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Nontangent, Developed Contour Bulkheads for a Single-Stage Launch Vehicle

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Dry weights for single-stage launch vehicles that incorporate nontangent, developed contour bulkheads are estimated and compared to a baseline vehicle with 1.414 aspect ratio ellipsoidal bulkheads. Weights, volumes, and heights of optimized bulkhead designs are computed using a preliminary design bulkhead analysis code. The dry weights of vehicles that incorporate the optimized bulkheads are predicted using a vehicle weights and sizing code. Two optimization approaches are employed. A structural-level method, where the vehicle's three major bulkhead regions are optimized separately and then incorporated into a model for computation of the vehicle dry weight, predicts a reduction of 4365 lb (2.2%) from the 200,679-lb baseline vehicle dry weight. In the second, vehicle-level, approach, the vehicle dry weight is the objective function for the optimization. For the vehicle-level analysis, modified bulkhead designs are analyzed and incorporated into the weights model for computation of a dry weight. The optimizer simultaneously manipulates design variables for all three bulkheads to reduce the dry weight. The vehicle-level analysis predicts a dry weight reduction of 5129 lb, a 2.6% reduction from the baseline weight. Based on these results, nontangent, developed contour bulkheads may provide substantial weight savings for single stage vehicles.

Nomenclature

$R1/R2$ = ratio of the local circumferential and meridional radii of curvature
r = normalized radius

Introduction

SINGLE-STAGE-TO-ORBIT (SSTO) reusable launch vehicles, currently proposed to meet future national space transportation needs, are intended to provide reduced launch and operations costs for cost-effective access to space. One wing–body SSTO vehicle concept is shown in Fig. 1. Aerospace vehicles are typically sensitive to weight growth, and SSTO vehicles are an extreme example of this behavior. Because small variations in structural weight can result in substantial changes in vehicle dry weight, vehicles with lightweight structures have a higher potential for improved performance.

Many reusable launch vehicle concepts being studied have ellipsoidal bulkheads[1] that are attached to the ends of cylindrical tank barrels. One common ellipsoidal bulkhead design chosen as the baseline design for this study is shown in Fig. 2. This ellipsoidal bulkhead is tangent to the tank barrel at their intersection and has an aspect ratio (major axis divided by minor axis) of 1.414. This configuration has been frequently used for pressure vessel bulkheads because only tensile membrane stresses exist for this geometry under internal pressure.

Ellipsoidal bulkheads that experience compressive stresses are either not tangent to the tank barrel or have aspect ratios that are greater than 1.414, or both. Because compressive stresses do not exist anywhere in the baseline bulkhead, buckling is not a failure mode. Because of the additional stiffening required, a bulkhead that must resist buckling will be heavier than one that experiences only tensile stresses. However, a bulkhead design with a lower height than a tension-only design may result in an overall weight savings for the vehicle.

Previous studies[2,3] have shown that the use of nontangent, nonellipsoidal bulkheads can lead to significant weight savings for expendable launch vehicles. Another study[4] also demonstrates the applicability of existing techniques for analysis, fabrication, and failure prediction of this type of bulkhead structure. In the present study, the impact of including nontangent, nonellipsoidal bulkheads on the dry weight (defined as the vehicle weight without propellants and payload)[5] of a wing–body SSTO vehicle[6] is evaluated.

The weight, volume, and height of the three major bulkheads of the wing–body vehicle are computed using the BLKHD bulkhead structural analysis[2,3] developed by the Lockheed Martin Corporation for preliminary sizing studies. These bulkhead data are used in two different approaches for evaluating the effect of nontangent, nonellipsoidal bulkheads on vehicle dry weight. In the first approach, denoted as a structural-level optimization, the bulkhead analysis code is integrated directly with the NPSOL nonlinear optimization code.[7] The objective function minimized in the optimization analysis is the total weight of a major bulkhead region. The bulkhead design is modified by the optimizer, and the analysis–optimization loop is repeated until a converged solution is reached. The three optimized bulkhead designs are then integrated into a vehicle weights model for analysis with the configuration sizing (CONSIZ) vehicle-level weights and sizing code[8] to estimate a vehicle dry weight.

In the second approach, denoted as a vehicle-level optimization, bulkhead weight, volume, and height data from BLKHD analyses of all three major bulkheads are incorporated directly into the CONSIZ vehicle weights and sizing model, and a vehicle dry weight is computed. The vehicle dry weight is then passed to NPSOL for minimization as the optimization objective function. Design variables for all three bulkheads are modified, and the analysis–weights–optimization cycle is continued until a converged solution is reached. This vehicle-level approach allows vehicle sizing effects to be directly incorporated into the optimization process through minimization of the vehicle dry weight.

Wing–Body Vehicle

The baseline wing–body single-stage vehicle for this study[6] is shown in Fig. 1. The vehicle has a length of 185.8 ft, a body diameter of 28.6 ft, and a dry weight of about 200,000 lb. The reference mission is to carry a 25,000-lb payload to the International Space Station in a 51.6-deg-inclination orbit. The vehicle has a dual-fuel propulsion system, which uses both liquid-hydrogen (LH_2) and hydrocarbon (RP) fuels and liquid-oxygen (LOX) oxidizer. The LOX is carried in a tank that is located in the nose of the vehicle ahead of the payload bay. The baseline LOX tank has a small ellipsoidal

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Table 1 Design variables for baseline ellipsoidal bulkhead

Equator angle, deg	$R1/R2$ at normalized radius r: 0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.75	0.80	0.85	0.90	0.95	1.00
0.00	1.00	1.01	1.02	1.04	1.08	1.14	1.22	1.32	1.39	1.47	1.57	1.68	1.83	2.00

