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Design Study for the Asteroid Redirect Vehicle (ARV) Composite Primary Bulkhead

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Summary

A design study was undertaken of a carbon fiber primary bulkhead for a large solar electric propulsion (SEP) spacecraft. The bulkhead design, supporting up to 16 t of xenon propellant, progressed from one consisting of many simple parts with many complex joints, to one consisting of a few complex parts with a few simple joints. The unique capabilities of composites led to a topology that transitioned loads from bending to in-plane tension and shear, with low part count. This significantly improved bulkhead manufacturability, cost, and mass. The stiffness-driven structure utilized high-modulus M55J fiber unidirectional prepregs. A full-scale engineering demonstration unit (EDU) of the concept was used to demonstrate manufacturability of the concept. Actual labor data was obtained, which could be extrapolated to a full bulkhead. The effort demonstrated the practicality of using high-modulus fiber (HMF) composites for unique shape topologies that minimize mass and cost. The lessons are applicable to primary and secondary aerospace structures that are stiffness driven.

Introduction

NASA recently completed studies for a two-part Asteroid Redirect Mission (ARM) in which the Asteroid Redirect Robotic Mission (ARRM) would send the Asteroid Redirect Vehicle (ARV) to the surface of an asteroid to retrieve a 20 t boulder. After departing the surface, the ARV, with boulder in hand, would then hover above the asteroid for a period of weeks to months, using the mutual gravitational attraction to deflect the asteroid by a measurable amount. After this demonstration of an “enhanced gravity tractor,” the ARV would take the boulder to cislunar space. In the 2026 timeframe, the Asteroid Redirect Crewed Mission (ARCM) would have sent the Orion crewed vehicle to dock with the ARV in lunar orbit and sample the captured boulder (Figure 1 and Figure 2).

The ARRM was enabled by high-power solar electric propulsion (SEP). Two large 25-kW flexible blanket solar array wings would power extremely high-throughput Hall effect ion thrusters. The ARV SEP system would be approximately 20 times better than that of NASA’s Dawn spacecraft (18 times the thrust, 23 times the total impulse, and 10 times the propellant load.) The total electrical power would be equivalent to almost half the power of the International Space Station. Yet, relative to current state-of-the-art (SOA) solar arrays, the ARV solar arrays would have only half the mass and one-quarter of the stowed volume for launch. Demonstration of this technology is critical for crewed missions to Mars.

During the formulation phases of the ARM project, the project performed multiple configuration studies of the ARV in order to assess feasibility, explore solution space, estimate mass and cost, and develop requirements (Figure 3). These studies eventually led to the configuration for the Mission Concept Review (MCR) (Figure 4). The overall configuration was driven by the requirement for an 8- to 16-t propellant load in SOA seamless-liner composite overwrapped pressure vessel (COPV) tanks.

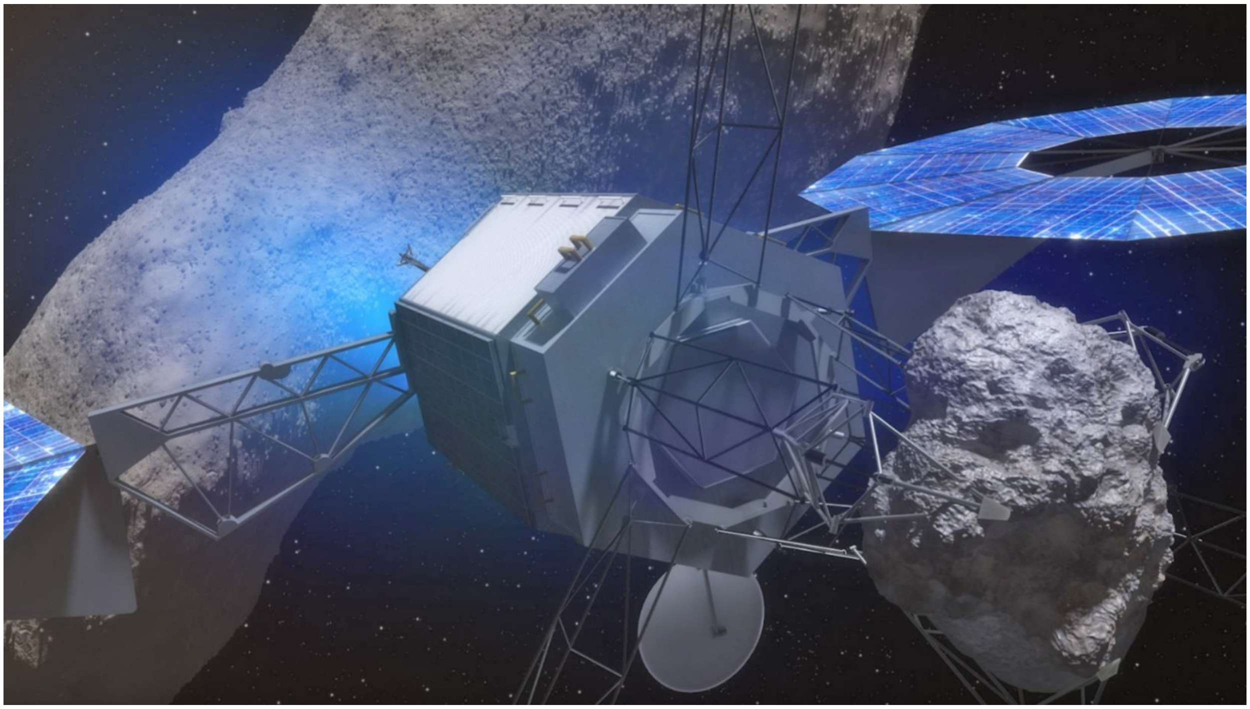


Figure 1.—Asteroid Redirect Robotic Mission (ARRM).

Figure 2.—Asteroid Redirect Crewed Mission (ARCM).

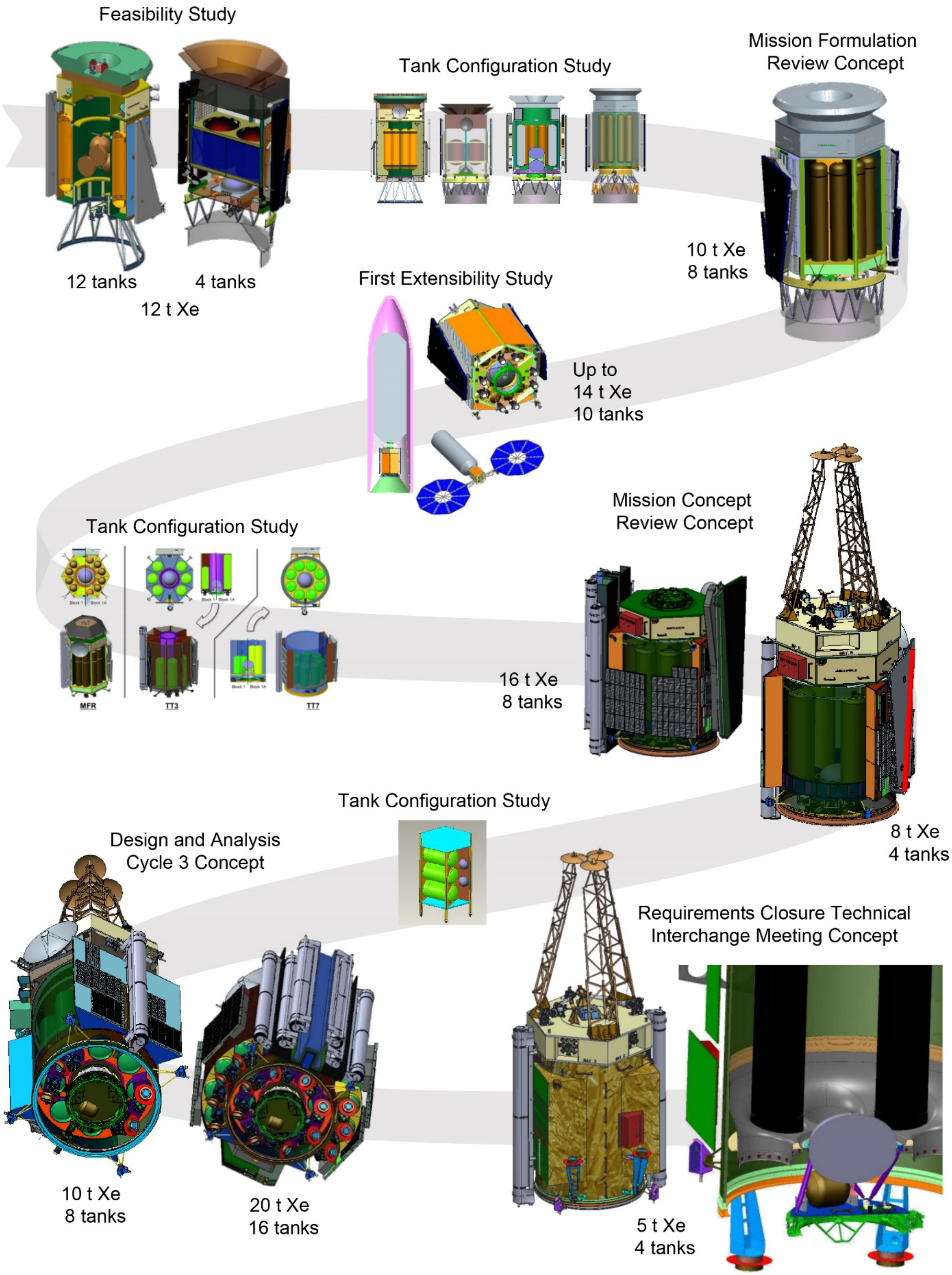


Figure 3.—Configuration studies.

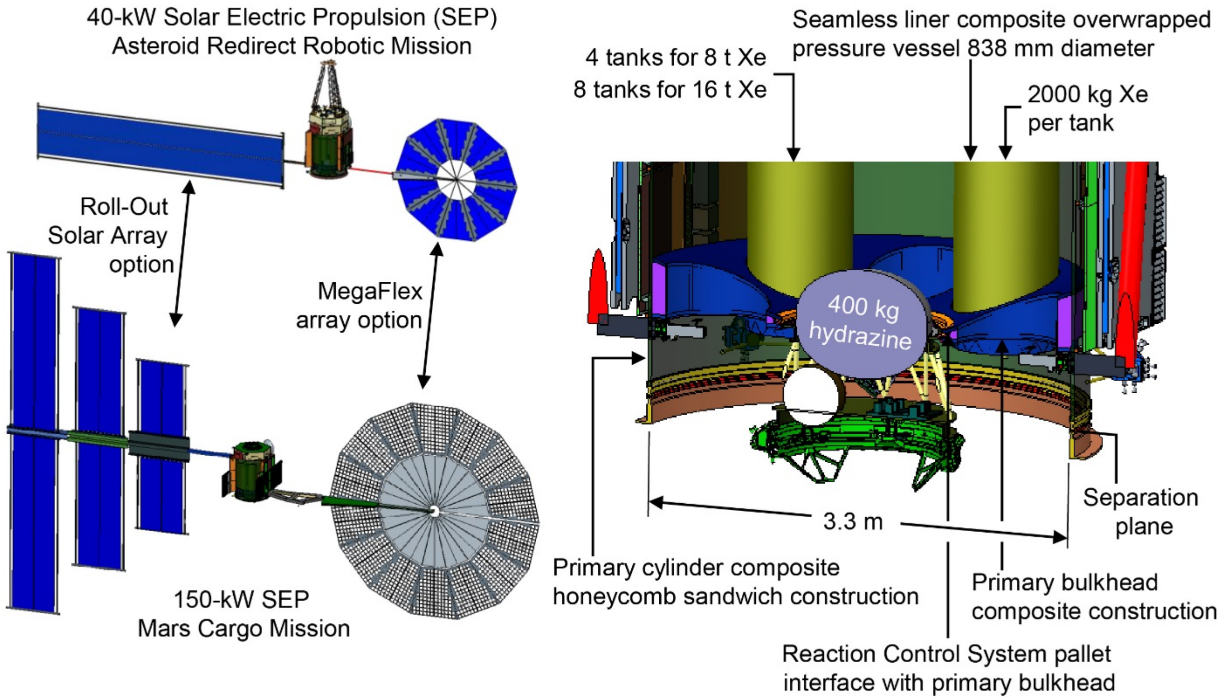


Figure 4.—Mission Concept Review (MCR) configuration.

