Defense Technical Information Center Compilation Part Notice

ADP020323

TITLE: Upper Stage Flight Experiment [USFE] Integral Structure Development Effort

DISTRIBUTION: Approved for public release, distribution unlimited

This paper is part of the following report:

TITLE: Proceedings of the International Conference on Composite Structures [12th] [ICSS/12] Held in Melbourne, Australia on 17-19 November 2003

To order the complete compilation report, use: ADA439334

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP020288 thru ADP020363

Available online at www.sciencedirect.com

SCIENCE DIRECT®

ELSEVIER

Composite Structures 66 (2004) 327–337

COMPOSITE STRUCTURES

www.elsevier.com/locate/compstruct

Upper stage flight experiment (USFE) integral structure development effort

Jim Guerrero [a,*], Brent Hamilton [a], Randy Burton [b], Dave Crockett [b], Zach Taylor [c]

[a] Air Force Research Laboratory/VS, Kirtland AFB, NM 87117, USA
[b] Orbital Sciences, Corporation Chandler, AZ, 85248, USA
[c] Aspect Engineering, Yorba Linda, CA 92687, USA

Abstract

The Air Force Research Laboratory's Space Vehicle Directorate (AFRL/VS) has established a customer focused composite tankage development program that is targeted to existing and future aerospace applications. AFRL/VS is developing a wide range of tank concepts that include linerless cryogenic tankage, self-healing cryogenic tankage, hydrogen peroxide compatible tankage, volumetrically efficient toroidal (donut shaped) geometries, and more.

This paper will summarize the Upper Stage Flight Experiment (USFE) composite integral structure development effort. The integral structure refers to the stage skirt and the propellant tankage. These two parts are bonded together to form an integral structure. The USFE tank is the world's first composite, common-bulkhead, medium-pressure vessel designed to be Class 1 Compatible with high concentrations of hydrogen peroxide. Lightweight hydrogen peroxide compatible tankage development is becoming increasingly important to the international aerospace community because it provides considerable benefits. Peroxide can be stored unpressurized and is relatively non-toxic, which makes it safer to handle and store compared to oxidizers such as hydrazine. In addition to being a viable bi-propellant oxidizer, hydrogen peroxide can also serve as a monopropellant for an attitude control system (ACS). Peroxide is not cryogenic, therefore, it does not require an on-board cryocooler, which makes it easier to meet mass budgets and to mitigate technical risk. Storability and ease of handling make high concentration hydrogen peroxide an ideal propellant for reusable launch vehicle (RLV) responsive upper stage applications.
Published by Elsevier Ltd.

1. Introduction

AFRL/VS teamed with Orbital Sciences Corporation and Aspect Engineering to create an innovative design and associated manufacturing process that meets the mission requirements for the Military Spaceplane's (MSP) responsive expendable upper stage, namely the modular insertion stage (MIS). The USFE is a flyable technology demonstrator for the operational MIS, which is conceived as a very low cost expendable liquid propellant upper stage for use with a RLV or responsive Expendable Launch Vehicle (ELV). The "modular" part of the name means that MIS is designed to be scaled and assembled to match the user's requirement for an upper stage payload.

MIS was conceived to satisfy the need for a highly operable and responsive upper stage which would have the flexibility to perform multiple burns to optimize stage performance for GTO/GEO missions using the same throttleable engine. Fig. 1 illustrates a two stage to orbit MSP concept with the MIS as it would be configured during launch and as it deploys a payload in space. MIS could also be produced less expensively than a solid propellant-based upper stage assembled from multiple \$1M+ solid rocket motors needed to perform multiple burns. MIS initial production cost is estimated at \$800K, less than one fifth the cost of a comparable currently available storable liquid propellant upper stage. Liquid upper stages also have the potential to provide higher performance than solid propellant stages, which is offset however, by the very high propellant fraction offered by solid stages, which can approach 95% propellant fraction.

