

Hardware-Based Non-Optimum Factors For Launch Vehicle Structural Design

K. Chauncey Wu

Structural Mechanics and Concepts Branch
NASA Langley Research Center
Hampton, Virginia

Jeffrey A. Cerro

Vehicle Analysis Branch
NASA Langley Research Center
Hampton, Virginia

Matthew L. Wallace

Rocky Mountain Space Grant Consortium
Utah State University
Logan, Utah

ACCIS DTC

University of Bristol, Bristol, UK

January 11, 2012

Part 1 – Propellant Tank Barrels

Introduction, motivation and approach

Super-Lightweight Tank (SLWT) description

Minimum orthogrid dimensions and unit cell weights model

Coarse panel weights and non-optimum factor (NOF) calculations

Refined panel weights and NOF calculations

Comparison of coarse and refined NOFs

Application to Ares V propellant tank

Concluding remarks

Introduction And Motivation

Classical and analytical methods are typically used to size launch vehicle structures during conceptual and preliminary design (e.g., $t = pR/\sigma$, Bruhn; HyperSizer).

These methods do not include weights of design and manufacturing details (e.g., weld lands, fillets, etc.).

Empirical non-optimum factors (NOFs) are applied to account for weight increases due to these details.

Overly conservative NOFs and predicted weights can result in lower predicted vehicle performance.

No traceability in, or understanding of contributors to, typical empirical NOFs.

Study Approach

Manufacturing drawings and component weights data for Space Shuttle Super-Lightweight Tank are obtained from Lockheed Martin and AMRO Fabricating Corp.

Minimum skin and stiffener thickness dimensions from LH₂ tank barrel panel drawings are combined with measured panel weights to:

- Calculate NOFs (defined as the ratio of actual and predicted weights) for flight hardware.
- Identify specific design details represented (e.g., subsystem attachments, weld lands, etc.) and their contributions to overall panel weights.

Note that the minimum skin and stiffener thicknesses ARE NOT material minimum-gage dimensions!

Super-Lightweight Tank Description



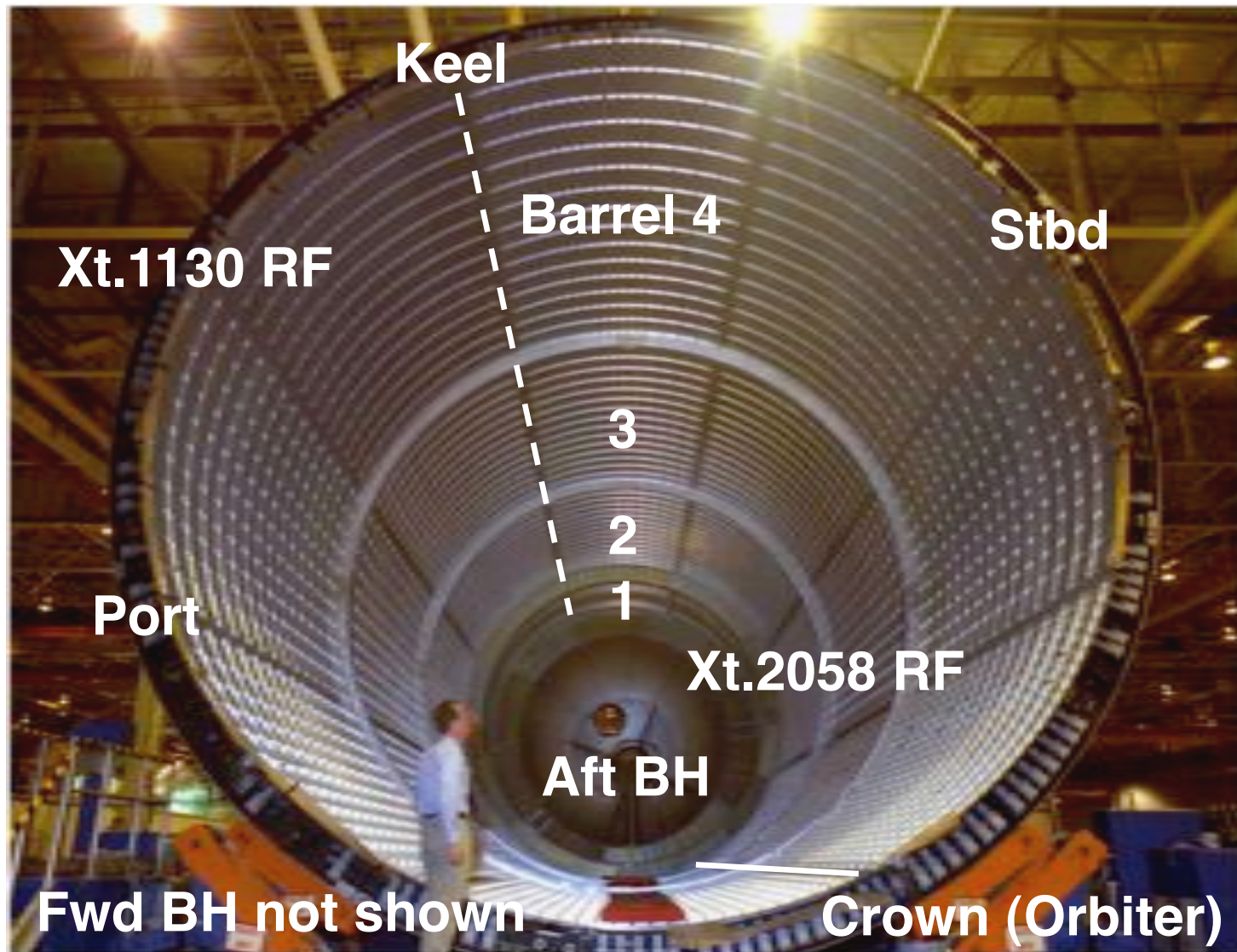
Carries all propellants for the 3 Space Shuttle Main Engines.

Comprised of LO₂ Tank, Intertank and LH₂ Tank structures.

First flown on STS-91 in June 1998.

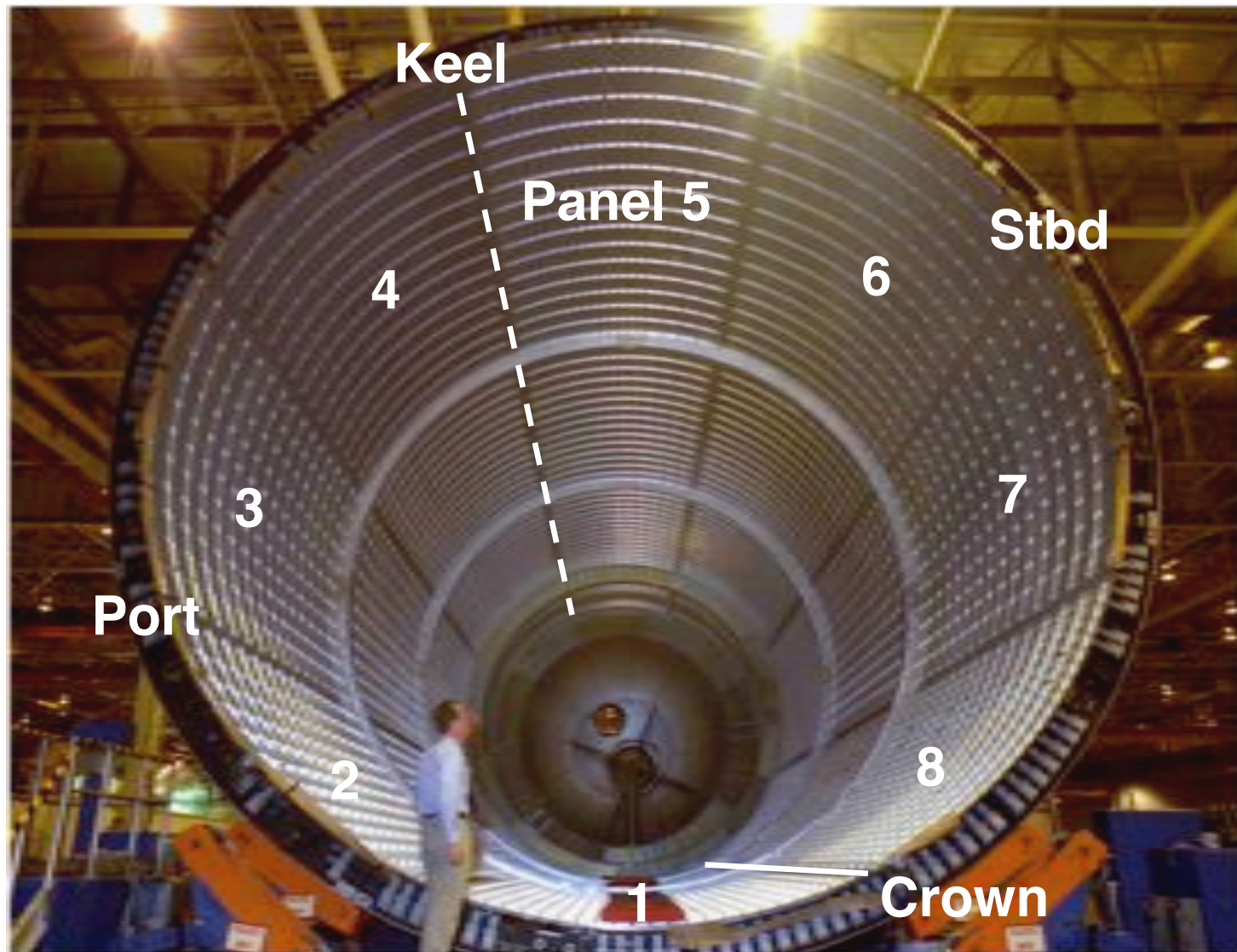


SLWT LH₂ Tank Barrel Assembly Interior



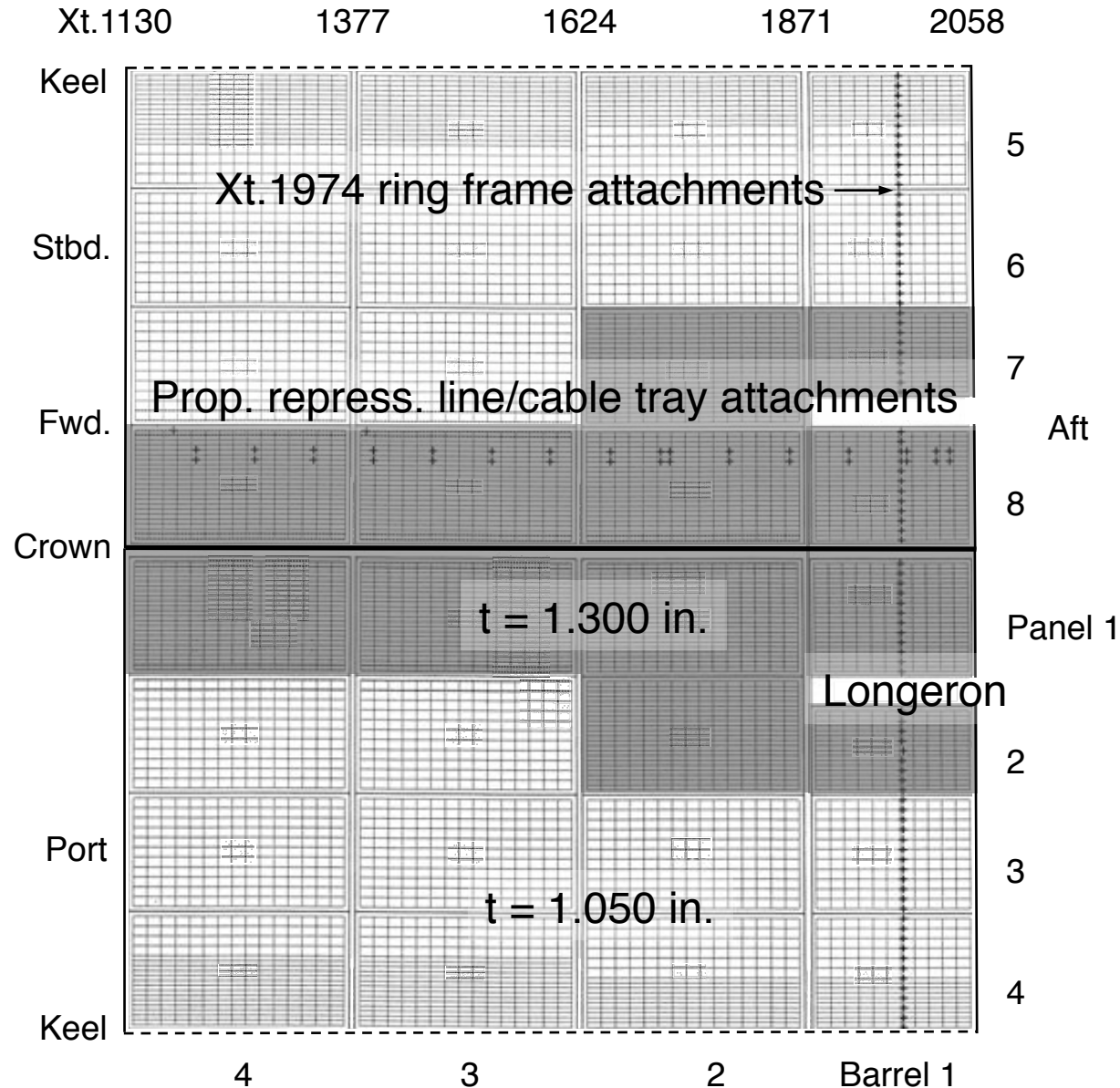
Lockheed Martin photo

SLWT LH₂ Tank Barrel Assembly Interior (2)