The primary cylinder and bulkhead of the MCR configuration were envisioned to be of carbon fiber all-composite construction, not only because of the potential mass savings relative to metallic construction, but also because of the low coefficient of thermal expansion (CTE) for composites. The vehicle would operate over a temperature range of –100 to 60 °C, thus thermal stresses could be excessive between a graphite composite primary cylinder and a metallic primary bulkhead. Carbon fiber composite spacecraft are common and typically consist of a center cylindrical thrust tube and radial shear panels. What makes the ARV concept unique is the complex primary bulkhead, which is expected to be difficult to make from composites.

For this reason, the primary bulkhead was the subject of a detailed design study as described in this paper. The work was performed primarily by composites design, analysis, and fabrication personnel at Langley Research Center, with structural integration and overall direction by personnel at Glenn Research Center, and with fabrication consulting from personnel at Marshall Space Flight Center.

Bulkhead Trade Study

The composite bulkhead developed for the MCR was recognized as a technical challenge. The concept consisted of simple composite shapes notionally joined together with bolted titanium clips and potted inserts or bushings. The tanks could be installed from above, but the tank skirts would be able to be fastened to the solid laminate bulkhead cylinders from below for easy access. Though the bulkhead parts would be easy to fabricate, there were concerns about the ability to join them together and to install the assembled bulkhead into the primary cylinder. Therefore, a trade study was initiated to (1) develop the MCR bulkhead further to address concerns with fabrication and assembly, (2) develop at least two alternate composite bulkhead concepts, and (3) downselect to one concept to carry forward.

Using the MCR concept as the point of departure, the requirements were as follows:

(1) An Xe tank wet mass of 17,000 kg (Block 1A configuration), a reaction control system (RCS) tank wet mass of 534 kg, and a docking adaptor mass of 162 kg.
(2) The bulkhead must be sized for Delta IV Heavy acceleration loads per the Delta IV Launch Services User’s Guide (Ref. 1), showing positive margins for stress and buckling.
(3) The spacecraft first bending mode must be >8 Hz with the first axial mode at least 40 percent above the first bending mode to preclude coupling.
(4) The materials under consideration were M55J/954-3 and/or IM7/977-3 unidirectional tape to maximize performance.
(5) Figures of merit (FOMs) were to be mass, cost, schedule, and risk.

Option 1—Mission Concept Review (MCR) Baseline

Considerable work was required to make the MCR concept able to be assembled (Figure 5). The titanium clips assumed to be joining the various composite panels were replaced with an all-composite, bonded, progressively cured construction. Figure 6 shows the assembly sequence of the resulting bulkhead. The current best estimate[1] (CBE) mass of the bulkhead was 283 kg (Table I) with the joint mass accounting for 61 percent of that value (Table II). Note that the mass for the modifications to the lower primary cylinder was not included. An evaluation of the fabrication and assembly sequence by a composites fabrication specialist concluded that it would require more than eight post-curing operations, which does not meet accepted practice. Each subsequent curing of the assembly can threaten the joints from the previous curing cycle, due to thermal cycling to elevated temperatures, which can induce thermal stresses and chemical changes in the various resins and adhesive. Additionally, each assembly step and curing cycle requires full fixturing, monitoring, and subsequent inspections. Multiple assembly and bonding steps can be very costly and risky to the final article. Nondestructive evaluation (NDE) would also be difficult if not beyond the SOA; many curing steps start to “wall off” compartments and joints that then become nearly impossible to inspect. The rough order of magnitude (ROM) cost was estimated to be more than $20 million for a flight-like structural test article, driven by the many steps involving complex fixturing, curing, inspections, and testing.

[1]The CBE is defined in this report as the mass estimate without mass growth allowance (MGA) applied.

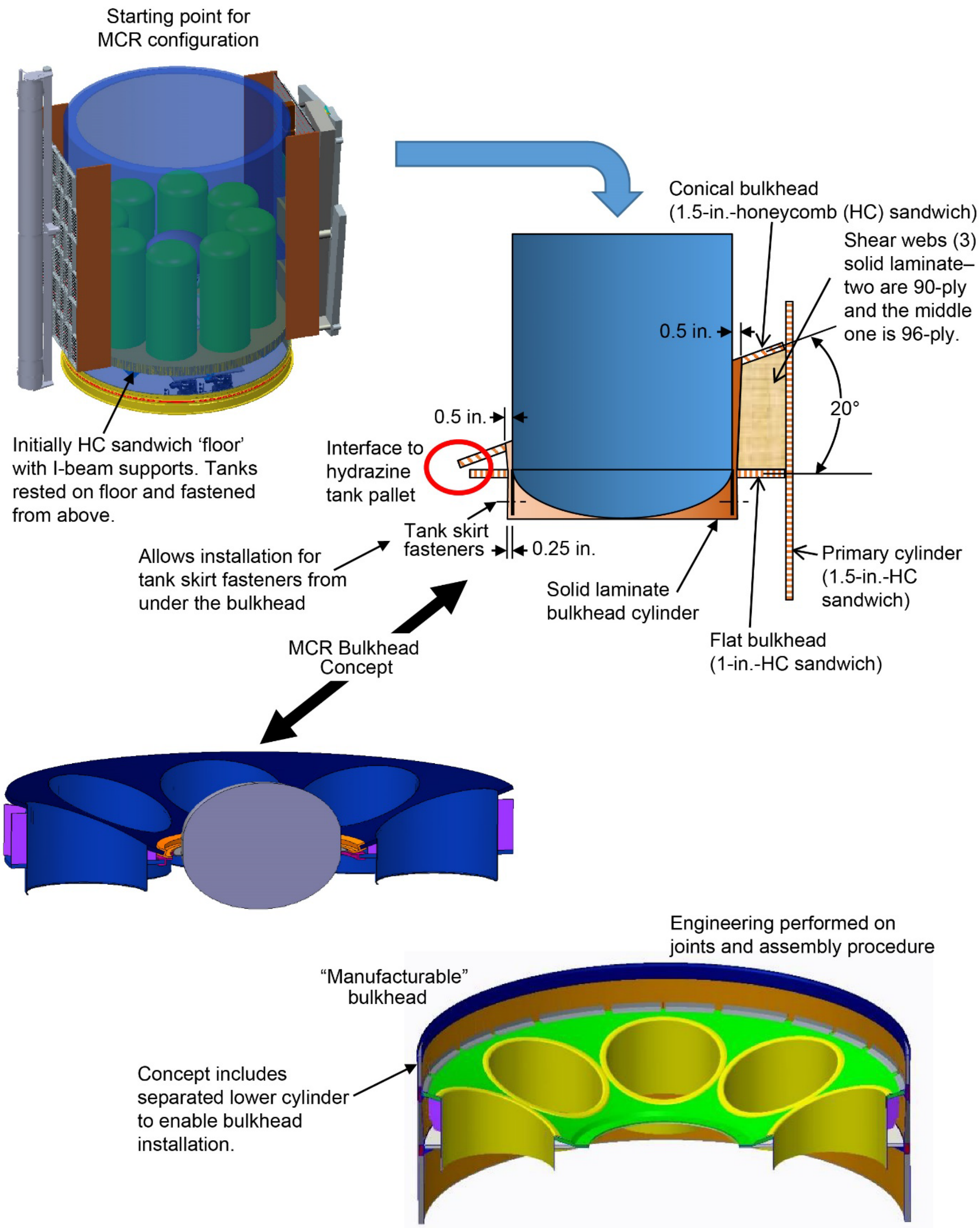


Figure 5.—Mission Concept Review (MCR) baseline bulkhead development.

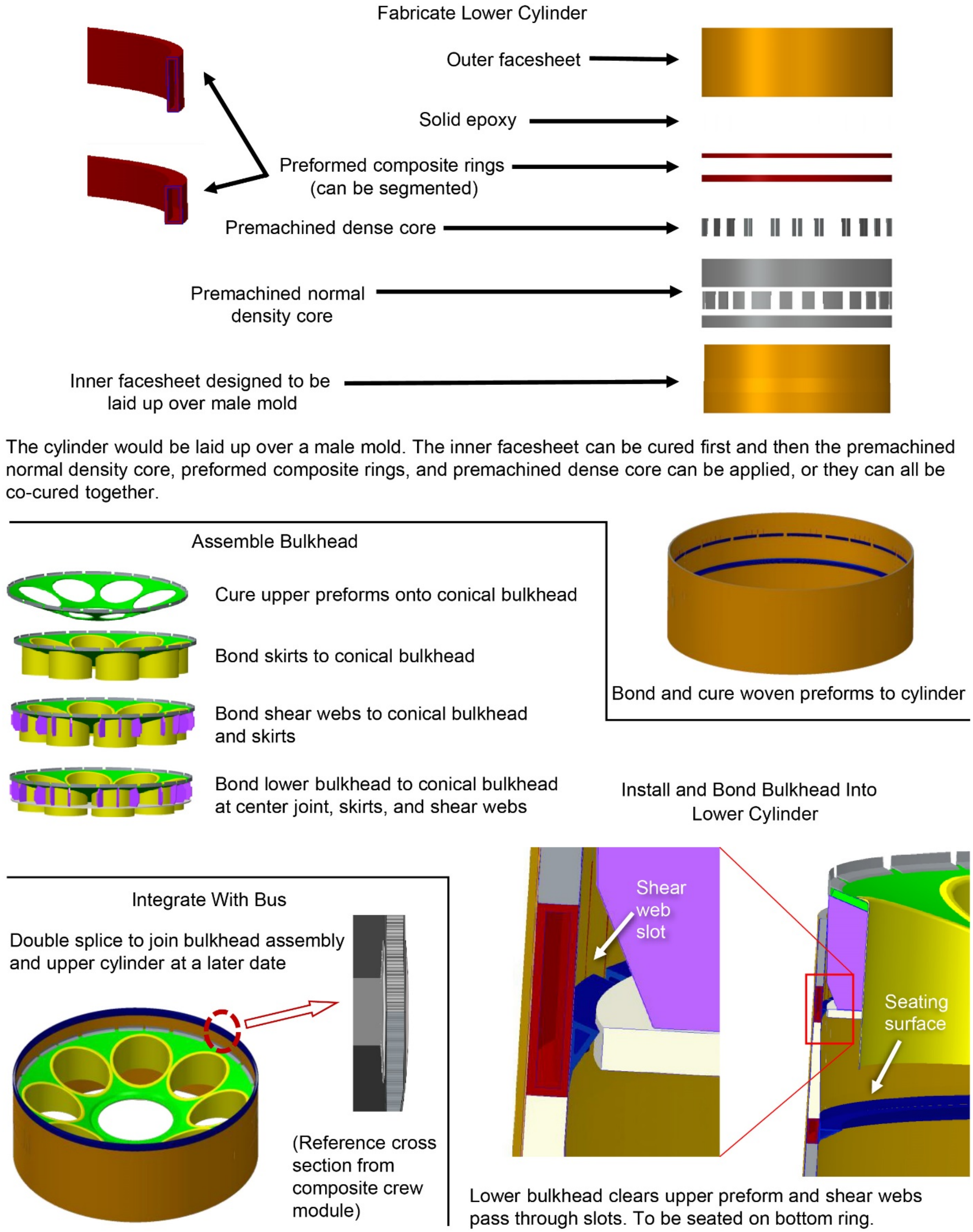


Figure 6.—Assembly process for Mission Concept Review (MCR) baseline bulkhead.