The USFE was designed for a suborbital flight demonstration from the Alaska Aerospace Development Center launch facility in Kodiak, Alaska, with the first and second stages of the Orbital/Suborbital (OSP)

* Corresponding author.
E-mail address: jim.higgins@kirtland.af.mil (J. Guerrero).

0263-8223/\$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.compstruct.2004.04.069

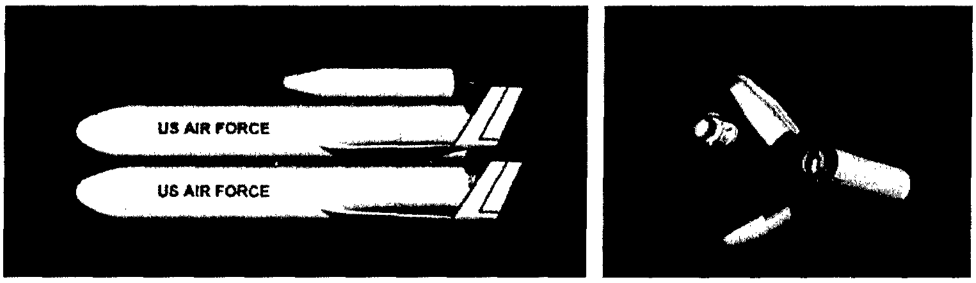

Fig. 1. MSP with MIS and MIS deploying payload.

expendable launch vehicle standing in for a future RLV or responsive ELV.

USFE is an all-composite, pressure-fed upper stage which uses 90% concentration hydrogen peroxide and JP-8 (standard Air Force jet fuel) as propellants. These less hazardous "green" storable propellants are a key factor in operability and responsiveness. The MIS, whose design would be based on technologies demonstrated in the USFE, would use similar propellants. MIS could be produced inexpensively enough to be manufactured in quantity, and stored fully fueled for up to a year with payload already integrated, greatly enhancing responsiveness.

USFE is to be ground tested at NASA Stennis Space Center. The same USFE stage will then be refurbished and refitted for a possible future flight test.

MIS and USFE demonstrate the potential to build upper stages for much less than the current cost of ELV upper stages. For both expendable launch vehicles and future MSP system use, MIS can provide both cost savings and a significant capability increase when compared with currently available upper stages using either solid or liquid propellants.

The USFE tank development program is enabling to the MIS and MSP architecture development effort if mass budgets are to be achieved. Its composite design and volume efficient common bulkhead configuration are tailored to the MIS application.

2. Integral structure design and analysis

The integral structure for the USFE stage is an all-composite single piece part consisting of the stage's external composite shell, or skirt, and the propellant tanks. Fig. 2 is an overview of the USFE stage. As shown in the figure, the integral structure encompasses the entire stage. In the forward end it houses the helium pressurization and attitude control system and forward bulkhead. The aft end houses the engine and propellant supply system. The aft end is also designed to interface to an OSP interstage for flight on an OSP vehicle. The propellant tanks are unique in that they are contained in a single pressure vessel with an internal bulkhead to separate the oxidizer and fuel. This improvement in volumetric efficiency reduces stage size.

Another aspect of the structure design is that it uses composite materials throughout. Thus the weight of the stage can be made significantly less than that of an all-metal design. A low cost manufacturing process supplemented the innovative composite material design. This combination resulted in a final USFE's integral structure that is a single piece part and volume optimized, while utilizing lightweight high strength materials and manufactured using automated low cost processes.

The flight unit USFE stage structure was based on an earlier developed subscale version [1], Fig. 3. The objective of the subscale structure was to proof out the design concept and analysis methodology to be used for the full scale structure. The subscale effort also developed and verified manufacturing methods. Lessons learned from this subscale effort were then applied to fabrication of the flight structure.

The design requirements for the flight structure encompassed numerous items. These included the structures ability to mate to the launch vehicle it is to fly on, safety factors and design criteria to meet range safety requirements, ability to survive ground handling and flight loads, material compatibility for the propellants to be used, propellant tank volumes, engine mounting interface, skirt volume for encapsulating other stage system hardware, and access requirements to name a few. Some of the structure's requirements are outlined in Table 1.