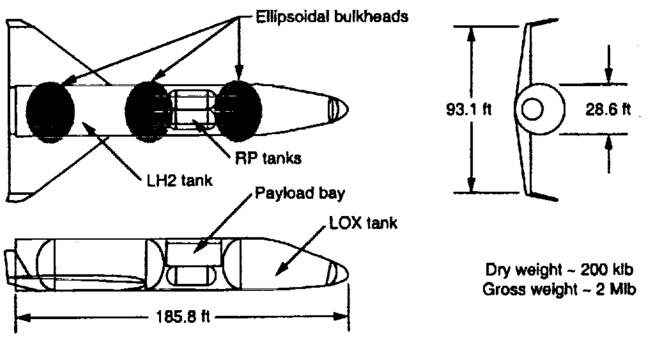


Fig. 1 Baseline wing–body, single-stage vehicle.

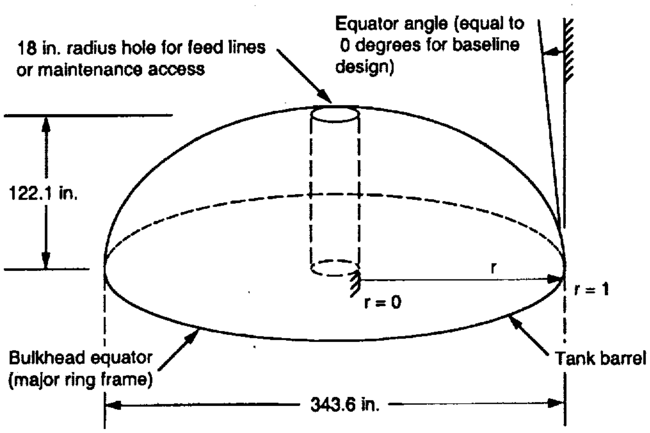


Fig. 2 Baseline ellipsoidal bulkhead (forward bulkhead shown).

bulkhead at the front of the tank and a large ellipsoidal bulkhead at the rear of the tank that will be replaced by an optimized design. The pressure-stabilized LH_2 tank is located in the aft part of the vehicle, behind the payload bay and RP tanks and ahead of the engine bay. The baseline LH_2 tank has two large ellipsoidal bulkheads that will each be replaced by an optimized design. Although further reductions in vehicle dry weight may result, optimization analyses of the smaller forward LOX and RP tank bulkheads are not considered in the present study.

Bulkhead Analysis Model

The baseline ellipsoidal bulkhead configuration with an aspect ratio of 1.414 is shown in Fig. 2. This axisymmetric design is tangent to the cylindrical tank barrel at the bulkhead equator (bulkhead-to-barrel intersection) and has a volume of 4368.9 ft^3. The equatorial radius of this configuration is set equal to 171.8 in., with a height of 122.1 in. Each of the three major bulkheads in this study have an 18-in.-radius hole at the axis of revolution for installation of feed lines or maintenance access. A ring frame that has a weight of at least 860 lb is located at the equator of each bulkhead. This ring frame reacts most of the compressive circumferential stresses from the bulkhead pressure loads. If the computed stress in the ring frame exceeds material limits, then additional material is added to the ring frame.

Each bulkhead is modeled with 15 design variables. The first variable is the equator angle at the bulkhead-to-barrel intersection that ranges from 0 (for a tangent bulkhead like the baseline design) to a maximum of 30 deg. The next 14 variables are the $R1/R2$ at user-specified radial locations from the bulkhead axis of revolution. Allowable values of $R1/R2$ are between 1 (all equal to 1 for a hemisphere) and 3. The upper bounds on $R1/R2$ are intended to preclude bending-dominated bulkhead designs. Nominal values of $R1/R2$ for the baseline ellipsoidal bulkhead are shown in Table 1 along with their corresponding radial locations. Each radial location is given as a normalized radius from the edge of the 18-in. central hole ($r = 0$) outboard to the equatorial radius ($r = 1$). Optimized values of $R1/R2$ are also determined at the values of r shown in Table 1. Profiles of these optimized bulkheads are typically not ellipsoidal, but are instead termed developed contours, where a smooth profile is fit through the listed values of $R1/R2$.

Load cases are developed for each of the three major bulkheads based on a nominal ascent trajectory for the wing–body vehicle. These axisymmetric load cases represent proof tests, liftoff, maximum axial acceleration, and partial-fill conditions. The load cases used for these analyses are described in Table 2 for the aft LOX, forward LH_2, and aft LH_2 bulkheads. Each load case contains the ullage pressure at the fluid interface, axial acceleration in g, location of the fluid interface (hydrostatic head) referenced to the bulkhead equator (positive direction toward vehicle nose), fluid density, and a load case description. These load cases are assumed to be constant for each bulkhead throughout the optimization analyses, even though the bulkhead geometry is allowed to change.

All bulkheads are assumed to be formed from aluminum–lithium (Al–Li) 2195 alloy plate. Because this material is anisotropic, with strength properties at 45 deg to the plate longitudinal axis that are significantly lower than the 0- and 90-deg properties, the more conservative 45-deg material properties are used for these analyses. The variation of material properties with ambient temperature must also be considered in these analyses because both the LOX and LH_2 are cryogenic fluids, with boiling points of −297 and −423°F. Nominal material properties for Al–Li 2195 at 45 deg to the plate longitudinal axis and at temperatures of +70, −297, and −423°F are shown in Table 3.

Computer Programs

Three major computer codes are used in this study: the bulkhead sizing code BLKHD is used for stress analysis, stability analysis and sizing of nontangent, developed contour bulkhead designs, and the vehicle weights, and sizing code CONSIZ is used to estimate the dry weight of specific vehicle configurations; and the nonlinear optimization code NPSOL is used to manipulate the design variables with the goal of minimizing a specified objective function. Each code is further described in the following sections.

