

Development Of Non-Optimum Factors For Launch Vehicle Propellant Tank Bulkhead Weight Estimation

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Non-optimum factors are used during aerospace conceptual and preliminary design to account for the increased weights of as-built structures due to future manufacturing and design details. Use of higher-fidelity non-optimum factors in these early stages of vehicle design can result in more accurate predictions of a concept's actual weights and performance. To help achieve this objective, non-optimum factors are calculated for the aluminum-alloy gores that compose the ogive and ellipsoidal bulkheads of the Space Shuttle Super-Lightweight Tank propellant tanks. Minimum values for actual gore skin thicknesses and weld land dimensions are extracted from selected production drawings, and are used to predict reference gore weights. These actual skin thicknesses are also compared to skin thicknesses predicted using classical structural mechanics and tank proof-test pressures. Both coarse and refined weights models are developed for the gores. The coarse model is based on the proof pressure-sized skin thicknesses, and the refined model uses the actual gore skin thicknesses and design detail dimensions. To determine the gore non-optimum factors, these reference weights are then compared to flight hardware weights reported in a mass properties database. When manufacturing tolerance weight estimates are taken into account, the gore non-optimum factors computed using the coarse weights model range from 1.28 to 2.76, with an average non-optimum factor of 1.90. Application of the refined weights model yields non-optimum factors between 1.00 and 1.50, with an average non-optimum factor of 1.14. To demonstrate their use, these calculated non-optimum factors are used to predict heavier, more realistic gore weights for a proposed heavy-lift launch vehicle's propellant tank bulkheads. These results indicate that relatively simple models can be developed to better estimate the actual weights of large structures for future launch vehicles.

I. Introduction

During conceptual and preliminary design of aerospace vehicles, the weights of individual parts are typically estimated using low- to moderate-fidelity computational and analytical methods.^{1,2} However, the results of these idealized analyses often do not include the additional weight of design details required to manufacture and integrate these structures into larger subassemblies and assemblies. Typical design details for large aerospace structures³ that are not included in these preliminary analyses may include localized skin and stiffener thickness variations, weld lands, machining fillets, and subsystem attachments and fittings.

Structural weights predicted early in the design process are usually multiplied by non-optimum factors⁴⁻⁶ to compensate for the anticipated weight of the unmodeled design details. These resulting adjusted weights are then used to predict mass properties for the assembled vehicle, which are then used in trajectory analyses to estimate the vehicle performance. Therefore, realistic values of these non-optimum factors are highly desirable to help ensure that predictions of a design's weight and payload to orbit are accurate. Since non-optimum factors are typically based on historical data or proprietary corporate knowledge, there is often an unfortunate lack of external insight into either their fidelity or traceability back to their sources.

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To help address these concerns, an empirical, hardware-based methodology for calculating non-optimum factors was developed⁷ using the 32 metallic orthogrid-stiffened panels that compose the Space Shuttle Super-Lightweight Tank (SLWT) liquid hydrogen (LH₂) tank barrel. In that study, minimum values for overall panel and skin thicknesses, axial and circumferential blade stiffener thicknesses and spacing from panel manufacturing drawings were used to estimate orthogrid unit cell and panel weights. Both coarse and refined panel weights models were defined, which differed in the inclusion of the weld lands and orthogrid-weld land transition details in the latter model. Predicted panel weights were calculated using these models, and were then compared to measured weights data provided by the tank manufacturer to estimate the panel non-optimum factors. In the present complementary study, the basic methodology in Ref. 7 is applied and extended to determine non-optimum factors for the SLWT's liquid oxygen (LO₂) and LH₂ tank bulkhead gores.

II. Space Shuttle SLWT Description

The Space Shuttle launch vehicle (Figure 1) has four major elements: the winged Orbiter Vehicle, two Solid Rocket Boosters (SRBs), and an expendable External Tank. The third-generation External Tank, designated as the Super-Lightweight Tank,^{3,8} became operational in June 1998 with its first flight on STS-91. The largest part of the system, the SLWT is the structural backbone for the assembled vehicle elements, and is approximately 153.8 ft long by 27.6 ft in diameter. It has an empty weight of 57.8 klbs, and contains the 1.62 Mlbs (73.6 kft³ volume) of LO₂ and LH₂ propellants consumed by the Orbiter's Space Shuttle Main Engines (SSMEs) during ascent.

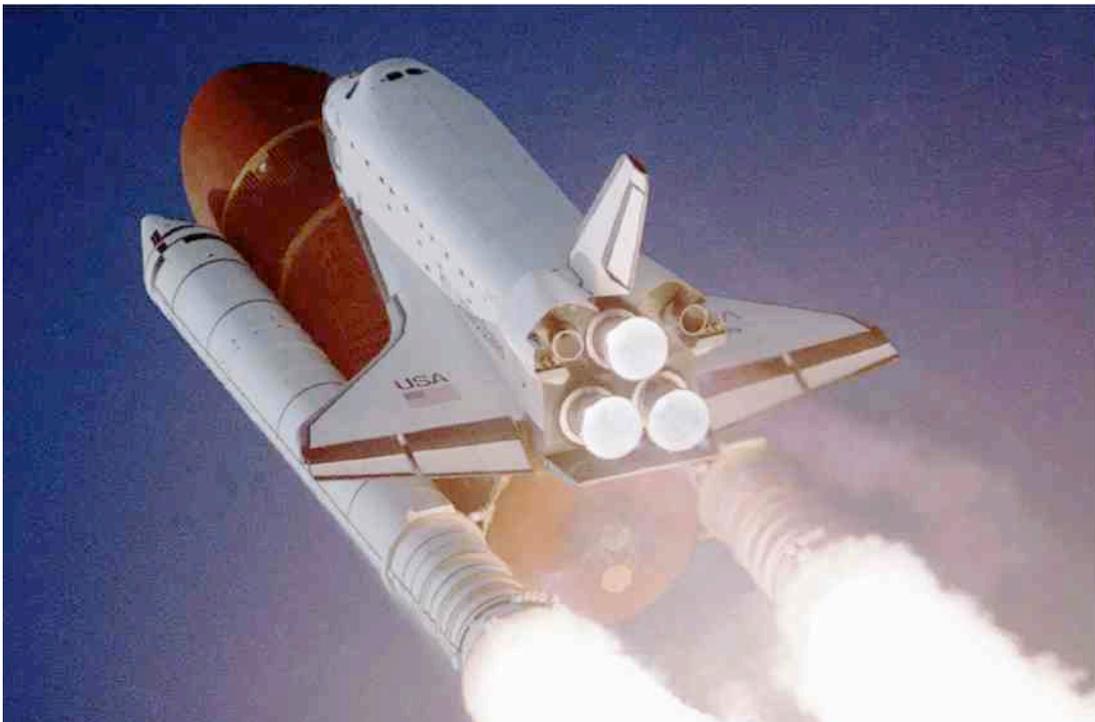


Figure 1. Space Shuttle launch vehicle.