TABLE I.—MASS OF MISSION CONCEPT REVIEW (MCR) BASELINE BULKHEAD

Solar electric propulsion (SEP) module	Mass, lb	Mass, kg	Assembly mass, kg	Current best estimate (CBE), kg	Mass growth, percent	CBE + mass growth, kg
Structure—total	---------	------	-------	283.35	---	354.18
Baseline bulkhead	---------	------	-------	283.35	25	354.18
Flat bulkhead assembly	---------	------	78.28	---------	---	---------
Flat bulkhead	31.94	14.49	-------	---------	---	---------
Inner ring	3.77	1.71	-------	---------	---	---------
Inner edge of upper/lower bulkhead	22.60	10.25	-------	---------	---	---------
Tank skirts to lower bulkhead	46.10	20.91	-------	---------	---	---------
Lower bulkhead outer edge	61.60	27.94	-------	---------	---	---------
Facesheet adhesive	6.59	2.99	-------	---------	---	---------
Conic bulkhead assembly	---------	------	78.63	---------	---	---------
Conic bulkhead	54.49	24.71	-------	---------	---	---------
Upper bulkhead outer edge	61.60	27.94	-------	---------	---	---------
Tank skirts to upper bulkhead	50.70	22.99	-------	---------	---	---------
Facesheet adhesive	6.59	2.99	-------	---------	---	---------
Tank skirt assembly	---------	------	44.76	---------	---	---------
Tank skirts	98.71	44.76	-------	---------	---	---------
Shear webs	---------	------	81.67	---------	---	---------
Center	10.35	4.69	-------	---------	---	---------
Outboard center shear web all	32.20	14.60	-------	---------	---	---------
Angled	31.44	14.26	-------	---------	---	---------
Angled shear web all	106.10	48.12	-------	---------	---	---------

TABLE II.—MASS OF MISSION CONCEPT REVIEW (MCR) BASELINE BULKHEAD JOINTS

Joint location	Total joint length, m	Joint mass factor, kg/m	Total joint mass, kg
Upper bulkhead outer edge	10.43	2.68	27.9
Lower bulkhead outer edge	10.43	2.68	27.9
Inner edge of upper/lower bulkhead	3.83	2.68	10.3
Tank skirt to upper bulkhead	21.46	1.07	23.0
Tank skirt to lower bulkhead	19.51	1.07	20.9
Outboard center shear web outer vertical	2.93	2.68	7.8
Outboard center shear web inner vertical	2.54	1.07	2.7
Outboard center shear web upper horizontal	1.08	2.68	2.9
Outboard center shear web lower horizontal	1.08	1.07	1.1
Angled shear web outer and inner vertical	11.70	2.68	31.3
Angled shear web upper and lower horizontal	6.26	2.68	16.8
Totals	94.5	------	172.8

Option 2—The Octopants

This option gets its nickname from a sea creature for which the bulkhead could be appropriate attire. The concept (Figure 7) is an attempt to minimize part count and joints and uses a shape, which tends to transition loads from bending to in-plane tension and shear. The upper bulkhead carries most of the load and is solid laminate. The lower bulkhead floats relative to the primary cylinder, and its chief function is to stiffen the tubular tank-interface structures ("pant legs") of the upper bulkhead. Its honeycomb (HC) sandwich construction facilitates attachment of equipment (such as thrusters) that would induce out-of-plane bending. The only connection to the primary cylinder is through the upper bulkhead.

The contour of the upper bulkhead was manually optimized for minimum weight by iterating between shape changes in Creo[2] and structural analysis in Creo Mechanica.[3] Once the contour was settled, the detailed sizing for the bulkhead was performed using HyperSizer[4] and NASA Structural Analysis (NASTRAN[5]) program for stress, buckling, and frequency constraints (Figure 8). Intermediate-modulus versus high-modulus unidirectional tape was traded (IM7/977-3 versus M55J/954-3). It was found that that the concept was primarily stiffness driven, with the M55J/954-3 resulting in lower mass. Mass for joints and other features not included in the finite element model (FEM) was added post analysis, giving a CBE mass of 216 kg (Table III). When frequency was removed as a constraint,[6] however, this mass decreased to 166 kg.

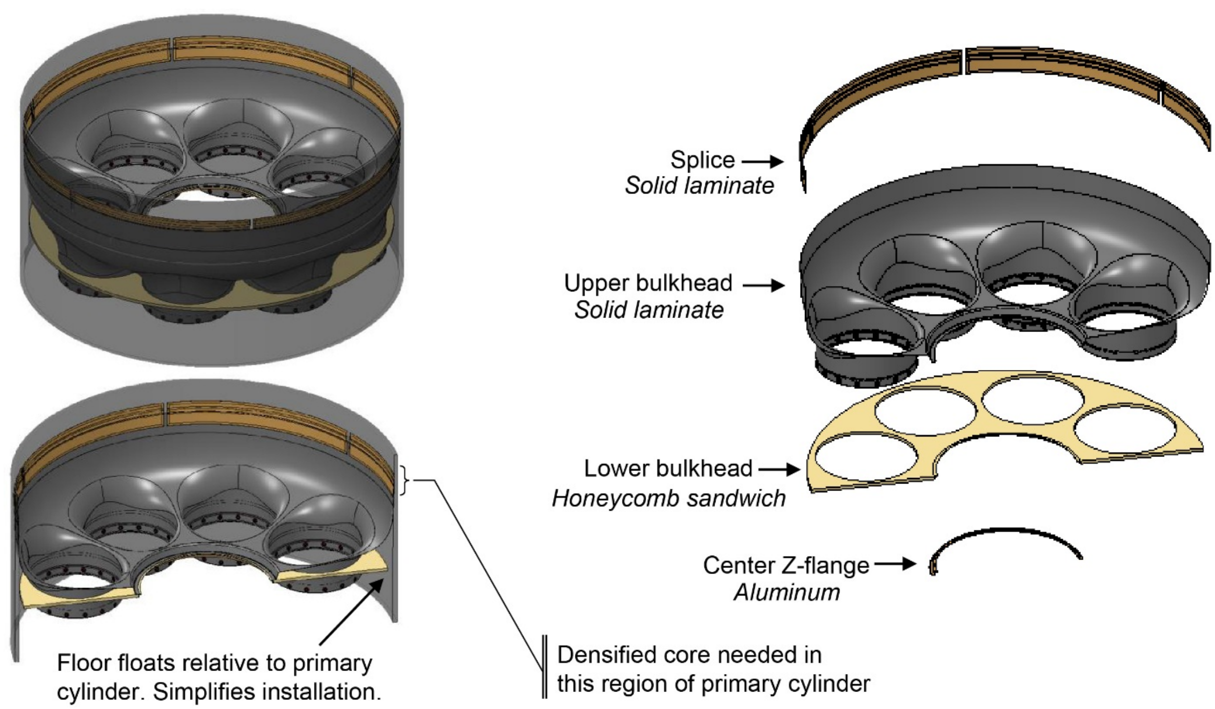
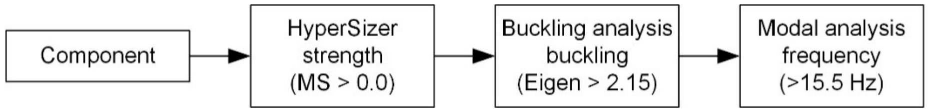
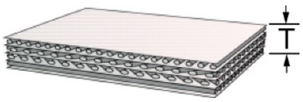


Figure 7.—Octopants bulkhead.

[2]Creo—three-dimensional CAD software tool by PTC.
[3]Creo Mechanica—a finite element analysis (FEA) package integral with Creo.
[4]HyperSizer—software by Collier Research Corporation that couples with NASTRAN for analysis, sizing, and optimization of metallic and composite structures. https://hypersizer.com/
[5]NASTRAN—an industry-standard general-purpose finite element program.
[6]The frequency constraint is really a requirement for the fundamental modes of the spacecraft and as such should be applied at the spacecraft level.

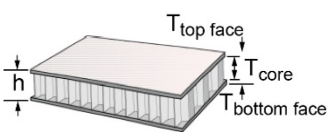




Fiber system—M55J/954-3 unidirectional tape

Component
2 “tank_ring_top_1”
3 “tank_ring_top_2
7 “skirt_top”
8 “skirt_bottom”
10 “tank_ring_bottom”
11 “internal_stiffner_1”
12 “internal_stiffner_2”
51 “pants_top_1”
54 “pants_top_2”
55 “pants_top_3”
61 “pants_bottom_1”
62 “pants_bottom_2”

Dimensions and weight	Comp. ID	T, mm	Area, m²	Mass, kg
After HyperSizer (strength, MS > 0.0)	2	0.00	3.090	0.0
	3	6.30	1.626	16.9
	7	0.79	1.024	1.3
	8	1.05	1.024	1.8
	10	6.43	1.595	16.9
	11	0.94	0.298	0.5
	12	7.48	0.365	4.5
	51	1.56	1.259	3.2
	54	5.03	1.077	8.9
	55	9.55	1.300	20.5
	61	0.45	1.019	0.8
	62	9.38	2.564	39.7
After buckling analysis (buckling, Eigen > 2.15)	2	1.31	3.090	6.7
	3	6.30	1.626	16.9
	7	2.18	1.024	3.7
	8	2.18	1.024	3.7
	10	6.43	1.595	16.9
	11	0.94	0.298	0.5
	12	7.48	0.365	4.5
	51	1.56	1.259	3.2
	54	5.03	1.077	8.9
	55	9.55	1.300	20.5
	61	1.08	1.019	1.8
	62	9.38	2.564	39.7
After modal analysis (frequency >15.5 Hz)	2	1.31	3.090	6.7
	3	6.30	1.626	16.9
	7	2.18	1.024	3.7
	8	2.18	1.024	3.7
	10	6.43	1.595	16.9
	11	0.94	0.298	0.5
	12	7.48	0.365	4.5
	51	1.56	1.259	3.2
	54	5.03	1.077	8.9
	55	9.55	1.300	20.5
	61	1.08	1.019	1.8
	62	11.81	2.564	49.9



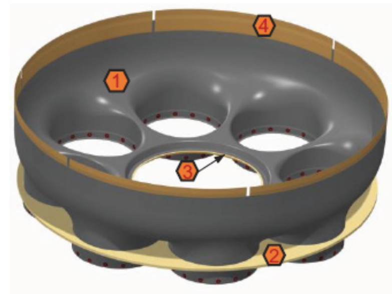
Component
41 “flat_panel_1”
42 “flat_panel_2”

Dimensions and weight	Comp. ID	$T_{top\ face}$, mm	T_{core}, mm	$T_{bottom\ face}$, mm	Height, mm	Area, m²	Mass, kg
After HyperSizer	41	1.131	25.4	2.322	28.9	0.862	7.04
	42	0.366	25.4	0.791	26.6	1.591	5.03
After buckling	41	1.131	25.4	2.322	28.9	0.862	7.04
	42	0.366	25.4	0.791	26.6	1.591	5.03
After modal	41	2.54	25.4	2.54	30.5	0.862	9.34
	42	2.54	25.4	2.54	30.5	1.591	15.3

Conditions	After HyperSizer	After buckling analysis	After modal analysis (with honeycomb (HC))	After modal analysis (without HC)
First mode, Hz	-------	13.92	15.52	-------
Increase in mass, kg	-------	5.3	22.9	10.3
Total mass, kg	133.7	139.0	161.9	157.2

Figure 8.—Octopants bulkhead structural sizing. Comp., component; ID, identification; MS, margin of safety. Red text denotes changes from previous analysis.

