Hydrogen Tank Design for the Material Handling Industry

Design Group #8
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Industry Sponsor: Raymond Corporation
Industry Advisor: Bryce Gregory

The Material Handling Industry

Refers to the movement and storage of products during every phase of life
- Manufacturing
- Distribution
- Consumption
- Disposal

Raymond Corporation

- Market leader in the US for electric fork lift trucks
- Owned by Toyota Material Handling Group
- Headquartered in Greene, NY
- Sells, rents, and leases lift trucks throughout the world
- Conducted 2 year study on fuel cell-powered lift trucks

Problem Statement

- Replacing lead-acid batteries with fuel cell systems
  - Ideal application for hydrogen
- Eventually the fuel cell system will be designed into the truck
- Raymond requires three design proposals for a compressed hydrogen tank

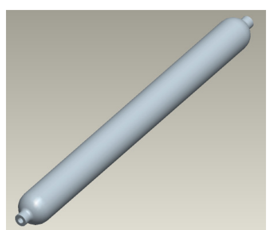
Project Scope

- Outside the scope
  - Everything except the hydrogen tank itself
  - The mounting design
  - Which specific lift trucks are using the tanks
  - Construction or testing of a physical prototype
- Two phase project
  - Fall semester research phase
  - Spring semester design phase

Design Requirements

- Store approximately 1kg (43 liters) of hydrogen at 5,000 psi (at 0℃)
- Operate from -28℃ to 45℃
- Be composed of steel to compensate for the lost weight of the lead-acid battery
- Survive 15,000 refueling cycles
- If mounted high above CG, must weigh less than approximately 500 pounds
- HGV5 and DOT Part 178 standards

Mast-Mounted Cylindrical Vessel



Seamless cylindrical pressure vessel
Threaded openings at both ends

Wall Thickness and Stress

Tangential Stress $\sigma_t = \frac{r_i^2 p_i}{r_o^2 - r_i^2}\left(1 + \frac{r_o^2}{r^2}\right)$

Radial Stress $\sigma_r = \frac{r_i^2 p_i}{r_o^2 - r_i^2}\left(1 - \frac{r_o^2}{r^2}\right)$

Longitudinal Stress $\sigma_l = \frac{r_i^2 p_i}{r_o^2 - r_i^2}$

Von Mises Stress

$$\sigma' = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_2)^2}{2}}$$

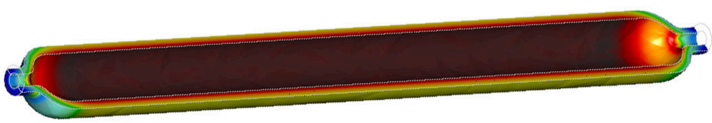
Combining and solving for r_i

$$r_i = r_o\sqrt{1 - \sqrt{3}\frac{p_i}{\sigma'}}$$

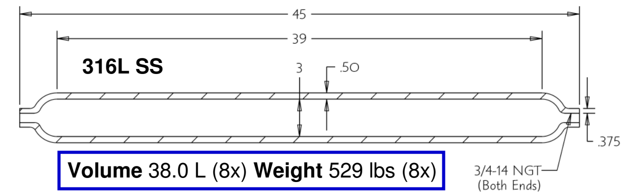
- Used DOT test pressure
  - 5/3 x 5,000 = 8,333 psi
- Material stress limits
  - 34,000 and 67,000 psi
- Nominal wall thickness
  - ½ and ¼ inch
- Theoretical wall stress
  - 32,990 and 61,580 psi

Finite Element Analysis

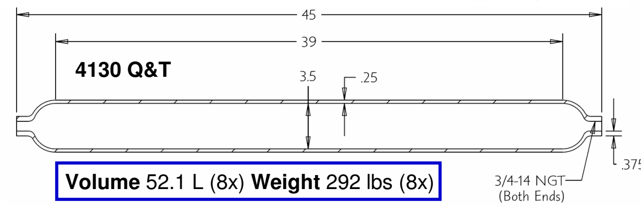
	316L SS	4130 Q&T
Theoretical Stress [psi]	**32900**	61580
FEA Stress [psi]	**33600**	63390
Stress Limits [psi]	**34000**	67000
Design Efficiency	**99%**	**94%**



Ready for Quoting



Volume 38.0 L (8x) **Weight** 529 lbs (8x)