Lockheed Martin photo

LH₂ Tank Barrel Assembly Planform View

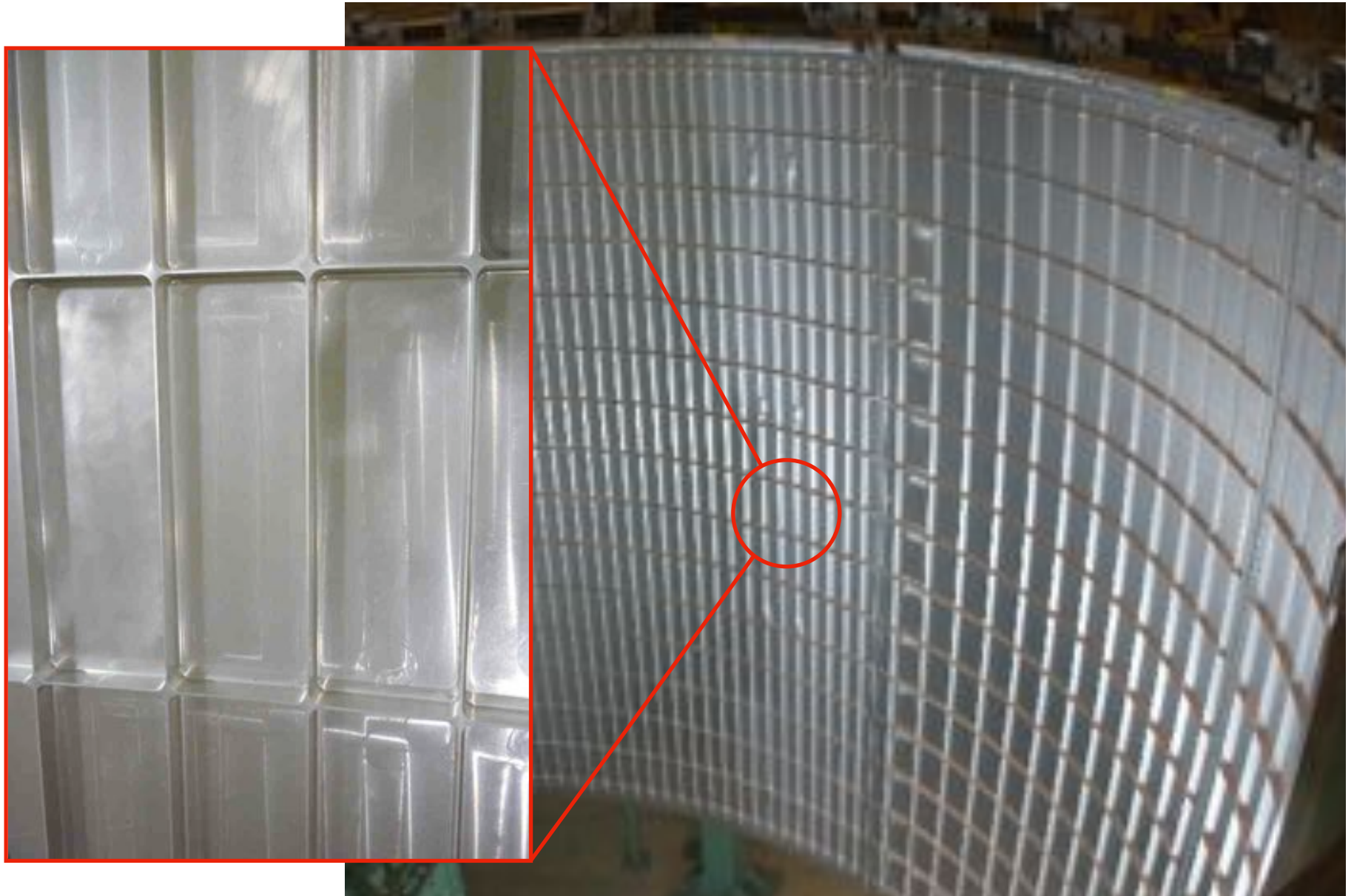


Total of 32 panels (30 unique).

Total panel thickness is 1.05 or 1.30 inches.

Panels are machined from Al-Li 2195 plate.

LH₂ Tank Barrel Orthogrid Panel Details



LH₂ Tank Barrel Measured Panel Weights

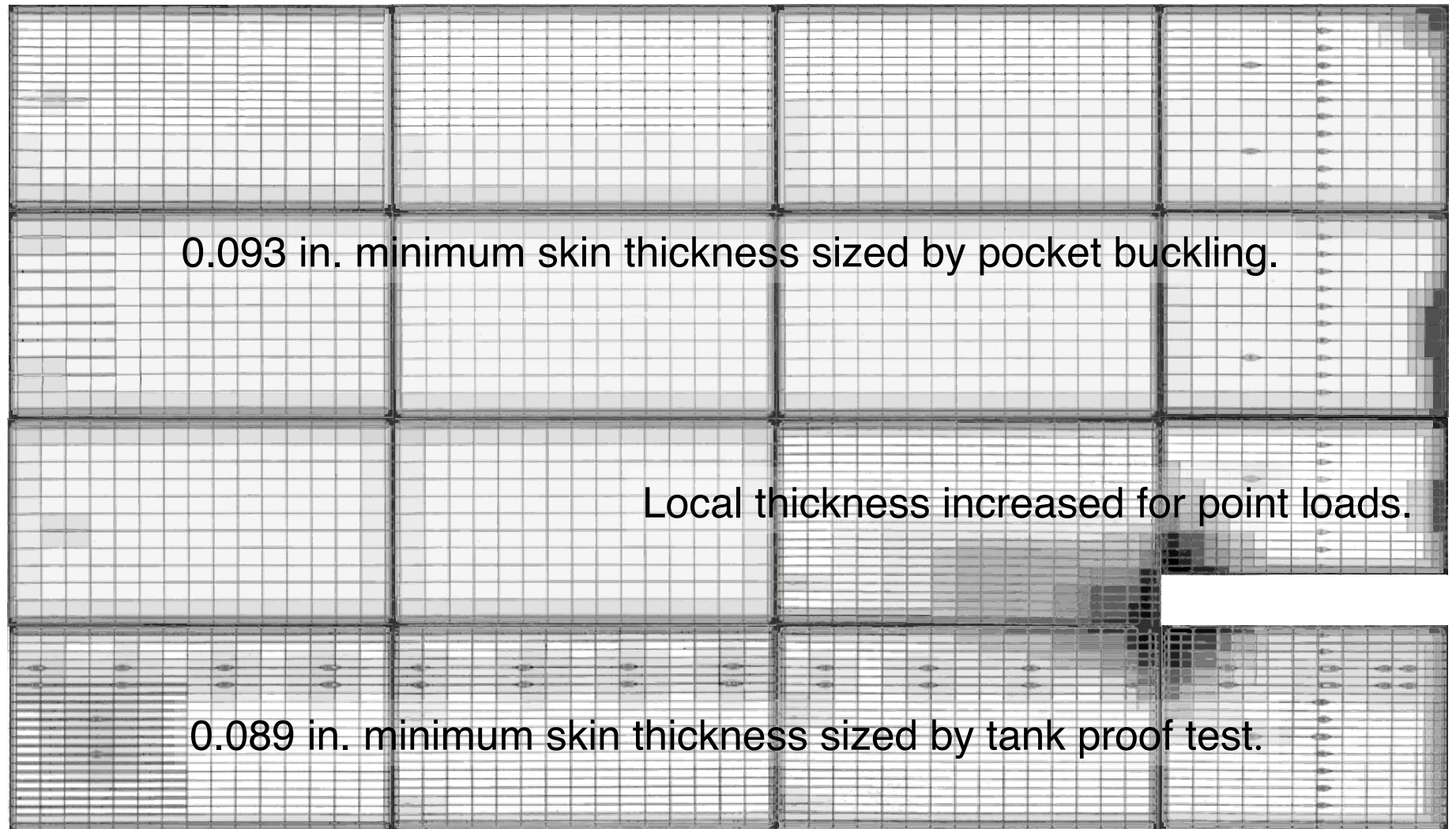
464.5/488.9	456.4/482.4	592.8/602.8	460.3/479.1	1/8
398.2/398.5	399.1/398.7	619.7/619.2	316.9/319.0	2/7
392.3/392.2	389.6/389.6	389.6/389.6	317.1/317.0	3/6
398.8/399.7	397.8/397.9	393.1/391.1	312.0/312.6	4/5

Actual port/starboard panel weights (lbs) from LM ET-121 data.

Estimate GO₂/GH₂ repress. line/cable tray support attachments
NOF = 1.04 from average (panel 8 wt. - panel 1 wt.)/panel 1 wt.

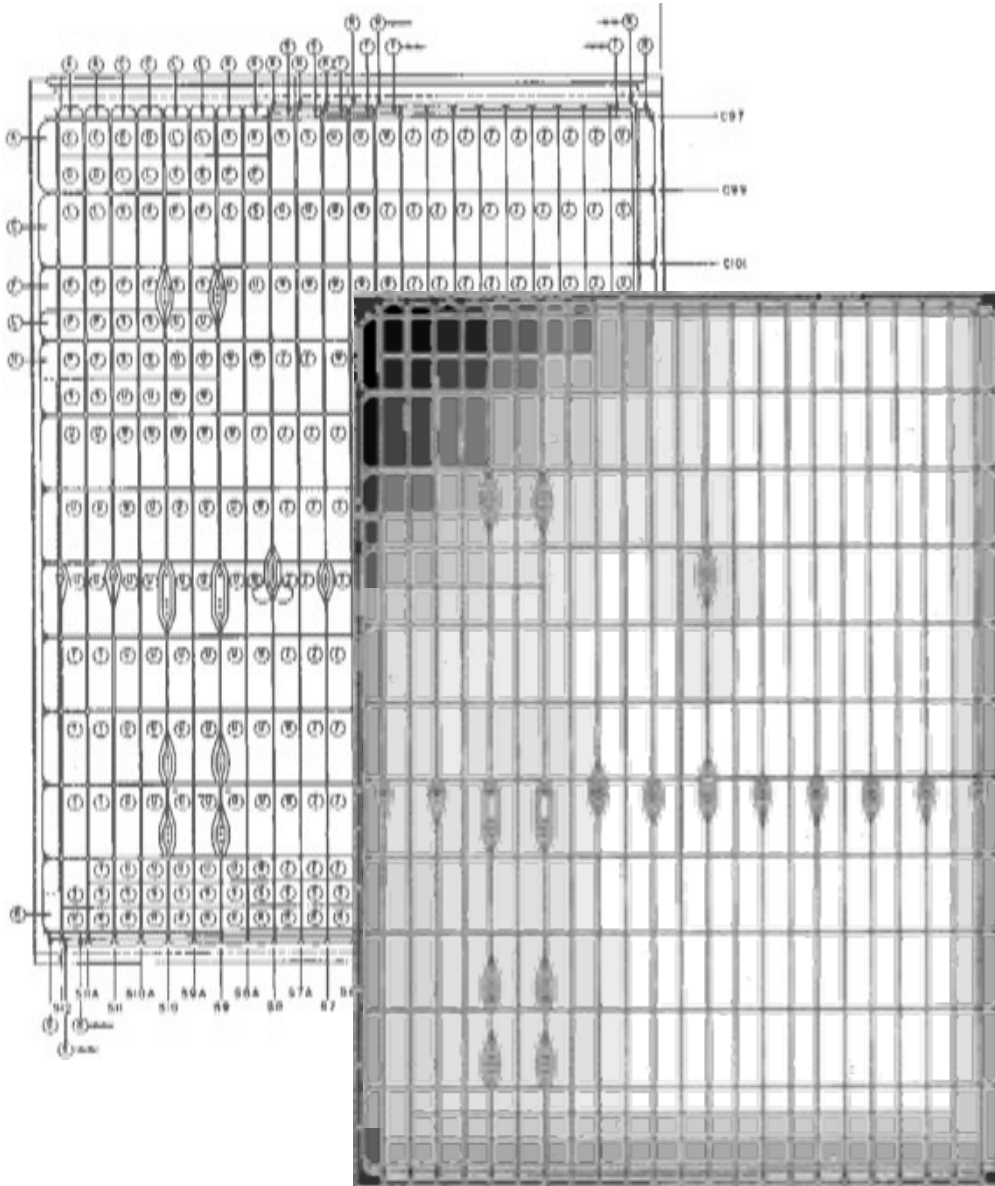
Estimate Xt.1974 intermediate ring frame attachments NOF =
1.08 from average (scaled barrel 1 wt. - barrel 2 wt.)/barrel 2 wt.

LH₂ Tank Panel Skin Thickness Variations



Starboard-side panels 5 to 8 shown.

Panel Manufacturing Drawings Evaluated



Barrel 1 - panel 8 shown
(178 x 130 in.).

Total panel thickness of 1.300 inches.

Skin thicknesses range from 0.089 to 0.550 inches.

Axial stiffener thicknesses range from 0.095 to 0.375 inches.

Circumferential stiffener thicknesses range from 0.125 to 0.300 inches.

Similar results obtained
for other panels.

