WEIGHT REDUCTION APPROACHES FOR HELIUM FLIGHT DEWARS*

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ABSTRACT

The dry weight of conventional helium flight dewars has been 3.4 to 7.2 times the weight of the contained liquid helium; the larger the dewar, the lower the weight ratio. For long life systems, the dewar weight can be the major weight subsystem of the satellite. To keep launch costs down, it is often necessary to reduce the satellite weight in order to launch on a smaller and lower cost launch vehicle. The cost of reducing the dewar weight is normally substantially less than the cost of upgrading to higher lift launch vehicles. The approaches described in this paper include going to lower density, higher modulus aluminum-lithium alloys, using advanced construction (waffle, ring stiffening) for the compression critical vacuum shell and helium tank, and changing to perforated aluminum honeycomb vapor cooled shields from monocoque shields. Weight savings as high as 22% of the dry weight are possible, using the Gravity Probe-B (GP-B) dewar as an example.

INTRODUCTION

A survey of free flyer superfluid helium flight dewars that have been built or will be constructed in the near future is shown in Figure 1. The STEP dewar is a version of the Lockheed ID dewar that has been built and tested but not flown; the IRAS and COBE dewars, built by Ball Aerospace, have flown; the ISO dewar built by DASA has been constructed but not yet flown; and the GP-B dewar has just completed its preliminary design review. Several points of interest arise from figure 1. As expected, the dry-to-helium weight ratio drops as the dewar size increases due to more efficient packaging. The small amount of data scatter is surprising since each dewar was designed to different sets of requirements; i.e., aperture openings, support techniques, use of guard tanks, launch vehicles, etc. However, for the large weight items such as helium tankage, vacuum shell and vapor-cooled shields, similar designs and aluminum alloys are used and the designing factor for both the subatmospheric tanks and vacuum shell is normally external pressure. Shells which can withstand these buckling pressures can usually withstand a wide range of internal pressures, launch loads and factors of safety with little or no increase in weight.

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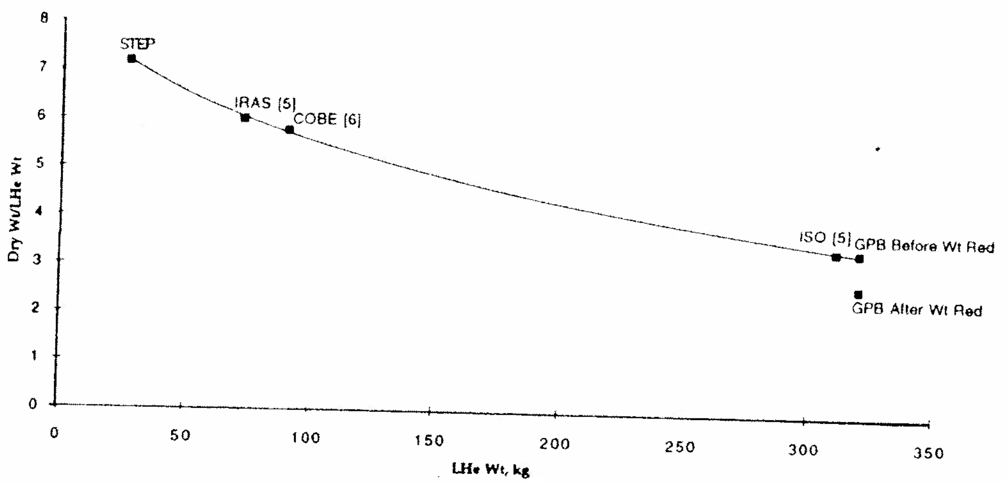

Figure 1. Comparison of helium flight dewar weights

This paper discusses the use of more advanced aluminum alloys (8090 aluminum-lithium) and design techniques (waffle and ring stiffening, honeycomb) for the GP-B dewar that reduced the cryostat dry weight by 22% while increasing total dewar program cost approximately 10%.

