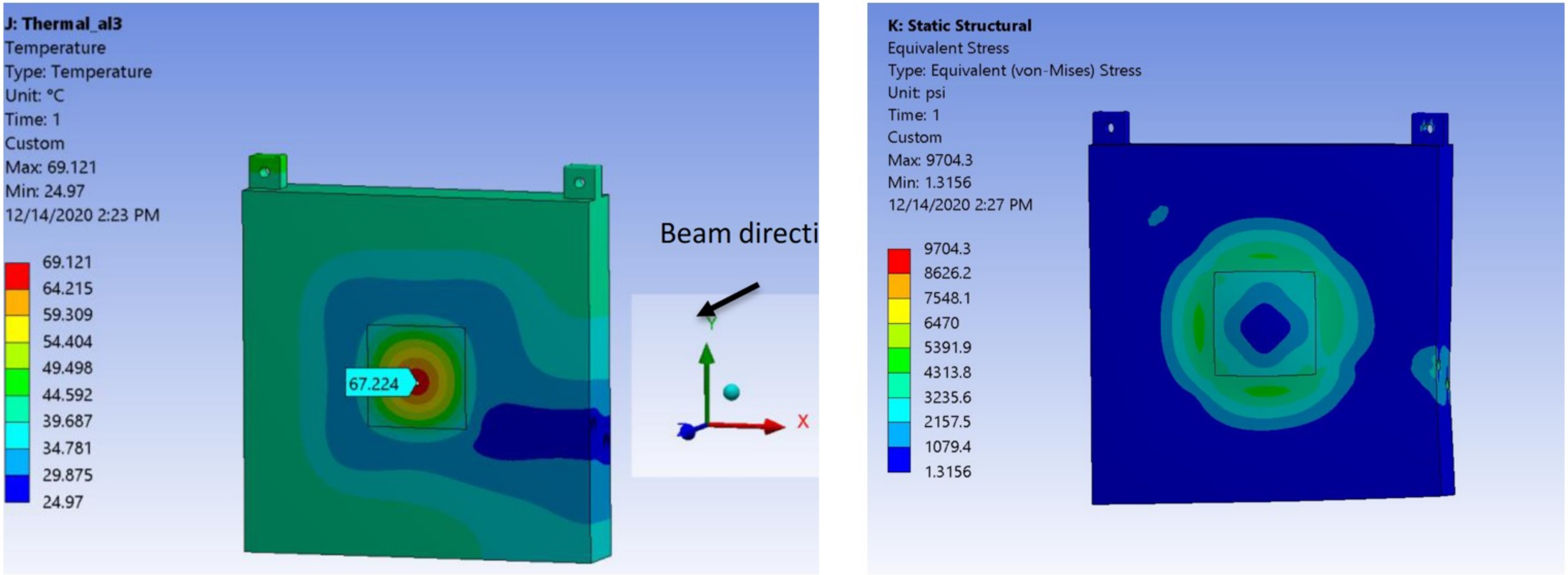


G: Thermal_al2
Temperature
Type: Temperature
Unit: °C
Time: 1
Custom
12/14/2020 2:00 PM

H: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 1
Custom
Max: 12004
Min: 2.3135
12/14/2020 2:03 PM

Aluminum Core 3 Temperature and Stress

Al Core 3 Steady-State Temperature and Stress



J: Thermal_al3
Temperature
Type: Temperature
Unit: °C
Time: 1
Custom
Max: 69.121
Min: 24.97
12/14/2020 2:23 PM

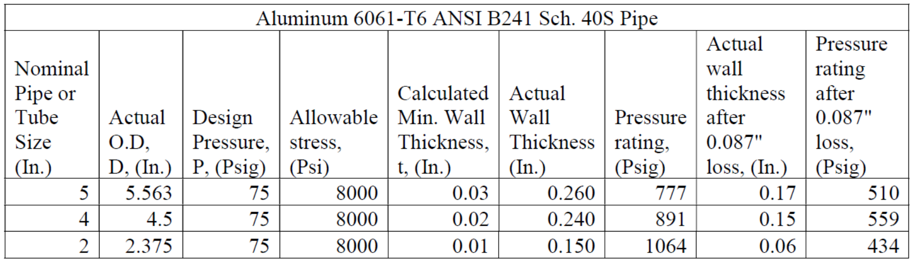
K: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 1
Custom
Max: 9704.3
Min: 1.3156
12/14/2020 2:27 PM