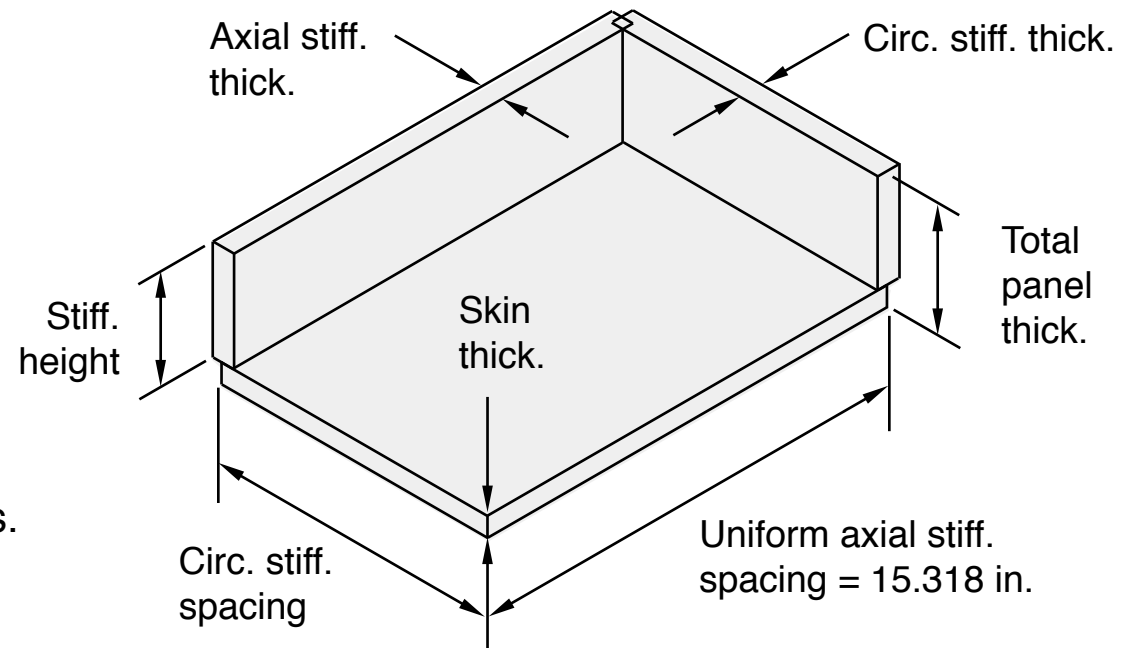
Unit Cell Weights Calc. From Min. Orthogrid Dimensions

Type ID	Tot. panel, thick, in.	Min. skin thick., in.	Circ. stiff. spacing, in.	Min. axial stiff. thick., in.	Min. circ. stiff. thick., in.
1	1.300	0.089	5.416	0.095	0.125
2	1.300	0.089	5.416	0.100	0.125
3	1.050	0.090	5.416	0.080	0.100
4	1.050	0.093	10.832	0.086	0.100

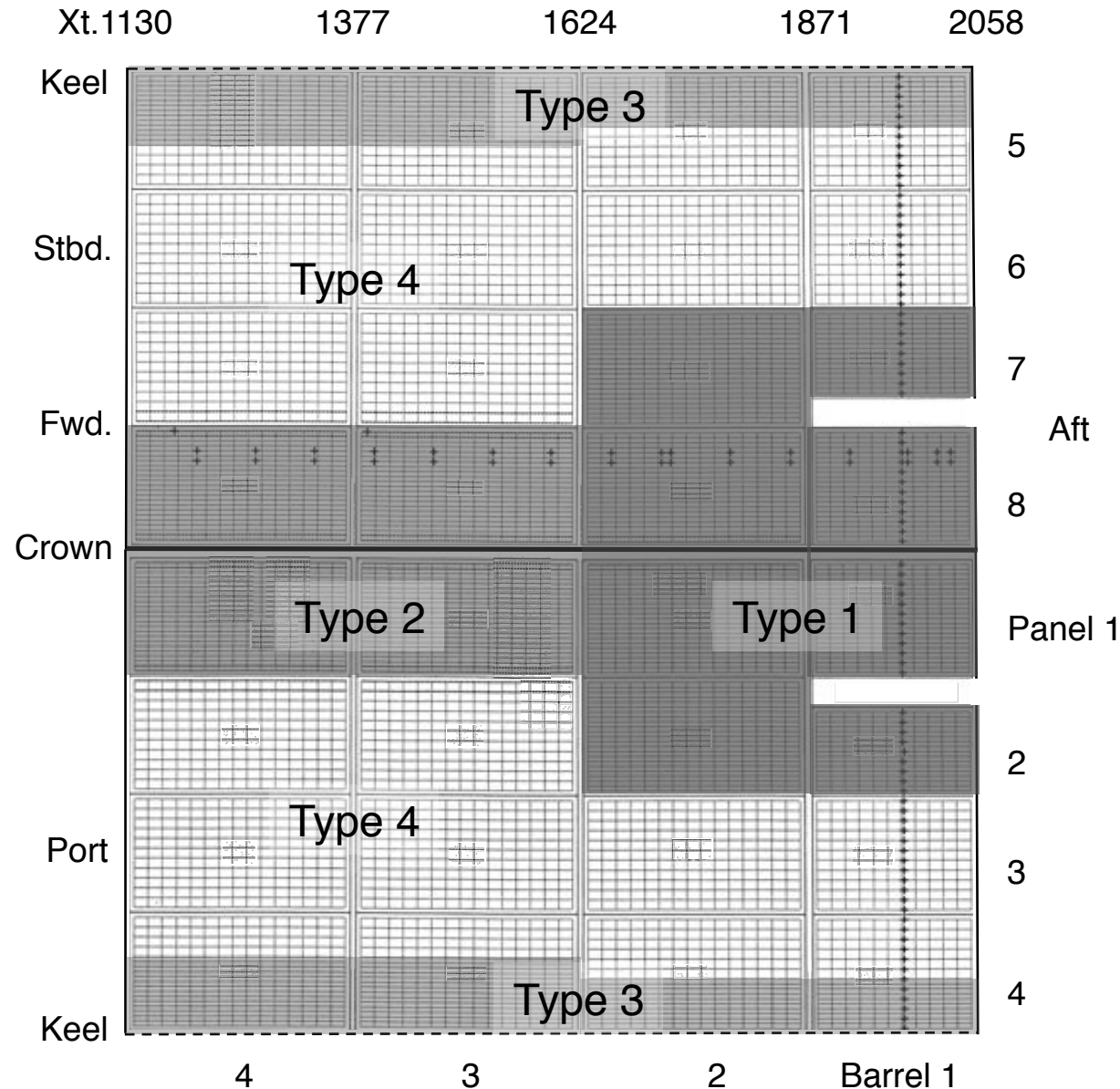
Type ID	Unit cell wt., lb	Areal wt., lb/ft ²
1	0.977	1.695
2	0.986	1.711
3	0.890	1.545
4	1.672	1.451

Stiffener height = Total panel thickness - minimum skin thickness.

Al-Li 2195 density = 0.098 lb/in³



Orthogrid Unit Cell Type Locations



Heavier Type 1 and Type 2 panels on tank crown.

Lightest Type 4 panels on tank sides.

Type 3 panels on tank keel.

Predicted Coarse Panel Weights

371.1	371.1	367.3	271.4	1/8
314.8	314.8	367.3	203.6	2/7
314.8	314.8	314.5	232.4	3/6
327.7	327.7	323.7	239.2	4/5

Coarse panel weight (lbs) equals (orthogrid type areal weight x panel planform area).

Predicted panel weights are identical port and starboard.

Calculated Coarse NOFs

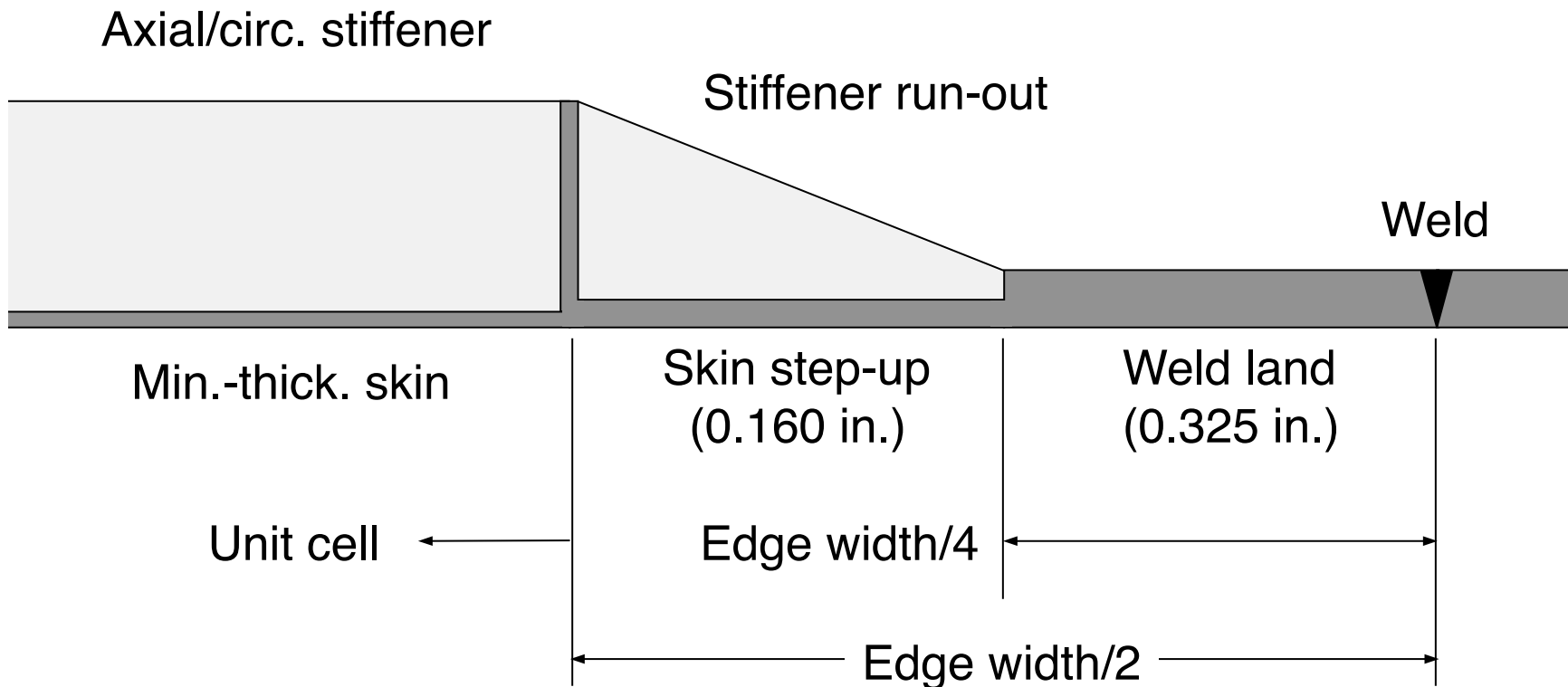
1.25/1.32	1.23/1.30	1.61/1.64	1.70/1.77	1/8
1.26/1.27	1.27/1.27	1.69/1.69	1.56/1.57	2/7
1.25/1.25	1.24/1.24	1.24/1.24	1.36/1.36	3/6
1.22/1.22	1.21/1.21	1.21/1.21	1.30/1.31	4/5

Panel

Panel NOF equals actual weight divided by predicted weight.

Average 24 percent NOF for acreage panels circled in red includes non-min. skin and stiffener thickness variations, stiffener run-outs, weld lands and skin step-ups, and fillets.

Orthogrid Panel Edge Model



Edge width is equally divided between skin step-up and weld land.

Average edge width = 10.20 in. (axial), and 10.75 in. (circ.).

Predicted Refined Panel Weights

422.4	422.4	418.3	311.1	1/8
381.9	381.9	418.3	240.0	2/7
381.9	381.9	382.0	283.1	3/6
386.9	386.9	384.4	286.5	4/5

Panel

Refined panel weight (lbs) equals (orthogrid type unit cell weight x number of unit cells), plus the calculated panel edge weight.

Predicted panel weights are identical port and starboard.

Calculated Refined NOFs

1.10/1.16	1.08/1.14	1.42/1.44	1.48/1.54	1/8
1.04/1.04	1.05/1.04	1.48/1.48	1.32/1.33	2/7
1.03/1.03	1.02/1.02	1.02/1.02	1.12/1.12	Panel 3/6
1.03/1.03	1.03/1.03	1.02/1.02	1.09/1.09	4/5

Panel NOF equals actual weight divided by predicted weight.

Average 3 percent NOF for acreage panels circled in red includes non-min. skin and stiffener thickness variations, and fillets.

Comparison Of Coarse And Refined NOFs

Average coarse and refined acreage panel NOFs are calculated as 24 and 3 percent, respectively, with standard deviations of 2 and 1 percent.

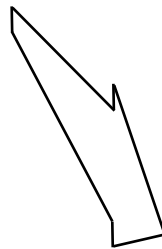
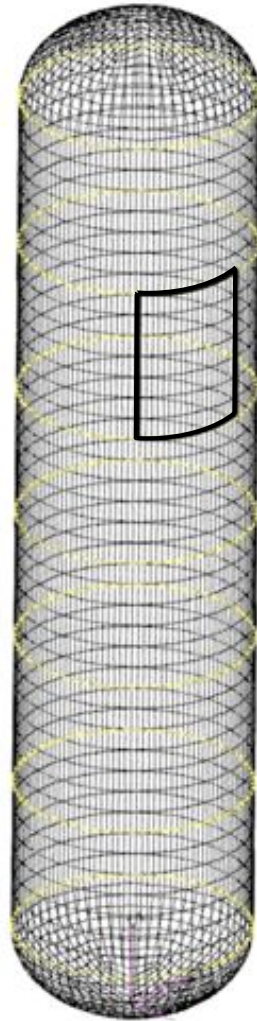
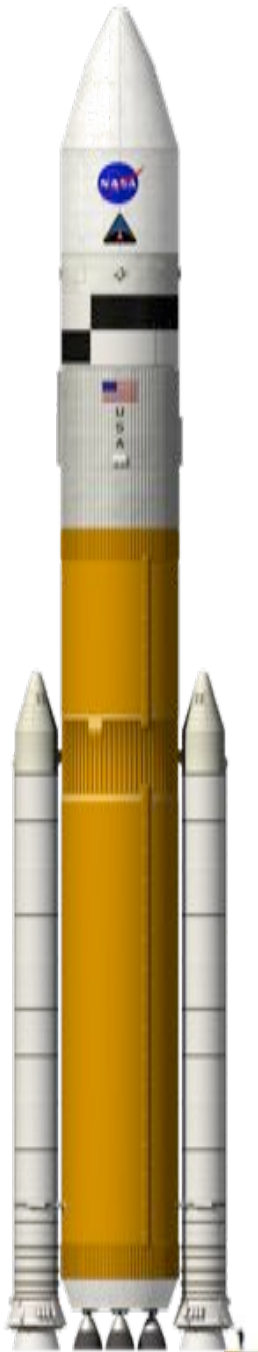
Therefore, for the acreage panels in this study, 76 percent of the panel weight is contained in the orthogrid central region.

About 21 percent of the panel weight can be attributed to the skin step-up and weld land details captured in the panel edge model.

The remaining 3 percent of the panel weight is due to machining fillets, as well as to non-minimum skin and stiffener thickness variations.

Future launch vehicle structures are assumed to have geometry and design details that are similar to SLWT structures used to generate these non-opts.