TABLE III.—MASS OF OCTOPANTS BULKHEAD

Floor = honeycomb sandwich					
Item no.	Description	Mass estimate per item, kg	Quantity	Total mass, kg	Comments
1	Main bulkhead	132.3	1	132.3	Incorporates finite element analysis (FEA) results dated 5-14-2015
2	Floor	24.7	1	24.7	Incorporates FEA results dated 5-14-2015
3	Center Z-flange	6.5	1	6.5	Incorporates FEA results dated 5-14-2015
4	Upper slice	1.1	6	6.6	
5	Xe tank inserts (not shown)	0.02	128	2.5	
--	Dense core, outside cylinder	21	1	21	
--	Adhesive application	------------	----	22.8	
--	1 to outside cylinder	0.80	1	.8	
--	4 to 1, outside cylinder	.014	6	.9	
--	2 to 1	20.9	1	20.9	
--	3 to 2	.11	1	.1	
--	5 to 1	.00078	128	.1	
--		Total		216	Strength/buckling-only solution = 166 kg

An evaluation of the fabrication and assembly sequence by a composites fabrication specialist resulted in concerns with the tight bend radius and compound curvature for plies in the area between adjacent tanks. A complex shape like this would typically be made from woven composites. There are many examples of the use of woven fabrics of intermediate-modulus carbon fiber, but not for high-modulus fiber (HMF). However, the desire for maximum stiffness drove towards the high-modulus unidirectional fiber. An initial assessment was made using Siemen's Fibersim[7] manufacturing simulation software. The assessment indicated that the use of the chosen material system was feasible. The cost was estimated to be $1.8 million (ROM) for a flight-like structural test article.

Option 3—The Sombrero

This option is also an attempt to minimize part count and joints, but instead of tying into the primary cylinder, it carries the load all the way down to the spacecraft separation system (Figure 9). This could provide some intriguing possibilities for the primary cylinder, since it would no longer be carrying the mass of the tanks. An optimization of the primary cylinder was out of scope for this trade study.

The contour of the upper bulkhead was manually optimized for minimum weight by iterating between shape changes in Creo and structural analysis in Creo Mechanica. Initially looking more like an upside-down, inside-out version of the octopants, the shape morphed into something suggestive of a sombrero (Figure 10). Once the contour was settled, the detailed sizing for the bulkhead was performed using HyperSizer and NASTRAN for stress, buckling, and frequency constraints (Figure 11). Mass for joints and other features not included in the FEM was added post analysis, giving a CBE mass of 257 kg (Table IV). However, when frequency was removed as a constraint, this mass decreased to 214 kg. As with Option 2, an evaluation of the fabrication and assembly sequence by a composites fabrication specialist resulted in concerns over the tight bend radius for plies in the area between adjacent tanks, so an initial assessment was made using the Fibersim manufacturing simulation software. The fabrication risk for this concept was judged to be somewhat higher than for Option 2. The estimated cost for this concept was $2.4 million (ROM) for a flight-like structural test article, about $0.6 million higher than for Option 2, primarily due to greater tooling costs and fabrication complexity.

[7] Fibersim—software used to define plies for composite structures. http://www.plm.automation.siemens.com/en_us/products/fibersim/fibersim-overview.shtml

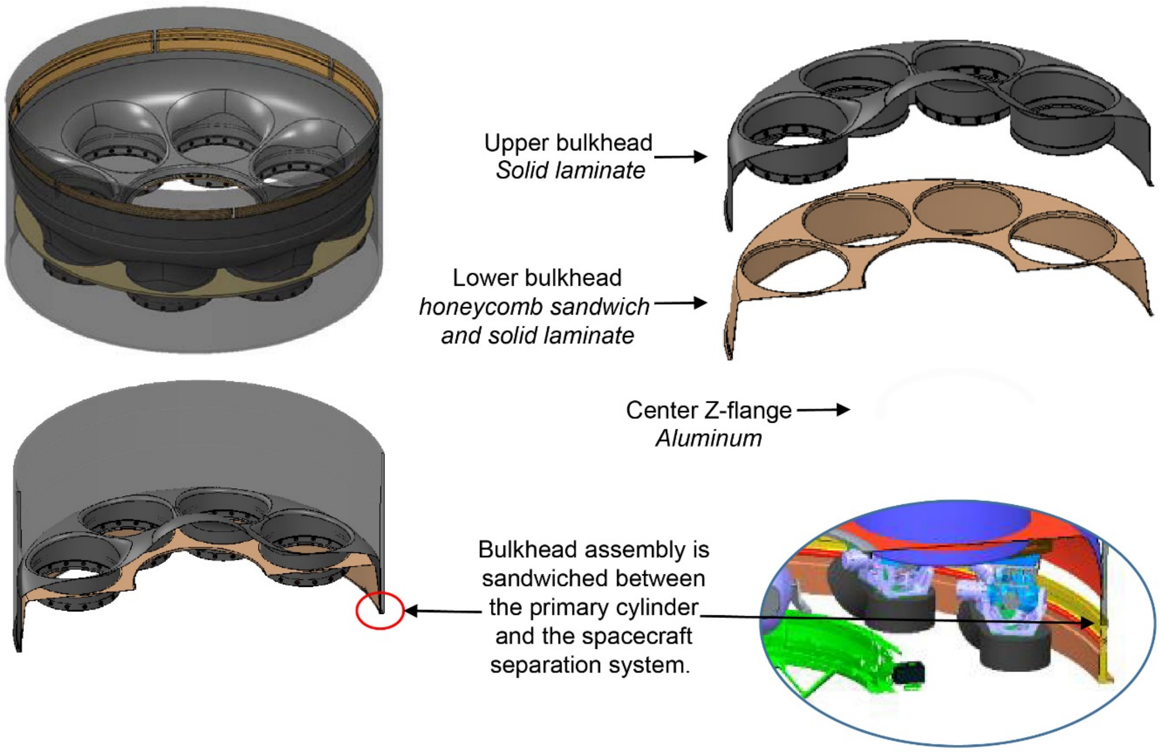


Figure 9.—Sombrero bulkhead.

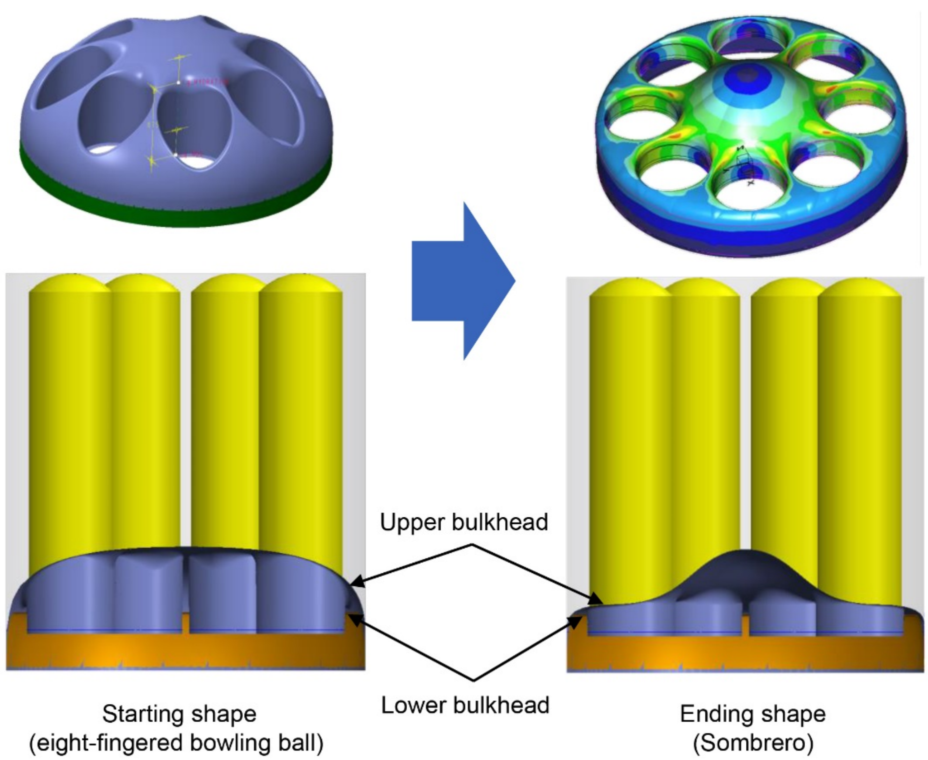
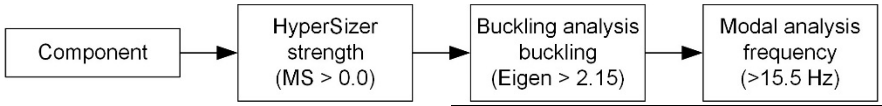
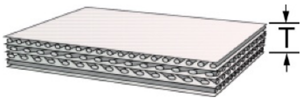


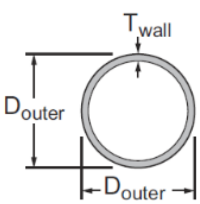
Figure 10.—Sombrero shape optimization.