Water Pipe Corrosion and Erosion

Water Pipe Corrosion/Erosion

- ED0021908 is mirrored in DUNE-doc-32351
- Downcomer pipes: 2-inch Sch. 40 6061-T6 ANSI B241 pipe
- Calculated corrosion/erosion limit from starting minimum allowable pipe size (based on pipe dimension standard)
  - Worst case: 0.087” (2.22 mm) loss of wall thickness
  - Based on extremely conservative combination of test data
    - one test had entrained sand particles, which would speed up erosion)
    - See ED0021908-A Note on Flow Induced Corrosion/Erosion of 6061-T6 Aluminum

Table 4.2: Minimum wall thickness and pressure ratings of aluminum pipes.



Aluminum 6061-T6 ANSI B241 Sch. 40S Pipe								
Nominal Pipe or Tube Size (In.)	Actual O.D, D, (In.)	Design Pressure, P, (Psig)	Allowable stress, (Psi)	Calculated Min. Wall Thickness, t, (In.)	Actual Wall Thickness (In.)	Pressure rating, (Psig)	Actual wall thickness after 0.087" loss, (In.)	Pressure rating after 0.087" loss, (Psig)
5	5.563	75	8000	0.03	0.260	777	0.17	510
4	4.5	75	8000	0.02	0.240	891	0.15	559
2	2.375	75	8000	0.01	0.150	1064	0.06	434

Water Pipe Corrosion/Erosion

- Pressure rating recalculated based on thinner pipe
  - Ample margin remains on design pressure (434 psi rating vs. 75 psi)
  - This is the nominal code rating, not the point at which the pipe exceeds yield stress.
  - Recall wavefront pressure from earlier is 812 psi – Above 35-year limit in vertical pipe?
    - Actual pipe yielding pressure after corrosion is 1857 psi (Barlow's formula)
  - Also note: This pressure would not make it to the vertical pipe
    - Attenuate in 1) increased area from joined gundrilled passages, and 2) through miter elbow

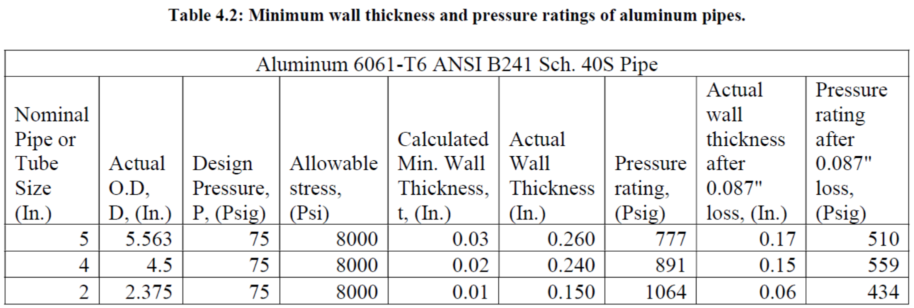


Table 4.2: Minimum wall thickness and pressure ratings of aluminum pipes.