Ares V LH₂ Tank Barrel Weight Estimation



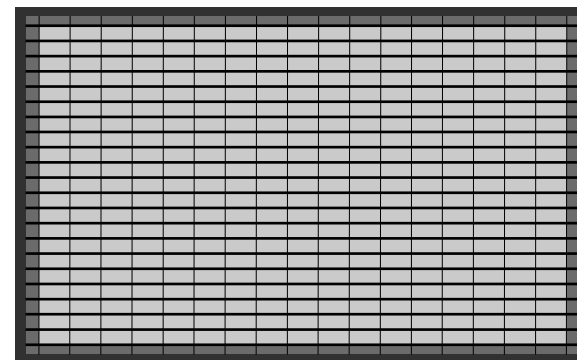
Orthogrid panel sized for proof pressure and flight load cases using HyperSizer.

Panel with 0.160-in. skin thickness is integrally machined from Al-Li 2195 plate.

Orthogrid unit cell wt. = 2.25 lbs, and areal wt. = 3.54 lb/ft².

Coarse panel wt. = 958 lbs; 1188 lbs after application of 1.24 NOF.

Refined panel wt. = 1100 lbs; 1133 lbs after application of 1.03 NOF.



251 x
155 in.

Part 1 – Concluding Remarks

Shuttle SLWT LH₂ tank barrel panel drawings and weights data are integrated and analyzed to estimate panel NOFs.

The coarse weights model predicts an average 24 percent NOF for tank acreage panels, while the refined weights model yields an average 3 percent NOF.

Therefore, 76 percent of a typical acreage panel weight is in the orthogrid cells, 21 percent in the weld lands and skin and stiffener transitions, and 3 percent in other design details.

Intermediate ring frame and GO₂/GH₂ repressurization line and cable tray support attachment NOFs are 8 and 4 percent.

These results should be applicable to Ares V and SLS metallic cryogenic propellant tanks, and may help increase fidelity of predicted weights.

Part 2 – Propellant Tank Bulkheads

Super-Lightweight Tank (SLWT) bulkheads
description and manufacturing

Reported bulkhead gore weights

SLWT proof test and bulkhead sizing

Proof-pressure and actual minimum skin
thicknesses

Coarse gore weights and non-optimum
factor (NOF) calculations

Refined gore weights and NOFs

Application to Ares V tank bulkheads

Concluding remarks

SLWT Bulkheads Description



LH₂ tank barrel

LH₂ aft ellipsoid

5 major bulkhead regions evaluated

LH₂ fwd ellipsoid

Bulkhead regions have 12 gores, except for LO₂ fwd ogive with 8 gores

LO₂ aft & fwd ogives



LO₂ tank barrel

LO₂ aft ellipsoid

SLWT Bulkhead Manufacturing

Flat aluminum plates are first machined to their tapered thicknesses, and then stretch-formed into 3-D shapes, or *gores*.



Gores are extensively chemically milled to tailor shell thicknesses for weld lands and local loads.

Gores are then fusion- or friction stir-welded into a complete bulkhead.

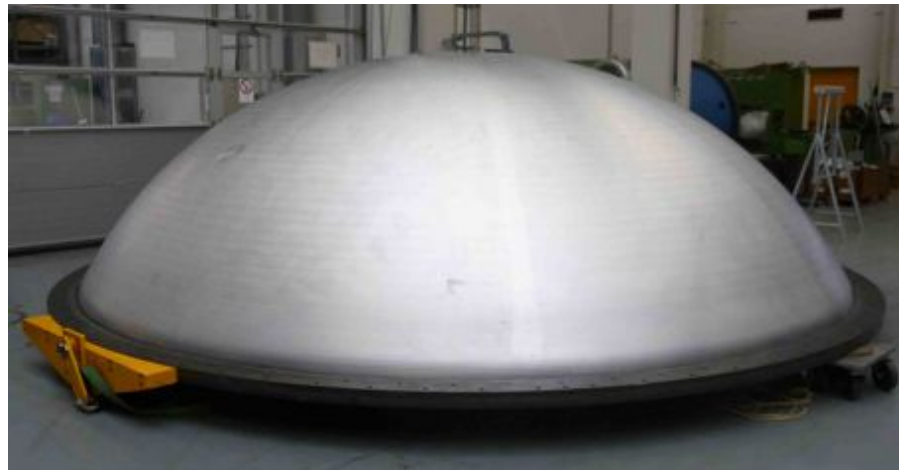


SLWT Bulkhead Manufacturing (2)

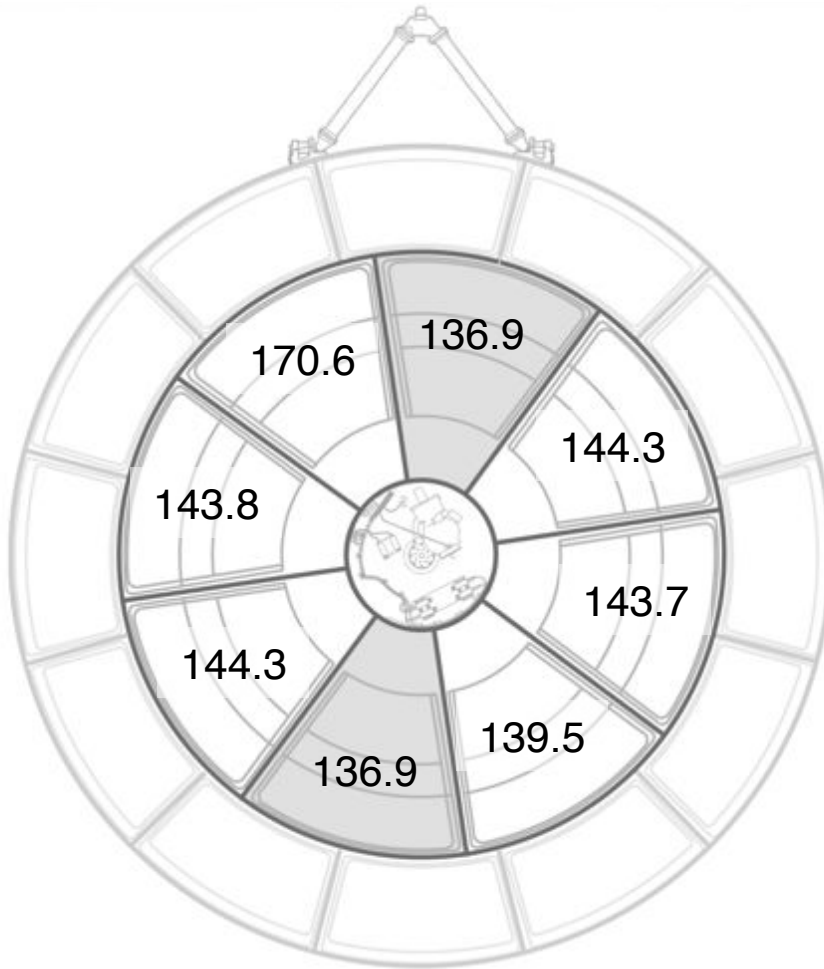
Note raised weld lands between individual gores on the assembled bulkhead.



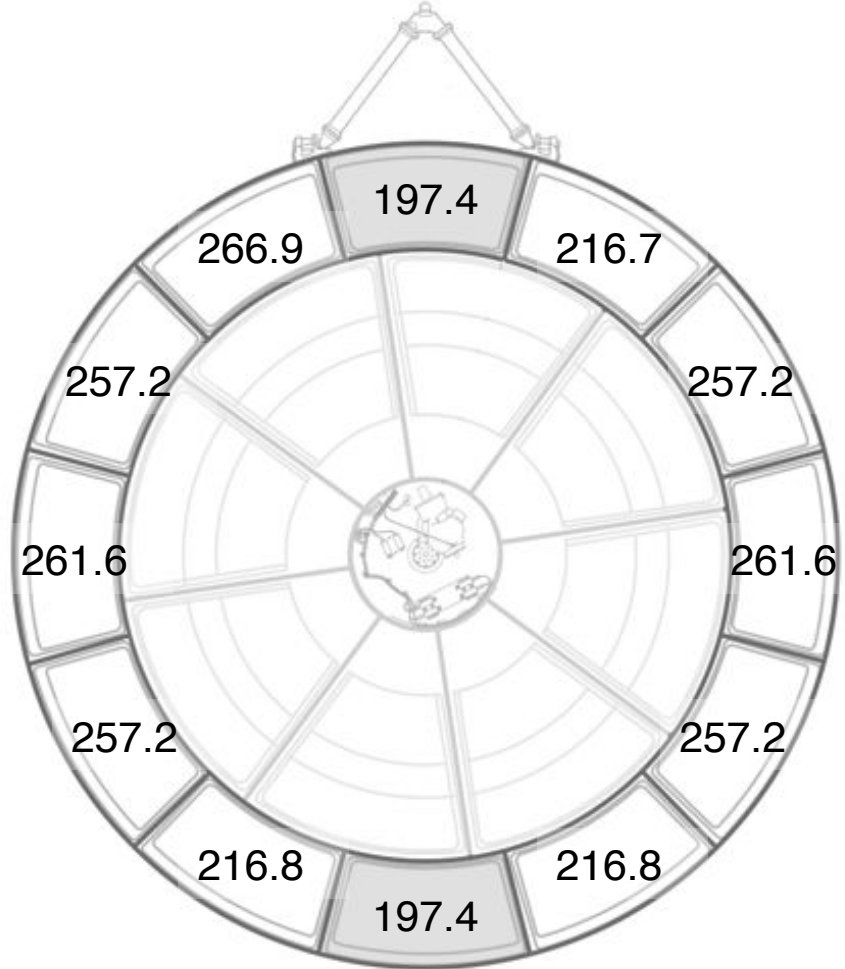
Spin-forming may also be used to build large bulkheads. This is an emerging technology which may save weight and mfg. time.



LO₂ Ogive Gore Reported Weights



Forward ogive (view aft)



Aft ogive (view aft)

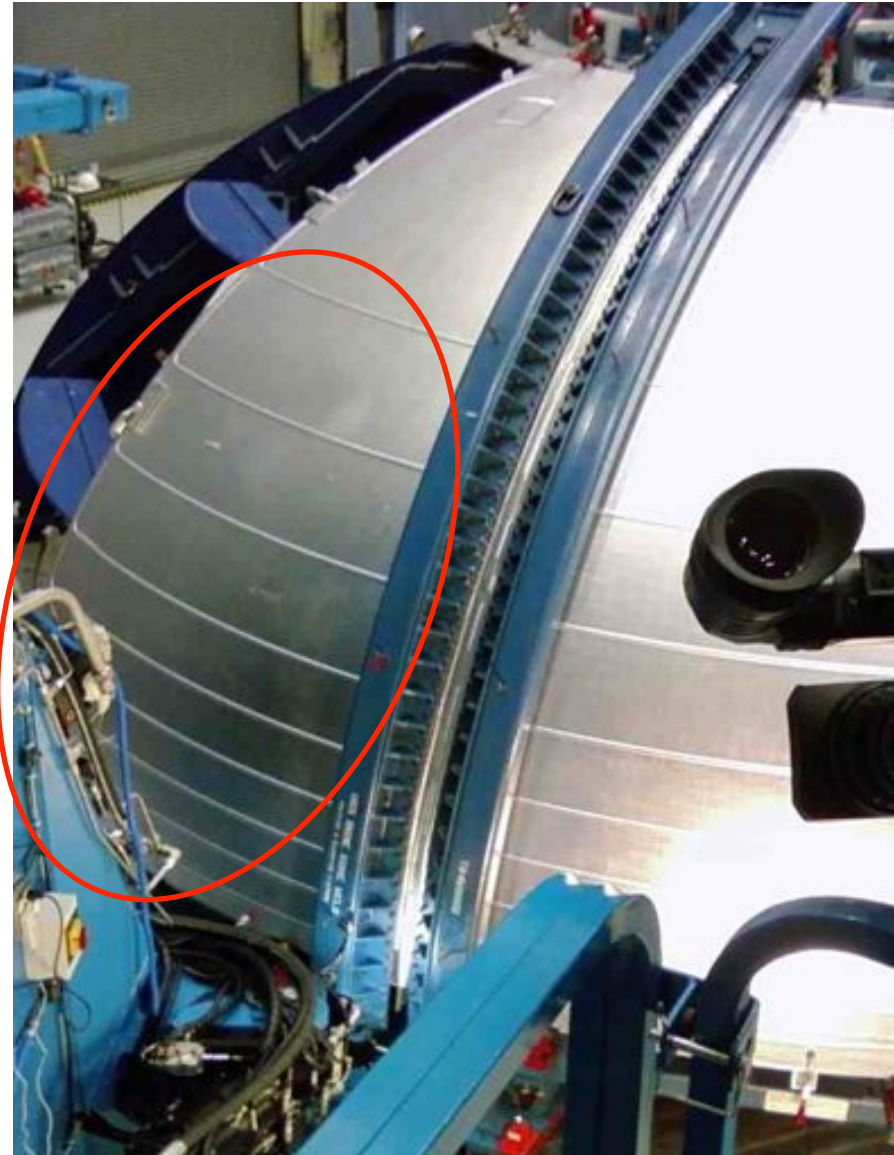
Reported weights (lbs) include manufacturing tolerances
Minimum-weight gore(s) shaded gray

LO₂ Aft Bulkhead Gore Reported Weights

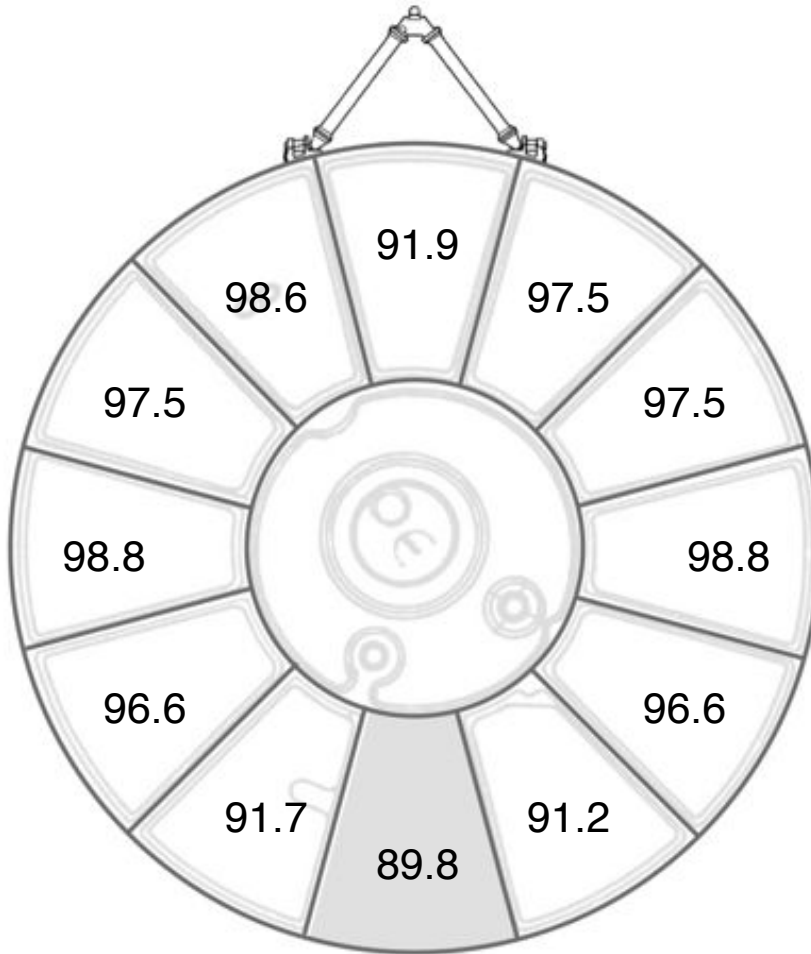
Reported weights for all 12 bulkhead gores are equal to 124.9 lbs.