As shown in Figure 2, the SLWT consists of three major components: the smaller LO₂ tank in the nose, the cylindrical Intertank with its stiff internal beam connecting the SRB thrust fittings, and the larger cylindrical LH₂ tank attached aft of the Intertank. The five bulkhead groups (LO₂ tank forward ogive, aft ogive and aft bulkhead, and LH₂ tank forward and aft bulkheads) evaluated in this study are also identified in these figures.

In a typical bulkhead construction, all gores are first stretch-formed into their three-dimensional shapes from flat, tapered-thickness plates, which are then extensively chemically milled to their tailored final thicknesses. Several individual gores are then welded together along their meridians, and to a partial ring frame along their equators. After several of these subassemblies are fabricated, they are then welded to each other and to a spin-

formed spherical cap (not evaluated in this study) to compose a bulkhead assembly. Two bulkheads are then welded to a barrel assembly (described in Ref. 7 for the LH₂ tank) to form the complete tank.

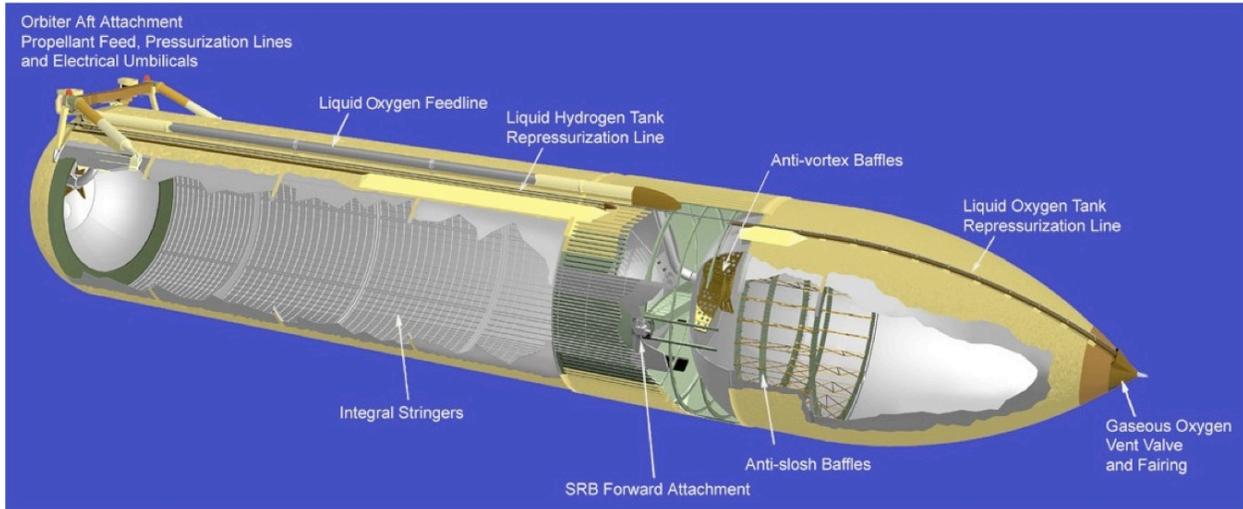


Figure 2. Super Lightweight Tank cutaway view.

The forward bulkhead of the LO₂ tank (Figure 3) has a rotated ogive profile with a 51.0-ft meridional radius and 27.6-ft base diameter, and is built up from an 8-gore forward section and a 12-gore aft section. Although these two groups are then welded together to form a single bulkhead, they are analyzed separately herein. The LO₂ aft bulkhead is assembled from 12 identical aluminum-lithium (Al-Li) 2195 gores and an Al 2219 spherical cap (11.7-ft diameter and 17.7-ft radius). The bulkhead profile outside of the spherical cap is half of an ellipsoid with a height-to-radius ratio of 0.75 and split across its 27.6-ft major diameter, that is welded to an aft ring frame and the 8.4 ft-long cylindrical barrel. Circumferential stiffeners are used to reinforce the LO₂ aft bulkhead gores.

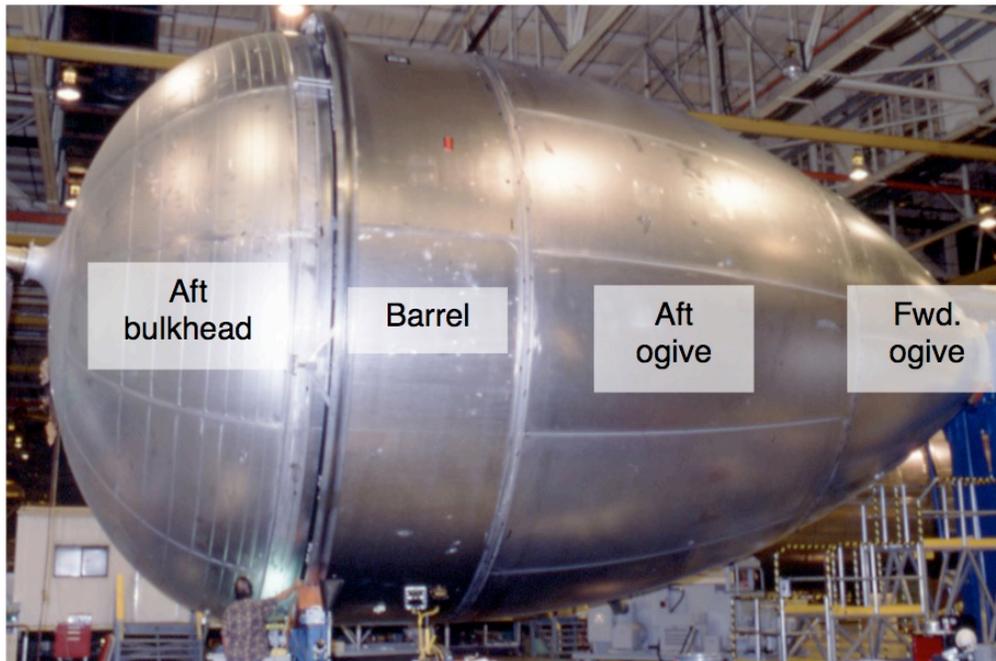


Figure 3. LO₂ tank.

The LH₂ tank (Figure 4) forward and aft bulkhead loads and gore skin thicknesses are generally much lower

than those of the LO₂ aft bulkhead because of the higher LO₂ fluid density (71.2 lb/ft³, versus 4.4 lb/ft³ for LH₂) and associated hydrostatic loads. Both LH₂ tank bulkheads have the same overall dimensions and material as the LO₂ aft bulkhead described above, but with unstiffened monocoque walls. The LH₂ aft bulkhead gore that is pierced by the 17-inch main feedline to the Orbiter and SSMEs is fabricated from Al 2219, which is 5 percent denser than the Al-Li 2195 alloy used for the other gores.