As previously mentioned, the USFE integral structure design is based on the subscale design. Scaling the subscale to the flight scale include physical dimensions and tank volume capacities in addition to flight load design criteria. Otherwise, the flight unit is very similar to the subscale version. Fig. 4 shows a cut away version of the structure.

The propellant tank liners are made of a flouropolymer material for chemical compatibility of hydrogen peroxide (oxidizer) and JP-8 kerosene (fuel). The bulkhead is constructed of a T1000 carbon cloth and epoxy resin. The epoxy resin used for the tank bulkhead and overwrap was developed by Bryte Technologies for its chemical compatibility of hydrogen peroxide and kero-

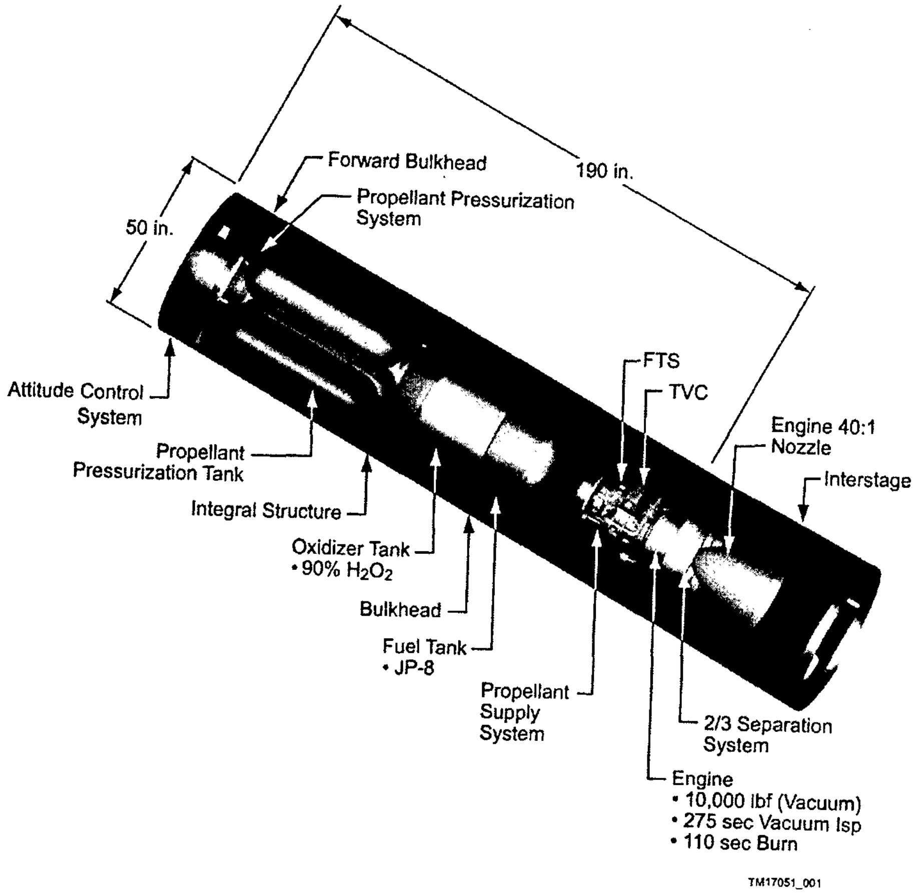

Fig. 2. USFE Stage with attached OSP interstage.