Uniform manufacturing tolerances of ~ 0.010 inches included in all reported weights.

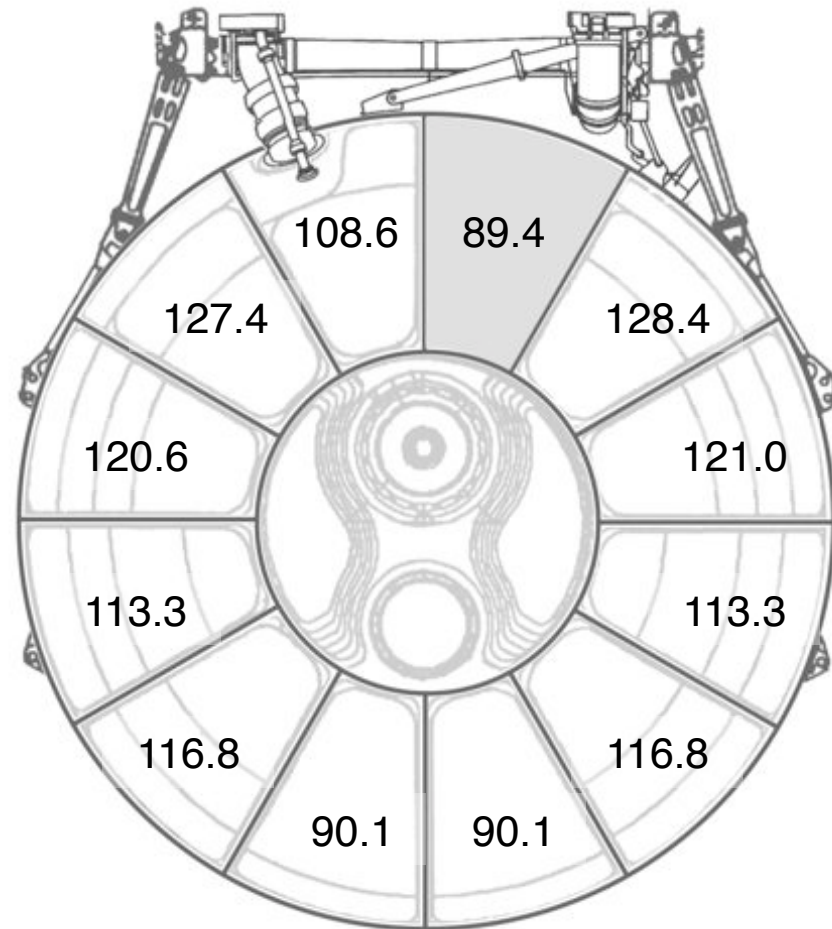
Circumferential stiffeners prevent shell buckling during tank loading (thermal) and end-of-flight loads (high-g).



LH₂ Bulkhead Gore Reported Weights



Forward bulkhead (view aft)



Aft bulkhead (view fwd)

Reported weights (lbs) include manufacturing tolerances
Minimum-weight gore(s) shaded gray

Stresses In Ellipsoidal Shells

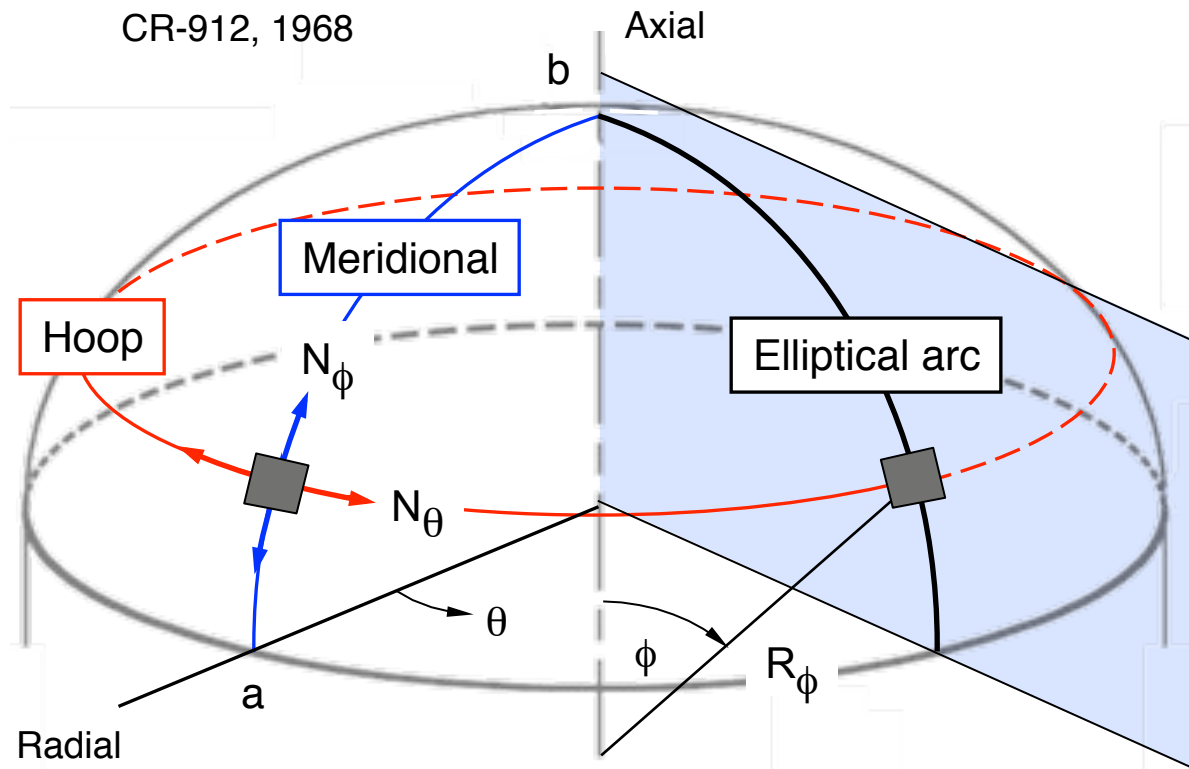
Meridional stress resultant*

$$\frac{N_\phi}{ap} = \frac{a}{2b} \left[1 - \left(\frac{r}{a} \right)^2 \left[1 - \left(\frac{b}{a} \right)^2 \right] \right]^{1/2}$$

Hoop stress resultant*

$$\frac{N_\theta}{ap} = \frac{N_\phi}{ap} \left[2 - \frac{1}{1 - \left(\frac{r}{a} \right)^2 \left[1 - \left(\frac{b}{a} \right)^2 \right]} \right]$$

* From NASA
CR-912, 1968



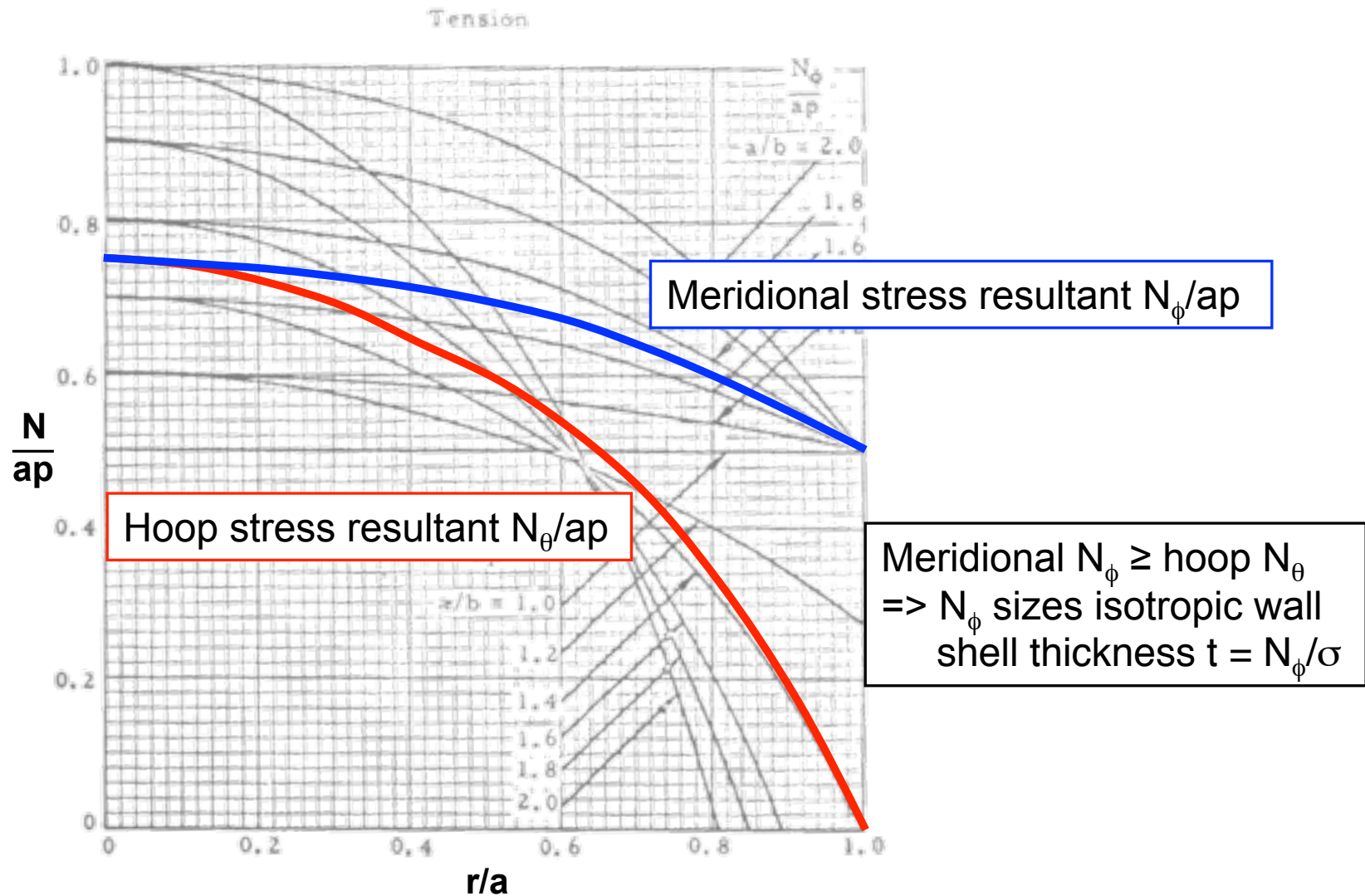
$N = \sigma \times \text{shell thickness } t$