A layout of the GP-B dewar is shown in Figure 2. The science package is mounted within a separate vacuum container called the probe which is inserted into the annular well of the 2400 liter superfluid helium main tank. Twelve passive orbital disconnect struts (PODS), arrayed in two sets of six, support the main tank from the vacuum shell. The forward set of PODS is attached to a graphite/epoxy ring structure, which also supports

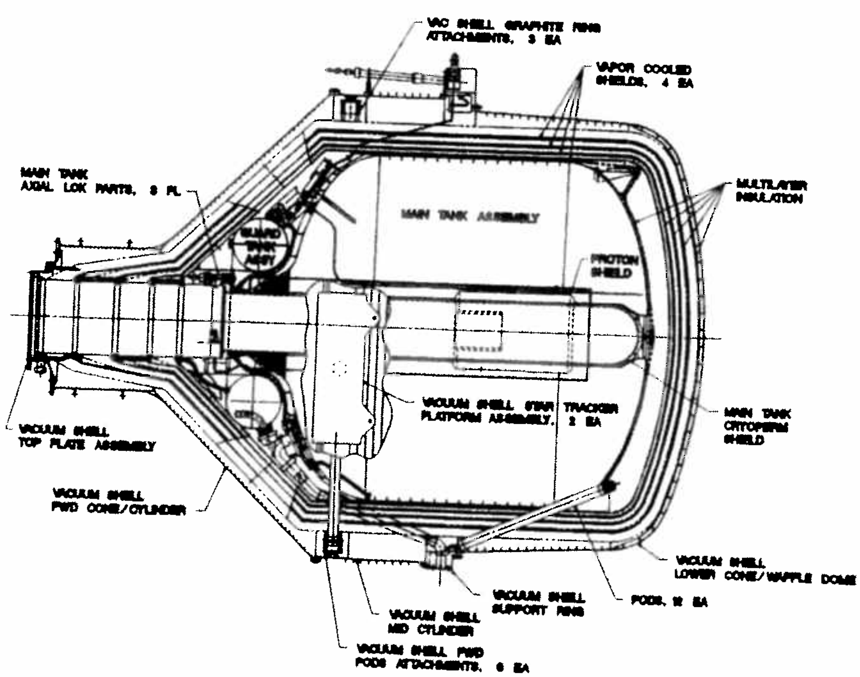

Figure 2. GP-B dewar layout

Material
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6063 - T6
2219 - T81
8090 - T8
UL30
UL40
UL50

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Table 1. Candidate GP-B structural materials

Material	Density (g/cc)	Modulus (MPa)	Yield Strength (MPa)	Ultimate Strength (MPa)
6061 - T6	2.71	69000	248	290
6063 - T6	2.71	69000	214	241
2219 - T81	2.85	72000	345	434
8090 - T8	2.55	79000	338	462
UL30	2.44	81000	414	517
UL40	2.41	83000	331	407
UL50	2.30	91000	310	379

two star tracker platforms. Concentric neck tubes for both the probe and dewar provide the required annular pressure barriers. The outer, or dewar, composite neck tube supports a 98 liter normal helium guard tank. The four vapor-cooled shields are supported by both the outer composite neck tube and the PODS supports. The items providing the largest potential weight savings are the main tank, vacuum shell, and vapor-cooled shields. Material selection for and design of these items are discussed in this paper.

MATERIAL SELECTION

In order to meet overall weight requirements without decreasing cryogen volume, particular attention has been paid to optimizing the materials used for all primary structure. These materials are chosen based on their elastic modulus, strength, density, thermal conductivity, and manufacturability. Depending on the structural and thermal constraints imposed on a particular structural component, metrics based on combinations of the above material characteristics can be developed to guide the selection of an optimal material.

For example, vacuum shell design is usually driven by stability (buckling) considerations. Consider the case of a capped monocoque cylinder subject to external pressure. The critical pressure is directly proportional to the elastic modulus of the cylinder material. The weight of the cylinder will be proportional to the density of the cylinder material. Hence, a reasonable metric for vacuum shell material selection will be the ratio of the elastic modulus-to-density. Similarly, the weight of optimized pressure vessels which are generally stress critical due to internal pressure considerations, such as a cryostat's primary tankage, will be sensitive to the strength of the tankage material. In this case the ratio of a material's strength-to-density would be a reasonable metric.

