Cooled Lead Shielding Preliminary Design

Isaac Earle
Mar 16, 2014

- Worst case total heat deposition in lead shielding: 17.854kW (75MeV beam) (9.469kW for 25MeV)
- Water flow: 26 LPM = $4.333 \times 10^{-4}\ m^3/s$
- Worst case (warmest) water supply temp = 35°C
  this is based on max low active water temp of 32°C (from Bill Richert) and assuming 3°C difference over heat exchanger

Materials:

316 Stainless Steel (tubes): Poisson Ratio = 0.29, E = 193GPa

Lead: Modulus Elasticity: 14.0GPa, Poisson Ratio: 0.42

A36 Structural Steel (shell): Used data for AISI 1015 steel

Water	316 Stainless Steel	Lead	A36 Structural Steel
$\rho = 998.2\ kg/m^3$	$\rho = 8000\ kg/m^3$	$\rho = 11{,}400\ kg/m^3$	$\rho = 7870\ kg/m^3$
$C = 4180\ J/kgK$	$C = 500\ J/kgK$	$C = 129\ J/kgK$	$C = 486\ J/kgK$
$k = 0.5984\ W/mK$	$k = 16.3\ W/mK$	$k = 33.0\ W/mK$	$k = 51.9\ W/mK$
	$\alpha_L = 16.0\ \mu m/mK$	$\alpha_L = 29.1\ \mu m/mK$ MP = 327.5°C	$\alpha_L = 11.9\ \mu m/mK$

From matweb.com. Values for material at 20°C, or where unavailable, 100°C

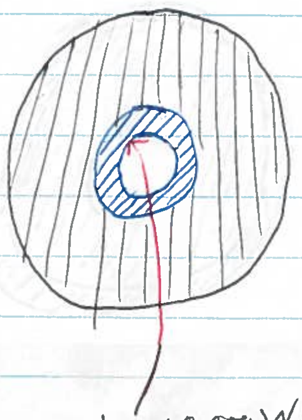
Water flow = 0.4325 kg/s, $\Delta T_{WATER} = \frac{17854\ J}{(4180\ J/kgK)(0.4325\ kg)} = 9.9°C$

For free stream temp of cooling water use worst case = 45°C

Assume no heat transfer to air on outside of shielding.

Rough Thermal Calculation and ANSYS Validation

Consider cylindrical arrangement:



Assuming 2cm max spacing between cooling lines at highest heat dep location.)

▨ Lead (ID:6.35mm, OD=26mm)

▨ 316 SS (ID:4.6mm OD:6.35mm)

conservative value, calculate exact later → $h = 10{,}000\ \mathrm{W/m^2K}$

Free stream = 45°C

Arbitrary Length = 100mm

Inside area = $\pi(0.0046\,\mathrm{m})(0.100\,\mathrm{m}) = 0.0014451\,\mathrm{m^2}$

Use $8.0\times10^6\ \mathrm{W/m^3}$ heat generation in all metal volumes (this is approximate value of highest heat deposition from FLUKA analysis for 75MeV beam)

Total Volume = $(5.30929\times10^{-5}\,\mathrm{m^3}) - (1.66190\times10^{-6}\,\mathrm{m^3}) = 5.1431\times10^{-5}$

Total Heat = 411.4 W

5th Ed. ↓

Fundamentals of Heat + Mass Transfer, Incropera, DeWitt, p 106, Eq 3.27

Convective h.t. eqn: $q = hA(T_s - T_\infty)$

$$T_s = \frac{q}{hA} + T_\infty = \frac{411.4\mathrm{W}}{(10000\,\mathrm{W/m^2K})(0.0014451)} + 45^\circ\mathrm{C}$$

$= 73.5^\circ\mathrm{C}$ at inside of SS tube

→ Radial Conduction: $q = \frac{2\pi L k}{\ln(r_2/r_1)}(T_1 - T_2)$

$T_1 - T_2 = 12.95^\circ\mathrm{C}$ ∴ $T_2 = 86.5^\circ\mathrm{C}$ at outside of SS tube

For lead: $T_1 - T_2 = 30.77^\circ\mathrm{C}$, $T_2 = 117.3^\circ\mathrm{C}$ at outside of lead

From ANSYS: 73.15°C, 86.90°C, 114.50°C respectively

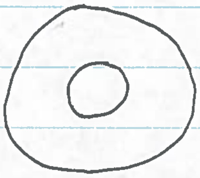
ok!

Note: 105.6°C max temp if heat gen. not flux used

Simple heat gen example for validation

Consider only lead volume

$k = 33.0$



OD = 26 mm

ID = 6.35 mm

ID set to 86.5°C

Internal heat gen = 8.0×10^6 W/m^3

3.51 → $T(r) = \frac{-\dot{q}}{4k} r^2 + C_1 \ln r + C_2$

3.50 → $r \frac{dT}{dr} = \frac{-q}{2k} r^2 + C_1 \xrightarrow[\text{outer surface}]{\text{at adiabatic}} \frac{dT}{dr} = 0$ $\qquad C_1 = \frac{q r^2}{2k}$

$= \boxed{20.4848}$

3.51 at inside $\qquad 86.5 = \frac{-\dot{q} r^2}{4k} + C_1 \ln r + C_2$

$C_2 = 86.5 + 0.61095 + 117.8377$

$= \boxed{204.949}$

3.51 at outside $\qquad T(r) = \frac{-\dot{q} r^2}{4k} + C_1 \ln r + C_2$

$= -10.24 - 88.9615 + 204.949$

$\boxed{= 105.7475°C}$

From ANSYS: 105.74 $\qquad$ ok!

Calculating heat transfer coefficient for cooling water in tube.

Flow: $4{,}333 \times 10^{-4}$ m^3/s

From Incropera, DeWitt, 5th Ed, Chp 8

$$Re = \frac{\rho u_m D}{\mu}$$

D is tube diameter
μ is dynamic viscosity = 0.000653 kg/ms for 40°C water from MatWeb
u_m is mean fluid velocity

$$\dot{m} = \rho u_m A$$

Fully developed turbulent flow for $x > 10D$ ∴ Assume fully developed if flow is turbulent

Reynolds number $10^4 < Re < 5 \times 10^6$ expected and Prandtl # for water at 315K ∴ Eqn 8.62 applies.

$$Nu = \frac{(f/8)\,Re\,Pr}{1.07 + 12.7(f/8)^{0.5}(Pr^{2/3} - 1)} = \frac{hD}{k}$$