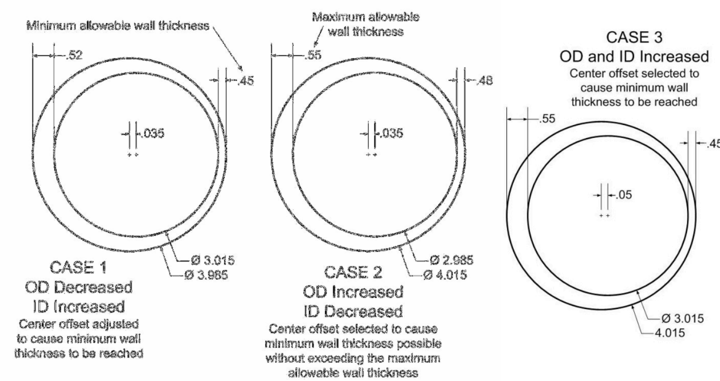


Volume 52.1 L (8x) **Weight** 292 lbs (8x)

Manufacturing Quote

- 316L Stainless Steel
  - 1,000-2,000 = $777 Each **(73% Material)**
  - 10,000 = $727 Each **(6% Discount)**
- 4130 Q&T Steel
  - 1,000-2,000 = $226 Each **(75% Material)**
  - 10,000 = $198 Each **(12% Discount)**

Dimensional Variations

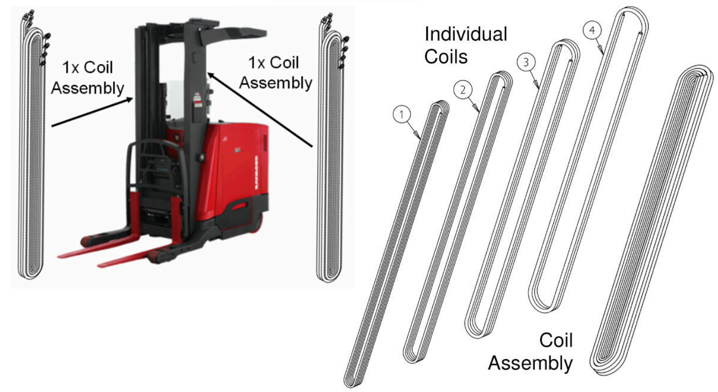


Case 1 Dimensional Variation FEA

	316L SS	4130 Q&T
FEA Stress [psi]	**35990**	**69440**
Stress Limits [psi]	34000	67000
Design Efficiency	**106%**	**103%**

- 316L Stainless Steel
  - Yield cannot be lower than 36,000 psi
- 4130 Q&T Steel
  - Not a problem, still meets DOT requirements

Mast-Mounted Nested High Pressure Tubing Coils



Tubing Selection

For one loop, the length the coil is given by:

$$L_1 = 2(100 - 2D - 2r_b) + 2\pi r_c$$
$$L_1 = 200 - 4D - 4r_b + 2\pi r_c$$

where

r_b = bend radius

r_c = center radius = $(r_b + D/2)$

Tube OD in.	Tube Wall Thickness, in.							
	0.028	0.035	0.049	0.065	0.083	0.095	0.109	0.120
1/16								
1/8	8500	10 900						
3/16	5400	7 000	10 200					
1/4	4000	5 100	7 500	10 200①				
5/16		4 000	5 800	8 000				
3/8		3 300	4 800	6 500	7500①②			
1/2		2 600	3 700	5 100	**6700**			
5/8			2 900	4 000	5200	**6000**		
3/4			2 400	3 300	4200	4900	5800	
7/8			2 000	2 800	3600	4200	**4800**	
1				2 400	3100	3600	4200	**4700**

Swagelok Working Pressure Table
316L SS Seamless Tubing

Theoretical Stress Calculations

Using same wall stress equations from the cylindrical vessel design

Outside Diameter [in]	1	0.875	0.625	0.5
Wall Thickness [in]	0.120	0.109	0.095	0.083
Swagelok Working Pressure [psi]	4700	4800	6000	6700
Test Pressure [psi]	8333	8333	8333	8333
Von Mises Stress [psi]	**34169**	32987	27866	26063
316L Yield Strength [psi]	**36000**	36000	36000	36000
Design Efficiency	**95%**	**92%**	**78%**	**72%**