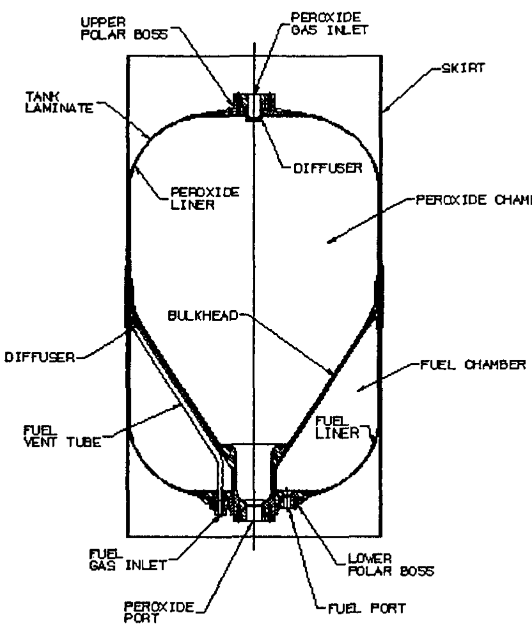

Fig. 3. Subscale integral structure configuration.

sene. Chemical compatibility of the propellant tank materials was important in the event of leak in the propellant tank liners.

The skirt uses a T1000 fiber with an industry standard epoxy. The propellant tank assembly (Fig. 4) is bonded into the skirt using a room temperature cure epoxy. The propellant tank's upper and lower dome profiles were developed using NASA generated codes. The codes assume that the composite dome is restrained only at the tangent (dome-to-cylinder transition). While the code generated an accurate profile for the upper dome, it was clear that the resultant profile for the lower dome would not be ideal due to the additional bulkhead restraint of the polar fitting. Further analysis of both domes was performed using finite element methods.

Two shell element models were created to perform static and buckling analysis of the structure. The first model illustrated in Fig. 5 included load path eccentricities between dome, bulkhead, boss, and skirt structures and was used as a basis for verifying structural stability under various load conditions. Combined loads due to internal pressure, external moment, and engine thrust were applied to the model to simulate worst-case conditions. Particular attention was paid to the stability of the skirt and bulkhead structure under load.

A second shell model was generated for global geometric non-linear analysis. This model was used to evaluate the interaction between key structures within

Table 1
Design requirements for the flight USFE integral structure

Item/description	Requirement
Oxidizer tank volume	44.8 ft^3
Fuel tank volume	15.5 ft^3
Structure length	190 in.
Structure diameter	50 in.
Burst safety factor of tanks	2.0
Proof safety factor of tanks	1.5
Ultimate safety factor of the skirts	2.0
Propellant tank operating pressure	1100 psia
Maximum pressure differential on the internal bulkhead	140 paid
Propellant tank liner material	Tefzel (Flouropolymer)
Material for polar bosses and plugs	316L stainless steel
Composite fiber	Toray T1000 GB
Composite resin	Bryte technology resin

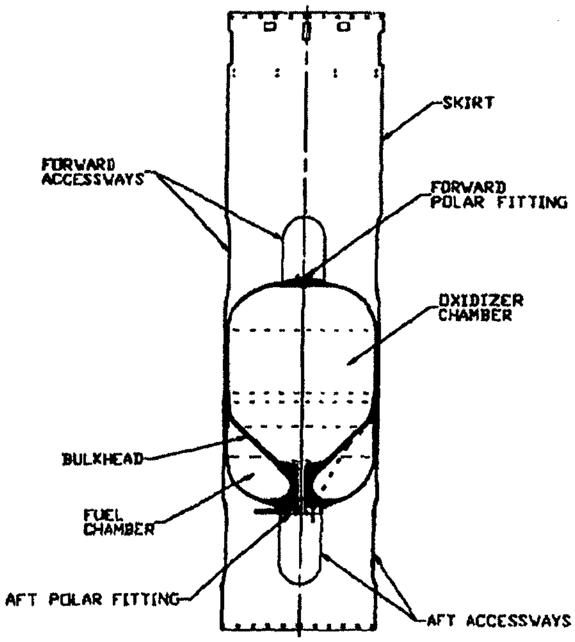

Fig. 4. Flight unit USFE integral structure configuration.