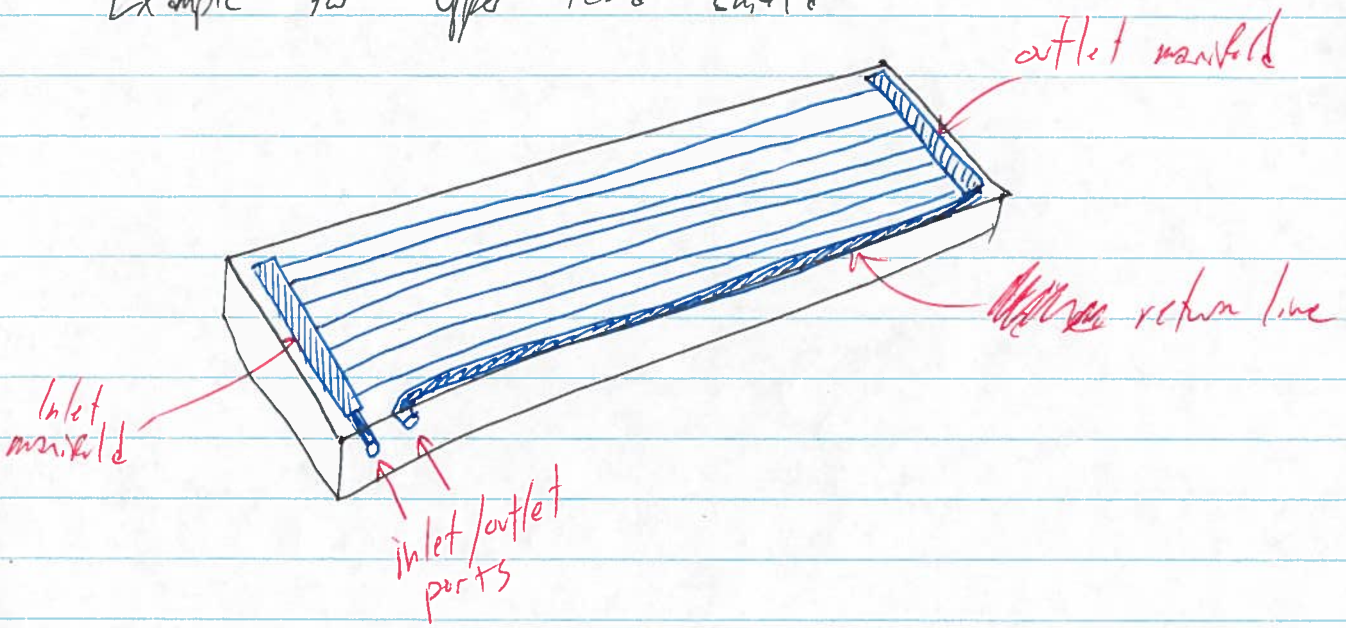
Use smooth surface friction factor formula 8.20b: (p470)

$$f = 0{,}184\ Re^{-1/5}$$

See interactive spreadsheet.

Preliminary pressure drop calculations (using spreadsheet) indicate there should be multiple lines in parallel with inlet and outlet manifolds.

Example for upper lead shield



Similar for lower plate (but will be more complicated)

Probably run lower and upper lead shields in series (not parallel), but needs more consideration.

Preliminary analysis shows ports, manifolds, and return lines should be 5/8" – 3/4" ϕ
(1/2" is too small!)

10 parallel lines: $h \simeq 14{,}400 \ W/m^2K$
15 parallel lines: $h \simeq 10{,}200 \ W/m^2K$

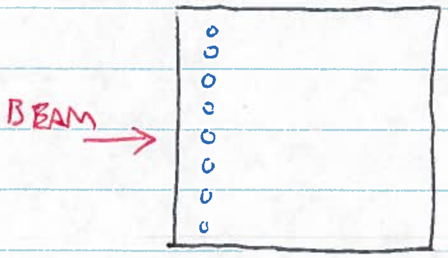
Model built of highest heat deposition sub-parts (PbSh1_25, 26, 27, 28, 29) with 1/8" thick steel shell on each end.

This is worst case section for lead shielding to determine min tube spacing and optimum tube location using ANSYS.

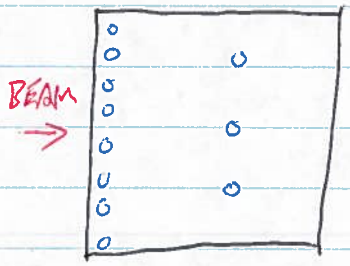
Thermal requirements:

- Temperature of ID of SS tube safely below 100°C to prevent boiling.
- Max temperature of assembly as low as possible (<< melting point of lead = 327°C)

Heat deposition highly concentrated in material just downstream of dump, therefore expect solution to be something like this:



OR



TOTAL # OF TUBES:

10 $\Delta p = \sim 10$ psi
$h = \sim 14000$ W/m

↓ TO

15 $\Delta p = \sim 5$ psi
$h = \sim 10{,}000$ W/m

* 3-4 tubes will be required on base of lower half

Analysis Steps:

- Determine ideal number of tubes in front row
- Determine ideal location of front row and back row (if back row is effective)
- Make complete model of lower half to confirm OK and find max temp and thermal expansion
- make upper half model (should be no prob)

or do as separate in series circuit

ANSYS Simulations:

To explore effect of different number of equally spaced tubes:
h = 10,000 W/m²K, Coolant temp = 45°C, Tube Center 15mm from outside face

# of Tubes	Temp at Tube ID	Upstream wall Temp	Downstream Wall Temp
6	85.0°C	147.4°C	170.13°C
8	74.8°C	120.8°C	145.3°C
10	66.1°C	107.1°C	131.8°C
12	64.4°C	97.9°C	122.9°C

Next check effect of different location of tube array:
h = 10,000 W/m²K, 45°C, 10 Tubes

Distance from Upstream Face (tube center)	Temp at Tube ID	Upstream Wall Temp	Downstream Wall Temp
10mm	68.2°C	92.9°C	145.7°C
15mm	66.1°C	107.1°C	131.8°C
20mm	67.5°C	124.0°C	120.8°C
25mm	66.6°C	144.0°C	112.3°C
35mm	65.0°C	187.8°C	100.0°C

Assuming only single row of tubes, explore effect of # of tubes using real 'h':

# of Tubes	Convective Coeff	Tube ID	Upstream Temp	Downstream Temp
6	21,600	63.4°C	125.5°C	148.2°C
8	16,900	62.5°C	108.3°C	132.8°C
10	14,000	59.8°C	100.2°C	124.8°C
12	12,000	61.1°C	94.5°C	119.5°C

45°C stream temp, Tube center 15mm from upstream wall, 12 tubes gives slightly lower temps,

Conclusions:

- 10 tubes seems to be ideal when h.t. coeff. is considered
- If a single row of tubes is used it should be located ~20mm from upstream face to minimize body temp (unless heat concentration study dictates otherwise)