Traditionally, cryostat construction at Lockheed has relied on extensive use of 6061 aluminum for its reasonable strength, manufacturability, ductility at cryogenic temperatures, and cost. Optimizing the GP-B structural materials has taken advantage of the relatively recent development of aluminum-lithium alloys, in addition to more traditional aluminum alloys where trade studies show a weight advantage can be gained. The aluminum-lithium alloys in general offer greater stiffness and strength while having a lower density than the 6061 aluminum alloy commonly used. The following table lists some general room-temperature properties of aluminum and aluminum-lithium alloys considered for use in the GP-B cryostat.

At a glance, the UL- series of alloys offer significant potential weight savings, when applied to the GP-B structure. However, these alloys were not selected for use in the GP-B structure due to manufacturability, cost, and technical risk. For example, the large forgings required for the GP-B structure are not presently available for the UL- series of alloys. Further, these materials are still under development; hence the cost and technical risk associated with their use eliminated them from selection.

For the GP-B vacuum shell, the 8090 aluminum-lithium alloy was selected. The modulus-to-density ratio of this alloy is 22% greater than that of 6061 aluminum. This material has been used for other flight programs at Lockheed, and is well characterized. It

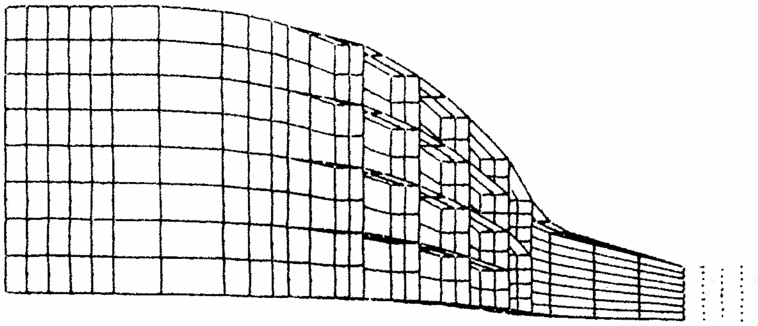

Figure 3. Rib stiffened upper tank dome finite element model

is available in virtually all forms, and has adequate weldability. For the primary tankage, the 2219 aluminum alloy was selected for it's superior strength-to-density ratio. The strength-to-density ratio (on yield) of 2219 is 32% greater than that of 6061 aluminum, while being in an extremely mature stage of development.

During the actual mission, guide star tracking stability is critical for success. This places a premium on the alignment of the star trackers to the experiment. These trackers are mounted on the exterior of the vacuum shell. Innovative structural design and the use of a composite mounting ring to which the star trackers are mounted has made meeting the difficult alignment stability requirement possible. In this case, vibration frequency requirements have driven the ring design. The ring must have sufficient local and global hoop stiffness to minimize the tendency of the PODS to "poke" the ring; i.e., it must have sufficient stiffness to minimize local in-plane bending deformations associated with lateral support of the primary tankage.