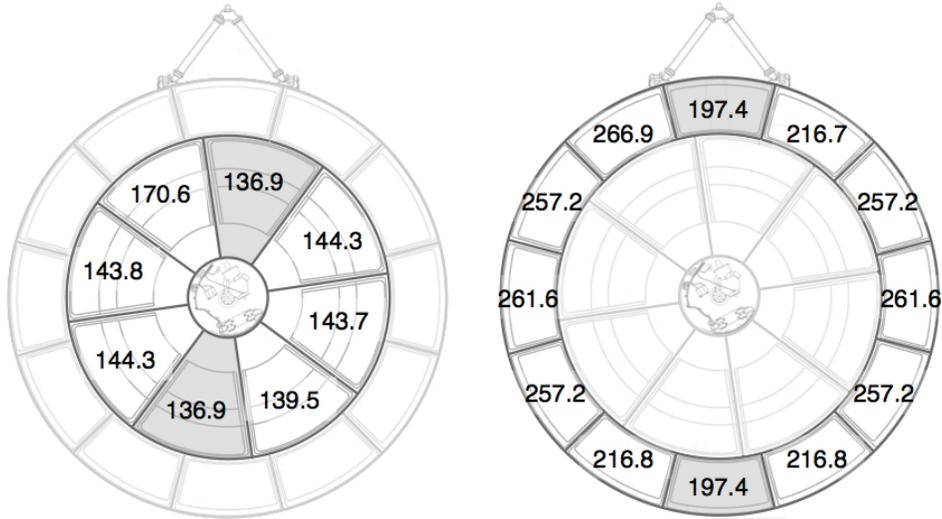
Figure 4. LH₂ tank.

III. Reported Gore Hardware Weights

Reported weights for the 56 gores of the SLWT LO₂ and LH₂ tank bulkheads are extracted from a mass properties database⁹ provided by the tank manufacturer. Although originally thought to be the actual flight hardware weights, further discussions with the tank manufacturer indicate that these are actually calculated values, and that they also contain unknown quantities of weight that represent the gore manufacturing tolerances. These weights are shown superimposed on sketches of the LO₂ forward and aft ogives in Figure 5, and on the LH₂ forward and aft bulkheads in Figure 6, and are also listed in Table 1 in clockwise order around the figures, starting at the tank crown (12 o'clock position). The Orbiter and SRB interface hardware are also shown for orientation purposes. Each of the 12 LO₂ aft bulkhead gores has a reported weight of 124.9 lbs, and are therefore not illustrated because of their uniformity.

Table 1. Reported SLWT bulkhead gore weights, lbs

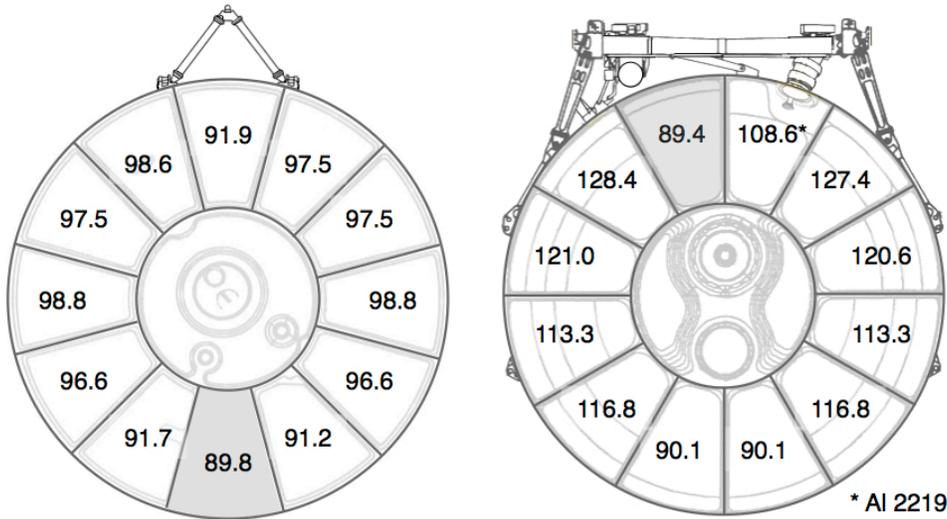
LO ₂ fwd. ogive	LO ₂ aft ogive	LO ₂ aft BH	LH ₂ fwd. BH	LH ₂ aft BH
136.9	197.4	124.9	91.9	108.6
144.3	216.7	124.9	97.5	127.4
143.7	257.2	124.9	97.5	120.6
139.5	261.6	124.9	98.8	113.3
136.9	257.2	124.9	96.6	116.8
144.3	216.8	124.9	91.2	90.1
143.8	197.4	124.9	89.8	90.1
170.6	216.8	124.9	91.7	116.8
—	257.2	124.9	96.6	113.3
—	261.6	124.9	98.8	121.0
—	257.2	124.9	97.5	128.4
—	266.9	124.9	98.6	89.4



a. Forward section (view aft)

b. Aft section (view aft)

Figure 5. Reported LO₂ tank ogive gore weights, lbs (with manufacturing tolerance weights).



a. Forward bulkhead (view aft)

b. Aft bulkhead (view aft)

Figure 6. Reported LH₂ tank gore weights, lbs (with manufacturing tolerance weights).

With the exception of the LO₂ aft bulkhead, the gore weights within each of the other four bulkhead groups may be subdivided into several distinct regions. The heavier gores with additional material appear to be located where concentrated Orbiter and SRB structural interface loads are introduced into the tanks, while the lighter “acreage” gores are located in the regions away from these more highly loaded areas. Other noteworthy elements are the heaviest gores on the LO₂ forward and aft ogives, which have increased local skin thicknesses for attachment of the LO₂ ullage gas repressurization line and electrical cable tray hardware. The LH₂ aft bulkhead gore penetrated by the 17-inch feedline has a reported weight of 108.6 lbs, and is noted in boldface in Table 1. This gore would weigh 103.4 lbs if it were fabricated from the lighter Al-Li 2195 alloy, and this reduced gore weight is used hereafter for calculation of the non-optimum factors.

IV. Actual Minimum Skin Thicknesses and Gore Weights

Production drawings for the lightest gores within each bulkhead group (shaded in Figures 5 and 6, with weights listed in Table 2) are obtained from the tank manufacturer and are evaluated to determine details of their

construction. Of these minimum-weight gores, the lightest gore is on the LH₂ aft bulkhead and weighs 89.4 lbs, and the heaviest gore is on the LO₂ aft ogive and weighs 197.4 lbs. All of the other, heavier, gores within each bulkhead group are assumed to have at least the same minimum skin thicknesses (and thickness distributions) as their associated minimum-weight gore.

Table 2. Bulkhead gore weights, lbs

	LO ₂ fwd. ogive	LO ₂ aft ogive	LO ₂ aft BH	LH ₂ fwd. BH	LH ₂ aft BH
Minimum reported	136.9	197.4	124.9	89.8	89.4
Actual min. skin	116.3	159.0	91.9	68.1	66.9
Manuf. tolerance	11.5	14.8	9.7	9.1	9.1
Proof skin	61.2	142.6	76.9	43.2	43.2
Gore edge	8.9	23.3	16.3	11.3	12.5
Circumf. stiffener	—	—	5.5	—	—

Nominal values for these minimum-weight gore skin thicknesses are then extracted from these drawings, and are plotted along the LO₂ and LH₂ tanks' longitudinal axes as solid black lines in Figures 7 and 8, respectively. These minimum thicknesses range from 0.160 inches on the LO₂ forward ogive, to 0.066 inches over most of the LH₂ aft bulkhead. This latter value, shown as a gray horizontal line in Figure 8, appears to represent a minimum gage skin thickness for this material and fabrication process. The bulkhead profiles are also shown in the figures as thick black lines, with their gore forward and aft edges denoted by gray vertical lines.