See graphical Plots 1-7

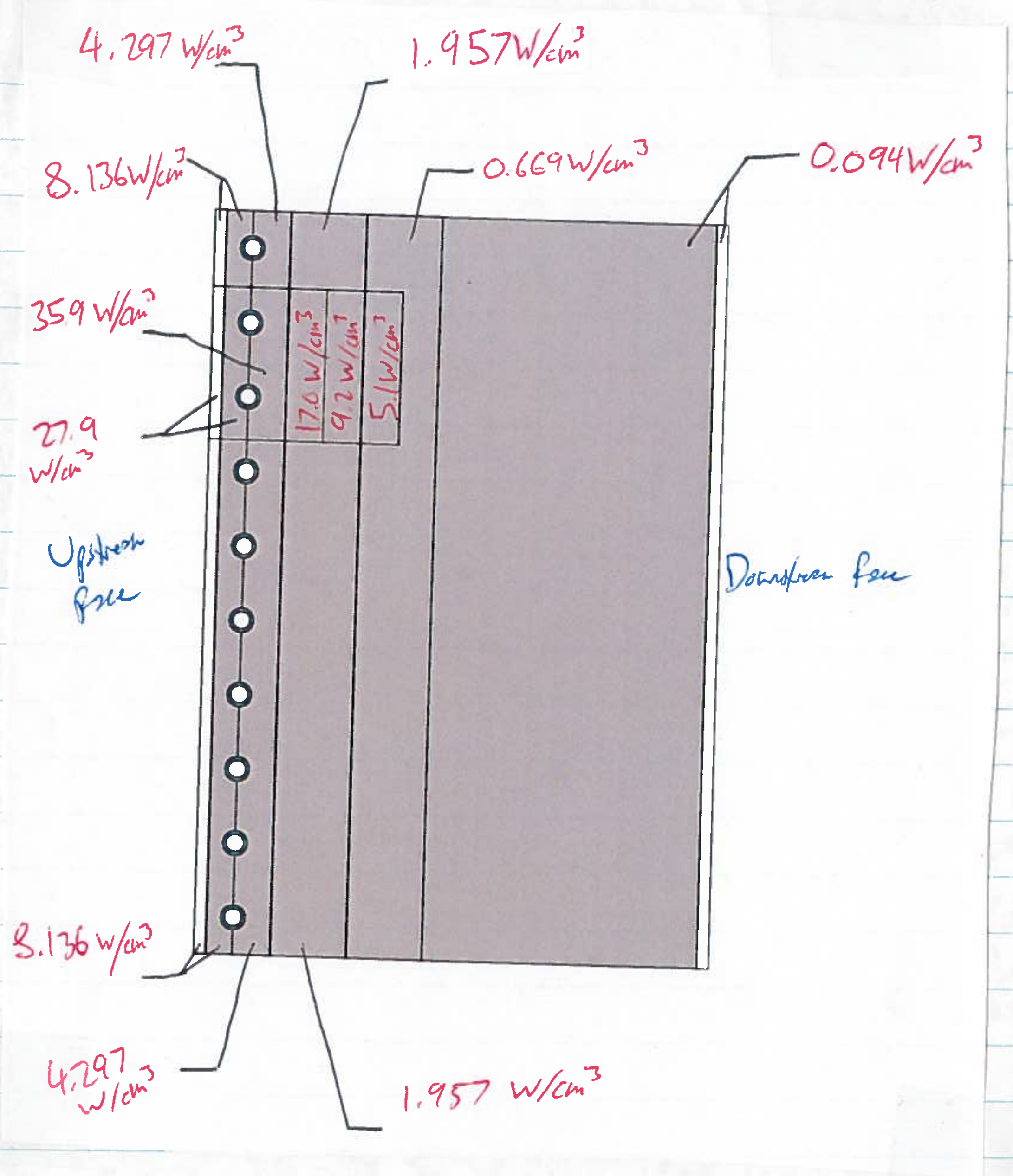
FLUKA heat deposition plots show a concentration of heat deposition at beam center in N-S direction, approx 6cm above beam height.

To simulate this, distinct volumes were created in model 4cm tall (because Plot 9 shows 4cm where heat deposition is > 10W/cm^3.

Five volumes, each 1cm thick in beam direction (b/c Plot 8 shows after 5cm, the heat deposition is $\simeq$ to background heat dep of volume average (PbSh1-28))

Heat deposition values taken from plot 8 (higher of the two). These values applied over full 4cm height (conservative). These volumes span full N-S width of model (conservative).

See labeled figure next page.



imulation run with 10 tubes, h=14,000 W/m²K, 45°C free stream,
ith tube array at varying distance from front face

e from Face	Tube ID Max at Hot Spot	Front Face Hot Spot Temp	Back Face Max Temp	Body Max Temp
	113.9°C	186.0°C	235.5°C	268.9°C
	110.1°C	227.0°C	200.7°C	227.0°C
	117.8°C	283.7°C	175.9°C	283.7°C
	120.3°C	413.1°C	144.3°C	413.1°C

e: Tried 15mm model w/ half size mesh, all temps within + 0.1°C

The best arrangement appears to be 15mm from upstream face. (from both lowest absolute temp + lowest tube ID temp perspective)

Next step is to adjust tube vertical spacing to achieve lowest tube ID temp (must be safely below 100°C)

Based on Plot 9, elevation 79 to 84cm requires higher density cooling than rest.

Layout #1: 4 tubes evenly spaced from 84 to 79, 6 tubes for rest
Layout #2: 5 tubes " from 84.5 to 78.5, 5 tubes for rest
Layout #3: 6 tubes " " " 4 "
Layout #4: 7 tubes " " " 3 "

Configuration	Tube ID Max	Front Face Max	Back Face Max	Body Max
Equal Spacing	110.1°C	227.0°C	200.7°C	227.0°C
Layout #1	105.1°C	212.3°C	193.3°C	219.7°C
Layout #2	99.8°C	196.2°C	190.1°C	206.3°C
Layout #3	90.6°C	177.7°C	187.2°C	196.4°C
Layout #4	85.6°C	166.1°C	191.8°C	194.5°C

↑ Ignoring false highs at base of model

Print-out of layout 4 on reverse

Layout #4 seems to be a good solution. Tighter spacing than this may become impractical and would be too sparse on lower end.

Body max ~195°C and tube ID max ~86°C both OK.

Proceed to full body analysis

Top Lead SS thermal

- Use sectioned model from FLUKA analysis
- Use 10 tube array w/ 26mm spacing (same for base of lower)
- Center of tubes 20mm from bottom of block
  (6.35mm plate thickness + $\frac{26.7}{2}$ for manifold thickness)
- $h = 14{,}000\ W/m^2K$ free stream 45°C

Min 0.035" wall, clean

- Model all pieces as lead except SS tubes (ignore steel shell)
  - Will add if first run of simulation shows any temps of concern

- Assume tubes travel full length of cooled block (in reality is ~1" short each side)

Result: Max 54.6 °C (@ downstream end, bottom surface)
Min 45.008°C

(Mesh sensitivity performed, ok)

No problem. Proceed with this design for upper lead shield

Lower Lead Full SS Thermal

- Use Sectioned Model from FLUKA analysis
- Split in half to reduce size / solve time (symmetric)
- Ignore steel shell (only lead and SS tubes)
- Lower tubes run full length from front to back (close approx. to actual) w/ same spacing as upper lead, tube centers 26mm from top surface (this is as close as possible
- Side tubes started 195mm from front face
  Center of side tubes 19.7 mm from inside walls
- Ignore cut-out for rear water transfer line
- Vertical spacing and rear tube distance from face same as "Layout #4" on p 10

Result: Max Temp: ~122.5°C
Back face max: ~99°C
Sides and base: ~45-50°C
} See results for various mesh sizes on p 13

Oh!