Aluminum 6061-T6 ANSI B241 Sch. 40S Pipe								
Nominal Pipe or Tube Size (In.)	Actual O.D, D, (In.)	Design Pressure, P, (Psig)	Allowable stress, (Psi)	Calculated Min. Wall Thickness, t, (In.)	Actual Wall Thickness (In.)	Pressure rating, (Psig)	Actual wall thickness after 0.087" loss, (In.)	Pressure rating after 0.087" loss, (Psig)
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Beam Strike on Core Water Passage

Also discussed in “Responses to Previous Recommendations” Talk

Beam Strike on Core Water Passage

- ED0025893, mirrored in DUNE-doc-32369
- An uninhibited 2.4 MW beam pulse striking a water passage in the Absorber core was identified as a credible accident scenario not previously addressed
  - TC array circle defines possible impact locations, water passages are within the circle

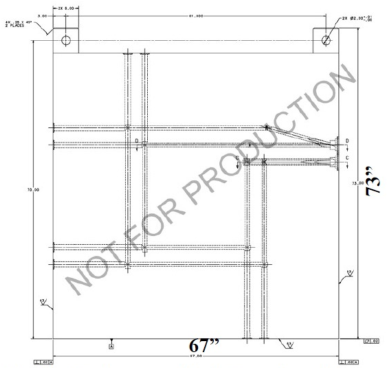


Fig 2.1: Aluminum core block front view with gun-drilled water channels shown.

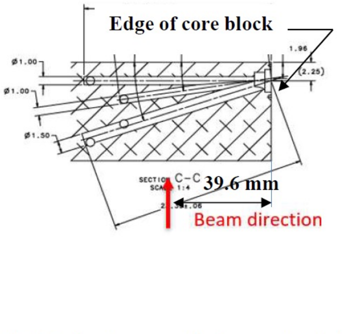


Fig 2.2: Aluminum core block top sectional view showng the water channels converging into a 2” port.

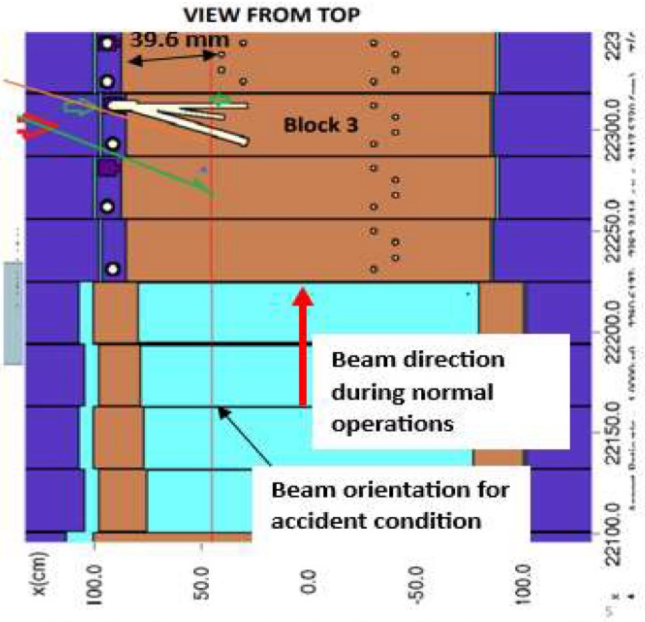


Fig 2.3: Top view of the Absorber core showing the accident beam and the operational beam.

Beam Strike on Core Water Passage

- Controlling code for the Absorber is ASME B31.3
  - Pressure spike in the water channel due to accidental beam pulse can be categorized as a dynamic/impact effect under Para 301.5.1 of ASME B31.3 .
  - Para 301.5.1 only mandates that dynamic impacts shall be considered. Appendix F of ASME B31.3 [4] offers guidance and cautionary statements but does not mandate how to take them into account.
- The following analysis shows that stresses developed in the elbow, fillet weld connecting elbow to the block, and the pipe are below allowable limits.
  - Due to the vague guidance of B31.3 for transient effects, “allowable limits” changes somewhat for each case. Assumptions are noted in each case that follows

Beam Strike on Core Water Passage

- Transient CFD analysis to simulate pressure spike in water channel
- Maximum wavefront pressure determined to be 812 psi
  - This is the pressure realized at the elbow
- In the actual geometry, several gundrilled holes intersect moving toward the elbow
  - Area increases, attenuates pressure
  - 812 psi is a worst-case estimate