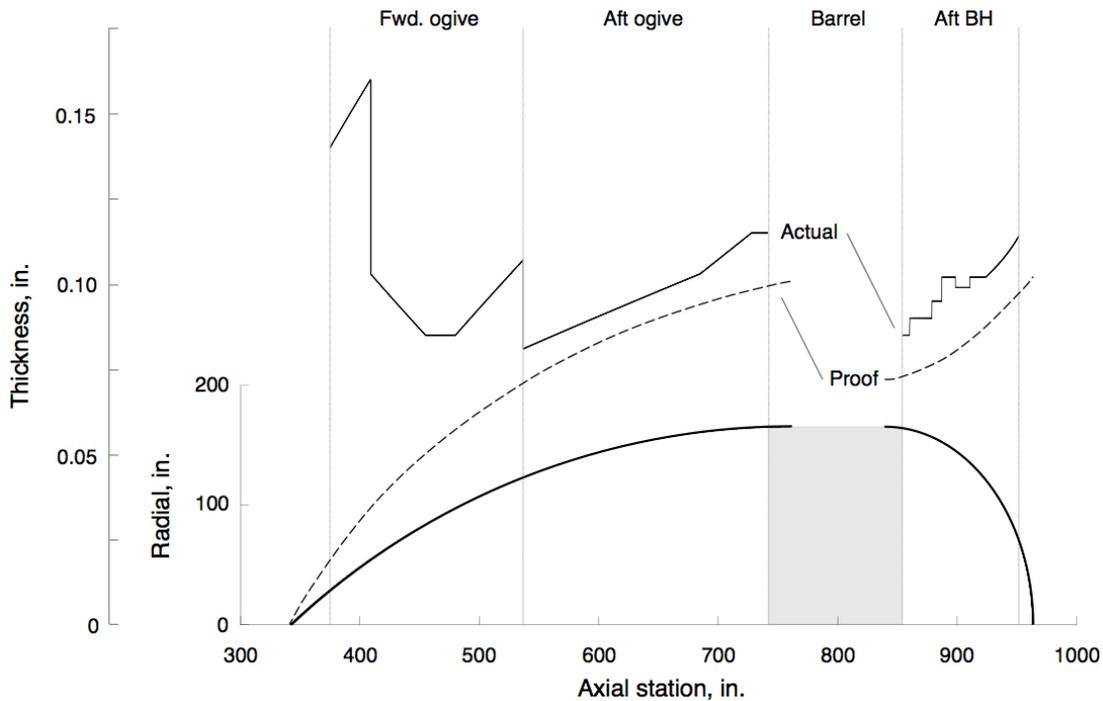


Figure 7. LO₂ tank bulkhead profile and minimum skin thickness, in.

To estimate the gore skin weights associated with these minimum skin thickness profiles, one principal axis of the bulkhead is first subdivided into small, equal-length differential increments in a computer spreadsheet. The associated points on the other principal axis are determined from the closed-form equation for the bulkhead cross-section, and the differential arc lengths and their revolved surface areas are calculated. The products of the Al-Li 2195 material density¹⁰ (0.098 lb/in³), corresponding minimum skin thicknesses from Figures 7 and 8, and differential surface areas are then summed over the bulkhead cross-sections to estimate the actual minimum-

thickness skin weights presented in Table 2. The LH₂ aft bulkhead skins are the lightest at 66.9 lbs, and the LO₂ aft ogive skins are the heaviest at 159.0 lbs.

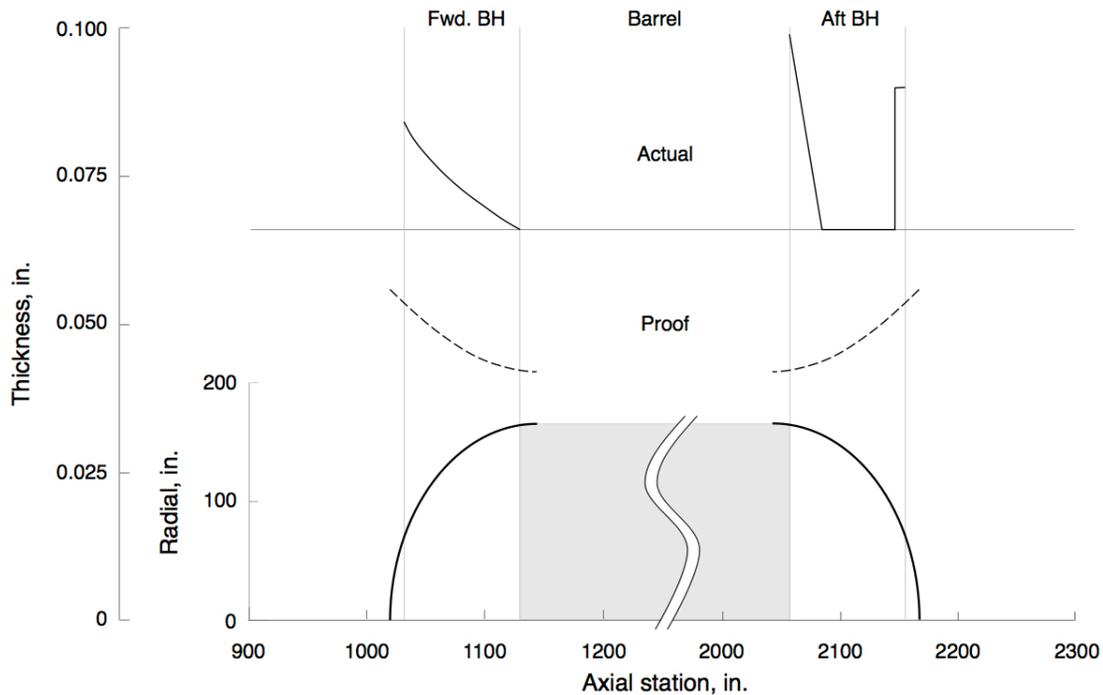


Figure 8. LH₂ tank bulkhead profile and minimum skin thickness, in.

While the nominal skin thicknesses are used in the above computations, manufacturing tolerances of -0.000 to $+0.010$ inches are also specified on the production drawings. This notation means that the skin thickness must be no less than the nominal value on the drawing, and no greater than that dimension plus 0.010 inches. These thickness variations are assumed to be distributed over both surfaces of each gore by the chem-milling process used to tailor the skin thicknesses. If these manufacturing tolerances are assumed to be normally distributed over their 0.010-inch range, the mean value would then be 0.005 inches. If this range also spans six standard deviations, one standard deviation would equal $0.010 \text{ in.}/6$, or approximately 0.0017 inches.