It's clear that the full body has significantly lower temps than just the down stream end (p 10)

Next step: Check thermal expansion / thermal stress

Test Model (for mesh analysis)

p13

	Elements	Temp	Error	Solve Time
100mm Mesh	346,177	74.15	10929	3718s
80mm Mesh	414,364	74.17	11086	2809s
60mm Mesh	379,328	74.33	2742	2739s
40mm Mesh	328,592	74.49	2559	2712s
30mm Mesh	349,548	NO	SOLUTION	
20mm Mesh	349,935	74.49	1.0×10^7	3115
15mm Mesh	363,440	74.56	4.3×10^6	2572
10mm Mesh	402,708	74.6	1.6×10^6	3233

Real Heat Deposition

	Max Temp	Error	Solve Time
40mm Mesh	116.48°C	1.056×10^9	2303s
30mm Mesh	NO	SOLUTION	
20mm Mesh	118.65°C	5.8×10^8	2459s
15mm Mesh	120.49°C	2.0×10^8	2670
10mm Mesh	121.67°C	3.6×10^7	3453
9mm Mesh	122.16°C	3.2×10^7	5366
7mm Mesh	122.15°C	5.4×10^7	4599
5mm	NO	SOLUTION	
15mm, 3 body w/ 5mm	122.3°C	7.6×10^7	2779
15mm, 4 body w/ 5mm	122.32°C	2.27×10^7	3890
15mm, 3 body w/ 3mm	122.35°C	7.6×10^7	2795
15mm, 5 body w/ 3mm	122.35	1.1×10^7	4614

Note: These results from 13.5mm side spacing. Later changed to 19.7mm – negligible change in results (see file)

- Upper and Lower detailed models created (finished May 9, 2014)

Used these parameters for cooling tubes →

Tube ϕ (OD)	Wall Thickness	Bend Radius
1/4"	0.035"	9/16" ,
1/2"	0.035"	1-1/2"
5/8"	0.049"	1.81"

(from bench top benders)

Upper Lead Stress Analysis

Approx mass: 0.100 × 0.386 × 1.494 = $0.05766\ m^3$

$\rho = 11,400\ kg/m^3$

m = 657.4 kg

F = 6449.3 N

ANSYS used to see stress / deflection in plates and bars

- Simplify details that have negligible impact on stress
- Assume all bodies bonded
- Suppress lid, lead, cooling lines
- Support at lift points, load on bottom face

Result: Max Deflection ~0.1mm

Max Stress: ~16 MPa

↑

F.O.S. > 10

Ok, see files.

What will happen with different thermal expansion of lead, steel shell, and SS tubes?

Look at upper lead block steel shell + lead filling first:

When pouring lead:

- Lead is min ~330°C, assume shell is same temp, lead poured into shell (must be single pour!), the assembly then cools to room temp

$$\Delta T = \sim 300°C, \quad \ell = \sim 1.5m$$

both shell and lead shrink by

$$x_{lead} = \alpha_{LB}\,\ell\,\Delta T = (29.1\,\mu m/mK)(1.5m)(300K) = 13095\,\mu m$$
$$= 13.1\,mm$$

$$x_{steel\ shell} = (11.9\,\mu m/mK)(1.5m)(300K) = 5.4\,mm$$

∴ There will be approx 4mm gap on each end once cool. This is good b/c lead will not stress shell when heated slightly during use

Note if shell is not preheated this gap will be bigger →

When heated during use:

both conservative {
- Assume shell stays at 20°C,
- Assume all lead is at max temp found from ANSYS analysis = 55°C ↑ see p11

$$x_{lead} = (29.1\,\mu m/mK)(1.5m)(\overset{\Delta T}{\downarrow}{35K}) = 1.5\,mm$$

< 4mm ∴ No problem

this is only for long edge

Next look at lead filling and SS cooling tubes.

When pouring lead:

- Poured lead and SS tubes will be at same temp when lead solidifies (328°C)
- Both will shrink as they cool to room temp

$\ell = \sim 1.4\text{m} \qquad \Delta T = \sim 300\text{K}$

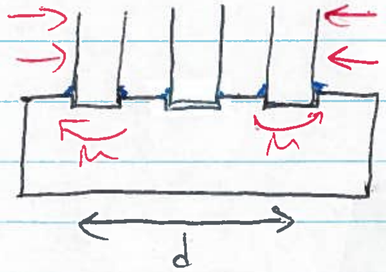
$x_{lead} = (29.1\mu m/mK)(1.4m)(300K) = 12.2mm$

$x_{SS\,tube} = (16.0\mu m/mK)(1.4m)(300K) = 6.7mm$

$\Delta X = 5.5mm$ ← This is the distance the lead wants to move but is resisted by steel tubes

Put bend in parallel tubes by offsetting alignment combs to prevent stress caused by axial compression. ← George's idea

Then area of highest concern is compression perpendicular to tubes which causes bending moment at weld



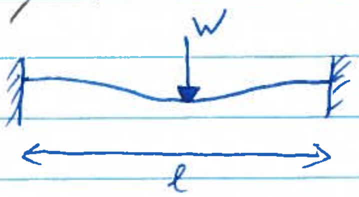
d = distance between outermost tubes = 234mm

$\Delta x_{steel} = (16.0\mu m/mK)(0.234m)(300K) = 1.12mm$

$\Delta x_{lead} = 2.04$

$\boxed{\Delta X = 0.92mm}$ ← lead distance wants to shrink, but steel resisti

Approximate the as fully supported beam at both ends
Machinery Handbook 28Ed p265



$$\text{Max deflection} = \frac{\Delta X}{2} = \frac{W\ell^3}{192EI} = 4.6\times10^{-4}\text{m}$$

ℓ = dist btwn header and first comb = various

E = 193 GPa

$$I = \frac{\pi(D^4 - d^4)}{64} = \frac{\pi(0.00635^4 - 0.0046^4)}{64} = 5.783\times10^{-11}\text{m}^4$$ SS-383

$$W = \frac{(192)\,E\,I\;\;(4.6\times10^{-4}\,m)}{\ell^3}$$

$\ell = 55mm \rightarrow W = 5925\ N \rightarrow M = 40.7\ Nm$

$\ell = 150mm \rightarrow W = 292.1\ N \rightarrow M = 5.5\ Nm$

$\ell = 250mm \rightarrow W = 63N\ N \rightarrow M = 2.0\ Nm$

$\ell = 383mm \rightarrow W = 18\ N \rightarrow M = 0.9\ Nm$

Normal Stress on weld: Shigley p 285/286

Case 9

$$I_u = \frac{\pi r^3}{2} = \frac{\pi(0.00635/2)^3}{2} = 3.3516\times10^{-8}\,m^3$$

$h = 1/16'' = 1.5875mm$

$= 0.0015875m$

$$I = I_u\, h\, 0.707 = 3.7617\times10^{-11}\,m^4$$

$$\sigma_{\ell=55mm} = \frac{M\overset{0.00635/2}{c}}{I} = 3435.2\ MPa$$

$$\sigma_{\ell=383mm} = 76.0\ MPa$$

SS yield = 290MPa

Also ignores yielding of lead, creep, friction and lead squeezing the tubes

Clearly this method is highly dependent on assumed length of beam and not reliable.

Try ANSYS analysis first starting w/ mini model to find best analysis parameters.