R_ϕ, R_θ normal to shell surface

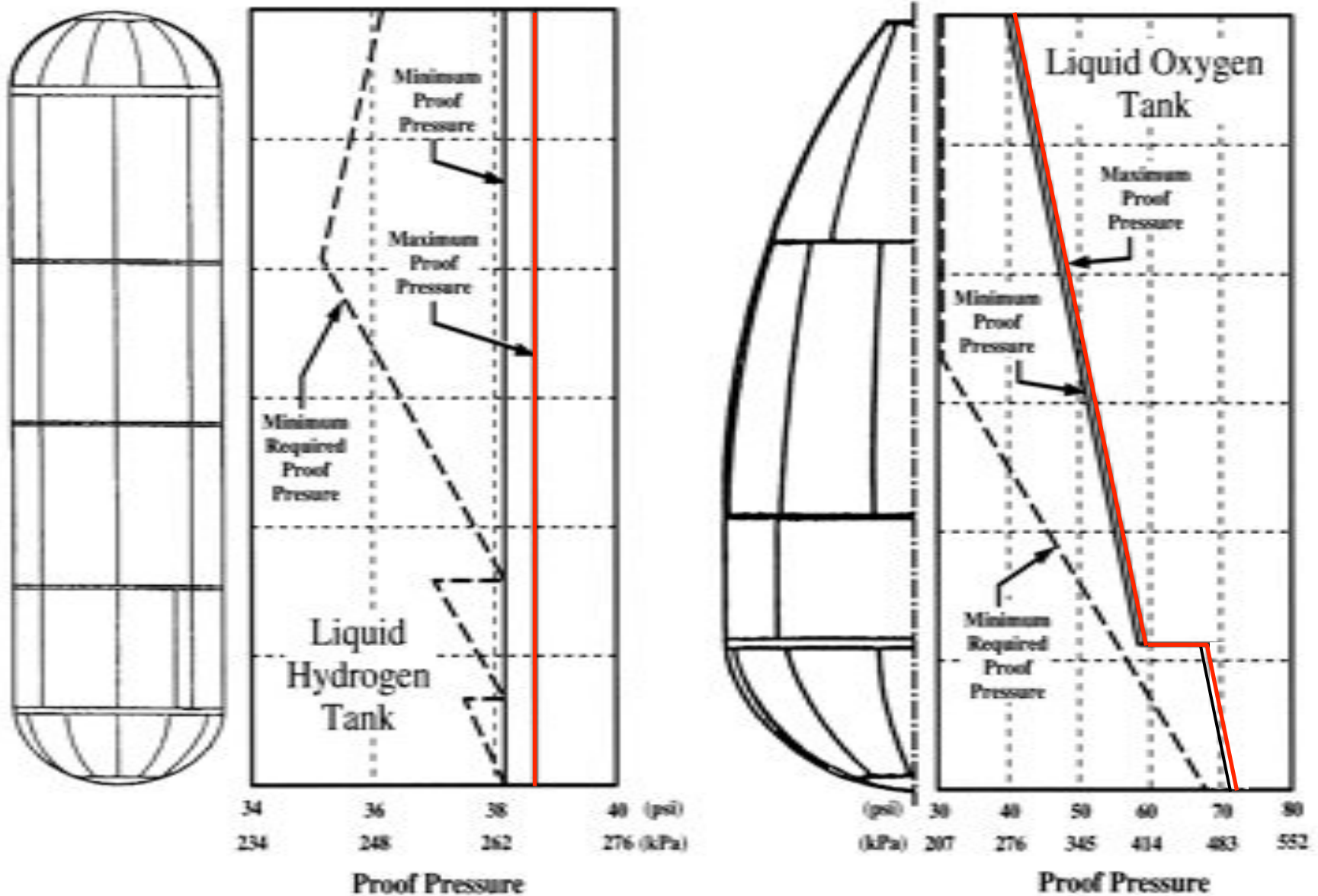
Membrane loads in skin; no bending

Uniform internal pressure load p

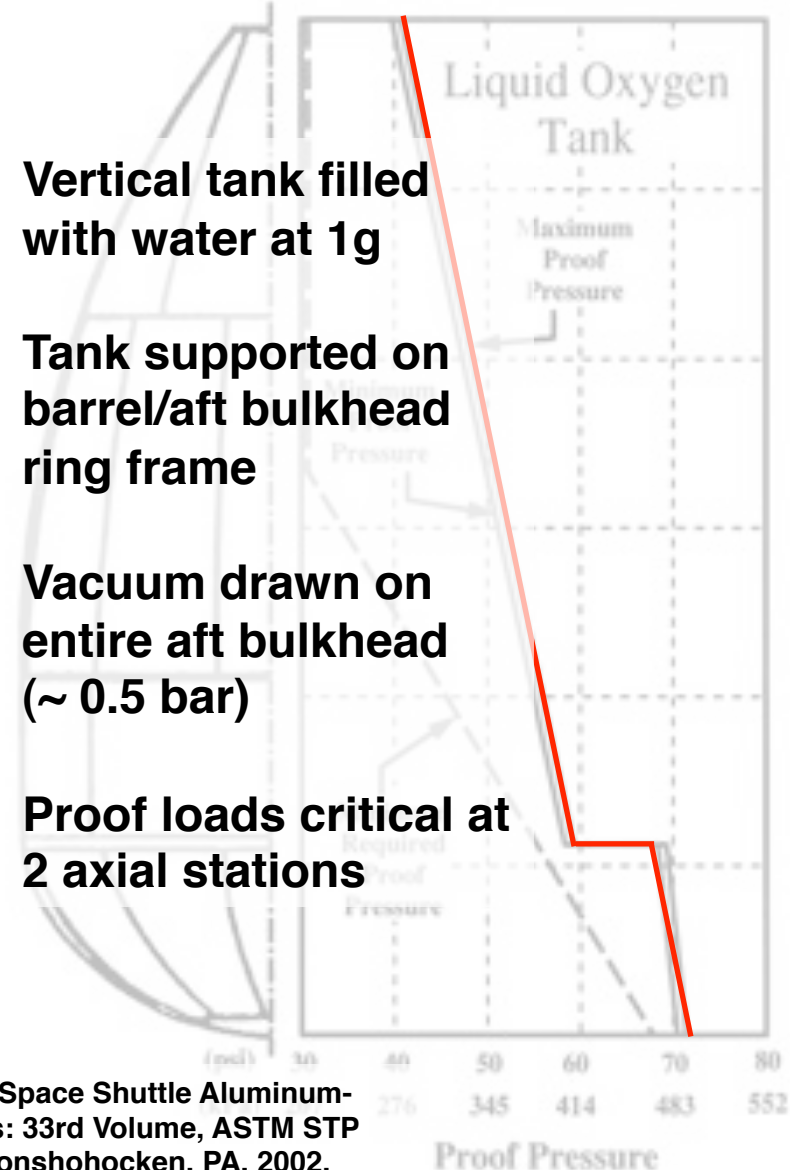
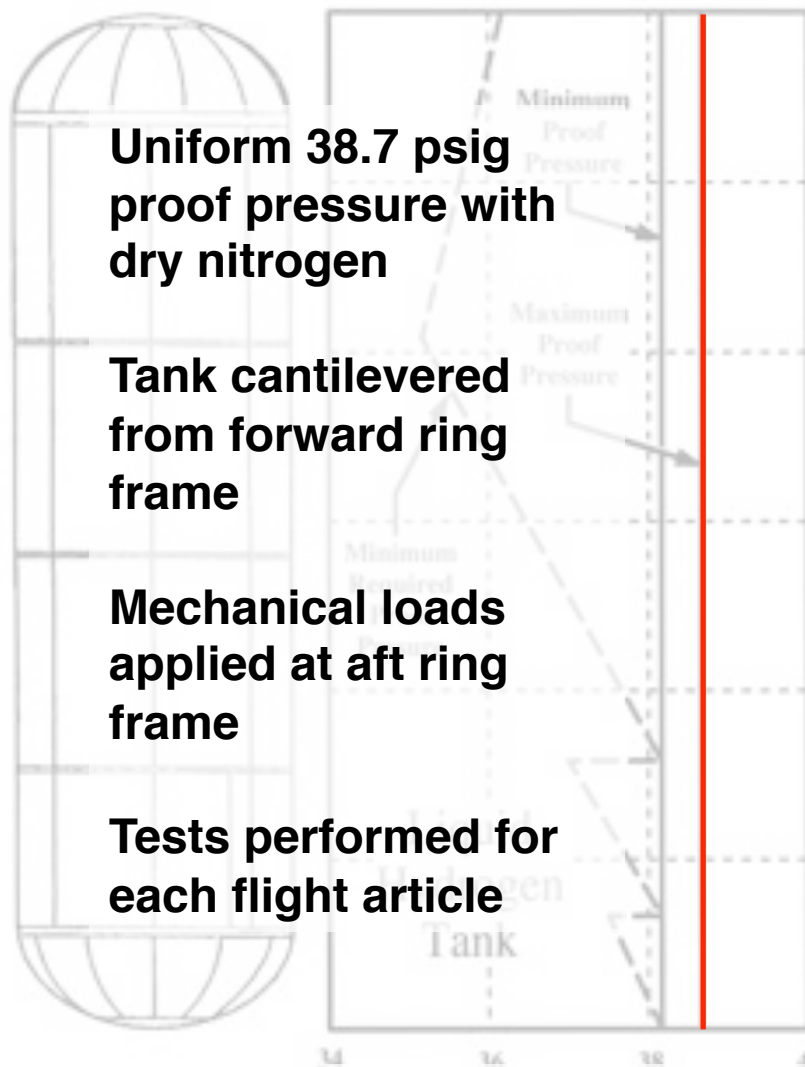
Stresses In Ellipsoidal Shells (2)



SLWT Proof Test Pressure Loads

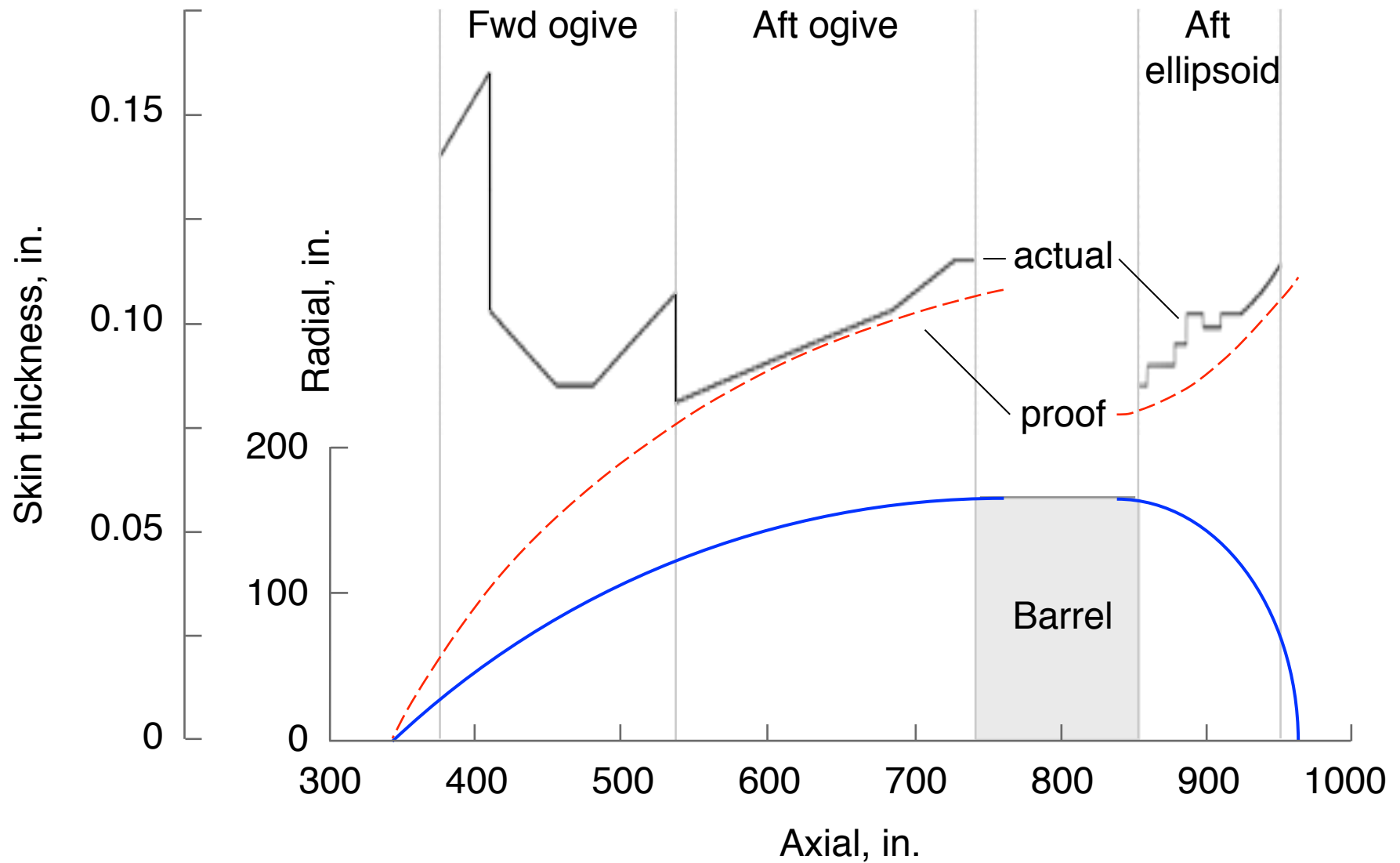


SLWT Proof Test Pressure Loads

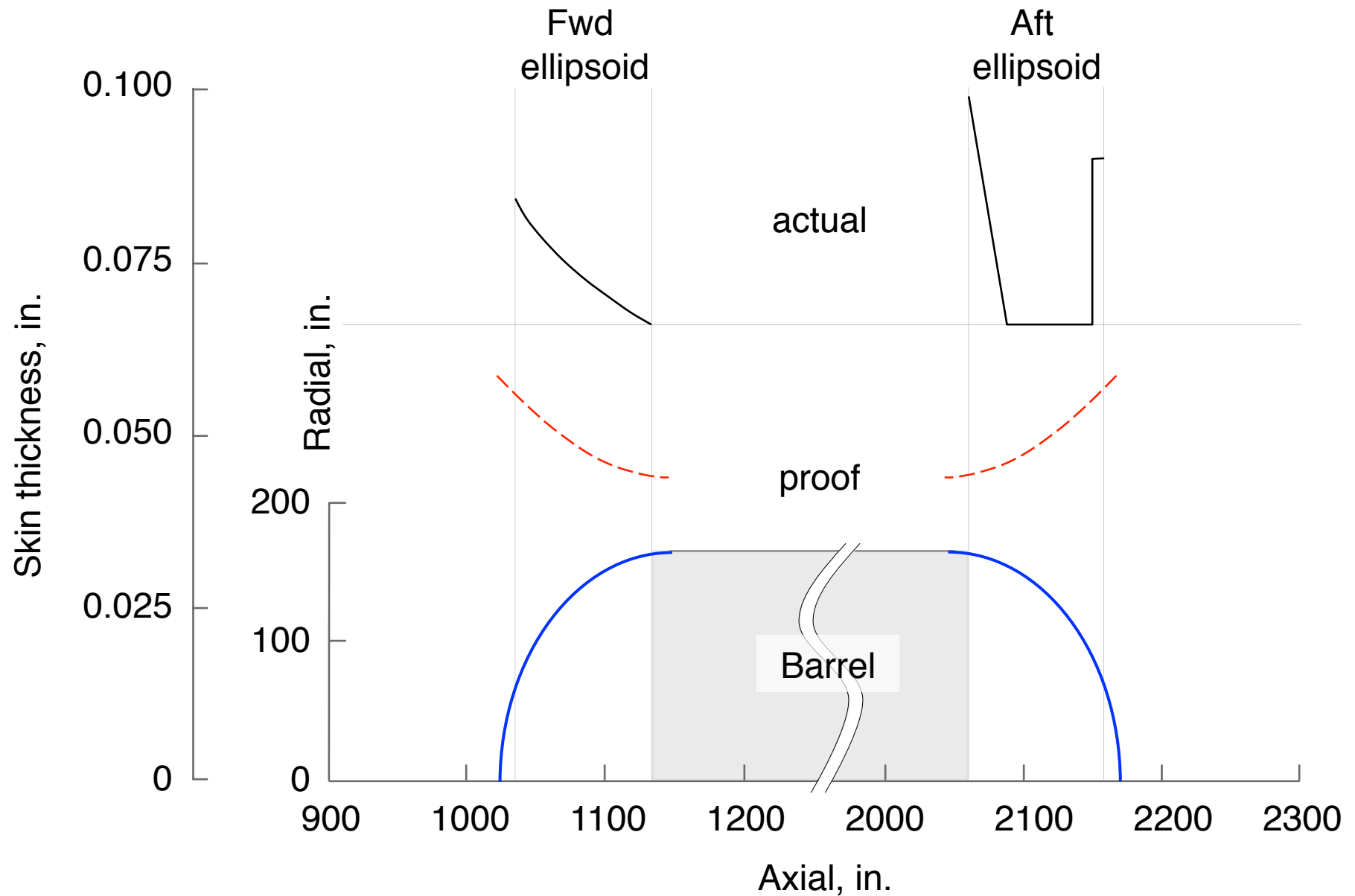


D.N. Wells et al., "Fracture Control Methodology for the Space Shuttle Aluminum-Lithium External Tank," Fatigue and Fracture Mechanics: 33rd Volume, ASTM STP 1417, W.G. Reuter and R.S. Piascik, Eds., ASTM, West Conshohocken, PA, 2002.