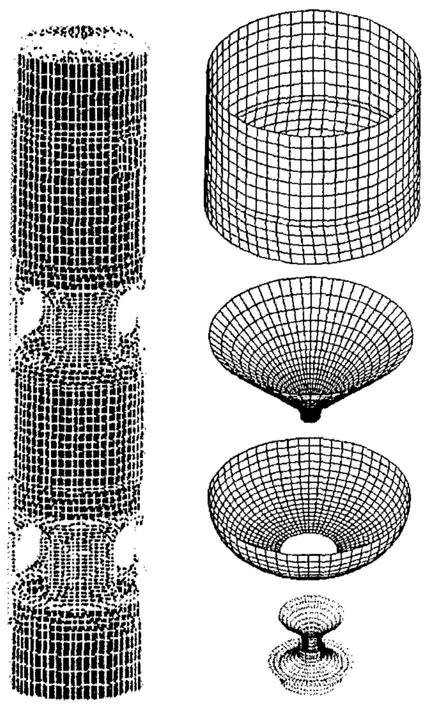

Fig. 5. FEA model of the structure.

the assembly. Several load cases were evaluated. The shell model was also used to establish laminate strain margins and to determine internal loads for use in subsequent localized analyses.

An axisymmetric structural model, Fig. 6, was generated to perform geometric non-linear analysis of the assembly. This model allowed a detailed evaluation of 3-D stresses in various parts of the assembly, including the polar fittings, the bulkhead/tank interfaces, and the tank/skirt interface. The model was also used to verify dome loading and deflections. This finite element verification of dome deflection was particularly important for the lower dome that would be constrained in an unconventional manner. Fig. 7 is an example of a strain contour plot of the forward skirt.

3. Manufacturing

As previously mentioned, the USFE "integral structure" refers to the combined tank/skirt structure. The completed tank assembly was bonded within the skirt inner diameter at a precise location, making the tank integral to the skirt structure. Bond strength is critical here because the engine thrust will be applied directly to the tank aft boss and there will be no other mechanism holding the tank to the skirt other than the adhesive. The USFE engine, fuel/oxidizer pressurization tanks, and a few other components were then integrated inside the integral structure, completing the USFE stage.

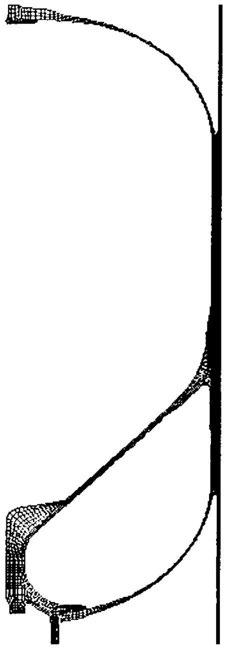

Fig. 6. Axisymmetric model.

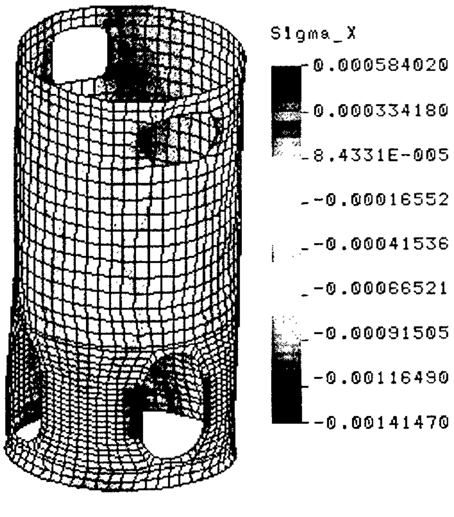

Fig. 7. Axial strains.

3.1. Skirt

The first major effort involved in the fabrication of the integral structure was the skirt. Fig. 8 shows the USFE skirt at Rocky Mountain Composites in Utah during the filament winding process that utilized a non-prepreg carbon fiber wetted with an epoxy resin. This resulted in an all-composite structure with hoop and helical plies that provide the required radial and axial strength necessary to withstand the aerodynamic loads that will be encountered during the launch while containing the stage components. Access panels were cut out of the cylindrical structure at various locations to enable technicians to integrate and maintain the engine, pressurization system, and other stage components. Even though this composite structure is an order of magnitude stiffer than its aluminum counterpart, special tooling was necessary to keep the skirt inner diameter "in-round" while the access panels and associated door bolt pattern bores were being machined at tight tolerances.