BLKHD Bulkhead Sizing

The BLKHD code[2,3] is proprietary software developed by Lockheed Martin Corporation to support their internal cryogenic tank technology studies. BLKHD is a structural analysis, weights, and sizing code that provides preliminary design-level weights for nontangent, developed contour bulkhead configurations. Program inputs are the bulkhead geometry and loads (both assumed axisymmetric), material properties, minimum gauge thicknesses and tolerances, stiffener sizing limits, and safety factors. BLKHD computes a membrane stress state for the input geometry and then sizes the shell wall to prevent failure due to yield, ultimate, or von Mises stresses, as well as meets minimum gauge thickness and stability criteria for all load cases. Circumferential stiffeners are included if they offer a reduced weight over increasing the shell wall thickness. If the major ring frame at the bulkhead equator is stressed beyond material limits, then BLKHD determines the amount of additional frame area necessary to reduce the stresses below critical values. The code also provides estimates for the weight, volume, and height of the bulkhead design.

Table 2 Load cases for aft LOX, forward LH_2, and aft LH_2 bulkheads

Load case	Ullage pressure, lb/in.^{2}	Acceleration, g	Fluid interface, in.	Fluid density, lb/in.^{3}	Load case description
		Load cases for aft LOX bulkhead			
1	54.60	1.000	0.00	0.081	Proof test
2	5.30	1.875	604.00	0.041	Liftoff
3	20.00	3.000	102.10	0.041	Maximum acceleration I
4	20.00	3.000	30.20	0.041	Maximum acceleration II
5	20.00	2.800	−30.00	0.041	Partial fill
6	20.00	2.900	−33.00	0.041	Partial fill
7	20.00	3.000	−37.00	0.041	Partial fill
8	20.00	3.000	−40.00	0.041	Partial fill
9	20.00	3.000	−45.00	0.041	Partial fill
		Load cases for forward LH_2 bulkhead			
1	28.50	1.000	0.00	0.000	Proof test, air
2	10.30	1.875	51.00	0.003	Liftoff
3	11.30	1.875	45.00	0.003	Partial fill
4	12.30	1.875	40.00	0.003	Partial fill
5	13.30	1.875	35.00	0.003	Partial fill
6	14.30	1.875	30.00	0.003	Partial fill
7	15.30	1.875	25.00	0.003	Partial fill
8	16.30	1.875	20.00	0.003	Partial fill
9	17.30	1.875	15.00	0.003	Partial fill
		Load cases for aft LH_2 bulkhead			
1	28.50	1.000	0.00	0.000	Proof test, air
2	10.30	1.875	652.50	0.003	Liftoff
3	25.00	3.000	298.80	0.003	Maximum acceleration I
4	25.00	3.000	213.80	0.003	Maximum acceleration I
5	25.00	3.000	31.10	0.003	Maximum acceleration I
6	25.00	2.800	−20.00	0.003	Partial fill
7	25.00	2.900	−30.00	0.003	Partial fill
8	25.00	3.000	−40.00	0.003	Maximum acceleration II
9	25.00	3.000	−50.00	0.003	Maximum acceleration II

Table 3 Nominal material properties for Al–Li 2195 at 45-deg orientation to the plate longitudinal axis

Parameters	Temperature, °F +70	−297	−423
Elastic modulus, Mlb/in.^{2}	11.00	12.14	12.32
Poisson's ratio	0.33	0.32	0.32
Density, lb/in.^{3}	0.098	0.098	0.098
Yield strength, klb/in.^{2} (tensile and compressive)	66.00	74.07	81.18
Ultimate strength, klb/in.^{2} (tensile and compressive)	73.00	88.11	100.01
Ultimate shear strength, klb/in.^{2}	43.80	52.87	60.01

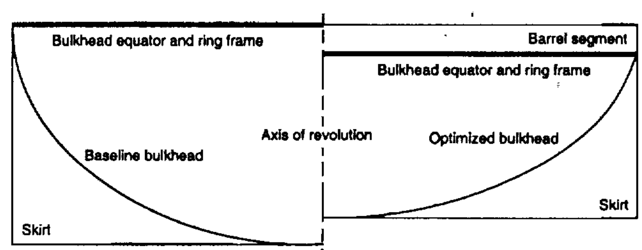


Fig. 3 Schematic of baseline and optimized bulkheads.

CONSIZ Vehicle Weights and Sizing

The CONSIZ code[8] is a conceptual-level vehicle weights and sizing code developed at the NASA Langley Research Center. CONSIZ is used to determine mass properties and vehicle size for both reusable and expendable launch vehicles given a fixed payload weight and final orbit inclination and altitude. Another option not used in this study is to determine payload weight capability to orbit given a fixed vehicle size. Vehicle resizing is performed by photographic scaling of a vehicle point design, based on a propellant volumetric packaging efficiency relationship, until propellant fraction requirements obtained from a trajectory simulation are satisfied. Weight estimating relationships corresponding directly to vehicle components are input to the program via a data file and can be easily modified or replaced as necessary during the design process. The weight estimating relationships are integral with a user-defined weight statement output format that allows up to three levels of detail.

NPSOL Nonlinear Optimization

The NPSOL code[7] uses a sequential quadratic programming algorithm to minimize a continuous objective function. Constraints allowed in the analyses include both upper and lower bounds on the design variables, but in this study no additional linear or nonlinear constraints are included. FORTRAN subroutines and UNIX shell scripts are written to pass design variables and objective function values between the various codes.