Fiber system:M55J/954-3
unidirectional tape

Component description
2 “dome_top”
3 “dome_middle”
4 “internal_panel_button”
5 “outer_panel_top”
6 “outer_panel_bottom”
7 “skirt”
8 “tank_bottom”
9 “tank_top”
10 “tank_cylinder_2”
11 “tank_cylinder_1”
12 “tank_curvature_1”
13 “tank_curvature_2”
14 “internal_panel_top_1”
15 “internal_panel_top_2”
16 “dome_bottom_1”
17 “dome_bottom_2”
18 “flat_panel_1”
19 “flat_panel_2”



Component description
1 “internal_beam”

Dimensions and weight	Comp. ID	T_{wall}, mm	D_{outer}, mm	Length, m	Mass, kg
After HyperSizer	1	0.536	127	3.71	5.52
After buckling analysis	1	0.536	127	3.71	5.52
After modal analysis	1	0.536	127	3.71	5.52

Conditions	After HyperSizer	After buckling analysis	After modal analysis (with HC)
First mode, Hz	------	14.63	--------
Increase in mass, kg	------	34.2	19.3
Total mass, kg	204.8	239.0	258.3

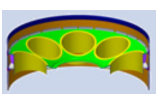
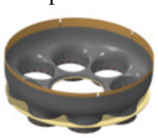
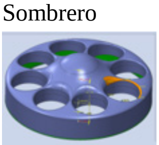
Dimensions and weight	Comp. ID	T, mm	Area, m²	Mass, kg
After HyperSizer (strength, MS > 0.0)	2	0.03	0.312	0.01
	3	0.03	0.720	0.03
	4	0.79	2.185	2.85
	5	0.13	2.791	0.59
	6	0.13	2.232	0.47
	7	0.79	0.306	0.40
	8	0.71	1.854	2.16
	9	0.54	3.608	3.19
	10	20.10	0.721	23.91
	11	6.76	1.491	16.64
	12	23.01	1.335	50.71
	13	6.92	2.548	29.08
	14	6.76	1.206	13.46
	15	1.05	1.550	2.67
	16	0.11	0.313	0.06
	17	13.85	0.393	8.98
	18	7.09	1.579	18.47
	19	19.35	0.936	29.86
After buckling analysis (buckling, Eigen > 2.15)	2	1.27	0.312	0.65
	3	1.27	0.720	1.51
	4	2.54	2.185	9.16
	5	2.54	2.791	11.69
	6	2.54	2.232	9.35
	7	4.57	0.306	2.31
	8	0.71	1.854	2.16
	9	0.54	3.608	3.19
	10	20.10	0.721	23.91
	11	6.76	1.491	16.64
	12	23.01	1.335	50.71
	13	6.92	2.548	29.08
	14	6.76	1.206	13.46
	15	2.54	1.550	6.49
	16	0.25	0.313	0.13
	17	13.85	0.393	8.98
	18	7.09	1.579	18.47
	19	19.35	0.936	29.86
After modal analysis (frequency, >15.5 Hz)	2	1.27	0.312	0.65
	3	1.27	0.720	1.51
	4	2.54	2.185	9.16
	5	2.54	2.791	11.69
	6	2.54	2.232	9.35
	7	4.57	0.306	2.31
	8	0.71	1.854	2.16
	9	0.54	3.608	3.19
	10	20.10	0.721	23.91
	11	6.76	1.491	16.64
	12	23.01	1.335	50.71
	13	6.92	2.548	29.08
	14	6.76	1.206	13.46
	15	2.54	1.550	6.49
	16	0.25	0.313	0.13
	17	13.85	0.393	8.98
	18	14.48	1.579	37.73
	19	19.35	0.936	29.9

Figure 11.—Sombrero bulkhead structural sizing. Red text denotes changes from previous analysis. Comp., component; HC, honeycomb; ID, identification; MS, margin of safety.

TABLE IV.—MASS OF SOMBRERO BULKHEAD

Inboard floor = honeycomb sandwich					
Item no.	Description	Mass estimate per item, kg	Quantity	Total mass, kg	Comments
1	Main bulkhead	166.2	1	166.2	Incorporates finite element analysis (FEA) results dated 5-14-2015
2	Floor	65.2	1	65.2	Incorporates FEA results dated 5-14-2015
3	Internal ringframe	1.3	1	1.3	Incorporates FEA results dated 5-14-2015
4	Xe tank inserts (not shown)	.02	128	2.5	
--	Adhesive application	------------	----	21.6	
--	1 to outside cylinder	.46	1	.5	
--	2 to 1	20.9	1	20.9	
--	4 to 1	.00078	128	.1	
--	3 to 2	.11	1	.1	
--	Total			257	Strength/buckling-only solution = 214 kg

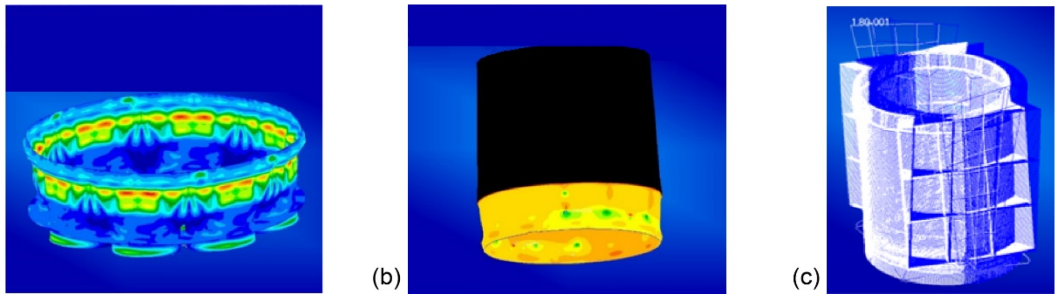
TABLE V.—SYSTEM EVALUATION OF BULKHEAD CONCEPTS
[All three concepts have adequate frequency margin. The “/” separates similar modules.]

Configuration	First bending frequency, Hz	First bending effective mass participation, percent	First axial frequency, Hz	First axial effective mass participation, percent	Bulkhead max. principal stress, MPa[a]
Baseline 	11.16/11.13	80/79	19.55/29.2	23/62.7	236
Octopants 	9.15/9.18	85.3/87.2	18.4/23.3	24.7/33.4	228
Sombrero 	12.41/12.49	72.4/71.2	19.41	43.7	262[b]

[a]Allowable stress = 238.56 MPa.
[b]Some local plies may need to be added to sombrero.

System Evaluation

Since the three concepts were optimized using stand-alone bulkhead models, all three options were then integrated into the MCR FEM of the entire ARV. Of interest were the effects on vehicle fundamental modes and stresses in the primary cylinder and bulkhead. Table V and Figure 12 summarize the results. All three concepts met the requirements for fundamental bending and axial modes. The analysis also indicated that some local plies may need to be added to the sombrero bulkhead. Some local plies may also need to be added to the primary cylinder. The global axial mode was higher than predicted by the bulkhead stand-alone model, confirming that bulkhead frequency did not need to be a design constraint.



(a) (b) (c)

Figure 12.—System analysis. (a) Bulkhead peak stress = 228 MPa (octopants). (b) Cylinder peak stress = 318.54 MPa (octopants). Some local plies may need to be added to the cylinder. (c) First bending mode (sombrero).

Downselection

Table VI gives the rating for the three options for each FOM. The Option 2 octopants bulkhead concept was the clear winner, having the lightest mass, lowest cost, shortest schedule, and lowest risk of the three options. For these reasons, Option 2 was selected as the bulkhead concept to carry forward. Of particular note for Option 2 is that the first axial mode frequency was double the first bending frequency whereas the requirement is a minimum of 1.4 times first bending. Thus, there was the possibility of eliminating the frequency constraint and sizing for stress and buckling only. This could result in a mass reduction of 50 kg, resulting in a mass of 166 kg CBE for Option 2. Table VII compares the three options with the bulkhead mass used for the MCR, with MGA included in a manner consistent with AIAA S-120-2006 and ARRM practices. A higher MGA was used for the MCR bulkhead since it was at the conceptual level. A lower MGA was applied to the trade study results because the maturity level was closer to a Preliminary Design Review (PDR) level. Even though Option 2 was the lightest of the three studied, additional mass reduction is highly desirable.

Design and Analysis Cycle 3 (DAC3) Concept Bulkhead

Subsequent to the bulkhead trade study, another vehicle configuration was developed as part of DAC3 (Figure 3). The new configuration was precipitated by the realization that the diameter of the Xe tanks for MCR was beyond the current fabrication capability of U.S. manufacturers. It was determined that 592-mm-diameter by 2048-mm-long seamless liners were within the realm of current U.S. manufacturers. The DAC3 configuration looks like a downscaled version of the MCR configuration (Figure 13). The primary cylinder is 3 m in diameter. The Block 1 configuration holds 10 t of Xe in eight tanks internal to the cylinder. The primary bulkhead is a downsized version of the octopants bulkhead. There is somewhat more space between tanks, so the bulkhead curvature between tanks is less severe. For extensibility missions, eight additional tanks can be added to the exterior of the primary cylinder, increasing the total Xe load to 20 t. As would be expected, the mass of the sized DAC3 bulkhead is less due to its smaller size and lower propellant load (Table VIII).

Because design of joints can be so critical to the performance, reliability, and mass efficiency in composite structures, the team designed and analyzed the bulkhead primary joints in detail. Interface loads were taken from the bulkhead finite element analysis (FEA). Several joint types for each interface were investigated and downselected, including permanent and separable joints, all-composite joints, and hybrids of metallic and composite materials. The chosen joint geometry was then modeled in computer-aided design (CAD) and included in the master equipment list (MEL).

TABLE VI.—ASSESSMENT AGAINST FIGURES OF MERIT (FOMs) FOR BULKHEAD TRADE

Bulkhead concept	Master equipment list (MEL) mass, kg	Structural test article cost, $M	Schedule, months	Risks	Comments
Baseline	283	>20	18	Fabrication—high Design—high	MEL mass is a compilation of Glenn finite element model (FEM) mass and Langley joint mass. Schedule Cost is Pelham rough order of magnitude 1×10^3—octopants Fabrication risk—Pelham (>8 post-curing operations) Design risk—Paddock
Octopants	216	2.1	9	Fabrication—medium Design—low	MEL mass—Paddock Cost is from Pelham estimate, includes $0.4 million manpower and other direct costs (ODC) Schedule includes material order and fabrication Fabrication risk—Pelham Design risk—Paddock
Sombrero	257	2.7	9	Fabrication—medium/high Design—medium	MEL mass—Paddock Cost is from Pelham estimate, includes $0.4 million manpower and ODC Schedule includes material order and fabrication Fabrication risk—Pelham Design risk—Paddock

TABLE VII.—MASS COMPARISON WITH MASS GROWTH ALLOWANCE (MGA)

Configuration	Basic mass, kg	MGA, percent	Current mass, kg
Mission Concept Review	160	30	208
Baseline with joints	283	15	325
Octopants	216	15	248
Sombrero	257	15	296