↓

p18

Mini Header Assy ANSYS Analysis

← To find optimum analysis parameters for full model

May 21, 2014

Lead at cap end	X-Def. of Tube from Center (where tube meets header)	Stress of Weld
5mm	~0.07	~450MPa
10mm	~0.07mm	~405 MPa
20mm	~0.08mm	~460MPa
50mm	~0.08mm	~450MPa

No effect from amount of lead either side of header. Use 10mm

Lead on outside of header	Stress at Weld	Stress at header inside face
3mm	~140 MPa	~60
5mm	~250 MPa	~92
7.5mm	~410 MPa	~120 MPa
10mm	~440 MPa	~140 MPa
15mm	~600	~160
20mm	~740	~175
25mm	~900	~175
30	~920	~175
40	~1150	~175
50	~1200	~175

No stress increase on header after ~20mm thick.
Minimal increase on weld stress after ~40mm
Note: - 3 or 5mm is probably representative of bellows design.
- Max stress is compressive in weld. Reverse side (tensile) is < ½

Mesh	Stress at Weld
Coarse	741
Medium	876
Coarse + 1 Mesh Refinement on Weld	843
" " on Weld and Tube	827
Coarse + 2 Mesh on Weld	863

Mesh	Stress at Weld
Coarse + 3 Mesh Weld + Tube	~1400
Med + 1 Mesh Welds	1014
" + 2 "	998
" + 3 "	923

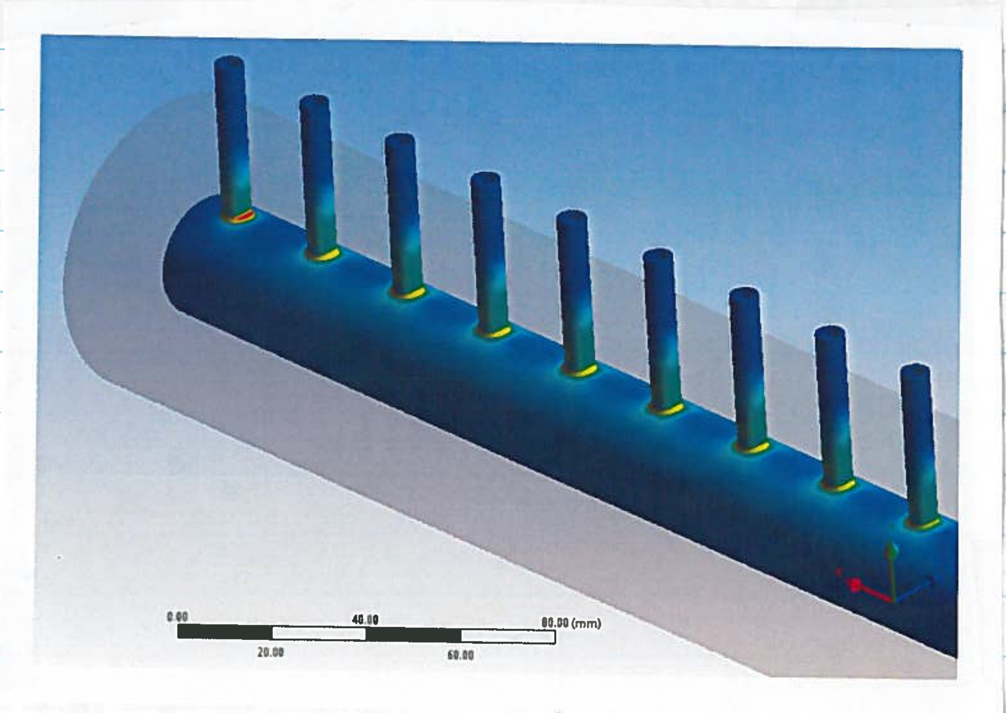
← Use this

Based on this a full scale (1 full header) model was created w/ 10mm lead on outside sides of header, 20mm lead around, Medium Mesh w/ 3x refinement at welds. Max stress in SS was ~1600MPa

~1.2mm

The model confirmed Δx, steel from p16 but other than that is meaningless b/c stress in lead exceeded the Ultimate Tensile Stress of lead (≈15MPa) ← matweb.com in almost all locations. (Was over 5x UTS at most edges contacting steel)
Also it does not account for creep.

However the model does give an idea about expected high stress locations. Welds have the highest stress with outermost tubes worst (others roughly equal),
← highest on inside face (compressive



Only realistic analysis method seems to be prototyping

Concept review held May 22. See minutes next page.

e-Linac 100kW Beam Dump Cooled Lead Shielding Concept Review

May 22, 2014

Present: Isaac Earle, Grant Minor, Ron Kuramoto, Allon Messenberg, Bill Paley

Agenda:

- Presentation of design concept
- Feedback and discussion

Action Items:

- Investigate if all tubes from the manifolds will have equal flow
- The welded vessels should be completely sealed and water tight
- Lead filling method should be as follows to minimize stresses to the tube networks: preheat the shell and tube assembly to >100C to remove all moisture, fill with lead pellets or pieces, slowly heat to above lead melting temperature then slowly cool (for the lower lead shield on the first fill this should be done with the shell at an incline to prevent air bubbles being caught under the center plate, add more lead and repeat until the vessel is full
- A prototype must be constructed to test if the lead filling method will cause weld failure (difficult to estimate with hand calculations or ANSYS simulation). The prototype should be vacuum pumped before (and characterized) then again after. Also water pressure test before and after. After testing, cut the prototype open to check for voids in the lead
- Investigate if the lead filling process will anneal the stainless steel
- Make one guide pin longer than the other for easier installation
- Use fully tapered guide pins for easier installation and to prevent binding
- Add bracket to support tubes close to welds (this will reduce stress)
- Add guide plates to lower lead shield if possible to aid in upper lead installation
- Make sure pins are "skookum"
- Lead shielding should sit on a steel frame which is bolted to the floor. Bolt the lower lead shield to this frame. Fill the steel frame with concrete bricks to meet shielding requirements

Next Meetings:

Next meeting will be the final design review to be scheduled after prototyping is complete

p21

Will the lead filling process anneal (or ~~otherwise~~ weaken) the steel? (~350°C)

matweb.com: 316SS annealed bar: 240 MPa yield
max temp for continuous service: 870°C

Material Handbook: p407 Thermal treatments of steel (including annealing) occur between 1300 - 1600 F
= 705 ~ 871°C

Seems OK

[redacted] ☒ Prototype designed May 27: TSH0292
☒ Quick ANSYS structural on prototype shell w/ 125 lbf on base (weight of lead fill).
Max 0.05 mm deflection, ~15 MPa stress

No prob!

Regarding if slots are req'd for bulkhead fittings

In both upper and lower shield there are sections of SS tube running ⊥ to direction of lead shrinkage ∴ should be OK. Let these sections ~~flex~~ bend

p15

Expected displacement = $x_{lead}/2 \simeq 6.5$ mm

Conservative figure assumes steel does not push back on lead

Lower Lead ANSYS Stress Analysis

- Simplified model created
- Fixed lift block upper surfaces
- Applied 2500 lbf on lower plate (weight of lead is 2233 lb)

15mm mesh, 'fine' relevance center:

Max stress: 7.7 MPa

Max Deflection: 0.03 mm

10mm mesh, 'fine' relevance center:

Max Stress: 11.6 MPa

Max Deflection: 0.03

Highest stress at sharp corner between base plate and center plate support (will be weld here)

FOS > 10 Ok!