Optimization Analyses

Two different approaches are employed for evaluating the effect of nontangent, developed contour bulkheads on vehicle dry weight. These two approaches, explained in detail hereafter, differ in how results from the BLKHD code are used in optimization and computation of the vehicle dry weight with CONSIZ. Results from both approaches are also presented and discussed.

Structural-Level Optimization

In the first approach, denoted as a structural-level analysis, the weight of each major bulkhead region of the wing–body vehicle is the objective function for the optimization. Each major bulkhead region, shown in Fig. 3 for a representative aft bulkhead, is optimized separately from the other two bulkheads in the vehicle. The baseline bulkhead design variables listed in Table 1 are used as a starting point for each optimization. The load cases in Table 2 and bulkhead equatorial radius are unchanged throughout these analyses.

A weight, volume, and height are computed for a bulkhead design using the BLKHD code described earlier. The total weight of the bulkhead region, defined as the sum of the scaled bulkhead weight (defined later), additional barrel segment weight, skirt weight, and

Table 4 Design variables for optimized bulkheads from structural-level analysis

Equator angle, deg	$R1/R2$ at normalized radius r: 0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.75	0.80	0.85	0.90	0.95	1.00
	Aft LOX bulkhead													
13.63	2.09	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.74	1.72	1.71	1.58
	Forward LH_2 bulkhead													
15.45	2.07	1.00	1.01	1.79	1.01	1.00	1.07	1.01	1.94	1.03	1.48	1.70	1.76	2.03
	Aft LH_2 bulkhead													
21.13	1.80	1.29	2.61	1.07	1.08	1.77	1.49	1.43	1.15	1.45	1.63	2.01	1.95	1.83

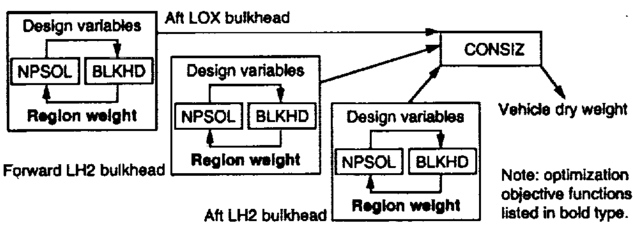


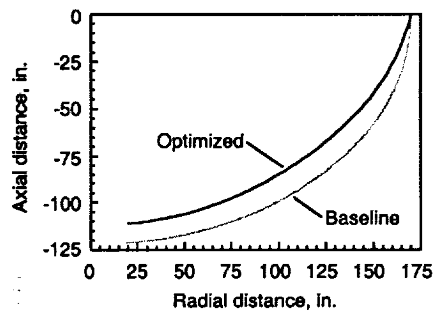
Fig. 4 Analysis flow for structural-level optimization.

additional ring frame weight, is passed to NPSOL for minimization. Changes in the design variables are computed with NPSOL, a modified BLKHD input file is written, and a new BLKHD analysis is performed. The BLKHD–NPSOL analysis-optimization loop is repeated until a converged solution is reached. This entire process is repeated two more times to generate an optimized design for each of the vehicle's three major bulkheads. The optimized bulkhead designs are then incorporated into a CONSIZ model of the wing–body vehicle, and a vehicle dry weight is computed. A diagram of this structural-level optimization process is shown in Fig. 4.

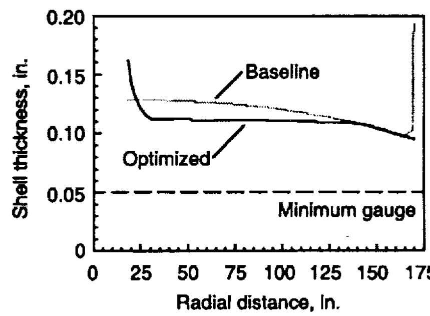
To obtain the scaled bulkhead weight, the computed bulkhead weight from the BLKHD code is multiplied by a scaling factor. The scaling factor is defined as the ratio of an empirically determined baseline bulkhead weight, derived from Space Shuttle external tank hardware weights, to a baseline bulkhead weight computed with the BLKHD code. The scaling factors represent nonoptimal factors (weld lands, subsystem attachments, etc.) that are not included in the BLKHD analysis. The scaling factors used in this study are 1.20 for the aft LOX bulkhead, 1.46 for the forward LH_2 bulkhead, and 1.83 for the aft LH_2 bulkhead.

After the scaled bulkhead weight is computed, the bulkhead volume is compared to the volume of the baseline design. Because the optimized bulkhead volume is typically smaller than the baseline bulkhead volume, an additional tank barrel segment (see Fig. 3) is required to make the sum of the optimized bulkhead and additional barrel segment volumes equal to the baseline bulkhead volume. The barrel segment is defined as a cylinder with a radius equal to the bulkhead equatorial radius and a height equal to the required barrel volume divided by the barrel cross-sectional area. The weight of the barrel segment is the product of the barrel areal weight and the barrel segment surface area. Skirt and barrel areal weights are estimated from analyses of similar launch vehicles.[1] The areal weight of the LOX tank barrel is assumed to be 2.85 lb/ft^2, and the areal weight of the LH_2 tank barrel is 2.26 lb/ft^2. These same areal weight values are used in the computation of the results that follow and later in the CONSIZ vehicle model.