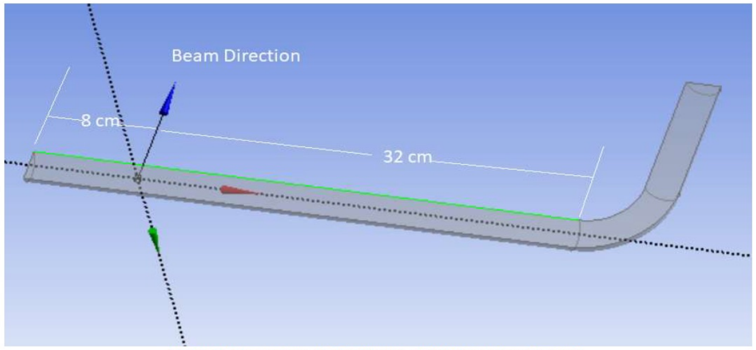


Fig 3.1: Geometry of the 1” gun-drilled cooling channel.

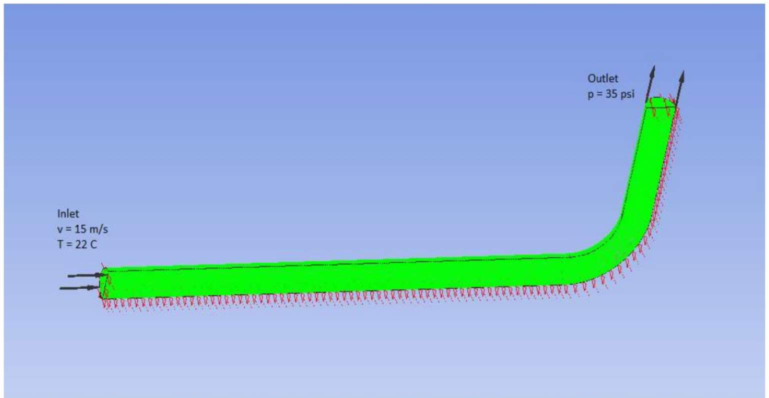


Fig 3.2: Boundary conditions for the static solution which would become the initial conditions for the transient analysis.

Beam Strike on Core Water Passage

- Wavefront generated at beam impact location
- Propagates through pipe towards elbow

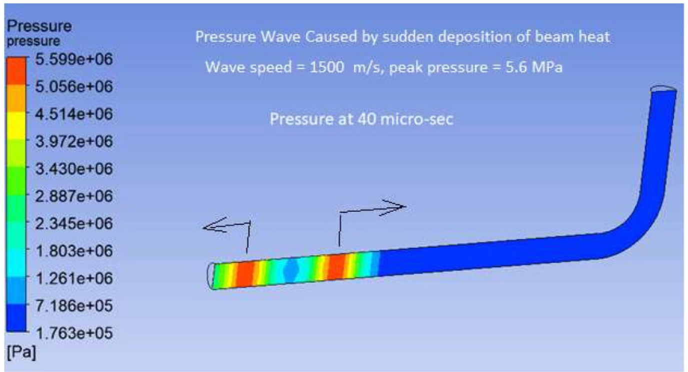


Fig 3.3: Pressure spike in cooling line at 40 µs caused by sudden deposition of energy.