Three-dimensional CAD models, available for about half of the 56 gores, are evaluated to determine their nominal volumes and to test these assumptions defined above. These calculated volumes are first multiplied by the material density to yield a set of predicted gore weights, which are compared with the corresponding reported gore weights from Table 1. The differences between these values are assumed to be equal to the manufacturing tolerance weights included in the reported gore weights. The associated manufacturing tolerance thicknesses can then be estimated by dividing their weights by the gore surface areas and material density. A statistical analysis of these data gives an overall average tolerance thickness of 0.0099 inches, or almost the maximum value specified on the production drawings, with a standard deviation of 0.0007 inches. The manufacturing tolerance weights listed in Table 2 range from 9.1 to 14.8 lbs, and are calculated using either the averaged CAD data (where available) or the average tolerance thickness above.

V. Proof-Test Skin Thicknesses and Gore Weights

Membrane shell theory and strength of materials are also used to calculate skin thicknesses for the LO₂ and LH₂ tank bulkhead gores. Axisymmetric pressure loads applied during actual LO₂ and LH₂ tank proof tests are estimated from data in Ref. 8. During the LO₂ tank proof test, a standpipe above the sealed vertical tank is filled with room-temperature water, and then a partial vacuum is drawn on the aft bulkhead. With a partial vacuum drawn on the aft bulkhead, the resulting hydrostatic pressures increase in a piecewise-linear manner along the tank length to meet target values at the aft bulkhead equator and apex. The LH₂ tank is proof-tested by cantilevering the assembled tank from its forward ring frame, applying a uniform 38.7 lb/in^2 internal pressure with gaseous

nitrogen, and then applying a series of simulated flight loads to the Orbiter and SRB attachments at the aft ring frame. Only the internal pressure load is modeled here for the LH₂ tank proof test. The tensile yield stress for Al-Li 2195 is assumed to be 73 klb/in² along the plate principal axes.^{8,10}

Formulas for the meridional and circumferential membrane principal stresses in ogive and ellipsoidal shapes under uniform internal pressure^{11,12} are coded into the spreadsheet described above, and used to calculate the skin thicknesses over the bulkhead cross-sections. The greater of the meridional and circumferential membrane thicknesses is used to size the shell wall. The shell thicknesses for the LO₂ ogive are determined by its circumferential stresses, while the ellipsoidal bulkheads are all sized by their meridional stresses. The calculated thickness values are then multiplied by a factor of 1/1.05 to account for the increased material fracture toughness at cryogenic temperatures.⁸

The predicted proof pressure-sized skin thicknesses for the LO₂ and LH₂ tank bulkheads are plotted as dashed lines in Figures 7 and 8, respectively. The actual minimum skin thicknesses described above are consistently greater than these theoretical values, and reflect the influence of fracture mechanics,⁸ additional load cases (e.g., Ref. 13), local bending and other considerations (e.g., buckling, thermal loads, minimum gage) that are also used to size the actual bulkhead skins. However, the predicted and actual minimum thicknesses match well over much of the LO₂ aft ogive skin, strongly suggesting that the proof test may be an important design load case for this portion of the tank.

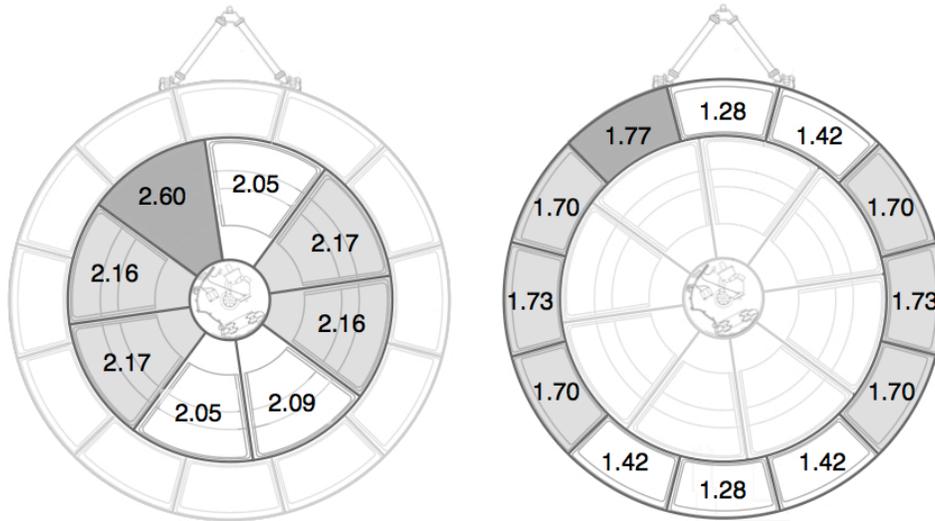
The corresponding proof skin weights are then calculated using the spreadsheet described above, and are reported in Table 2. The lightest skin (43.2 lbs) is on the LH₂ bulkhead gore, while the heaviest are the LO₂ aft ogive gores at 142.6 lbs. Comparison of the skin weights computed using the actual minimum and proof pressure-sized thicknesses shows that the actual skin weights are between 1.12 and 1.90 times heavier (for the LO₂ aft and forward ogives, respectively) than the corresponding proof pressure-sized skin weights. The average ratio of actual minimum and proof pressure-sized skin weights is equal to 1.47, meaning that the actual gore skin (without weld lands) is most likely to weigh almost 50 percent more than a skin sized for proof pressure alone.

VI. Gore Coarse Non-Optimum Factors

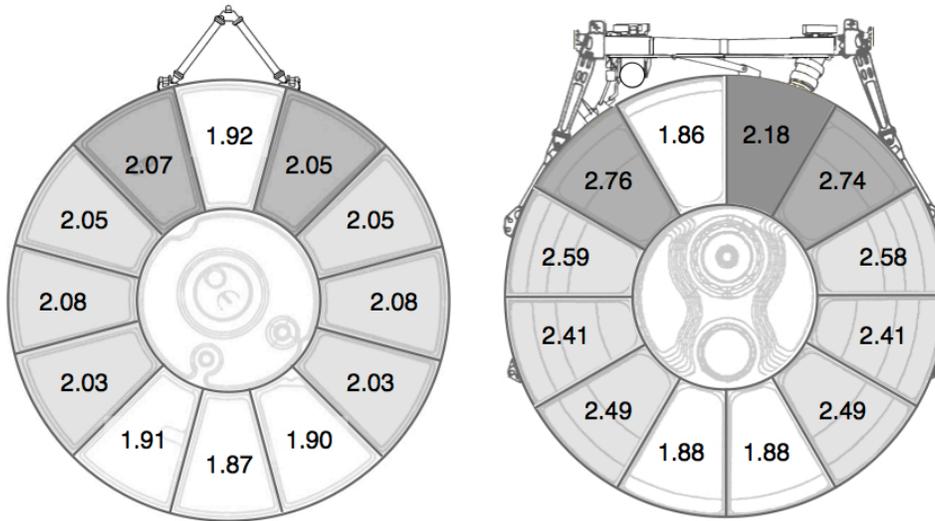
Because of its relative simplicity, the tank internal pressure from a proof test is a load case that is often analyzed during launch vehicle conceptual design. Therefore, a comparison of flight hardware weights to the proof pressure-sized skin weights should be useful when estimating the weight of future launch system subcomponents. The manufacturing tolerance weights listed in Table 2 are first subtracted from the reported gore weights in Table 1. Coarse non-optimum factors for the LO₂ and LH₂ tank bulkhead gores are then calculated by dividing these adjusted reported gore weights by the corresponding proof pressure-sized skin weights from Table 2. The full set of coarse non-optimum factors are presented in Table 3 in the same order as Table 1, and are plotted on the corresponding LO₂ tank ogive and LH₂ tank bulkhead gores in Figures 9 and 10, respectively.