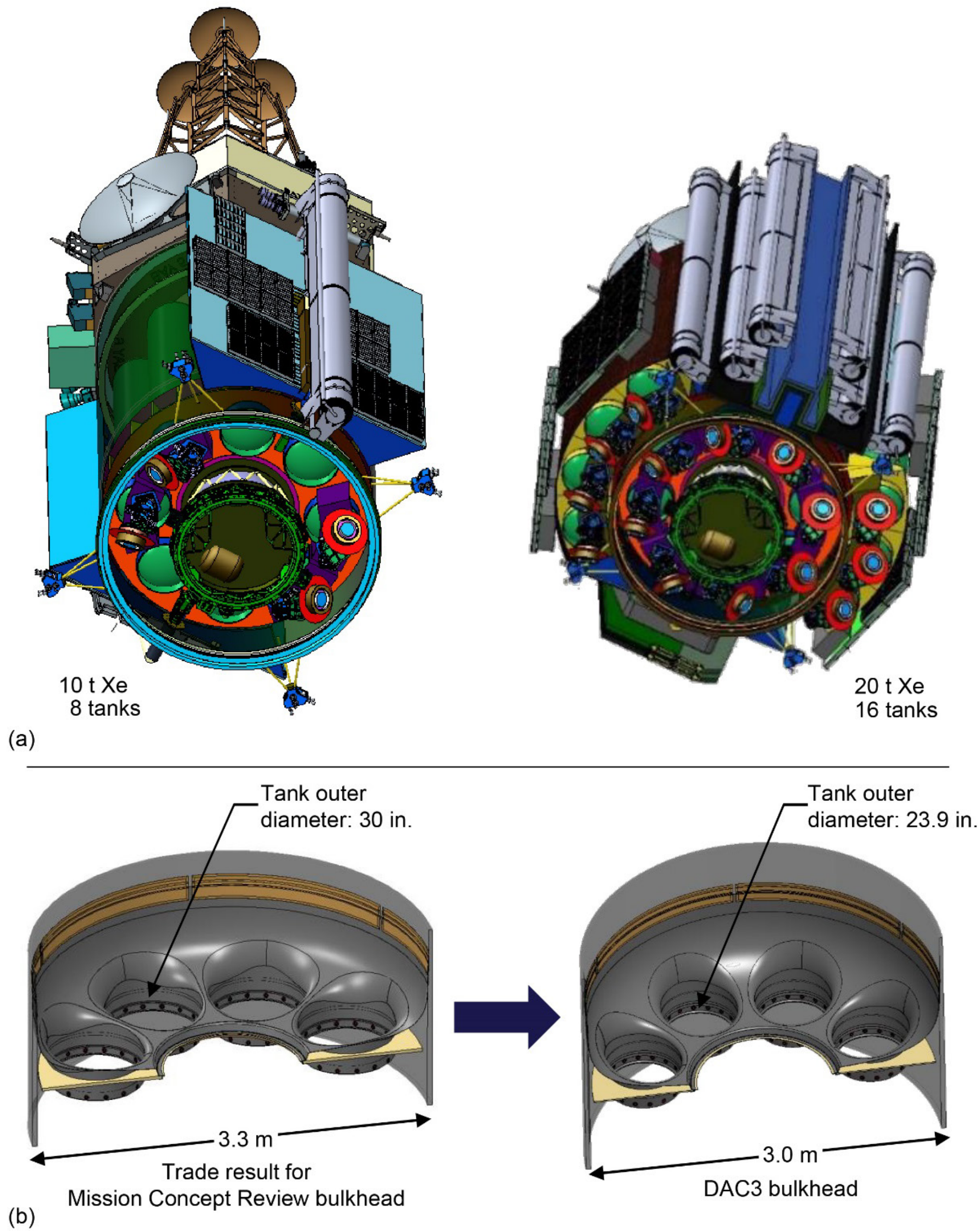
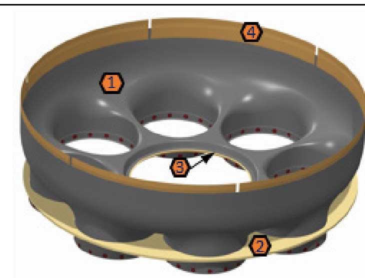


Figure 13.—(a) Design and Analysis Cycle 3 (DAC3) concept. (b) Revised bulkhead for DAC3 concept.

TABLE VIII.—MASS OF DESIGN AND ANALYSIS CYCLE 3 (DAC3) BULKHEAD

Eight tanks full					
Item no.	Description	Mass estimate per item, kg	Quantity	Total mass, kg	Comments
1	Main bulkhead	33.5	1	33.5	Incorporates finite element analysis (FEA) results dated 8-25-2016
2	Floor	14.5	1	14.5	Incorporates FEA results dated 8-25-2016
3	Center Z-flange	6.8	1	6.8	Incorporates FEA results dated 8-25-2016
4	Upper slice	1.1	6	6.6	Incorporates joint analysis results dated 12-9-2015
5	Xe tank inserts (not shown)	.02	128	2.5	--
--	Dense core, outside cylinder	21	1	21.0	Incorporates joint analysis results dated 12-9-2015
--	Adhesive points	----------	1	8.4	--
--	1 to outside cylinder	.80	----	.8	Incorporates joint analysis results dated 12-9-2015
--	4 to 1, outside cylinder	.14	6	.9	Incorporates joint analysis results dated 12-9-2015
--	2 to 1	.81	8	6.5	Incorporates joint analysis results dated 11-16-2016, with eight ~24 in. diam. edge fills
--	3 to 2 and 1	.07	2	.1	Incorporates FEA results dated 8-25-2016
--	5 to 1	.00078	128	.1	
--			Total	93	--

Bulkhead to Primary Cylinder Interface

Nine distinct concepts were brainstormed for the joints for the primary cylinder interface. Of these, four were sized and compared, three involving fasteners and inserts, and one bonded lap joint (Figure 14 and Table IX). Total joint masses ranged from 5.3 to 29.4 kg. Fastener counts ranged from 180 to 271 fasteners required. One bolted option, using hybrid metal/carbon fiber inserts (Refs. 2 and 3) (Design 01 Hybrid Insert), was slightly lighter than the baseline (Design 02) and would be desirable if the ability to remove the bulkhead was needed, for example, for ease of repair. However, it was decided to remain with the baseline-bonded lap joint based strictly on the judgment of the author.

Bulkhead to Hydrazine Tank Interface

The bulkhead’s inner edge has a bolted interface to the RCS pallet (Figure 15), which is installed from beneath the bulkhead during spacecraft integration. This was initially considered as an all-composite interface. But structural sizing with HyperSizer indicated that the very narrow region in the upper bulkhead around this joint required ⅓ of the total global ply count for the entire bulkhead. The high ply count was needed because of the rapid change in the load path direction. A machined aluminum ring, sandwiched between the upper and lower bulkheads, was studied as an alternative. Four concepts for this

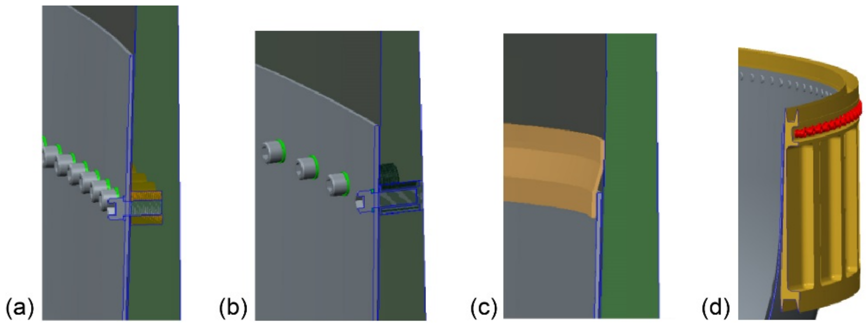


Figure 14.—Bulkhead-to-cylinder joint trade. (a) Design 01. (b) Design 01, hybrid insert. (c) Design 02, adhesive lap joint. (d) Design 04, HI-LOK™ pins. NAS, National Aerospace Standard. Source: Asteroid Redirect Robotic Mission–Special Emphasis Program Manager (ARRM–SEPM) status 3 December 2015.

TABLE IX.—BULKHEAD-TO-CYLINDER JOINT TRADE DESIGNS

Design	Failure mode	Margin
Design 01 (Figure 14(a)): Use of National Aerospace Standard (NAS) hardware and inserts 271 inserts required, adding 32.1 lb of mass Potting spacing of each insert may become an issue	Insert	0.0003
	Tear out	.871
	Bearing	2.10
	Hardware	10.30
Design 01 hybrid insert (Figure 14(b)): Use of carbon composite hybrid insert 180 inserts required, adding 11.6 lb of mass Novel insert type (less mature), easier assembly	Insert	.0007
	Tear out	.242
	Bearing	1.055
	Hardware	4.25
Design 02 adhesive lap joint (Figure 14(c)): Use of composite sections and adhesive Six composite sections/adhesive, adding 14.55 lb Nonseparable joint	Adhesive	.234
Design 04 HI-LOK pins (Figure 14(d)): Use of HI-LOK pins and aluminum ring 218 pins and aluminum ring, adding 64.79 lb of mass Easier assembly and set preload	Tear out	.004
	Bearing	.046
	Hardware	5.72

ring were sized and compared: three with bonded interfaces and one with fastened joints. Total joint masses for all concepts were nearly equal to each other. But the chosen concept won on simplicity of manufacturing and assembly. The concept was then integrated with the bulkhead FEM and sizing was updated for all loads. The sized ring, integrated with the bulkhead, is shown in Figure 16. There will be a CTE mismatch between the aluminum and composite materials. Since the RCS hydrazine propellant tank must be heated anyway, to maintain the propellant operating temperature between 10 to 20 °C, the induced thermal stresses are expected to be relatively small. However, a composite ring made of three-dimensional woven fibers could be substituted for the aluminum and would eliminate any concerns with a CTE mismatch.

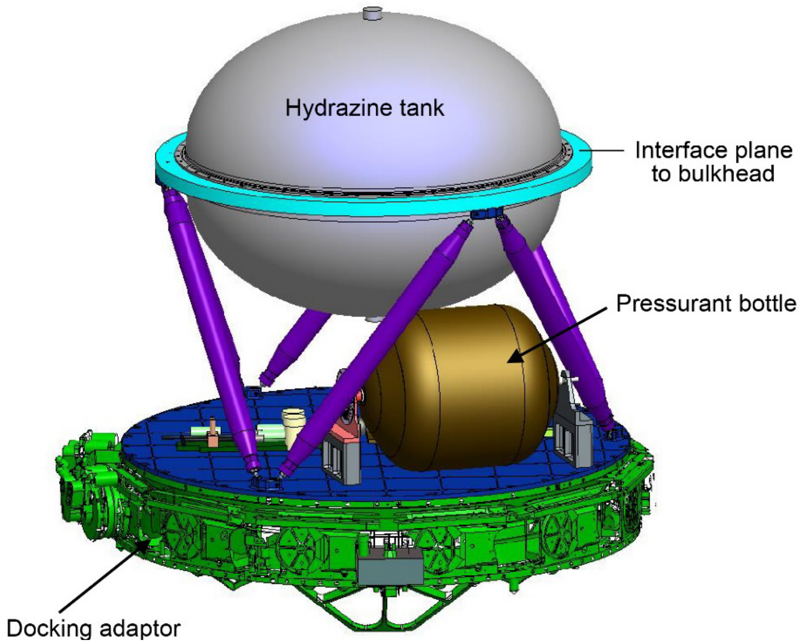


Figure 15.—Reaction control system (RCS) pallet.