The weight of a structural skirt, shown in Fig. 3, is also included in the total weight of the bulkhead region. The skirt is defined as a cylinder with a radius equal to the bulkhead equatorial radius and a height equal to the bulkhead height. The weight of this skirt is the product of the skirt areal weight and the skirt surface area. For the aft LOX and forward LH_2 tank bulkheads, the skirt areal weight is equal to the intertank areal weight of 1.64 lb/ft^2. In the case of the aft LH_2 tank bulkhead region, the skirt is the heavily loaded thrust structure behind the LH_2 tank, with an areal weight of 4.00 lb/ft^2. As with the tank barrel weights listed earlier, these skirt areal weights are used in both the bulkhead optimization and the CONSIZ model. The weight of any additional ring frame area added by BLKHD is included as the product of the additional ring frame area, equator circumference, and material density.



a) Bulkhead profiles



b) Bulkhead shell thicknesses

Fig. 5 Baseline and optimized designs for aft LOX bulkheads (structural-level analysis).

Structural-Level Analysis Results

Optimized designs from the structural-level bulkhead analyses are presented in this section. As noted earlier, the total weight of each bulkhead region is the objective function for the NPSOL optimization analysis. The aft LOX bulkhead region of the wing–body vehicle is discussed first. Design variables for the optimized bulkhead profile are presented in Table 4. The baseline and optimized aft LOX bulkhead profiles and shell thicknesses are compared in Figs. 5a and 5b. The optimized aft LOX bulkhead profile differs somewhat from the baseline design, with an optimized height 11 in. lower than the baseline design and an initial angle at the equator of approximately 14 deg. The shell thicknesses in Fig. 5b are generally lower for the optimized bulkhead except in the region near the central hole. The dashed line in Fig. 5b indicates the minimum gauge shell thickness of 0.050 in. Note that the thicknesses in Fig. 5b are for the shell only and do not include any discrete stiffeners required by the bulkhead design.

A weight breakdown for the baseline and optimized aft LOX bulkhead regions is shown in Table 5 and described here. The scaled weight of the baseline aft LOX bulkhead is 2213.1 lb, and the corresponding intertank skirt is 1520.3 lb, for a total weight of 3733.4 lb for the baseline aft LOX bulkhead region. For the optimized aft LOX bulkhead design, the scaled bulkhead weight is 1664.9 lb. An additional 762.5 ft^3 of tank volume is required to compensate for the reduced volume of the optimized bulkhead. This additional barrel segment is a cylinder with a height of 14.2 in. that

Table 5 Structural weight breakdown for baseline and optimized bulkheads from structural-level analysis

Bulkhead region	Aft LOX	Forward LH_2	Aft LH_2
Baseline design weights, lb			
Scaled bulkhead	2213.1	1328.9	1390.5
Skirt	1520.3	1518.1	3710.9
Total baseline weight	3733.4	2847.0	5101.4
Optimized design weights, lb			
Scaled bulkhead	1664.9	1193.0	1396.0
Barrel segment	303.5	332.6	480.9
Skirt	1372.1	1247.9	2608.0
Ring frame	0.1	0.0	0.0
Total optimized weight	3340.6	2773.5	4484.9
Optimized minus baseline weight, lb	−392.8	−73.5	−616.5

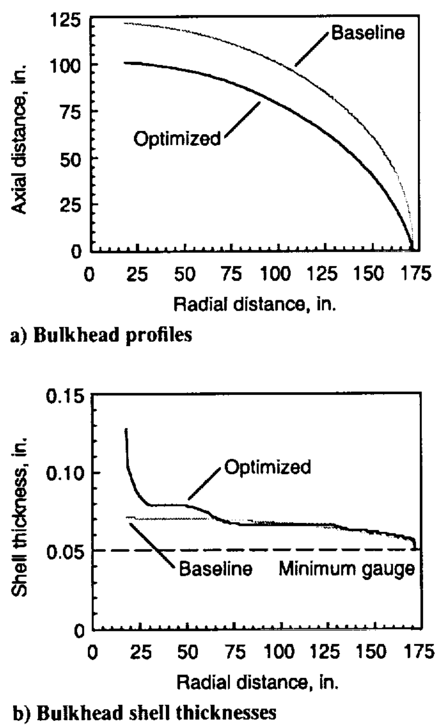


Fig. 6 Baseline and optimized designs for forward LH_2 bulkheads (structural-level analysis).

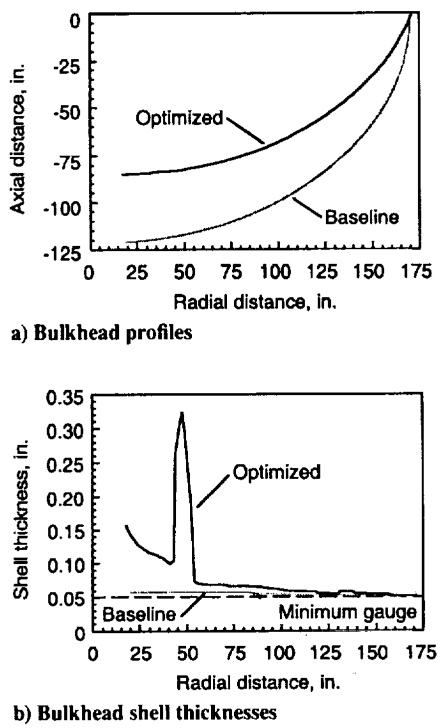


Fig. 7 Baseline and optimized designs for aft LH_2 bulkheads (structural-level analysis).

weighs 303.5 lb. The intertank skirt for the optimized bulkhead is 111.6 in. tall and weighs 1372.1 lb. Additional frame weight of 0.1 lb is required to carry the equatorial compressive loads. The total weight of the optimized aft LOX bulkhead region is 3340.6 lb, a weight reduction of 392.8 lb from the baseline design.