3.2. Liners

Once the skirt structure was completed, efforts were focused on the tank fabrication. A "roto-molding" technique was chosen as the most cost effective approach to fabricate the liners for both the hydrogen peroxide and the fuel tank chambers. The mold used for this operation is shown in Fig. 9. A fluoropolymer powder was placed inside the mold, then the mold was heated and rotated about two axes, followed by a cooling cycle and eventual separation of the mold to withdraw the finished liner. A formed and welded aluminum sheet metal mold was designed and manufactured for the oxidizer liner. The oxidizer liner, produced with this mold, was out of tolerance at several locations; therefore, a decision was made to machine the fuel liner mold to ensure this liner would be of higher dimensional quality relative to the oxidizer liner. We were correct and the fuel liner held tolerances much better than the

Fig. 8. Skirt structure during filament winding and post-cutout work.

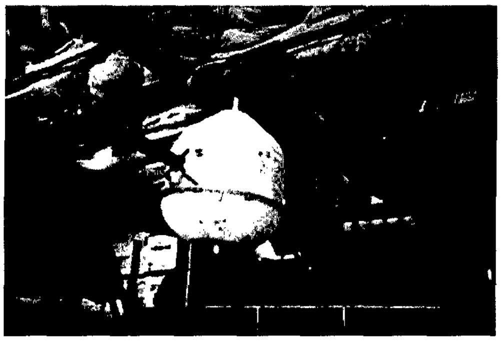

Fig. 9. Liner roto-molding process.

oxidizer liner. Due to budget constraints, we did not fabricate a machined tool for the oxidizer liner, instead, the oxidizer liner was reworked by "welding" additional material onto the liner at various locations to eliminate small air pockets trapped within the liner wall. In addition, heat combined with weights to strategically apply force at specific locations physically reformed the liner and brought it within the necessary tolerances. Since high concentration hydrogen peroxide will decompose if contaminated, a Class 1 compatible material to high concentration hydrogen peroxide was absolutely necessary for the oxidizer liner. A fluoropolymer material was chosen and subsequently qualified as Class 1 compatible to peroxide.

3.3. Bulkhead

The composite bulkhead was fabricated by wetting and laying up a carbon fiber fabric by hand against the bulkhead layup tool shown in Fig. 10. Once the part was laid up, it was vacuum bagged and placed in an autoclave for curing. After the part was removed from the autoclave, the outer diameter of the cylindrical portion of the bulkhead was machined to ensure a correct tolerance between the tank and skirt inner diameter. The inner conical section of the bulkhead was also machined smooth.

Fig. 10. Bulkhead lay up tool.

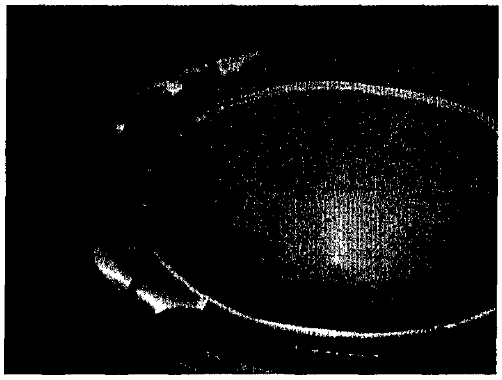

Fig. 11. Cap ply layup.

3.4. Cap ply

After the machining process, a cap ply containment ridge was bonded to the bulkhead to mitigate the probability of fuel liner creep when the fuel chamber is pressurized to the tank operating pressure. Fig. 11 shows the cap ply laid up against the fuel liner "tool" during the vacuum bagging process. To make the containment ridge, a carbon fiber fabric mess was wetted with an epoxy resin, cut so that the fiber is at 45 degrees, and laid up by hand against the fuel liner, which served as a tool. After this process, the cap ply was vacuum bagged and cured in an oven. The cap ply was then removed from the fuel liner and bonded to the bulkhead with an epoxy adhesive.