Table 3. Gore coarse non-optimum factors

LO ₂ fwd. ogive	LO ₂ aft ogive	LO ₂ aft BH	LH ₂ fwd. BH	LH ₂ aft BH
2.05	1.28	1.50	1.92	2.18
2.17	1.42	1.50	2.05	2.74
2.16	1.70	1.50	2.05	2.58
2.09	1.73	1.50	2.08	2.41
2.05	1.70	1.50	2.03	2.49
2.17	1.42	1.50	1.90	1.88
2.16	1.28	1.50	1.87	1.88
2.60	1.42	1.50	1.91	2.49
—	1.70	1.50	2.03	2.41
—	1.73	1.50	2.08	2.59
—	1.70	1.50	2.05	2.76
—	1.77	1.50	2.07	1.86



a. Forward section (view aft) b. Aft section (view aft)
Figure 9. LO₂ ogive coarse non-optimum factors.



a. Forward bulkhead (view aft) b. Aft bulkhead (view aft)
Figure 10. LH₂ tank coarse non-optimum factors.

The computed coarse non-optimum factors range from 1.28 for two gores on the LO₂ aft ogive, to 2.76 for the heaviest gore on the LH₂ aft bulkhead. The average coarse non-optimum factor computed over the entire gore population is 1.90, with a standard deviation of 0.39 and a 21 percent coefficient of variation. The coarse non-optimum factor for all of the LO₂ aft bulkhead gores is equal to 1.50. Average coarse non-optimum factors for the other four bulkhead groups range from 1.57 to 2.36 (for the LO₂ aft ogive and LH₂ aft bulkhead groups, respectively). The non-optimum factors within the LO₂ forward ogive and LH₂ forward bulkhead groups are very close, with an average coefficient of variation of 6 percent. The average coefficient of variation for the LO₂ aft ogive and LH₂ aft bulkhead groups is 13 percent.

When used to design a launch vehicle, application of the overall average non-optimum factor of 1.90 means that there is a 50 percent probability that the actual gore hardware will weigh more (or less) than 1.90 times the skin of a gore sized only by proof test pressure. However, if a more conservative non-optimum factor of 2.29 (mean plus 1 standard deviation) is used instead, then the probability that any actual hardware will weigh more decreases to 16 percent, and the probability that the hardware will weigh less increases to 84 percent. Conversely, use of a less conservative non-optimum factor of 1.51 (mean minus 1 standard deviation) would reverse these

probabilities. These shifts in likelihood of bounding the “actual” structural weight should then be traded against the resulting higher or lower predicted subcomponent weights.

VII. Weld Land and Circumferential Stiffener Dimensions and Weights

To more accurately model the gore weights, dimensions of the primary and secondary weld lands along the gore edges are extracted from the manufacturing drawings. An illustration of these weld lands is shown in Figure 11. As a result of the chem-milling process used to manufacture the gores, the thickness variations are symmetric with respect to the gore mid-surface. The meridional primary weld land thicknesses are linearly tapered along the shell arcs, while circumferential primary weld lands have uniform thicknesses. Primary weld land widths range from 1.32 to 1.75 inches, and their overall thicknesses range from 0.140 to 0.385 inches across all of the bulkhead gores. The secondary weld lands are all 1.50 inches wide, with overall circumferential secondary weld land thicknesses ranging from 0.106 to 0.175 inches. Overall thicknesses for the meridional secondary weld lands are 0.040 or 0.060 inches greater than the adjacent skin thickness. Using these dimensions, the combined weights of the primary and secondary weld lands, ranging from 8.9 to 23.3 lbs, are calculated and listed in Table 2 for the different bulkheads.

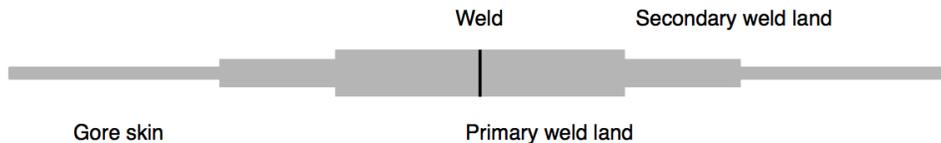


Figure 11. Weld land schematic.

In addition to its crenellated skin thickness profile, the LO₂ aft bulkhead has 8 circumferential stiffeners (located between the circumferential weld lands) that resist shell buckling from thermal loads, and when the LO₂ tank is almost empty. These conditions occur while the tank is being filled before launch, as well as during high axial acceleration near the end of powered flight.¹³ Most of these stiffeners are located where the dissimilar skin thicknesses transition from one value to another. After the machined, tapered plate has been stretch-formed into a curved shape during fabrication, circumferential strips are masked off at the stiffener locations. The raised stiffeners then appear during the chem-milling process as the areage skin thicknesses are reduced. As specified in the manufacturing drawings, the stiffener widths range from 0.36 to 0.50 inches, and vary in overall thickness from 0.323 to 0.358 inches. The calculated cumulative weight of these stiffeners is 5.5 lbs, as noted in Table 2.

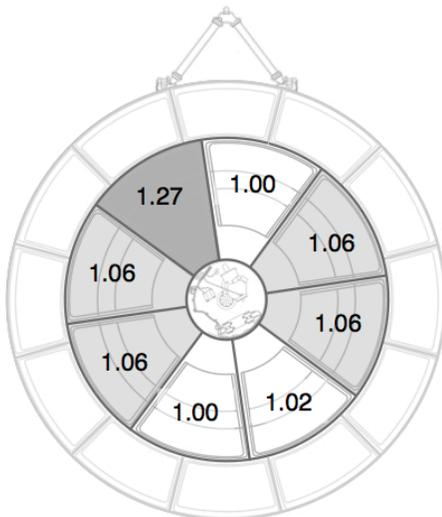
VIII. Gore Refined Non-Optimum Factors

Refined estimates of the LO₂ and LH₂ tank bulkhead gores weights are now computed by including the weight of selected design details. While these details are most probably not available during conceptual design, their impact is investigated here to develop confidence in the methodology. Calculated weld land weights are added to those of the actual minimum skin thickness gores to provide refined estimates of the minimum gore weights. The circumferential stiffener weight described above is also included with the calculated LO₂ aft bulkhead gore weights. These refined weight estimates are on average within 1 lb of the corresponding reference gore weights (after subtraction of the estimated manufacturing tolerance weights). The LH₂ forward and LO₂ aft bulkhead gores show the worst correlation, with differences of 1.3 and 1.5 lbs, respectively. These adjusted reported gore weights are then divided by these refined minimum gore weights to generate the refined non-optimum factors, listed in clockwise order, shown in Table 4. These refined non-optimum factors are also overlaid on the LO₂ tank ogives and LH₂ tank bulkheads in Figures 12 and 13, respectively.