The structural-level optimization analyses just described are also performed for the forward and aft LH_2 tank bulkhead regions. The baseline and optimized bulkhead profiles and unscaled shell thicknesses are shown in Figs. 6 and 7 for the forward and aft LH_2 bulkheads, with design variables for the optimized configurations listed in Table 4. The optimized LH_2 tank bulkhead profiles bear little resemblance to the baseline designs. The optimized bulkhead heights are both much lower than the baseline designs with equator angles of between 15 and 21 deg, a significant amount of nontangency. These optimized bulkheads represent designs that take full advantage of the compressive load-carrying capability of the massive major ring frames, but are near the limits of current launch vehicle structural design practice. The majority of both bulkheads are sized by the proof test load case, which is a uniform internal pressure because of the small hydrostatic load of the low-density LH_2 fluid.

The optimized bulkhead thicknesses shown in Figs. 6b and 7b are generally higher than the corresponding baseline designs. The localized increase in the optimized aft LH_2 bulkhead thickness (Fig. 7b) is additional material placed there to resist the large circumferential compression load in that portion of the shell. The optimized shell thicknesses are higher than the baseline designs because of the higher loads associated with the developed contour configurations. However, the optimized bulkhead regions are lighter than the corresponding baseline values as a result of the structural-level optimization process.

Weights for the baseline and optimized forward and aft LH_2 bulkhead regions are provided in Table 5. Significant weight savings also accrue from the lower LH_2 tank bulkhead heights that result in greatly reduced skirt weights, especially in the aft LH_2 bulkhead region. Elimination of over 1100 lb of skirt structure results in an optimized aft LH_2 bulkhead region that weighs 616.5 lb less than the baseline, a 12% weight reduction. However, the optimized forward LH_2 bulkhead region weighs only 73.5 lb less than the baseline because the weight savings from the bulkhead and skirt are offset by the weight of the additional barrel segment required to make up for the lost bulkhead volume. The total structural weight reduction including all three bulkhead regions is 1082.8 lb from the structural-level optimization.

The three optimized bulkhead designs are then incorporated into a CONSIZ model of the wing–body vehicle to estimate the reduction in vehicle dry weight. Information passed from the BLKHD code to CONSIZ includes the bulkhead scaled weights, heights and volumes, and the ring frame weights. A modified vehicle volumetric packaging efficiency is also computed and passed to CONSIZ to account for the changes in the shapes of the bulkheads because flatter bulkheads result in longer tank barrels and improved packaging efficiency. The wing–body vehicle dry weight with the baseline bulkhead designs is 200,679 lb. Inclusion of the optimized bulkheads and resizing of the vehicle in CONSIZ reduces the dry weight to 196,314 lb, a reduction of 4365 lb or 2.2%. Thus, a 1-lb reduction in structural weight is reflected in a reduction of 4.03 lb in dry weight through vehicle resizing. It is important to note that the converse is also true: a 1-lb increase in structural weight will result in an increase of about 4 lb in vehicle dry weight, demonstrating the high level of sensitivity to weight growth of this class of vehicle.

Vehicle-Level Optimization

In this approach, denoted as a vehicle-level analysis, the vehicle dry weight is now the objective function for the optimization, instead of the bulkhead region weights used earlier in the structural-level analysis. In addition, this vehicle-level analysis directly includes relations that represent the improved propellant volumetric packaging

Table 6 Design variables for optimized bulkheads from vehicle-level analysis

Equator angle, deg	$R1/R2$ at normalized radius r: 0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Aft LOX bulkhead														
3.55	1.05	1.00	1.02	1.05	1.11	1.17	1.26	1.37	1.44	1.52	1.63	1.72	1.63	1.50
Forward LH_2 bulkhead														
1.69	1.01	1.00	1.05	1.08	1.15	1.22	1.32	1.41	1.46	1.54	1.65	1.78	1.96	2.02
Aft LH_2 bulkhead														
27.44	1.51	1.00	1.09	1.16	1.24	1.35	1.49	1.57	1.59	1.70	1.85	2.00	2.00	2.00

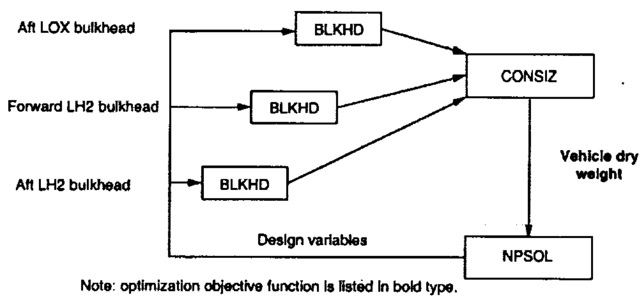


Fig. 8 Analysis flow for vehicle-level optimization.

efficiency of the redesigned bulkheads as part of the vehicle optimization process. As in the structural-level analysis, the baseline bulkhead designs generated using the data in Table 1 are used as a starting point for the optimization. The three major bulkheads are analyzed consecutively using the BLKHD code, then the bulkhead results described earlier are passed directly to CONSIZ for integration into the vehicle weights and sizing model. CONSIZ is then used to predict a vehicle dry weight that is passed to NPSOL for minimization as the objective function. Changes in the bulkhead design variables are determined by NPSOL, and a new BLKHD input file that reflects these changes is written. The BLKHD–CONSIZ–NPSOL analysis-optimization loop is repeated until a converged solution is achieved. A schematic of this process is shown in Fig. 8.