Finite Element Analysis

Straight Section
Maximum stress
34,314 psi

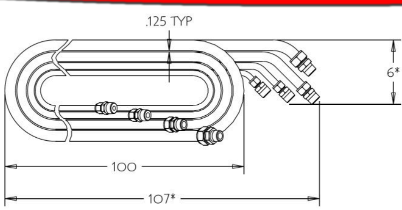
Bent Section
Maximum stress
36,068 psi

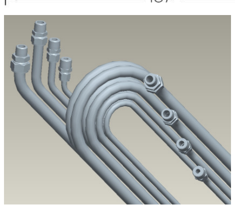
Theoretical vs FEA

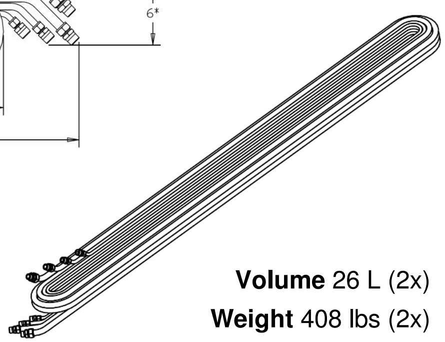
Outside Diameter [in]	1	0.875	0.625	0.5
Von Mises Stress by Hand [psi]	34169	32987	27866	26063
Von Mises Stress from FEA (Straight Section) [psi]	**34314**	33213	28084	26317
Von Mises Stress from FEA (Bent Section) [psi]	**36068**	34950	29514	27583
Stress Ratio Between Straight and Bent Sections	**1.05**	1.05	1.05	1.05
316L Yield Strength [psi]	**36000**	36000	36000	36000
Design Efficiency (Straight)	95%	93%	77%	71%
Design Efficiency (Bend)	**100%**	97%	83%	77%

Conclusion: The HGV5 7,500 psi hydrostatic test pressure should be used instead of the DOT 8,333 psi

Finished Design







Volume 26 L (2x)
Weight 408 lbs (2x)

Material Quote

- Assumes order of 10,000 assemblies
- Fittings and caps from Swagelok
  - $155 per assembly
- Tubing from Swagelok
  - $5,206 per assembly
- Tubing from Handy & Harman
  - $2,220 per assembly **(57% Reduction)**

Dimensional Variations

-10% Wall variation, +0.005" OD Variation

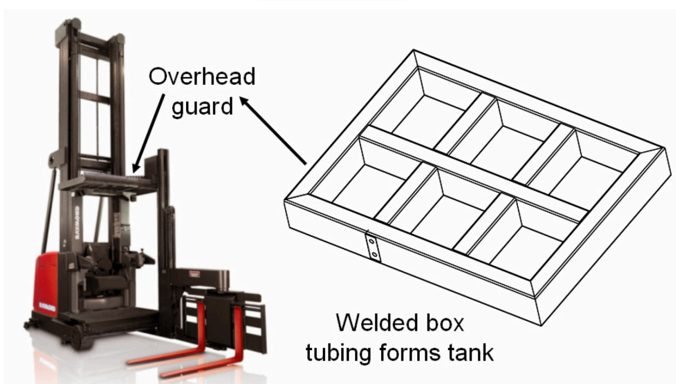
Outside Diameter [in]	1.005	0.880	0.630	0.505
Wall Thickness [in]	0.108	0.098	0.086	0.075
Test pressure [psi]	7500	7500	7500	7500
Estimated Von Mises Stress (Bent Section) [psi]	**38317**	**37179**	32219	30667
Yield Strength [psi]	**36000**	**36000**	36000	36000
Design Efficiency (Bend)	**106%**	**103%**	89%	85%

Dimensional Variations

Allowing only 5% variation in the wall

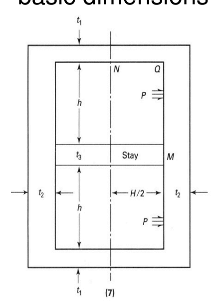
Outside Diameter [in]	1.005	0.880
Wall Thickness [in]	0.114	0.098
Test pressure [psi]	7500	7500
Estimated Von Mises Stress (Bent Section) [psi]	**35411**	**34347**
Yield Strength [psi]	**36000**	**36000**
Design Efficiency (Bend)	**98%**	**95%**

Rectangular Tank (Overhead guard)



Cross-Section Design

Excel sheet and ASME equations used to select basic dimensions

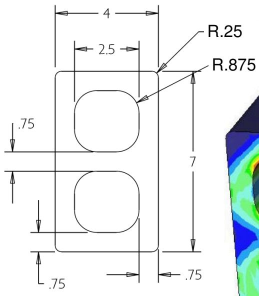


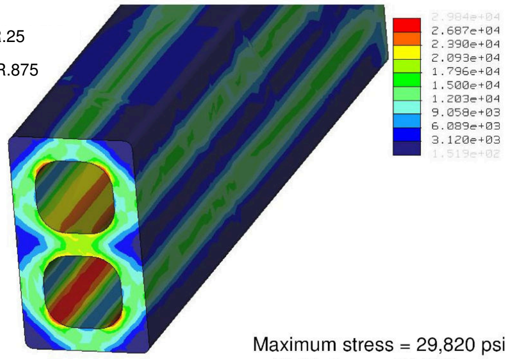
Reinforced (1-stay) tank with six sections

Length (in)	Width (in)	Height (in)	Wall (in)	Volume (in^3)	Volume (L)
252	3	2	0.5	252	4.13
252	3	2.5	0.5	504	8.26
252	3	3	0.5	756	12.39
252	3	3.5	0.5	1008	16.52
252	3	4	0.5	1260	20.66
252	3	4.5	0.5	1512	24.79
252	3	5	0.5	1764	28.92
252	3	5.5	0.5	2016	33.05
252	3	6	0.5	2268	37.18
252	3	6.5	0.5	2520	41.31
252	3	7	0.5	2772	45.44
252					
252					
240					