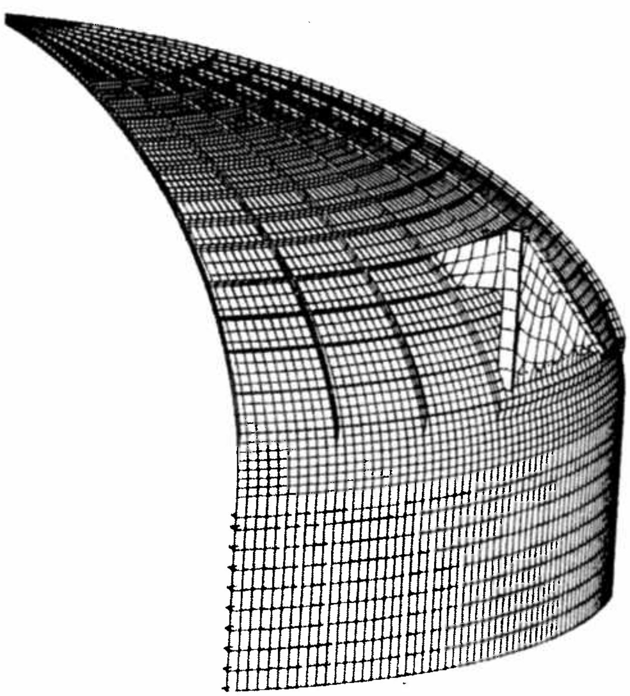

Figure 4. Rib stiffened lower tank dome finite element model

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The mounting ring must also be extremely stable with respect to thermal contractions. This requirement is the result of the flowdown of the star tracker pointing alignment requirement. Both the stiffness and thermal stability constraints imposed on the mounting ring are met with the use of a graphite/epoxy (Gr/Ep) material. The ring will utilize a Thornel P120S graphite fiber, wound such that the fibers are oriented in the hoop direction. These fibers have an extremely high modulus of elasticity and an extremely low coefficient of thermal contraction down to the expected vacuum shell temperature of 220 K. Using a simple rule-of-mixtures approach, the expected modulus of the composite ring in the hoop direction is expected to be approximately 4.8×10^5 MPa. Preliminary structural analysis of the composite ring, designed to the frequency requirement, has shown the envisioned ring design to have ample structural margins-of-safety, while being extremely lightweight.

A new materials approach to the vapor-cooled shields also resulted in significant weight savings over conventional designs. The vapor-cooled shields must support multilayer insulation and be sufficiently stiff to preclude buckling or excessive motion and damage which can adversely effect critical radiation gaps, when subjected to the launch environment. The shield design is also driven by thermal conductance considerations. Typically, monocoque shields will have more than adequate conductance when sized to satisfy structural constraints. The new GP-B vapor-cooled shield design takes advantage of this by using an extremely lightweight perforated 5052 aluminum honeycomb core with thin 1100 perforated aluminum facesheets. The honeycomb facesheets can be sized to provide the required thermal conductance while the honeycomb construction is extremely efficient, structurally. The new design proved to be approximately 40% lighter than adequately designed monocoque shields.

DEWAR TANK DESIGN

The dewar tank design unique to GP-B is driven not only by internal and external pressure requirements but axial stiffness as well. The axial stiffness requirement is driven by coupling of the axial vibration modes of the dewar with the axial modes of the Delta-II. This coupling may be unique to the GP-B tank design; the large tank diameter and the shallowness of the upper tank dome combine to lower the "diaphram" vibration mode. It is this diaphram mode of the upper tank dome which was found to couple with the axial modes of the Delta-II. The starting point for the design incorporated purely monocoque shells for the upper and lower tank domes, and a rib-stiffened tank cylindrical section.

Upper Tank Dome Optimization

Vibrational modes of the baseline dewar were determined using the MSC/NASTRAN[3] finite element code. The frequency goal was 35 Hz; however, the flexibility of the upper tank dome lowered the frequency to 24 Hz. To increase the dome's stiffness, rib stiffening was investigated using a coarse dynamic finite element model of the dewar, as shown in Figure 3.

The height of the ribs was limited by space constraints between the main tank and the coldest vapor- cooled shield. Since the dome needed the maximum stiffening possible with the lightest weight, the ribs were made to be the maximum available height (making the ribs higher is more efficient by a power of three than making them wider). The thickness of the ribs was then varied until the upper dome was no longer the most axially flexible element in the dewar. This determined the amount of material needed in the radial ribs.

The next step in the optimization process was to make the upper dome acceptable for stress. 15 radial ribs were picked as a starting point, with circumferential ribs added at intervals to make roughly square membrane panels. Because stresses in the membrane were initially too high, intermediate radial ribs had to be added as radius increased. With the final rib spacing, the membrane was able to be made extremely thin (1.5 mm in some places). Thickness was modified until most areas were loaded to just below their critical stresses due to internal pressure loading. At this point in the optimization, the axial dewar mode was raised to 33.4 Hz and the weight of the upper dome was about 14 kg less than the original monocoque design.