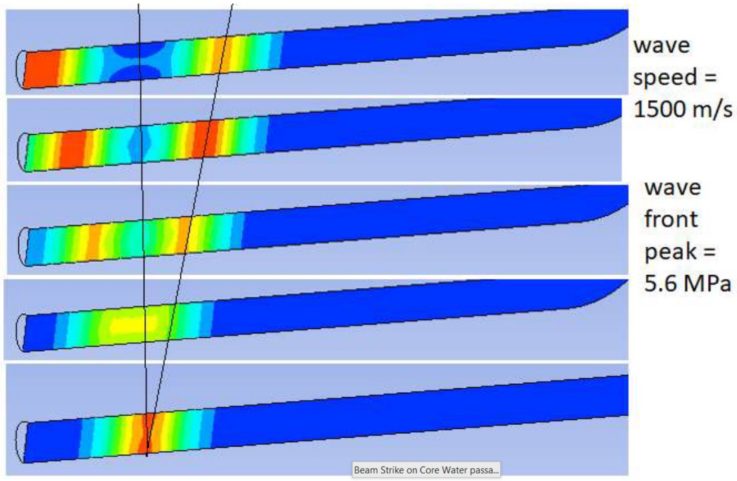
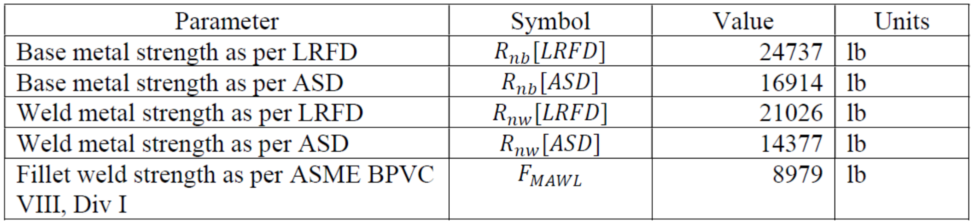


Fig 3.4: Wave speed and wavefront peak.

Beam Strike on Core Water Passage – Fillet Weld

- Weld details shown at right
- Governing code for Absorber water systems is ASME B31.3 Normal Fluid Service
- Effect on elbow determined by:
  - calculating strength of elbow according to various codes (take lowest value)
  - applying pressure load from wavefront and comparing strengths to allowable

Table 4.1: Calculated weld strengths as per various criteria.



Parameter	Symbol	Value	Units
Base metal strength as per LRFD	$R_{nb}[LRFD]$	24737	lb
Base metal strength as per ASD	$R_{nb}[ASD]$	16914	lb
Weld metal strength as per LRFD	$R_{nw}[LRFD]$	21026	lb
Weld metal strength as per ASD	$R_{nw}[ASD]$	14377	lb
Fillet weld strength as per ASME BPVC VIII, Div I	F_{MAWL}	8979	lb

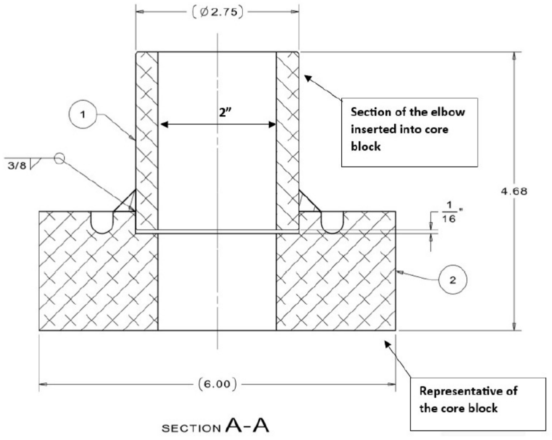


Fig 4.1: A representative drawing of the elbow welded to the side of the core block.

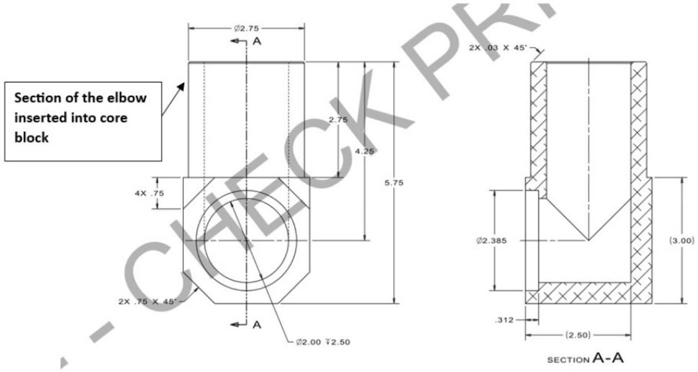


Fig 4.2: Miter elbow model.