Total Stress (SSM)	Total Stress (SSC)	Total Stress (LSM)	Total Stress (LSC)
-3171	71829	-9881	59605
-16667	58333	-5208	57292
-21066	53934	1439	55715
-22500	52500	10000	55000
-22121	52879	20424	55246
-20265	54735	32670	56534
-17047	57953	46705	58933
-12500	62500	62500	62500
-6628	68372	80031	67281
577	75577	99279	73317
9130	84130	120226	80642
19048	94048	142857	89286
30344	105344	167161	99273
-5531	163219	-34094	126781

Finite Element Analysis



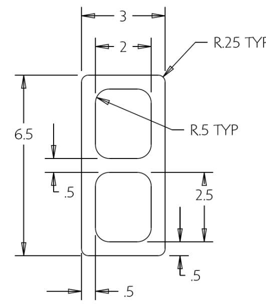


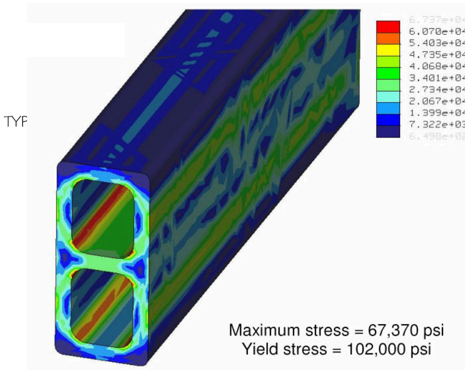
316L Stainless Cross-Section

Maximum stress = 29,820 psi
Yield stress = 34,000 psi

Cross-Section Revision

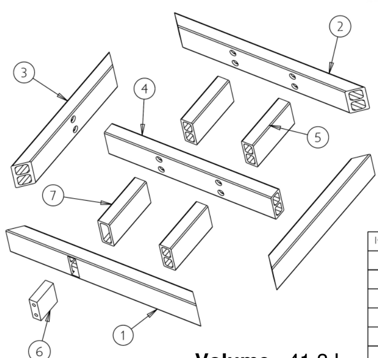
4130 Q&T Steel Cross-Section

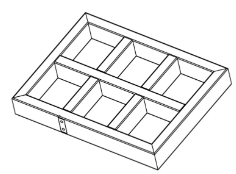




Maximum stress = 67,370 psi
Yield stress = 102,000 psi

Full Assembly Design





Weight ~719 lbs

Volume ~41.3 L

Item	Part Name	Qty	Dwg No.
1	Long member with valve opening	1	7
2	Longside member	1	6
3	Shortside member	2	5
4	Middle member	1	4
5	Cross member	3	3
6	Valve member	1	8
7	Cross member with valve opening	1	9

Junction FEA Results

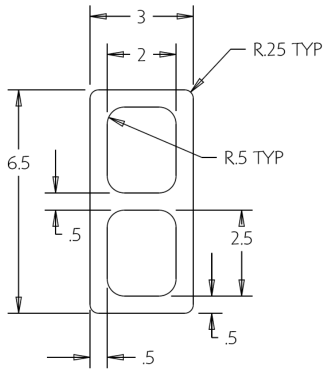
6,250 psi

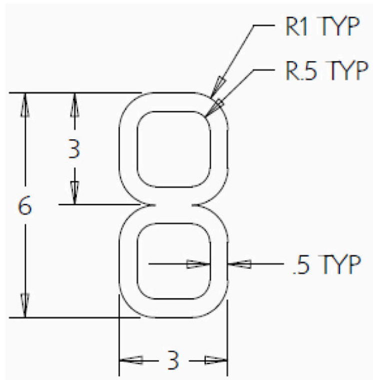
	Maximum Stress [psi]	Design Efficiency
Single Member	67370	66%
L-Junction	82497	81%
T-Junction	67260	66%
X-Junction	71840	77%
Valve T-Junction	66240	65%

7,500 psi

	Maximum Stress [psi]	Design Efficiency
Single Member	80850	79%
L-Junction	98990	97%
T-Junction	79370	78%
X-Junction	96050	94%

Box Tube Manufacturability





Recommendations

- Practicality of design proposals
  - Cylindrical vessels
  - Nested high pressure tubing
  - Rectangular tank
- Future work
  - Address welding and cycling
  - More expansive, up-to-date standards review
  - Construct prototypes and conduct testing

Accomplishments

✓ Reviewed applicable design standards
✓ Generated, evaluated, and selected three design concepts
✓ Created detailed design proposals
✓ Documented design iterations and results
✓ Generated functional specifications
✓ Consulted with industry experts
✓ Acquired a quote for one design

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