LO₂ Tank Proof And Actual Skin Thicknesses



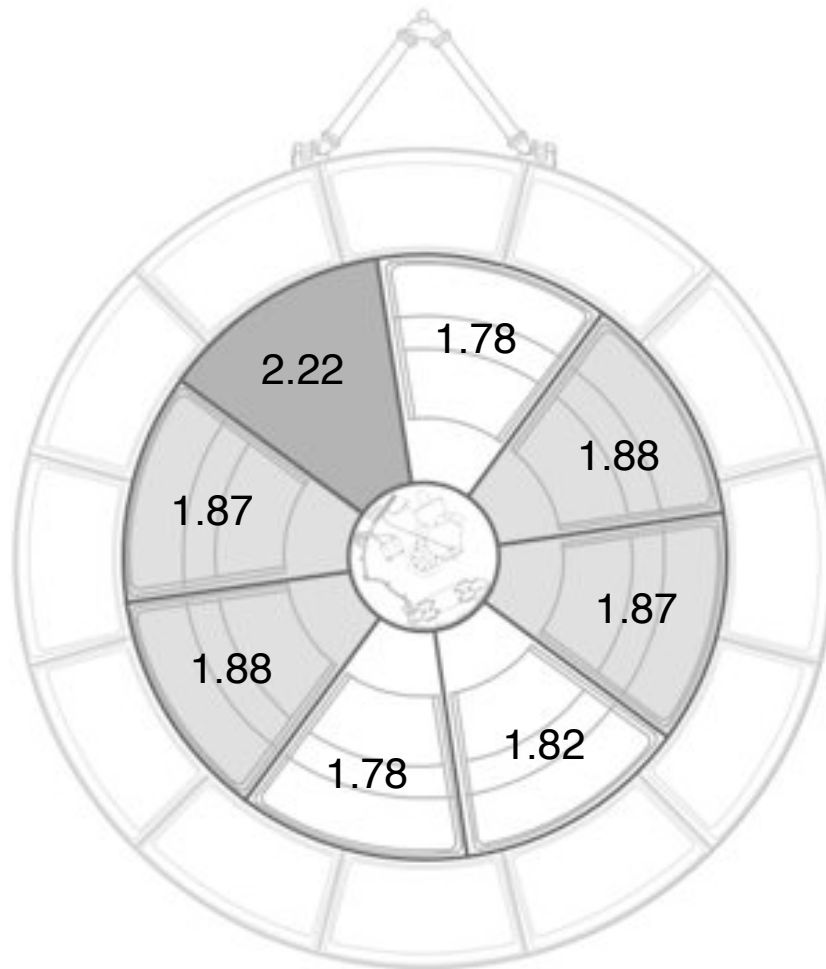
LH₂ Tank Proof And Actual Skin Thicknesses



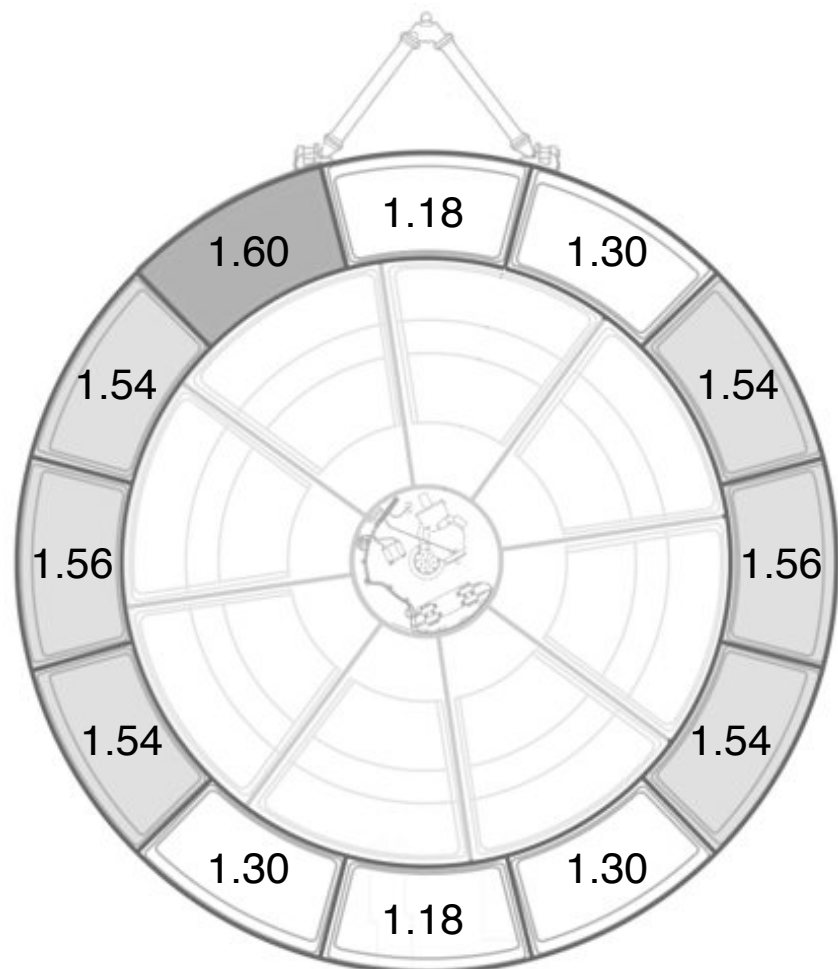
Predicted Minimum Gore Weights (lbs, skin sized by tank proof test)

	Proof skin + Mfg tols = Predicted			Reported	NOF
LO₂ fwd ogive	65.3	11.5	76.8	136.9	1.78
LO₂ aft ogive	152.5	14.8	167.3	197.4	1.18
LO₂ aft BH	83.0	9.7	92.7	124.9	1.35
LH₂ fwd BH	45.3	9.1	54.4	89.8	1.65
LH₂ aft BH	45.3	9.1	54.4	89.4	1.64

LO₂ Ogive Gore Coarse Non-Optimum Factors

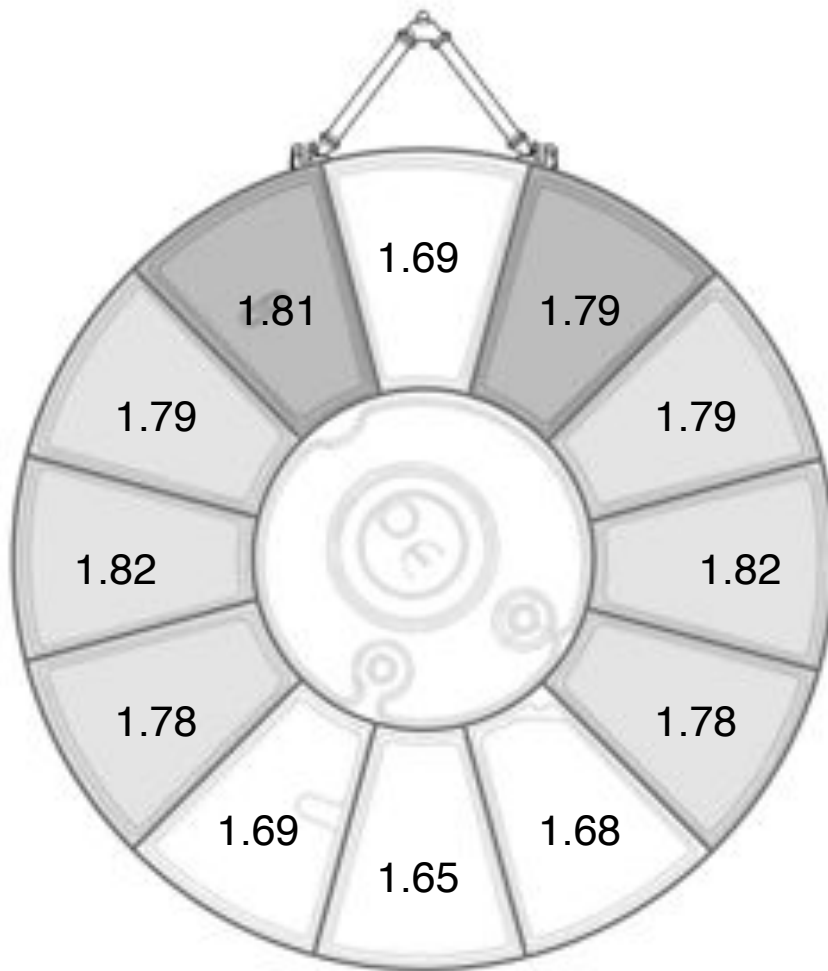


Fwd non-opt factors (view aft)

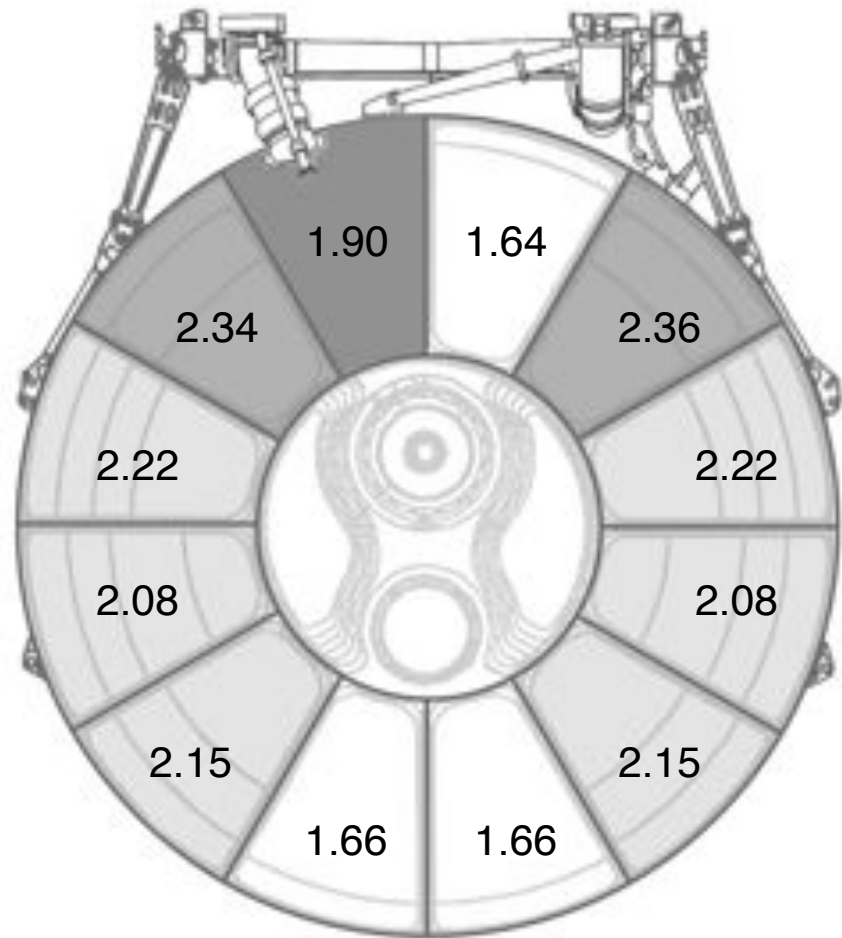


Aft non-opt factors (view aft)

LH₂ Bulkhead Gore Coarse Non-Optimum Factors

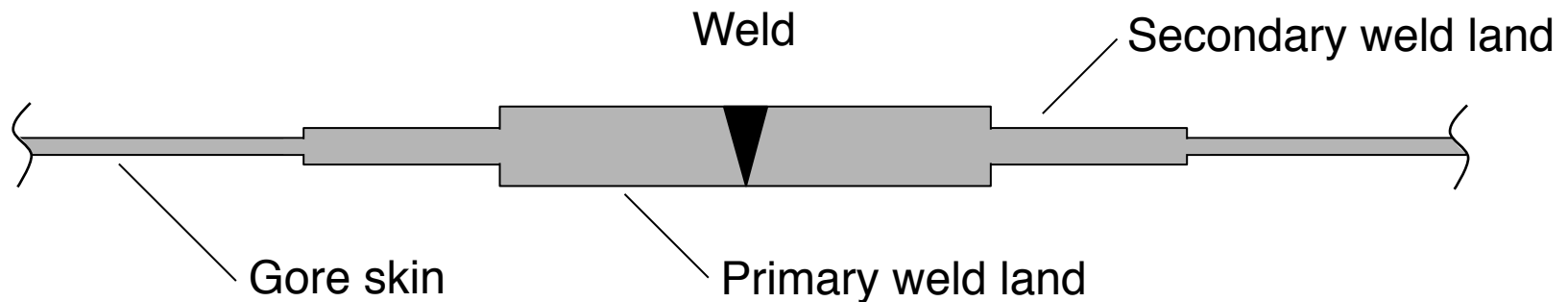


Fwd non-opt factors (view aft)



Aft non-opt factors (view fwd)