Vehicle-Level Analysis Results

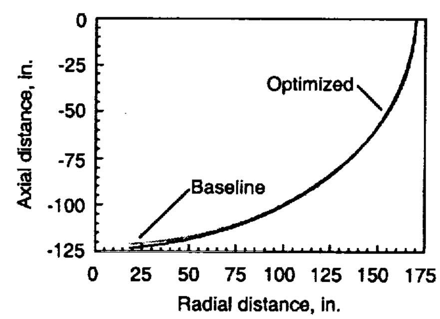
Results from the vehicle-level analysis of the wing–body vehicle are presented and discussed here. Design variables for the optimized bulkheads are shown in Table 6, and profiles for the baseline and optimized bulkheads are compared in Figs. 9–11. Profiles for the baseline and optimized aft LOX bulkheads are compared in Fig. 9a. Because of the large hydrostatic head loads, the optimized aft LOX bulkhead profile is very similar to the baseline design. The optimized aft LOX bulkhead shell thickness, shown in Fig. 9b, is also very close to the baseline shell thickness, except near the bulkhead equator. The shell thicknesses plotted in Fig. 9b are for the unscaled bulkheads, and the dashed line in the Fig. 9b indicates the 0.050-in. minimum gauge shell thickness. The baseline aft LOX bulkhead design also has seven discrete stiffeners that weigh a total of 148.2 lb, whereas the optimized bulkhead does not require additional stiffening.

A comparison of the baseline and optimized aft LOX bulkhead region weights for the vehicle-level optimization is shown in Table 7 using the tank barrel and skirt areal weights described earlier. The scaled weight of the baseline aft LOX bulkhead is 2213.1 lb, and the corresponding intertank skirt weight is 1520.3 lb, for a baseline bulkhead region total weight of 3733.4 lb. For the optimized aft LOX bulkhead design, the scaled bulkhead weight is 1911.4 lb. An additional 21.2 ft^3 of tank volume is provided in the optimized aft LOX bulkhead. Thus, the LOX tank barrel may be shortened by 0.2 in., which reduces the barrel weight by 8.4 lb. The intertank skirt for the optimized bulkhead is 124.4 in. tall and weighs 1529.8 lb. No additional frame area is required to carry the equatorial compressive loads. The total weight of the optimized aft LOX bulkhead region is 3432.8 lb, a reduction of 300.6 lb from the baseline weight.

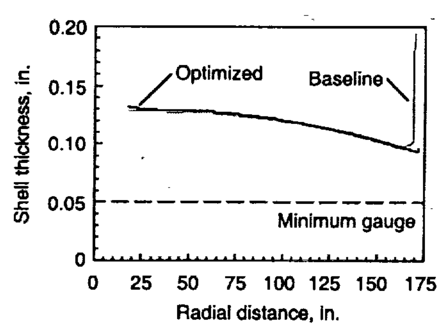
The baseline and optimized bulkhead profiles and unscaled shell thicknesses are compared in Figs. 10 and 11 for the forward and aft

Table 7 Structural weight breakdown for baseline and optimized bulkheads from vehicle-level analysis

Bulkhead region	Aft LOX	Forward LH_2	Aft LH_2
Baseline design weights, lb			
Scaled bulkhead	2213.1	1328.9	1390.5
Skirt	1520.3	1518.1	3710.9
Total baseline weight	3733.4	2847.0	5101.4
Optimized design weights, lb			
Scaled bulkhead	1911.4	1323.9	1261.8
Barrel segment	−8.4	76.8	613.0
Skirt	1529.8	1436.5	2302.6
Ring frame	0.0	0.0	0.0
Total optimized weight	3432.8	2837.2	4177.4
Optimized minus baseline weight, lb	−300.6	−9.8	−924.0



a) Bulkhead profiles

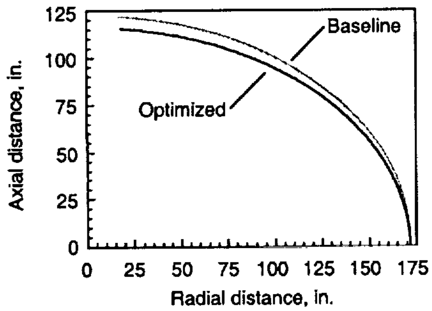


b) Bulkhead shell thicknesses

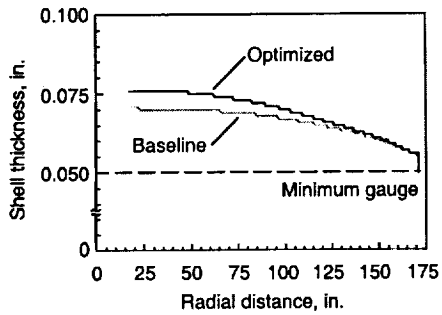
Fig. 9 Baseline and optimized designs for aft LOX bulkheads (vehicle-level analysis).

LH_2 bulkheads. The optimized forward LH_2 bulkhead is similar to the baseline design, with a small reduction in height and a slight increase in shell thickness. However, the optimized aft LH_2 bulkhead height is significantly lower than the baseline design, reducing weight by eliminating as much of the heavy skirt structure as possible. In addition, the optimized aft LH_2 configuration has a shell thickness that is much higher than the baseline design, especially near the central hole.

A weight breakdown for the baseline and optimized LH_2 tank bulkhead regions is shown in Table 7. The optimized forward LH_2 bulkhead region weighs only 9.8 lb less than the baseline, but the

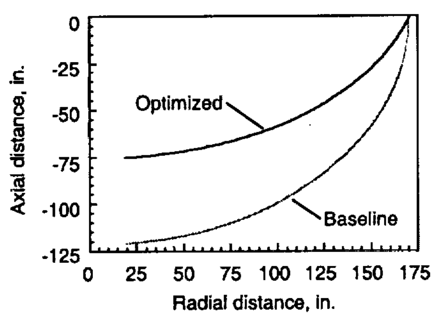


a) Bulkhead profiles

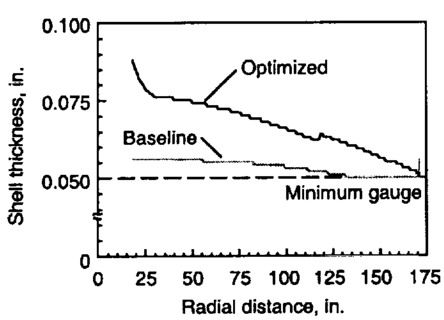


b) Bulkhead shell thicknesses

Fig. 10 Baseline and optimized designs for forward LH_2 bulkheads (vehicle-level analysis).