Beam Strike on Core Water Passage

- Steady state structural analysis performed
  - Allowable weld stress: 3921 psi
  - Maximum weld stress developed: 1540 psi
  - Allowable bulk Al stress (per B31.3): 8000 psi
  - Maximum bulk Al stress developed: 7187 psi

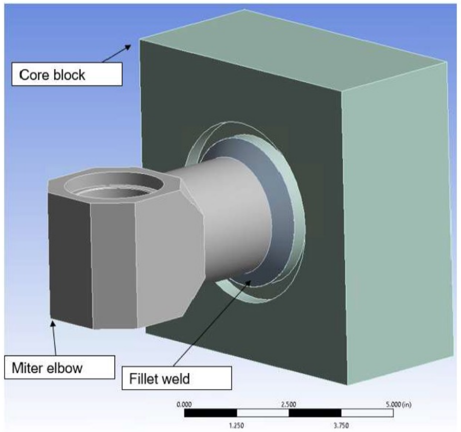


Fig 4.3: Miter elbow welded to aluminum core block.

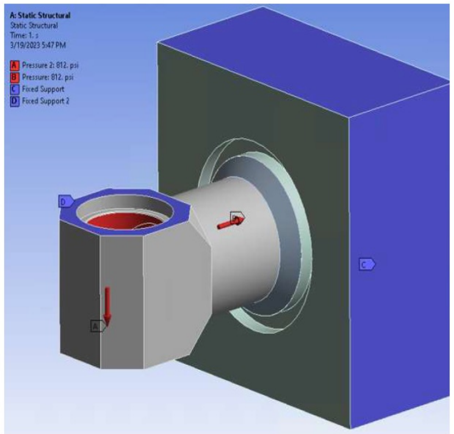


Fig 4.4: Boundary loading and restraint conditions on assembly

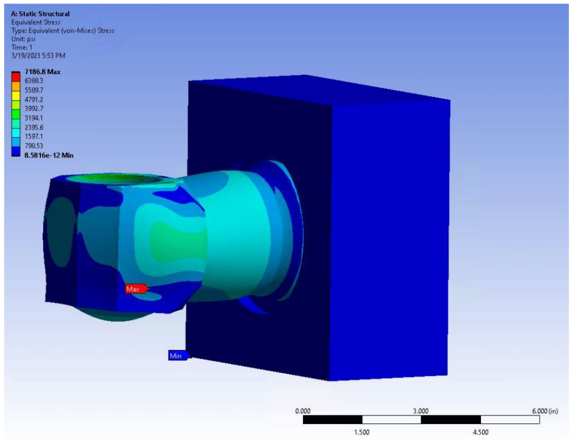
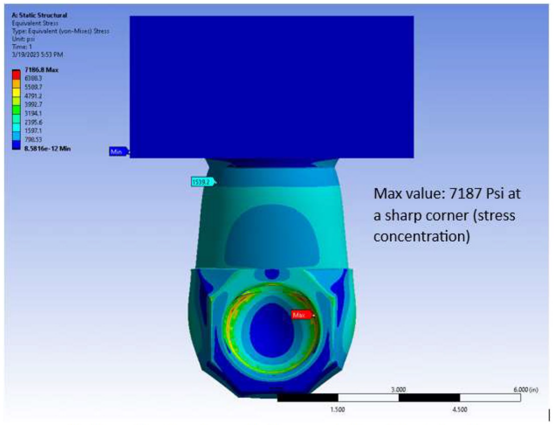


Fig 4.5: von Mises stresses in the assembly and the weld.