Total Pressure Drop through Shielding

- Calculated using viscous duct flow + minor loss methods
- See Excel file

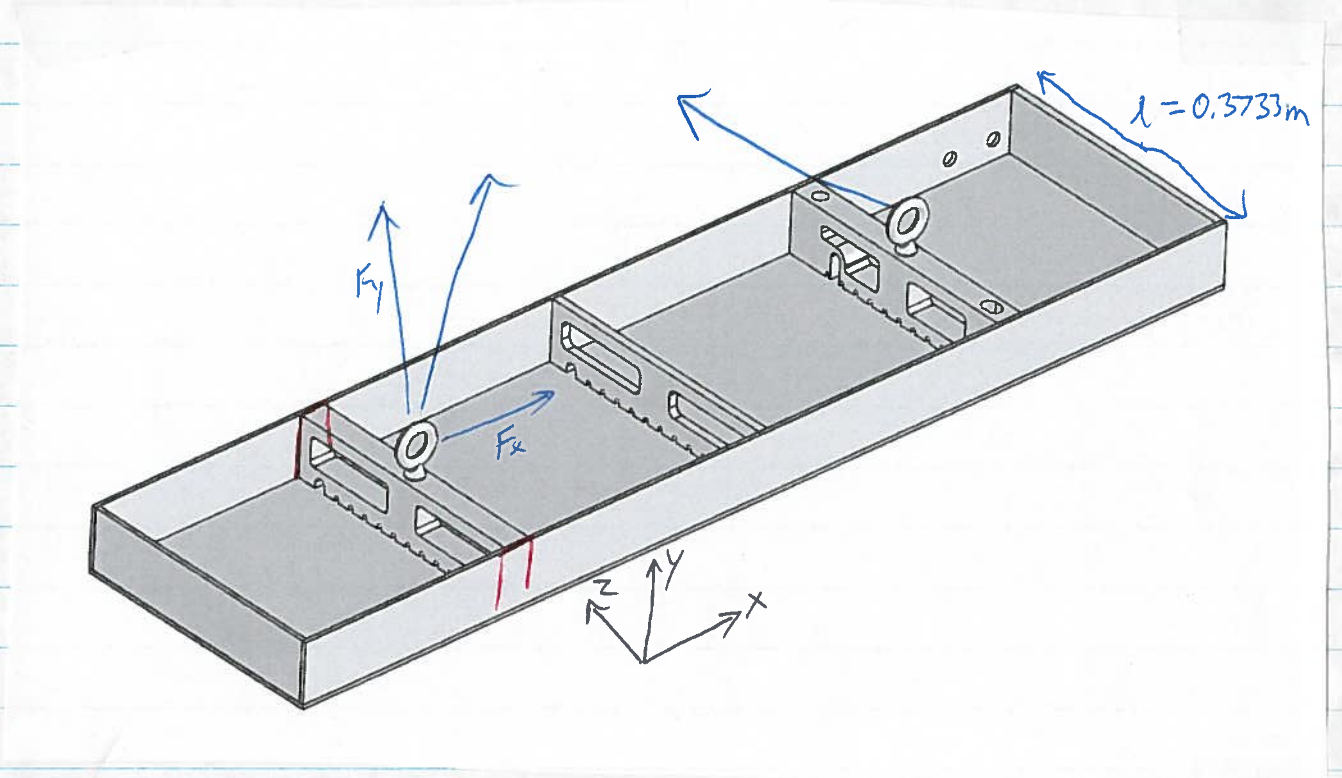
Lower Lead Shield → 23.9 psi

Upper Lead Shield → 8.3 psi

Using 7gpm flow (10°C ΔT)

Total: 32.1 psi

Upper Lead Shield Weld Analysis



Approx mass: m = 657.4 kg ← p14

.2 Lift Points, Assume 45° lift angle

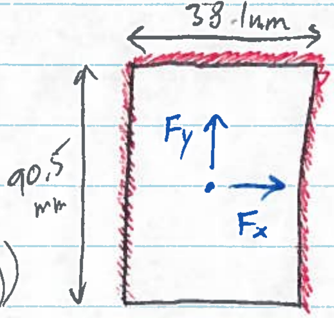
$$F_x = F_y = \frac{657.4\,kg}{2} \times 9.81\,m/s^2 = 3225\ N$$

Assume applied at vertical center of lift bar.

Assume only sides and top are welded as shown (conservative)

1/4" welds → $h = 0.00635m$

Weld cross-section



Weld Area:

$$A = (2)(.707)(h)(0.0381 + (2 \times 0.0905))$$

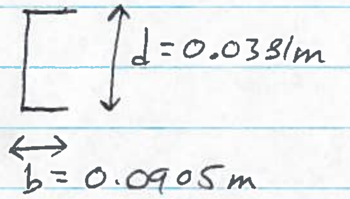
$$= 0.0019673\,m^2$$

Weld Stress Caused by Fx

Primary Shear: $\tau_x' = \frac{F_x}{A} = 1.64\ \text{MPa}$

Direct Stress from Bending:

- Shigley's, p285, Case 4



$$I_u = \frac{d^2}{12}(6b+d)$$
$$= 7.029\times10^{-5}\ m^3$$

$$I = 0.707\,h\,I_u = 3.156\times10^{-7}\ m^4$$

- Calculating Bending Moment: Roark's p190 Case 1d

$$M_{F_x} = \frac{-Wa}{\ell^2}(\ell-a)^2$$

$W = F_x = 3225N$
$\ell = 0.3733\ m$
$a = \ell/2 = 0.18665m$

$$= 150.5 Nm$$

$$\sigma_{BV} = \frac{Mc}{I} = \frac{(150.5Nm)(0.0381m/2)}{(3.156\times10^{-7} m^4)}$$

$$\sigma_{BV} = 9.08\ \text{MPa}$$

Weld Stress Caused by Fy

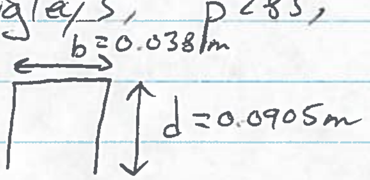
Primary Shear: $\tau_y' = \frac{F_y}{A} = 1.64\ \text{MPa}$

Weld Stress Caused by F_y cont'd

Direct Stress from Bending:

$$M_{F_y} = M_{F_x} = 150.5\ \text{Nm}$$

Shigley's, p285, Case 5



$$\bar{x} = b/2 = 0.01905\text{m}$$

$$\bar{y} = \frac{d^2}{b+2d} = 0.03738\text{m}$$

$$I_u = \frac{2d^3}{3} - 2d^2\bar{y} + (b+2d)\bar{y}^2$$

$$= (4.9415\times10^{-4}\text{m}^3) - (6.123\times10^{-4}\text{m}^3) + (3.0614\times10^{-4}\text{m}^3)$$

$$= 1.8799\times10^{-4}\text{m}^3$$

$$I = 0.707hI_u = 8.4397\times10^{-7}\text{m}^4$$

$$\sigma_{BH} = \frac{Mc}{I} = \frac{(150.5\text{Nm})(.0905/2)\text{m}}{(8.4397\times10^{-7}\text{m}^4)} = 8.07\ \text{MPa}$$