a) Bulkhead profiles



b) Bulkhead shell thicknesses

Fig. 11 Baseline and optimized designs for aft LH_2 bulkheads (vehicle-level analysis).

optimized aft LH_2 bulkhead region weighs 924.0 lb less than the baseline, trends that are consistent with those observed for the structural-level analysis. The total structural weight reduction from all three major bulkheads is 1234.4 lb. The corresponding vehicle dry weight is 195,550 lb, a reduction of 5129 lb or 2.6% from the baseline dry weight of 200,679 lb. In the vehicle-level optimization, a 1-lb reduction in structural weight results in a reduction of 4.16 lb in dry weight after vehicle resizing, a 3% increase over the structural-level analysis sensitivity.

Discussion

In this section, results from the structural- and vehicle-level optimization analyses for the wing–body vehicle are compared and discussed. Examination of the optimized bulkhead designs shown in Figs. 5–7 and 9–11 indicates that the two optimization paths result in quite different designs for all three bulkheads. Despite the differences in the bulkhead configurations, the final vehicle dry weights (196,314 lb for the structural-level optimization, and 195,550 lb for the vehicle-level optimization) are fairly close. This result suggests that many different vehicle designs may have dry weights that are close to the values predicted by the two different optimization approaches. Existence of a wide variety of designs with similar weights should allow more freedom in the vehicle preliminary design process.

The structural-level analysis has the advantage of a straightforward optimization path, where a single total weight for each bulkhead region is computed and minimized with NPSOL. Only after these designs are incorporated into the CONSIZ model does any vehicle scaling occur. However, there are two obvious disadvantages to the structural-level approach. First, the quantities that are being optimized (the bulkhead region total weights) are not the actual quantity of interest, the vehicle dry weight. Thus, it may be possible for the vehicle with the lowest dry weight to not incorporate the optimized bulkhead designs. In addition, results from both the structural- and vehicle-level analyses are sensitive to the areal weights assumed for the tank and skirt regions.

The primary advantage of the vehicle-level analysis is that the quantity of interest, the vehicle dry weight, is the objective function for the optimization process. Therefore, structural weight and sizing effects are directly linked to computation of the vehicle dry weight. The major disadvantage of the vehicle-level analysis is that scaling and resizing of the vehicle occurs on each pass through CONSIZ, making traceability of the design through the optimization process much more difficult.

Each of the results presented are generated from a single converged NPSOL optimization run. Experience has shown that further reductions in the vehicle dry weight may be possible with repeated optimization analyses, in which the final design from a converged iteration is used as the starting design for the next iteration. However, this possibility is not investigated here because the objective of this study is to generate a preliminary design-level estimate of the reduction in vehicle dry weight achievable with the nontangent, developed contour bulkhead technology.

Conclusion

A study is performed to investigate the weight savings in a representative SSTO vehicle that may result from the use of nontangent, developed contour bulkheads, as compared to the commonly used ellipsoidal bulkhead with an aspect ratio of 1.414. A preliminary design bulkhead sizing code is used to compute the weight, volume, and height of nontangent, developed contour bulkhead designs. A vehicle-level weights and sizing code is used to predict the dry weight of a vehicle that incorporates the optimized designs from the bulkhead analysis code.

Two different optimization approaches are evaluated in this study. First, a structural-level analysis is performed in which the weight of each of the three major bulkhead regions of the vehicle is minimized separately, after which the three optimized bulkhead designs are incorporated into the vehicle weights and sizing model and a vehicle dry weight is computed. In the second vehicle-level approach, the vehicle dry weight is the objective function of the optimization process. During the vehicle-level optimization, the three modified bulkhead designs are incorporated into the vehicle weights and sizing model for computation of a vehicle dry weight. The optimization code is then used to manipulate the bulkhead design variables with the aim of reducing the vehicle dry weight.

The structural-level analysis shows a reduction in vehicle dry weight of 4365 lb, a 2.2% reduction from the 200,679 lb dry weight of the baseline vehicle with 1.414 aspect ratio ellipsoidal bulkheads. Similarly, the vehicle-level analysis predicts a reduction in vehicle dry weight of 5129 lb, a 2.6% reduction from the baseline vehicle dry weight. Despite significant differences between the two optimization approaches taken in this study, as well as the final bulkhead designs, the predicted reductions in optimized vehicle dry weight differ by only 764 lb, or 0.4% of the baseline vehicle dry weight.

From the structural-level analysis, a 1-lb savings in structural weight results in a reduction of 4.03 lb in vehicle dry weight after resizing, a ratio that demonstrates the extreme weight sensitivity of this class of vehicle. The vehicle-level optimization yields a reduction of 4.16 lb in resized-vehicle dry weight for each 1-lb reduction in structural weight, a 3% increase over the sensitivity computed for the structural-level analysis.

The results of this preliminary study suggest that nontangent, developed contour bulkheads may provide substantial weight savings for SSTO vehicles. Much additional work in the areas of manufacturing and detailed analysis and design of hardware is still required to prove this concept for large structural components. Despite these open issues, nontangent, developed contour bulkhead technology, as well as all other potential avenues of weight reduction, must be vigorously pursued because of the extreme weight sensitivity of SSTO vehicles.

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