3.5. Aft boss, fuel liner, bulkhead, and transition tube assembly

To ensure a smooth transition between the metallic bosses and the liners, a boss flange extension was cast into place using a special mold and Scotchweld 2216 adhesive (Fig. 12). A smooth transition is also necessary to design out potential stress risers that could rupture the liners under pressure. To assemble the lower boss to the fuel liner, it was necessary to heat the liner ports to enable sufficient flexibility so they could be moved sufficiently to mate with the boss ports. The bulkhead was then mated with the fuel liner so that the conical sections of both the bulkhead and the fuel liner are adjacent. A specially designed transition tube was threaded onto the lower boss, capturing both the fuel liner and the lower boss in the process (Fig. 13).

To install the oxidizer liner, it was first necessary to bolt two aluminum beams onto the lower boss and then rotate that assembly vertically so that the ends of the beams support the structure on the shop floor. Fig. 14 shows the liner assembly once the oxidizer liner is snuggly positioned against the bulkhead. A threaded shaft was passed thru the aft oxidizer port and out the forward oxidizer port to hold the assembly in place

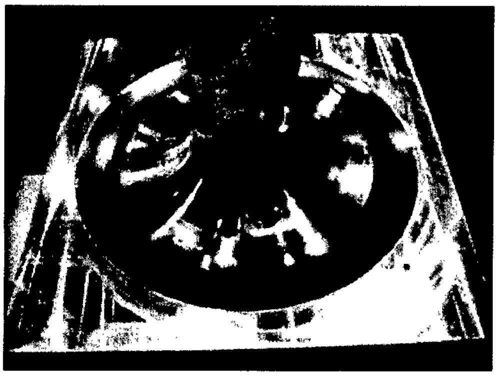

Fig. 12. Boss flange extension.

Fig. 13. Tightening the transition tube.

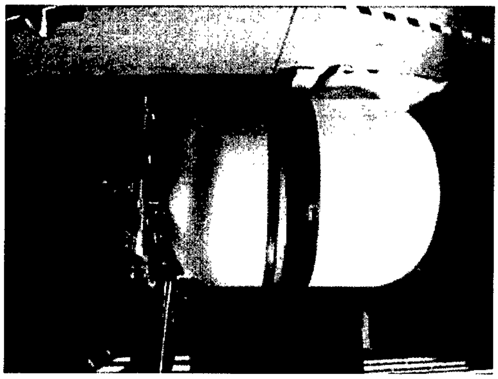

Fig. 14. Oxidizer liner assembly.

while both fuel ports and the aft oxidizer port were flared using special flaring tools. The flare tooling was heated with a propane torch and then pressed up against the liner port openings. A special alignment tool, bolted onto the centering disk, kept the flaring tools concentric with the liner ports. The beveled tool ends dictated the resultant port flare angle. The combination of heat and pressure deformed the liner ports. The upper tank boss was installed onto the forward port of the oxidizer liner and the liner port flared using the same basic procedure.

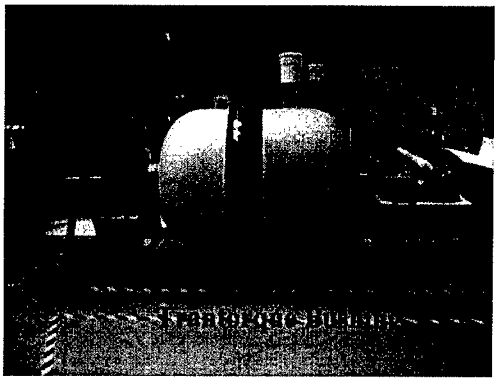

Fig. 15. Liner assembly on winding cart.

Since the liner assembly was used as a mandrel tool during the filament winding process, a pressurization shaft was designed to provide a means to pressurize the liner assembly during the winding process. Another important function of the pressurization shaft was to keep the liner assembly concentric, and to provide a means for the filament winding machine to interface with the liner assembly during the winding process. A Trantorque bushing was installed into the oxidizer liner vent fitting to secure the forward fitting and boss to the pressurization shaft.