The upper dome was then checked for buckling using BOSOR4[1], a finite difference code developed at Lockheed for analyzing shells of revolution. Because of the large ribs, the dome was found to be stress critical, and no changes were required to accomodate buckling performance.

Main Tank Cylinder Optimization

Optimization of the main tank was fairly straightforward. Using the Lockheed-developed structural optimization code PANDA[2], the optimal combination membrane thickness, ring height, spacing and thickness (see Figure 5 in the next section) resulting in minimum weight is determined to preclude global buckling of the entire cylinder and different types of localized buckling and stress. The final design was found to be buckling critical for external pressure.

Lower Tank Dome Optimization

The lower tank dome was rib stiffened in a waffle pattern to save weight, as shown in Figure 4. The basic rib configuration (number of radial and circumferential ribs) was determined by lumping ribs into a BOSOR4 model of the aft dome and iterating to find the right combination of membrane thickness and rib height. Once the basic configuration was complete, a detailed finite element model of the dome was made to determine the stresses in the ribs and membrane more exactly.
Using the finite element model, stress levels were adjusted by varying thicknesses of ribs and membranes until stresses were near critical levels in most areas. Because the ribs on the aft dome were lower than on the forward dome, the design had to then be slightly modified to have a positive buckling margin. The final design was very balanced, with small positive margins for both stress and buckling, indicating a highly optimized design.

The baseline tank had a heavy ring attached to the aft dome to accomodate the aft set of PODS supports. This ring was replaced by brackets which bolt to thickened local areas on the aft dome. As the localized loads from these attachments did not trigger buckling in the dome, the bracket and thickened areas were optimized for stress. Removal of the mounting ring saved 20 kg.

VACUUM SHELL DESIGN

Shell structures such as the GP-B vacuum shell are generally designed for three conditions: internal pressure, external pressure, and acceleration. In this case, the shell carries only its own mass under acceleration loads, resulting in relatively low stresses. Consequently, the shell was designed for stress under internal pressure and for buckling under external pressure.

If the design was to be purely for internal pressure, a monocoque shell would have been ideal for all except the aft dome, for which a monocoque design may buckle under internal pressure. This is due to the shallowness of the dome design. However, this shell must also be capable of carrying a full atmosphere vacuum with a factor of safety of 2.0, which results in a design vacuum capability of 0.2 MPa. A monocoque shell which could survive this type of pressure would be extremely heavy compared to ring stiffened shells.

When a cylindrical or conical shell buckles, it causes severe bending in the shell wall. The bending stiffness, I, is proportional to the cube of the thickness, t, while the membrane stiffness is proportional to the cross sectional area. Thus, if the effective

Table 2. Vacuum shell design

Section	t (mm)	h (mm)	b (mm)	s (mm)
Forward Cylinder	1.3	8.6	0.53	18.3
Forward Cone	2.3	16.0	0.76	19.3
Mid Cylinder	2.1	17.8	1.14	35.9
Lower Cone	2.1	17.8	1.14	36.8

Table 3 Aft dome design

Wall Thickness (mm)	2.54
Ring Height (mm)	19.0
Radial Stiffener Thickness Inner Bays (mm)	1.3
Radial Stiffener Thickness Outer 4 Bays(mm)	2.8
Radial Stiffener Spacing (deg)	10°
Ring Thickness (mm)	1.0
Ring Spacing (mm)	76.0

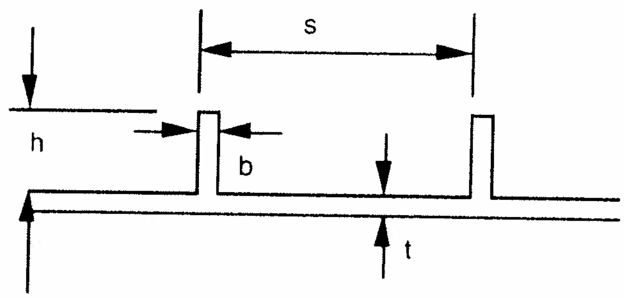

Figure 5. Anatomy of a ring stiffened shell

thickness of the shell is increased without significantly changing the cross-sectional area, the buckling strength will be increased without a corresponding increase in the weight.