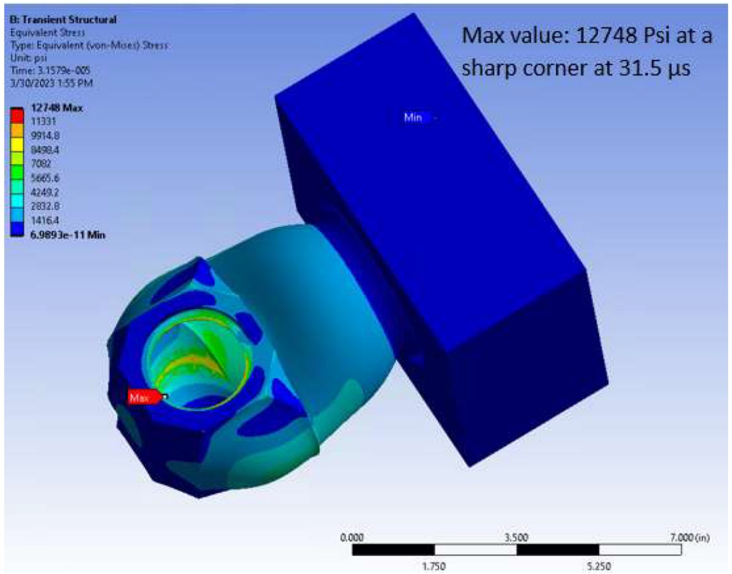


Max value: 7187 Psi at a sharp corner (stress concentration)

Fig 4.6: von Mises stresses in assembly. Stress concentration and stress in the weld.

Beam Strike on Core Water passage

- Transient Structural Analysis
  - Allowable sum of membrane and bending stress per ASME BPVC VIII Div II: 21,000 psi
    - 1.5x the tabulated allowable for materials listed in BPVC II D for materials with a ratio of yield to ultimate tensile stresses greater than 0.7 (6061-T6 satisfies)
  - Stresses analyzed on a stress classification line (SCL) in ANSYS
    - Peak von Mises stress 12748 psi
    - SCL drawn through this location, output plot at right ->
    - Sum is below the 21 ksi allowable



Max value: 12748 Psi at a sharp corner at 31.5 µs

Fig A3: Maximum von Mesis stress values on the sharp edge of the elbow.

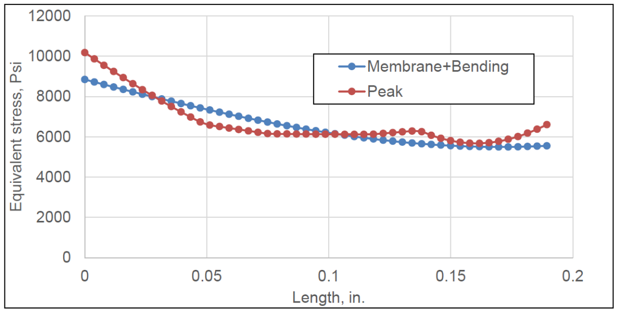


Fig A5: Equivalent membrane+bending and peak stresses along the SCL.

The summation of membrane and bending is less than the allowable limit of 21,000 Psi.

Beamline Requirements

- The LBNF Beamline shall have an uptime (including the uptime of the accelerator complex) of at least 55%.
- The LBNF Beamline shall be designed for a beam power of 1.2 MW, with the exception of a few subsystems.
- The LBNF Beamline shall be upgradeable to 2.4 MW primary proton beam power without modifications to the main elements of civil construction and shielding, assuming an uptime of 90% for a given year.
- The beam absorber shall be designed to absorb the remaining flux of hadrons at the end of the decay pipe. The design shall include consideration of the muon flux measurements
- The Beamline running lifetime is assumed to be 20 years. 5 years running at 1.2 MW and 15 years running at 2.4 MW.

Absorber Requirements

- The absorber shall provide radiation protection to people, in compliance with the FRCM.
- The absorber shall absorb the energy of the particles exiting the decay pipe and transfer this energy away using an active cooling system.
- The absorber shall sustain the beam energy deposition under all accident situations that may occur with some reasonable probability.
- The absorber shall sustain at least 2 successive accident beam pulses without damage to components or loss of functional ability.
- The absorber shall include an Interlock system that limits the accident pulses to 2.
- The actively cooled absorber core blocks shall have the ability to be repairable and/or replaceable during the lifetime of the experiment.

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