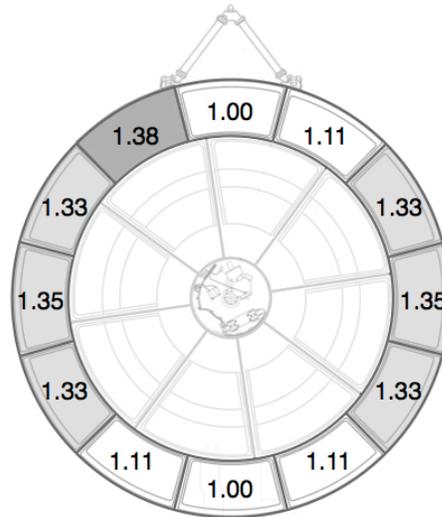
The refined non-optimum factors range from 1.00 for several gores on the LO₂ forward and aft ogives to 1.50 for the heaviest LH₂ aft bulkhead gore. The average refined non-optimum factor computed for the complete population is 1.14, with a standard deviation of 0.15 and a 13 percent coefficient of variation. The refined non-optimum factor for each of the LO₂ aft bulkhead gores is equal to 1.01. The average refined non-optimum factors of the remaining four bulkhead groups are between 1.07 and 1.28 (for the LO₂ forward ogive and LH₂ aft bulkhead groups, respectively). The average coefficients of variation for the LO₂ forward ogive and LH₂ forward bulkhead groups are 6 percent, and 13 percent for the LO₂ aft ogive and LH₂ aft bulkhead groups.

Table 4. Gore refined non-optimum factors

LO ₂ fwd. ogive	LO ₂ aft ogive	LO ₂ aft BH	LH ₂ fwd. BH	LH ₂ aft BH
1.00	1.00	1.01	1.04	1.19
1.06	1.11	1.01	1.11	1.49
1.06	1.33	1.01	1.11	1.40
1.02	1.35	1.01	1.13	1.31
1.00	1.33	1.01	1.10	1.36
1.06	1.11	1.01	1.03	1.02
1.06	1.00	1.01	1.02	1.02
1.27	1.11	1.01	1.04	1.36
–	1.33	1.01	1.10	1.31
–	1.35	1.01	1.13	1.41
–	1.33	1.01	1.11	1.50
–	1.38	1.01	1.13	1.01

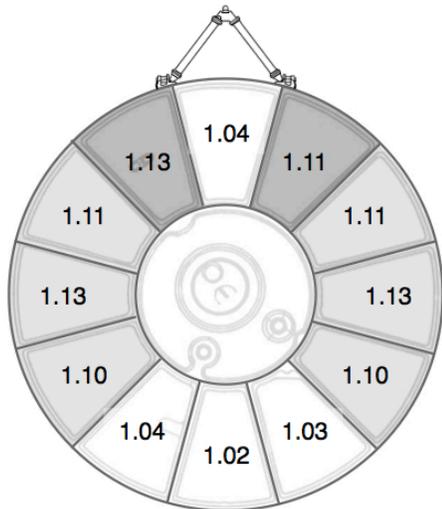


a. Forward section (view aft)

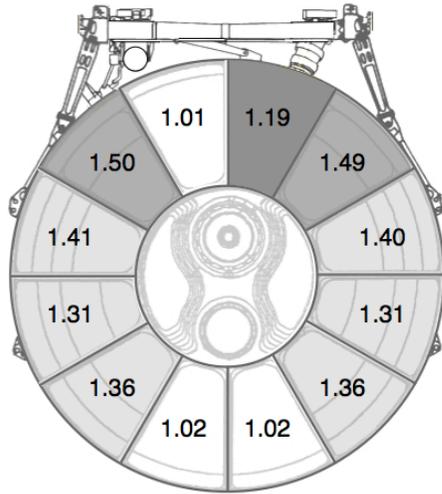


b. Aft section (view aft)

Figure 12. LO₂ ogive refined non-optimum factors.



a. Forward bulkhead (view aft)



b. Aft bulkhead (view aft)

Figure 13. LH₂ tank refined non-optimum factors.

IX. Observations and Discussion

In addition to the average non-optimum factors computed for the entire gore population as described above, the non-optimum factors can be further subdivided based on their location within each bulkhead. Examining the non-optimum factors in Figures 9 and 12, the unshaded acreage gores on the LO₂ ogive crown and keel have average coarse non-optimum factors of 2.06 and 1.36 on the forward and aft groups, and corresponding refined values of 1.01 and 1.07. The acreage gores on the LH₂ forward and aft bulkheads have coarse non-optimum factors of 1.90 and 1.87, and refined non-optimum factors of 1.03 and 1.02, respectively.

The gores located on the sides of the LO₂ forward and aft ogives (shaded light gray in Figures 9 and 12) have non-optimum factors that are on average 5 percent higher than the adjacent unshaded acreage gores. These higher non-optimum factors are a result of the additional material needed to distribute the large concentrated SRB thrust loads into the LO₂ tank. In addition, the non-optimum factor for the gore on the LO₂ forward and aft ogives (shaded a darker gray in the figures) containing the subsystem attachment reinforcements is 26 percent higher than the surrounding acreage gore values.

The LH₂ forward bulkhead gores that are aft of the Intertank's SRB thrust panels and the Orbiter forward bipod attachment (shaded light gray and medium gray, respectively, in Figures 10a and 13a) have average non-optimum factors that are 8 percent higher than those of the acreage gores. Similarly, the heavier LH₂ aft bulkhead gores that are shaded light gray in Figures 10b and 13b have, on average, 34 percent higher non-optimum factors than the neighboring acreage gores. The additional material in these gores is needed to react the point loads from the SRB aft attachment struts.

The highest non-optimum factors (47 percent greater than the acreage) on the tank bulkheads are identified for the gores (shaded medium gray in Figures 10b and 13b) that are located aft of the LH₂ tank barrel longeron forgings used to introduce the SSME loads from the Orbiter into the SLWT. The gore that supports the 17-inch feedline between the LH₂ tank and Orbiter (shaded dark gray in the figures) has a non-optimum factor that is 17 percent greater than the associated acreage value.

X. Application of Non-Optimum Factors to Launch Vehicle Structural Sizing

Bulkhead gore weights for a proposed future launch system are estimated using the coarse non-optimum factors calculated above. Four ellipsoidal bulkheads with aspect ratios of 0.75 are used to close out the ends of the core stage propellant tanks for an Ares V heavy-lift launch vehicle¹⁴ (Figure 14). The largest raw plate stock used for the SLWT bulkhead gores is 11 ft x 24 ft. Although the Ares V core stage diameter is larger than the SLWT (33 ft versus 27.6 ft), these plates are still large enough to allow the tank bulkheads to be assembled from 12 individual gores. Since the new gore arc length is lower than the maximum 24-ft plate length, the same 11.7 ft-diameter spun-formed spherical caps developed for the SLWT can also be used for the Ares V bulkheads.