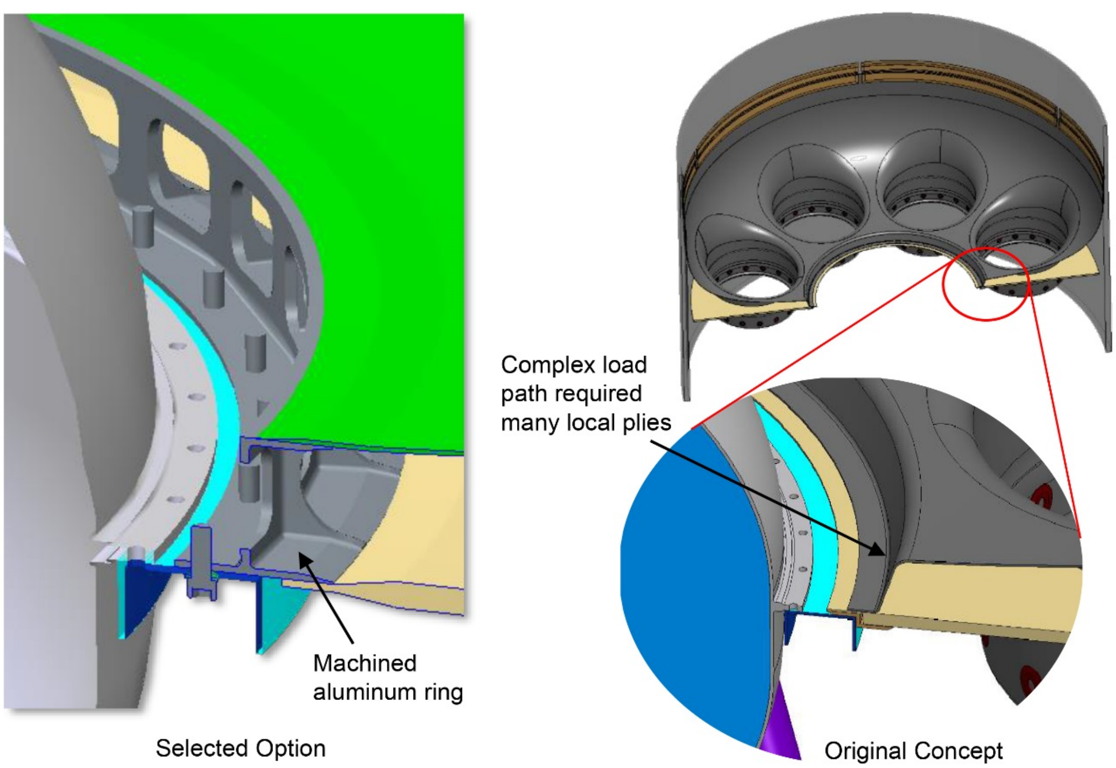


Figure 16.—Bulkhead to reaction control system (RCS) pallet joint trade.

Bulkhead to Xe Tank Interface

Figure 17 shows the interface between the aft composite tank skirt and the bulkhead skirts (pant legs). The solid laminate at the bottom of each pant leg (“the cuff”) is thickened, metal bushings are included to provide a bearing surface for the bolts, and a composite “L” ring is bonded on for additional radial stiffness. Loads between the tank skirt and cuff are transferred via shear. The CAD model was used to verify that the fasteners could be installed and torqued.

Upper Bulkhead to Lower Bulkhead Interface

This interface is intended as a bonded butt joint as shown in Figure 18. A “ring” of HC is removed from the edges of the holes in the bottom bulkhead and the void is filled with adhesive. The face sheets are trimmed to assure proper fit with the pant leg. The two bulkheads are then bonded together. Margins were checked using radial and shear interface loads obtained from the bulkhead FEA and an ultimate factor of safety of 2.0 (required for joints and discontinuities). The shear load results in a slight increase in bond width, which could be accomplished with additional plies locally.

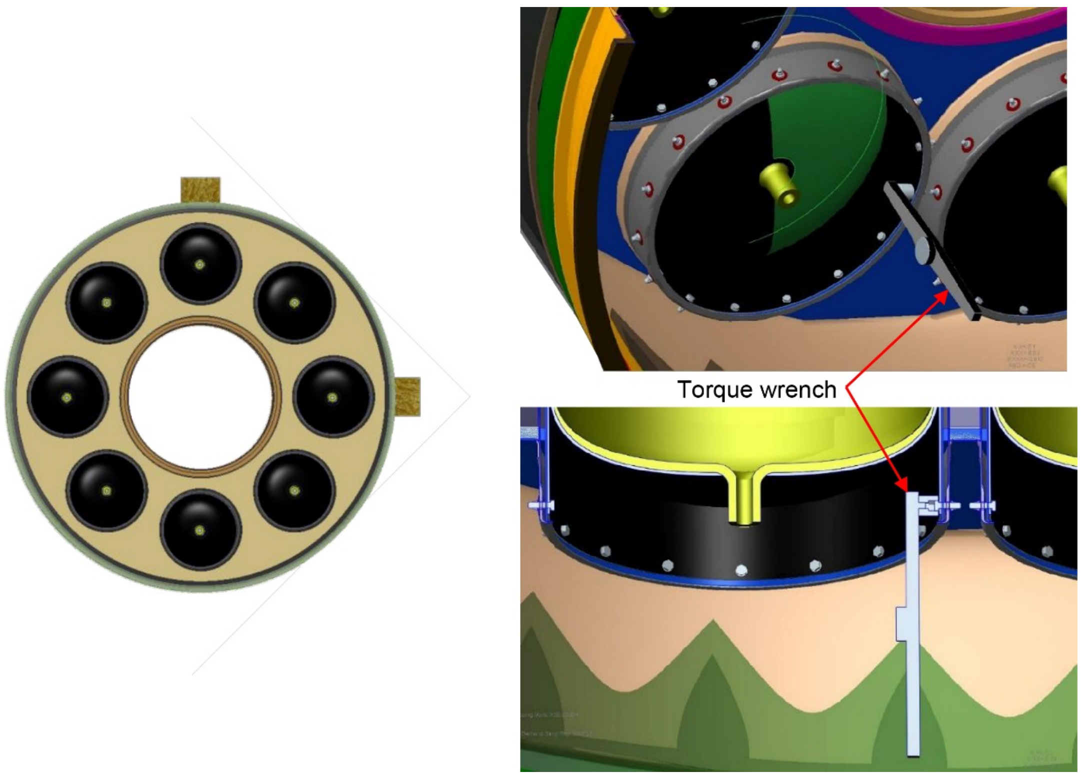


Figure 17.—Bulkhead to Xe tank interface.

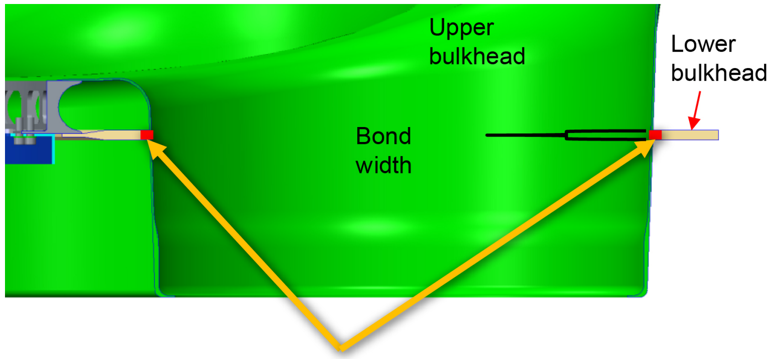


Figure 18.—Upper bulkhead to lower bulkhead interface.

Engineering Demonstration Unit (EDU)

Because of the complexity of the bulkhead contours and the use of carbon HMFs in unidirectional prepreg resin forms, the EDU was undertaken to prove out the manufacturability of the bulkhead concept. The entire process from ply definition through curing would be demonstrated (Figure 19). The benefits were the advancement of NASA's precision, composite, and fabrication techniques, including use of Fibersim software, laser projection, automated ply cutting, and hand layup of HMF prepreg unidirectional plies.

The EDU was a full-scale portion of the bulkhead that could fit inside the 5-ft autoclave at Langley's composite fabrication shop. Although it included 1½ pant legs it was in reality a ⅛ portion, with some complete plies spanning across one leg and the others spanning between two legs. Its mass would be ⅛ the mass of a total bulkhead, and ⅛ the total number of plies.

IM46J/RS-3C prepreg was substituted for IM55J/954-3 due to material availability within the needed timeframe. The M46 was also 75 percent of the cost of the M55. Although not as stiff, IM47 is still classified as a HMF. The RS-3C resin is a toughened cyanate ester, good to 350 °F service temperature, which was a very close match to the 954-3 Hexcel® product used in the analysis.

One exterior tool was made from dense but inexpensive Styrofoam, allowing engineers and fabricators to practice Fibersim ply design, automated ply cutting, and laser-projection system setup and usage. The final tool was manufactured from high-temperature stable foam, which was used for final article layup and curing (350 °F). This preparation and practice time proved invaluable when procurement delays allowed for only 1 month in which to cut, lay up, and cure the final plies onto the mold.

To address the challenge of compound curvature, a draping test was performed using high-modulus prepregs over a dome-shaped tool. This determined how much curvature could be handled before edge wrinkling would occur. The data from the test was provided as input to Fibersim, along with the simplified layup derived from the HyperSizer database and the geometry from Creo. Fibersim was used to develop the individual ply flags, which were then exported to Creo for creating the Plybook—a book of drawings containing a page for each flattened ply flag—for a total of 205 ply flags. DXF[8] geometry files were exported for the automated ply cutter (APC), as well as files for laser projection.

[8]DXF—file format used for defining two-dimensional geometry.

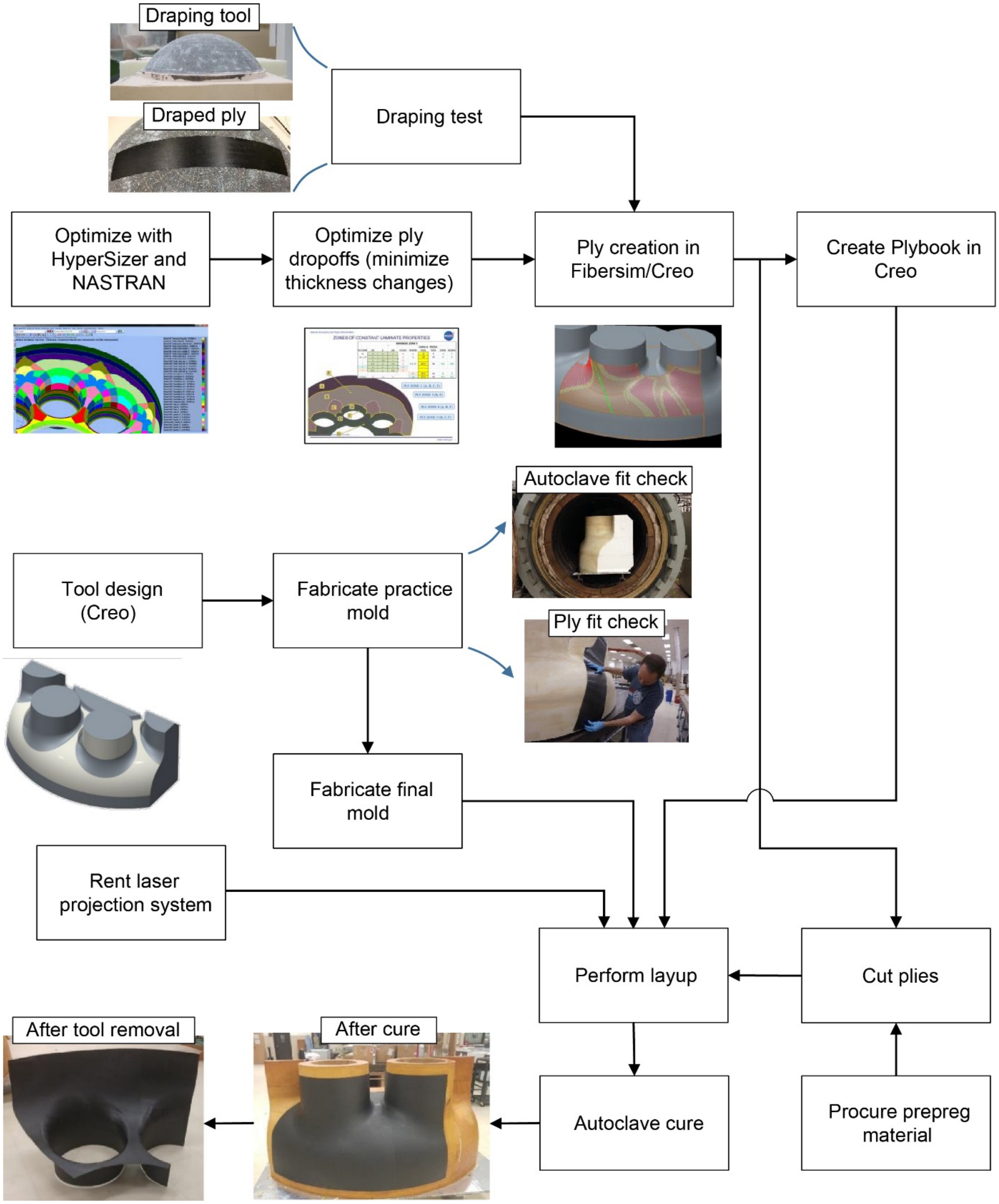


Figure 19.—Engineering demonstration unit (EDU) NASA Structural Analysis (NASTRAN).