Gore Weld Land Schematic



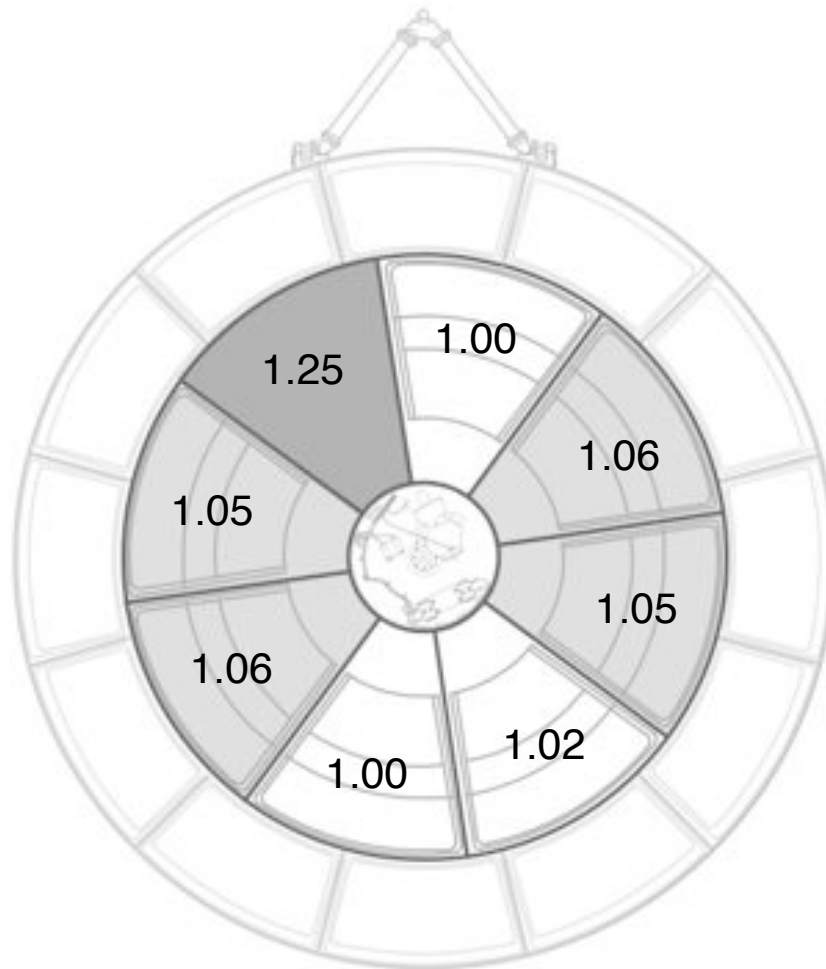
Weld land dimensions from gore production drawings
width / thickness ranges, inches

	Primary	Secondary
Meridional	1.32-1.62 / 0.140-0.385	1.50 / skin+0.040-0.060
Hoop	1.32-1.75 / 0.135-0.385	1.50 / skin+0.040-0.060

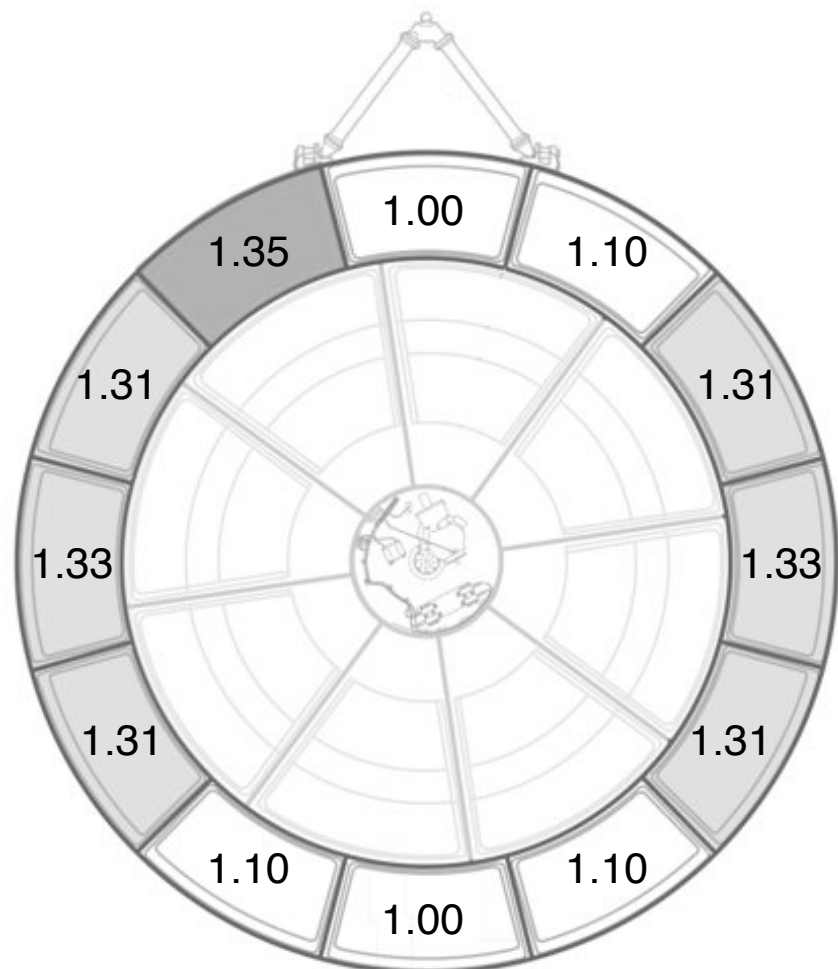
Predicted Minimum Gore Weights (lbs, actual gore dimensions)

	Act skin + Weld lands + Mfg tols = Predicted				Reported	NOF
LO₂ fwd ogive	116.3	8.9	11.5	136.7	136.9	1.00
LO₂ aft ogive	159.0	23.3	14.8	197.1	197.4	1.00
LO₂ aft BH (includes 5.5 lbs for circumferential stiffeners)	91.9	16.3	9.7	123.4	124.9	1.01
LH₂ fwd BH	68.1	11.3	9.1	88.5	89.8	1.01
LH₂ aft BH	66.9	12.5	9.1	88.5	89.4	1.01

LO₂ Ogive Gore Refined Non-Optimum Factors

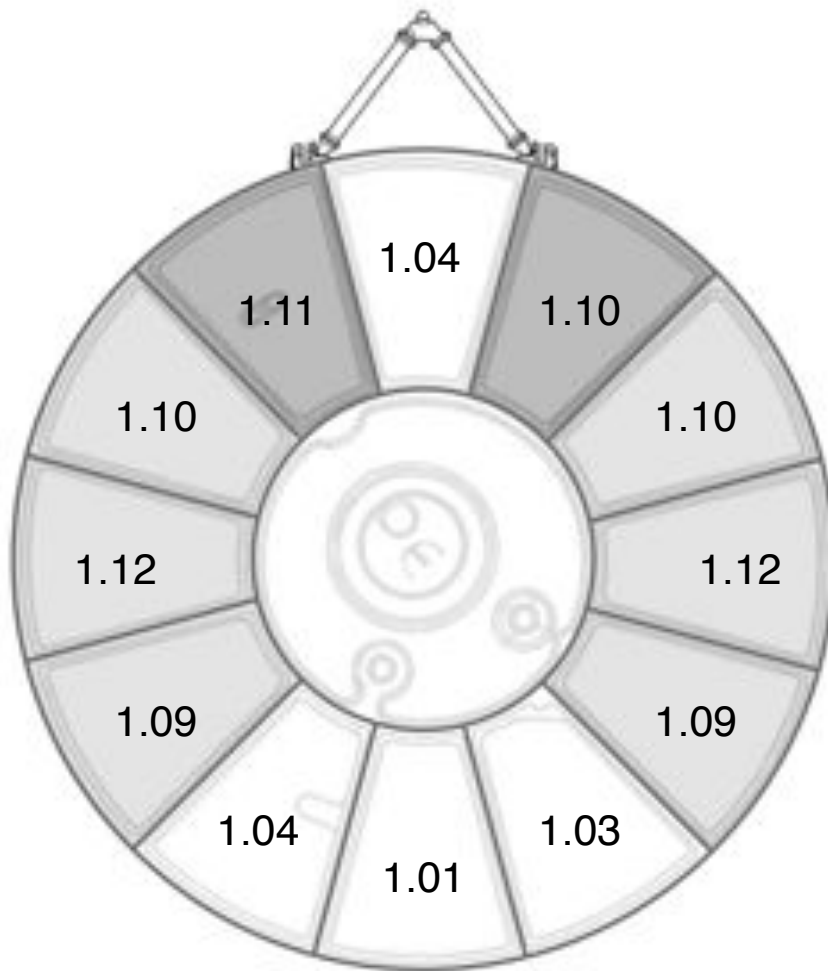


Fwd non-opt factor (view aft)

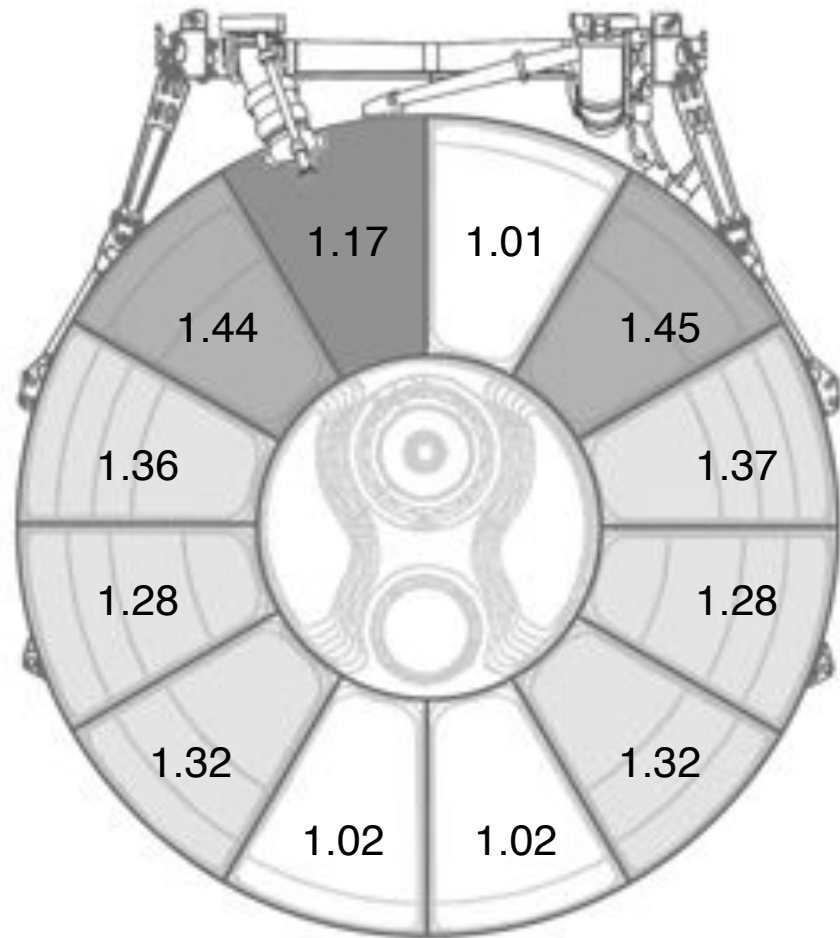


Aft non-opt factor (view aft)

LH₂ Bulkhead Gore Coarse Non-Optimum Factors



Fwd non-opt factor (view aft)

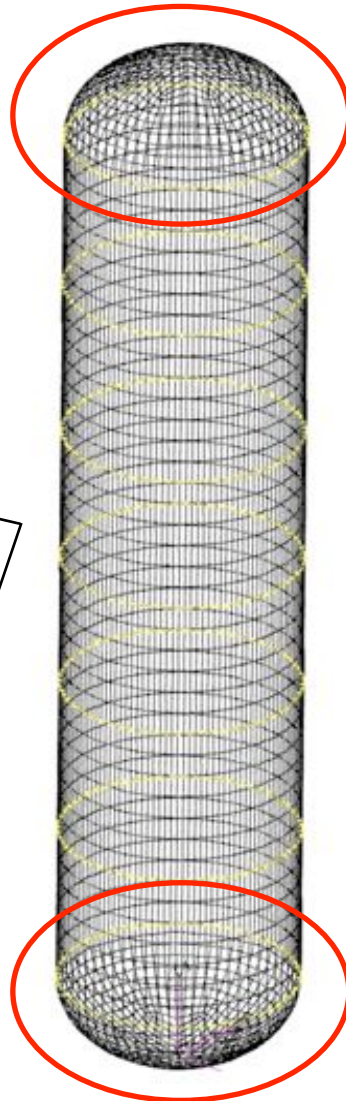


Aft non-opt factor (view fwd)

Ares V LH₂ Tank Bulkhead Weight Estimation



fwd BH



aft BH

Al-Li 2195 tank sized for uniform 40 psig proof pressure (no mech. loads).

Gore skin thicknesses tapered from 0.059 to 0.076 inches => Proof-sized gore weight = 93 lbs (12 req'd).

Coarse NOFs applied: Average fwd BH acreage NOF = 1.68, and reinforced NOF = 1.80. Average aft BH acreage NOF = 1.65, and reinforced NOF = 2.15.

Application of above NOFs increases fwd BH weight from 1116 lbs to 1942 lbs (+74 pct), and aft BH weight from 1116 lbs to 2214 lbs (+98 pct).

Part 2 – Concluding Remarks

Shuttle SLWT bulkhead gore drawings and weights data are integrated and analyzed to estimate gore NOFs.

The coarse weights model returns an average 68 percent NOF for the SLWT bulkhead gores => The tank proof test sizing underpredicts the bulkhead gore weights.

A more refined weights model yields an average 13 percent NOF, with a 12 percent coefficient of variation.

Gores located adjacent to large point loads are from 7 to 42 percent heavier than acreage gores. GO₂ repress line/cable tray support NOFs average 26 percent higher than acreage gores.

These results should be applicable to Ares V and SLS metallic cryogenic propellant tanks, and may help increase fidelity of predicted weights.

Acknowledgements

The authors are grateful to the technical staff of the Lockheed Martin Space Systems Company and the AMRO Fabricating Corporation for providing the SLWT panel drawings and weights database used as a basis for this study.

Questions?