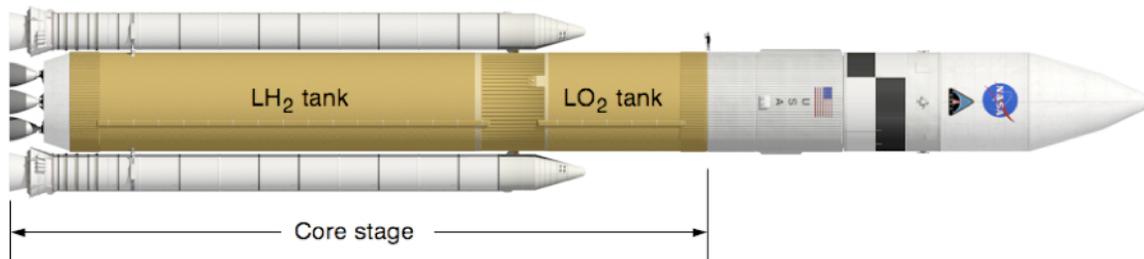


Figure 14. Ares V launch vehicle.

Hydrostatic- and uniform-pressure proof loads are developed for the Ares V LO₂ and LH₂ tanks (respectively) that encompass the structural loads resulting from the liftoff, maximum axial acceleration and maximum bending moment cases. These proof test pressures are then applied along with the same material properties (density, yield strength and cryogenic correction factor) described above to discretized analytical models of the bulkheads. The calculated wall thicknesses are then used with the shell geometry to estimate the gore weights. The predicted proof pressure-sized LO₂ forward and aft bulkhead gore weights are 110.4 and 167.7 lbs, and the corresponding LH₂ bulkhead gores all weigh 88.7 lbs each. While the Ares V LO₂ forward bulkhead gore cannot be compared

directly to an SLWT part, the other two predicted gores are about twice as heavy as the corresponding proof pressure-sized gores in Table 2.

The coarse non-optimum factor of 1.50 calculated for the aft bulkhead gores of the SLWT LO₂ tank is applied to both the forward and aft bulkhead gores of the Ares V LO₂ tank, resulting in a forward bulkhead gore weight of 165.6 lbs and an aft bulkhead gore weight of 251.6 lbs. The cumulative result of application of these coarse non-optimum factors is to increase the predicted Ares V LO₂ forward bulkhead total gore weight from 1324.8 lbs to 1987.2 lbs, and the corresponding LO₂ aft bulkhead total gore weight from 2012.4 lbs to 3018.6 lbs. These cumulative gore weights do not include the additional weights of the 11.7 ft-diameter spherical caps, which should remain very close to the SLWT weights.

The SLWT LH₂ tank gore coarse non-optimum factors listed in Table 3 are grouped into acreage and reinforced regions (unshaded and shaded light gray in Figure 10, respectively), averaged, and applied to the calculated weights for the Ares V LH₂ tank gores. These acreage and reinforced non-optimum factors are, respectively, 1.90 and 2.06 for the LH₂ forward bulkhead gores, and 1.87 and 2.50 for the LH₂ aft bulkhead gores. The resulting predicted acreage and reinforced weights for the Ares V LH₂ tank bulkhead gores are shown in Figure 15, and range from 165.9 to 221.8 lbs after multiplication by the appropriate non-optimum factors. Application of these coarse non-optimum factors increases the predicted Ares V LH₂ forward bulkhead total gore weight from 1064.4 lbs to 2107.2 lbs, and the LH₂ aft bulkhead total gore weight from 1064.4 lbs to 2438.0 lbs, or 98 and 129 percent, respectively.

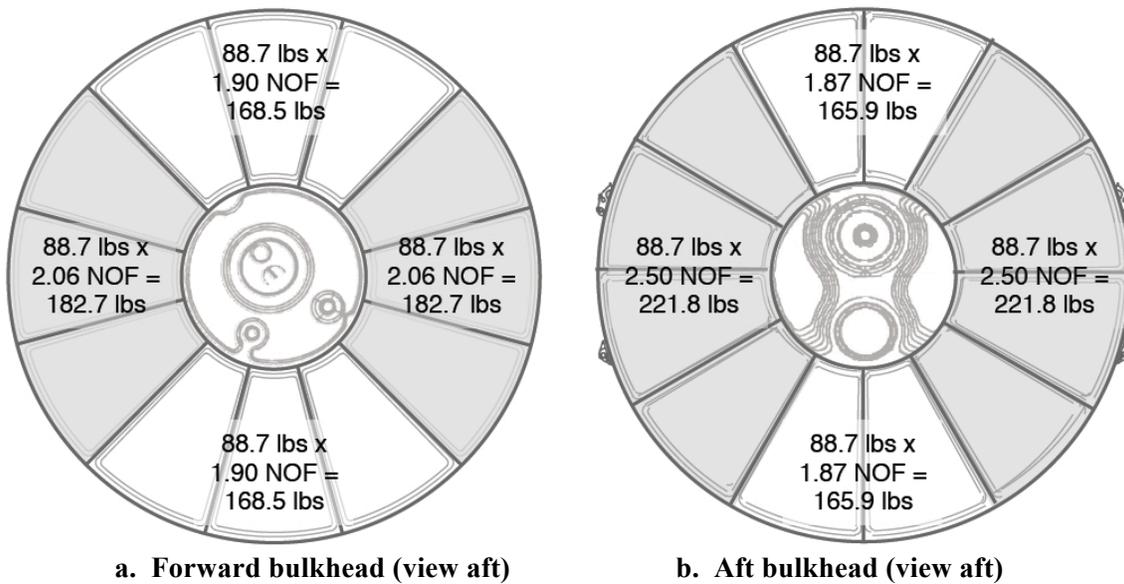


Figure 15. Predicted Ares V LH₂ tank gore weights (without manufacturing tolerance weights).

XI. Concluding Remarks

Coarse and refined non-optimum factors are developed for the Space Shuttle SLWT liquid oxygen and liquid hydrogen tank bulkhead gores. These non-optimum factors account for future manufacturing and design details during the early stages of the design process, and are intended to provide better estimates of a vehicle's as-built weights and performance. Gore hardware weights from a mass properties database are used as a baseline for comparison with predicted gore weights. Contributions to the gore weights of proof pressure-sized skin thicknesses, skin thicknesses of the actual flight hardware, primary and secondary weld lands, manufacturing tolerances and subsystem attachments are identified and assessed. The use of these non-optimum factors for launch vehicle conceptual design is also demonstrated through application to weight estimation of the Ares V core stage propellant tank bulkheads.

While the overall or bulkhead-level non-optimum factors described above can be easily used to size the launch vehicle structural subcomponents, the more detailed non-optimum factors computed for specific bulkhead regions can also be applied where appropriate depending on the configuration of a proposed design. For example,

structural weights and sizing analyses of an axisymmetric vehicle (e.g., Saturn V) may only require application of the acreage non-optimum factors, since the loads on this class of launch vehicle would also probably be symmetric. However, the bulkheads of an in-line Shuttle-derived launch vehicle with attached SRBs (e.g., Ares V, SLS) would probably exhibit variations in gore weights that are similar to those noted here for the SLWT parts, but without the increased gore weights required to accommodate the eccentric aerodynamic and thrust loads from the Orbiter and SSMEs.

Acknowledgements

The authors are grateful to the engineers of the Lockheed Martin Space Systems Company for providing the information used as the foundation for this research.

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