Fibersim accurately predicted when compound curvature would cause wrinkling. To minimize the number of flags to be cut, ply flags were often made larger than what Fibersim would indicate as practical, knowing that they might need to be sliced later. As needed during layup, plies were slit or otherwise sliced when excessive edge wrinkling occurred. Resulting v-shaped notches were filled with custom-cut prepreg triangles. Based on the judgment of the lead engineer, the notch would remain unfilled because it was narrow and would be covered with a cross-ply. Any slitting or cutting of a ply flag was documented in the Plybook. A video of the layup process can be viewed at https://youtu.be/wJb23jsybI8.

The final product is shown in Figure 20. Some resin bleeding was manifested in the fillet region due to the plies lifting off of the tool slightly before or during curing. This could be addressed with local temperature-expanding blocks (also called intensifiers) that provide extra pressure into the concave radius contours. Some tool cracking was also observed and is theorized to have happened sometime during or after curing, although it did not appear to affect part quality. More research is needed for compatible sealants and adhesives, as well as tool design using high-temperature foams.

The EDU experience demonstrated the practicality of this type of fabrication of a complex-contoured, thin-walled laminate bulkhead using three-dimensional CAD, design-for-manufacture software Fibersim, automated ply cutting, and laser-projection tools. Many invaluable lessons were learned informing both engineering and fabrication personnel. A detailed list of lessons learned is included in Appendix B.

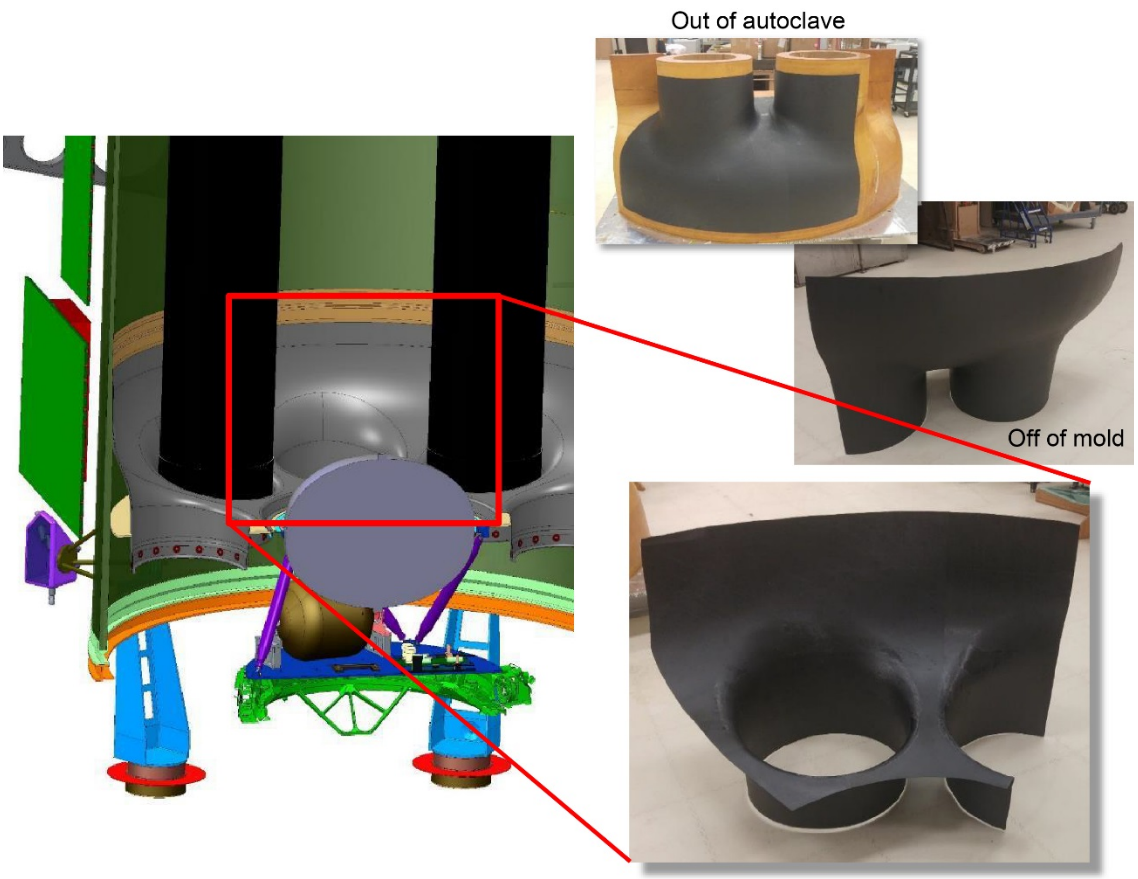


Figure 20.—Engineering demonstration unit (EDU) bulkhead.

Had funding continued, the next line of investigation would have been to modify the design so that it could be fabricated with the Integrated Structural Assembly of Advanced Composites (ISAAC) Tape Laying Robot at Langley (https://www.nasa.gov/larc/robot-isaac-will-help-nasa-langley-speed-toward-innovation). Bulkhead contours between the tank support cylinders are inaccessible to the robot's fiber placement head. Therefore, the cylinders (or pant legs) and bulkhead would be laid up separately on the ISAAC. These cured shells would be joined together after curing most likely with adhesively bonded lap-joints. Benefits would include the elimination of laser projection, ply flag definition, plybooks, and the ply slitting and slicing required during layup. This could result in significant labor savings and improved process control.

Conclusions

This paper documented the development of a primary bulkhead concept for a large solar electric propulsion (SEP) spacecraft. The design progressed from one consisting of many simple parts with complex joints, to one consisting of few complex parts with a few simple joints. The unique capabilities of composites led to a topology that transitioned loads from bending to in-plane tension and shear, with low part count. This significantly improved bulkhead manufacturability and reduced mass. The concept proved scalable to a smaller bus diameter with smaller tanks. A full-scale engineering design unit (EDU) of the concept was used to demonstrate manufacturability of the concept, which utilized high-modulus fibers (HMFs). Actual labor data was obtained, which could be extrapolated to a full bulkhead. This gave the NASA nonproprietary hands-on experience in developing a complex composite structure using high-modulus carbon fiber prepregs. The effort demonstrated the practicality of using HMF composites for unique shape topologies that minimize mass and cost. The lessons are applicable to primary and secondary aerospace structures that are stiffness driven.

Appendix A.—Abbreviations and Acronyms

APC	automated ply cutter
ARCM	Asteroid Redirect Crewed Mission
ARM	Asteroid Redirect Mission
ARRM	Asteroid Redirect Robotic Mission
ARV	Asteroid Redirect Vehicle
CAD	computer-aided design
CBE	current best estimate
COPV	composite overwrapped pressure vessel
CTE	coefficient of thermal expansion
DAC3	Design and Analysis Cycle 3
EDU	engineering demonstration unit
FEA	finite element analysis
FEM	finite element model
FOM	figure of merit
HC	honeycomb
HMF	high-modulus fiber
ID	identification
ISAAC	Integrated Structural Assembly of Advanced Composites
MCR	Mission Concept Review
MS	Margin of Safety
MEL	master equipment list (mass statement)
MGA	mass growth allowance
NAS	National Aerospace Standard
NASTRAN	NASA Structural Analysis
NDE	nondestructive evaluation
ODC	other direct costs
PDR	Preliminary Design Review
RCS	reaction control system
ROM	rough order of magnitude
ROSA	Roll-Out Solar Array
SEP	solar electric propulsion
SEPM	Special Emphasis Program Manager
SOA	state-of-the-art

Appendix B.—Engineering Demonstration Unit (EDU) Lessons Learned

(1) Creation of 124 unique plies took 60 h in Fibersim. A zone-based design could allow for multiple engineers to define plies in parallel. Start points (origins) of plies were often not optimal. It is recommended to involve an experienced fabrication technician when defining plies in Fibersim.

(2) The Plybook creation (book containing a drawing of each ply with detailed information on orientation) took 12 h. Table data and three-dimensional views were automatic, but flat pattern view generation was a manual process (it is not yet implemented in Creo). The Plybook was considered essential to process, and the hardcopy was used for note-taking and sketching in real time.

(3) Computer-aided design (CAD) Fibersim draping views were projected on a screen in the workarea during layup. This proved invaluable to successful first-try ply layups.

(4) Laser projection was essential for accurate ply placement. It allowed 205 plies to be placed in 66 h (single shift operation). However, better data verification is needed; sometimes the file being projected was outdated when compared to the ply-cutter files. It is important to plan the laser-projection targets into the tool design; these targets are used for aligning the laser-projection system to the tool, must have real estate for mounting, and must be viewable from multiple projector locations. The laser-projection system malfunctioned several times and it would have been good to have better on-call technical support.

(5) The automated ply cutter (APC) process worked well. A total of 205 plies were cut in 24 to 36 h. There were some issues with “poly-lines” in the DXF files exported for ply cutting. Recommend that these be expunged. The cut plies were organized into ply “sets” in marked bags that facilitated layup.

(6) Tool cracking occurred sometime during or after curing, although it did not appear to affect part quality. More research is needed for compatible sealants and adhesives.

(7) Numerous debulks were performed for compacting plies and pulling out entrapped air: After the first ply (to help it to stick to the mold, which was coated with mold release), then after each day’s work (two to six layers). Premade bags were used and they took 1 h to assemble and apply each time. Debulking was performed for 20 min at >28 inHg.

(8) The engineers were onsite and helping during layup and this proved beneficial. It allowed questions to be answered and decisions to be made right away, as well as providing invaluable education for engineers for future composites design endeavors.

(9) In order to prevent wrinkling in areas of compound curvature, plies often required slitting and insertion of very thin tow pieces. In fact, most ply flags ended up requiring slitting. The worst case was the oblique angle up the skirt cylinders. More smaller ply flags are recommended but this would add significantly to the time and effort required with Fibersim.

(10) Bagging for the curing cycle took 6 h. The high-temperature bagging material did not stretch much and was hard to work with.

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