Experience has shown that a ring stiffened cylinder has a higher buckling strength under external pressure than a stringer stiffened cylinder. This is mostly due to the fact that the pressure stress is twice as large in the hoop direction than that in the axial direction. Consequently, ring stiffened shells are commonly used for cylindrical structures. The aft dome is a combination of spherical shells, so the pressure stress state will be essentially the same in all directions. For this region, a combination of rings and radial stiffeners was used (waffle pattern).

Table 4. Weight savings summary

Assembly	Weight (kg)	Savings (kg)	Comment
Main Tank (including 68 kg of Baffles)	294	80	Waffle Domes, 2219 Al, PODS attch.
Composite Neck Tube Assembly	28	0	
Guard Tank	17	5	Lightening Holes in Support Cone
Vapor-Cooled Shields	66	44	Al Perforated Honeycomb Shields
MLI	53	0	
Vacuum Shell	334	111	Ring Stiffening & Waffle Dome, 8090 Al
PODS	11	<1	Lighter Supported Weight
Plumbing	31	-3	Two Additional Valves
Instrumentation	13	-1	Added Magnetometer

For the initial design of the cylinders and lower cone, the LMSC developed optimization code PANDA [2] was used. Unfortunately, PANDA does not analyze cones. The lower cone is nearly cylindrical, so PANDA gives reasonable results there. However, for the forward cone, an approximate initial design was selected by experience.

Final analysis of the whole vacuum shell structure was performed using BOSOR4 [1]. This indicated that the forward cone was not strong enough for external buckling, and the design was modified until an optimal design was reached.

A 3-D finite element model of the internally waffle-stiffened aft dome was generated using DIAL [4] for design and analysis of the dome structure. Using this model, the critical locations for stress and buckling were observed. This allowed the design to be optimized, using different sections for the rings, radial stiffeners near the center, and radial stiffeners near the edge of the dome.

The final designs for some of the sections of the vacuum shell are shown in Tables 2 and 3.

CONCLUSIONS

For the GP-B dewar, weight savings of 22% were achieved by using advanced materials and innovative but low-risk structural design and optimization, while incuring a modest dewar program cost increase of 10%. Table 4 summarizes the weight of major components and assemblies, and weight savings achieved in the current effort. The dry weight of the dewar is 847 kg. With 320 kg of helium, the total dewar weight is 1167 kg.

Even greater weight reductions can be achieved using more advanced aluminum-lithium alloys (UL50), honeycomb or composite vacuum shells, etc. However, these techniques will significantly increase program cost and risk. For these reasons, even more advanced designs and materials for the GP-B dewar were not selected.

REFERENCES

1. Bushnell, D., " BOSOR4 - Program for Stress, Stability, and Vibration of Complex, Branched Shells of Revolution", in STRUCTURAL ANALYSIS SYSTEMS, Vol. 2, edited by A. Niku-Lari, Pergamon Press , pp 25-54(1986)
2. Bushnell, D., "PANDA - Interactive Program for Minimum Weight Design of Stiffened Cylindrical Panels and S9hells", Computers and Structures, Vol. 16, No. 1-4, pp. 167-185 (1983)
3. MCS/NASTRAN User's Manual, Version 67, MacNeal-Schwendler Corporation, Los Angeles, Ca, 1991
4. DIAL Structural Analysis System User's Manual, Version L3D3, Lockheed Missiles and Space Co., Sunnyvale, Ca.
5. Mason, P. , Jet Propulsion Laboratory, Pasadena, Ca., Telephone conversation
6. Castles, S.H., "Design and Status of the COBE Dewar", pp 5-13, 1983 Space Helium Dewar Conference

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ABSTRACT

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