Summary Stresses:

$$\tau = \sqrt{\tau_x'^2 + \tau_y'^2} = 2.32\ \text{MPa}$$

$$\sigma = |\sigma_{BH}| + |\sigma_{BV}| = 17.15\ \text{MPa}$$

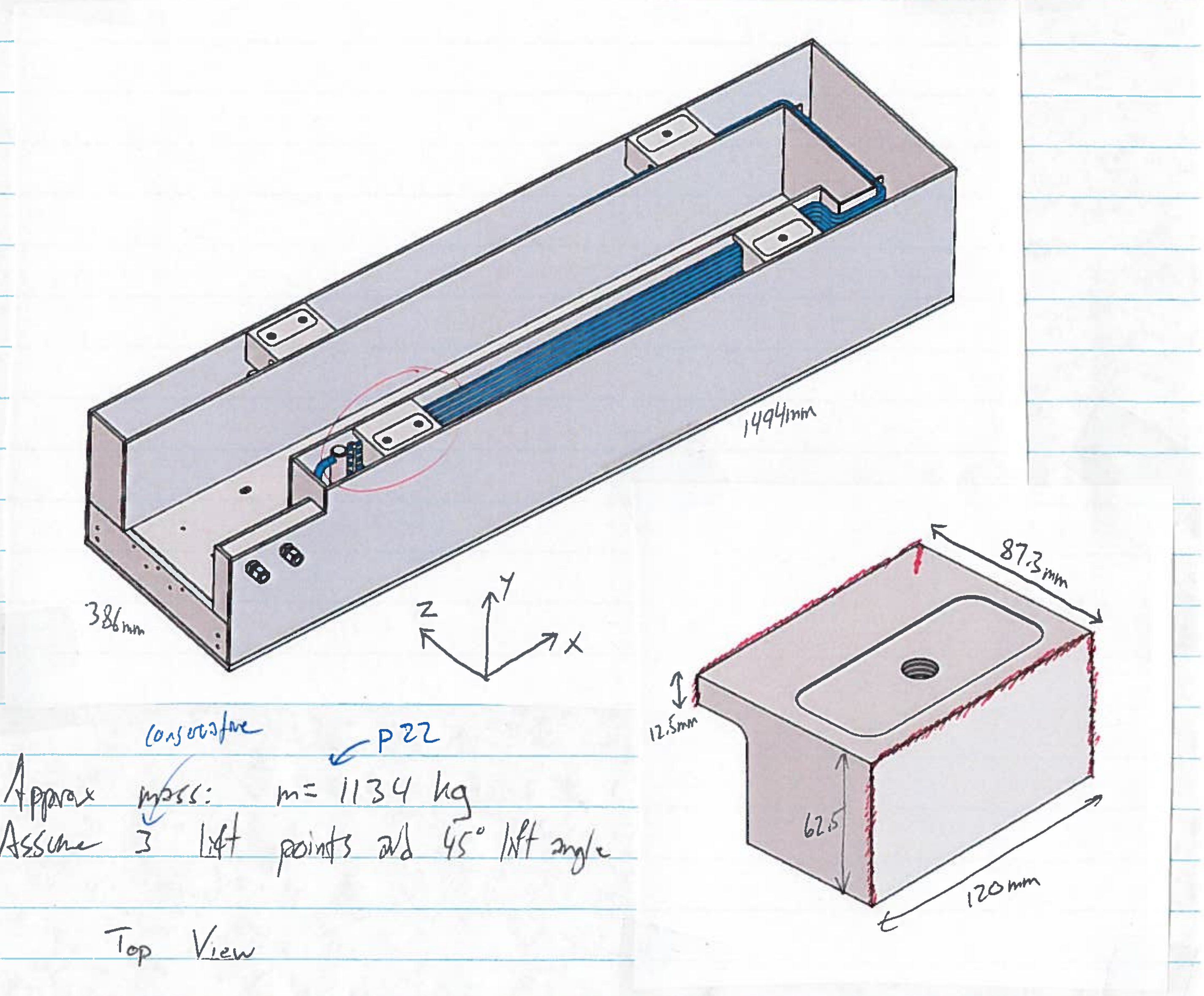
$$\tau_{max} = \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2} = 8.88\ \text{MPa}$$

$$\sigma_{yp} = 248\ \text{MPa}$$

$$\boxed{\text{F.O.S.} > 10}$$

p26

Lower Lead Shield Weld Analysis



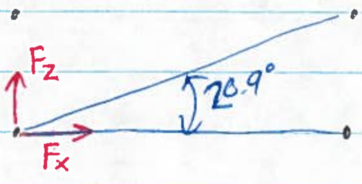
conservative

p22

Approx mass: m = 1134 kg

Assume 3 lift points and 45° lift angle

Top View



$$F_y = \frac{1134\,kg}{3}(9.81\,m/s^2) = 3708\,N$$

$$F_x = (3708\,N)\cos(20.9°) = 3464\,N$$

$$F_z = (3708\,N)\sin(20.9°) = 1323\,N$$

1/4" welds → $h = 0.00635\,m$

$A_{SHORT\ SIDE} = (.707)(h)(0.0125 + 0.0125 + 0.120) = 6.5097\times10^{-4} m^2$

$A_{TALL\ SIDE} = (.707)(h)(.0625 + .0625 + .12) = 0.001100\ m^2$

$A_{TOTAL} = 0.00175 m^2$

Assume loads applied at vertical center of short side.
Assume loads applied at horizontal center btwn welded sides.

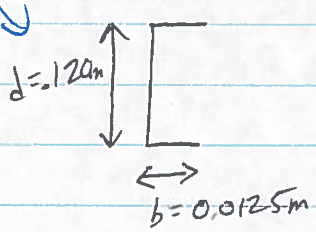
Weld Stress Caused by Fx

Primary Shear: $\tau_x' = \frac{F_x}{A_{TOTAL}} = 1.98\ MPa$

Direct Stress from Bending:

- Shigley's, p285, Case 4

Use short side for bending analysis



$$I_u = \frac{d^2}{12}(6b+d) = 2.34\times10^{-4} m^3$$

$$I = 0.707\, h\, I_u = 1.0505\times10^{-6} m^4$$

Bending Moment: Roark's p190 Case 1d

$$M_{Fx} = \frac{-Wa}{\ell^2}(\ell - a)^2$$

$W = F_x = 3464N$
$\ell = 0.0873m$
$a = \ell/2$

$$= 37.8\ Nm$$

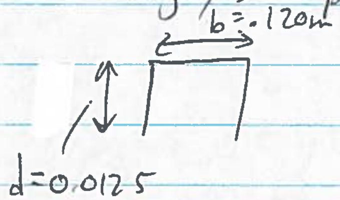
$$\sigma_{BV} = \frac{Mc}{I} = \frac{(37.8Nm)(.120m/2)}{(1.0505\times10^{-6} m^4)} = 2.16\ MPa$$

Weld Stress Caused by Fy

Primary Shear: $\tau_y' = \frac{F_y}{A_{TOTAL}} = 2.19 \text{ MPa}$

Direct Stress from Bending:

Shigley's p285, Case 5



$\bar{x} = b/2 = 0.06m$

$\bar{y} = \frac{d^2}{b+2d} = 0.001078$

$$I_u = \frac{2d^3}{3} - 2d^2\bar{y} + (b+2d)\bar{y}^2$$
$$= (1.3021\times10^{-6}) - (3.369\times10^{-7}) + (1.685\times10^{-7})$$
$$= 1.1337\times10^{-6} m^3$$

$$I = 0.707h\, I_u = 5.08969\times10^{-9} m^4$$

$$M_{F_y} = \frac{-Wa}{\ell^2}(\ell-a)^2$$

$W = F_y = 3708 N$
$\ell = 0.0873m$
$a = \ell/2$

$$= 40.5 Nm$$

$$\sigma_{BH} = \frac{Mc}{I} = \frac{(40.5Nm)(0.0125/2)}{(5.08969\times10^{-9} m^4)} = 49.7Nm$$

Weld Stress Caused by F_z

Primary Shear: $\tau_z' = \frac{F_z}{A_{TOTAL}} = 0.76\ \text{MPa}$

Summing Stresses

$$\tau = \sqrt{\tau_x'^2 + \tau_y'^2 + \tau_z'^2} = 3.05\ \text{MPa}$$

$$\sigma = |\sigma_{BH}| + |\sigma_{BV}| = 51.9\ \text{MPa}$$

$\sigma_{yp} = 248\ \text{MPa}$

$$\tau_{max} = \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2} = 26.1\ \text{MPa}$$

$$F.O.S. = \frac{0.5\ \sigma_{yp}}{\tau_{max}} = \boxed{4.75}$$

Ok.

Check Weld Stress on Baseplate

$F_y = 3708\text{N}$

$A = (0.707)(h)((2 \times .386) + (2 \times 1.494))$
$= 0.0169\ \text{m}^2$

$$\tau_x' = \tau_{max} = 0.22\ \text{MPa}$$

$F.O.S > 10$

Same weld area on Upper Lead Shield base plate, but lower F_y ∴ also fine.

Hoist Ring for Pb shield lifts

1179 lbf

- Up to 45° lift angle
- Lower Lead: $\sqrt{3708^2+3708^2} = 5244\,N$
- Upper Lead: $\sqrt{3225^2+3225^2} = 4561\,N$

Total load at 45°

1025 lbf

Can use Carr Lane CLM-2500-SHR-1

2300 lbf rating, M12 screw,
27 ft lbs installation torque
Safety Factor = 5

* Must design RH pole tool for installing hoist ring remotely

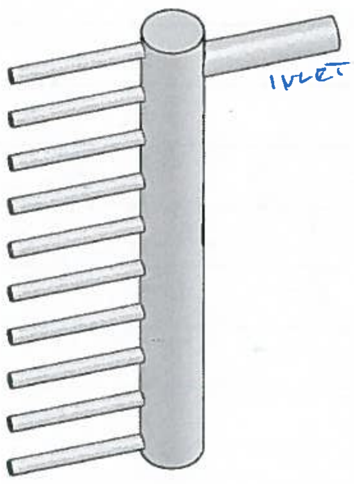
* May be best to have lift frame for lower block

Investigation of flow distribution in tubes

- Modeled water volume at side network inlet manifold with approx 40mm of tube length for inlet and outlets ↓

In ANSYS Fluent:

- used "k-epsilon" viscous model
- Inlet defined 4.7m/s velocity
- outlets at 200kPa (≈30psi)
- default mesh (200,000 elements)

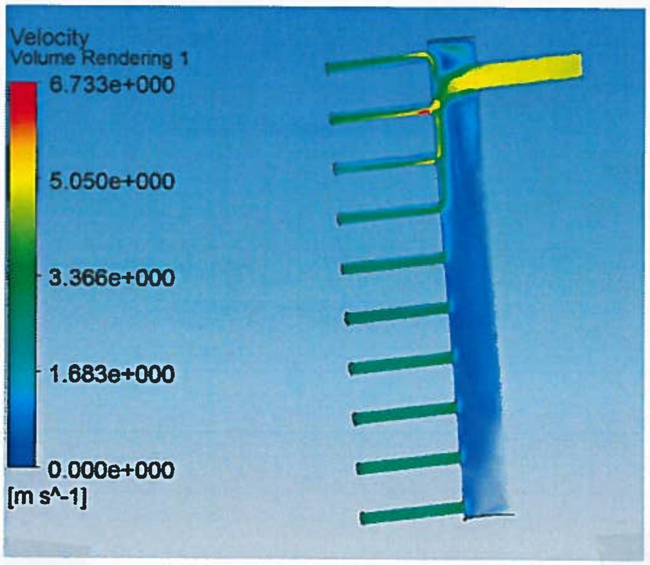


- Volume rendering w/ split plane shows roughly equal flow in each tube ≈ 3m/s ↓

- Velocity analyzed at plane set at exit location with the following velocities from lowest to highest

1) 2.75
2) 2.75
3) 2.75
4) 2.75
5) 2.75
6) 2.50
7) 2.25
8) 2.0
9) 3.25
10) 2.75

All approximate visual average of cross-section velocity



next ↓

This amount of variation seems acceptable. (if correct)

- Ran 2nd simulation with fine relevance center and high smoothing (~201,000 elements)
  ↖ very little change
  → No noticeable change in solution

See ANSYS File

Lowest flow velocity is 2.0m/s (Tube #8), which gives h = 11,800 W/m²K heat transfer coeff.

Thermal Calculations assumed 14,000 in all tubes

Compared thermal models using the two 'h' values for all surfaces:

h	Max temp
14,000 W/m²K	121.7°C
11,800 W/m²K	125.2°C

From 10mm mesh model in "Lower Lead Analysis" ANSYS file p 33

June 19:

- Prototype lead fill completed by Vancouver Heat Treaters in Surrey according to following procedure

Lead Melting Procedure:

1) Heat the shell to 150°C (300F) to remove all moisture
2) Place all lead ingots into shell on top of cooling network (5x5 pieces, 5lbs each = 125 lbs total)
3) Load shell into furnace and ensure that it is level (shim as necessary)
4) Heat to 350°C (662F) and hold for 1 hour
5) Perform visual check to see if lead has melted; If not, heat an additional 30 minutes and check again
6) Reduce set point to 300°C (572F) and hold for 30 minutes
7) Reduce set point to 250°C (482F) and hold for 30 minutes
8) Reduce set point to 200°C (392F) and hold for 30 minutes
9) Shut-off furnace and allow to cool slowly to room temperature (configure furnace for cooling as slowly as possible)

* Ensure furnace is ventilated or area is evacuated when lead is molten to protect workers from fumes
* Wear gloves when handling lead ingots
* Record furnace temperature as a function of time if possible

Note: melting point of lead is 327°C (621F)

- Procedure was successful. Operators checked at 1hr and lead was not fully melted, left approx 20 min extra

- See photos and temp plot

- Vacuum pumpdown and static water test performed before and after. No indications of tubes being compromised. See notes.

Final design review tmrw then will release dwgs + manufacture