Fig. 15 shows the liner assembly mounted on the winding cart, which was designed to support the liner/bulkhead assembly from either end, with additional support downstream of the fuel liner to prevent unacceptable flexure of the winding shaft during composite filament winding. A bearing adapter sleeve was installed over the forward end of the pressurization shaft and pillow block bearings were installed onto the adapter sleeve and shaft support assembly. Using a hoist, the liner assembly was lifted onto the oven/winder cart assembly. The liner assembly was then pressurized to withstand the tension of the fiber tows during the winding operation.

3.6. Tank winding and cure procedures

The liner assembly, including the cap plies, was masked off. Scotchweld 2216 adhesive was used to fill grooves between the cap lies and the bulkhead tangent so that the exposed area is level and therefore satisfactory for the winding operation. The bulkhead face was covered with film adhesive. Fig. 16 illustrates the filament winding operation. Once the filament winding operation was complete, the cylindrical portion of the tank was covered with peel ply fabric. The peel ply was then covered with perforated release ply, then shrink tape was wrapped over the release ply. A heat gun was then used to consolidate the peel ply into the tank surface and squeeze out the surplus resin. The cart and tank assembly was then cured at 250 F for 3 h with an

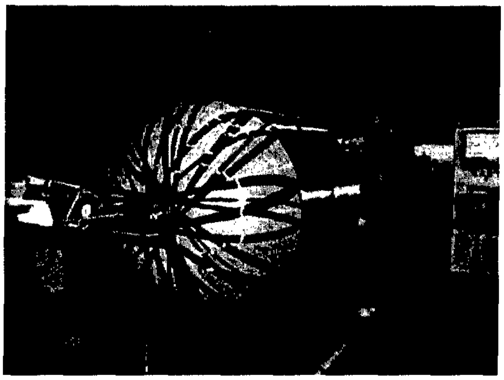

Fig. 16. Winding operation.

Fig. 17. Tank in oven, pre-cure.

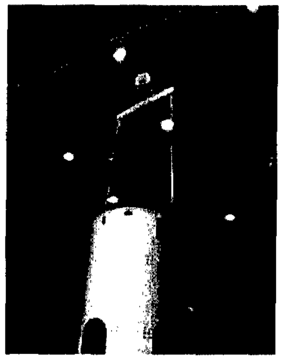

Fig. 18. Skirt positioning.

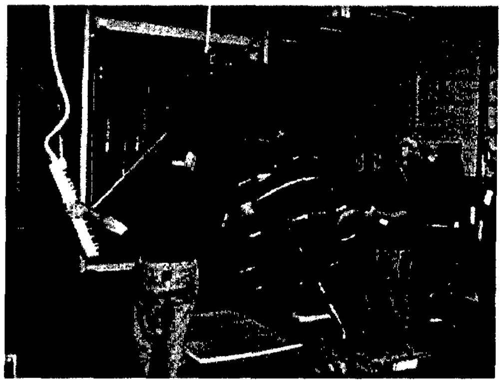

Fig. 19. Tank to skirt centering disk.

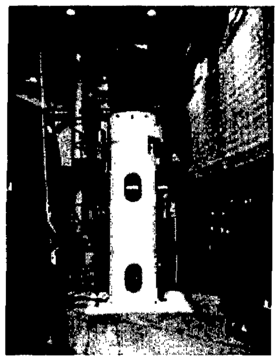

Fig. 20. Tank to skirt installation disk.

adequate ramp and cool down cycle. Fig. 17 shows the assembly being positioned within the oven. It is very important to ensure that tank pressure is maintained during the winding procedure and cure cycle, otherwise tank exterior dimensions will creep and may not be within the necessary tolerance to fit snuggly inside the stage skirt. The tank should also be rotated slowly during the cure cycle to ensure uniform resin distribution.

3.7. Tank to skirt installation

Special handling fixtures were developed to allow the facility overhead crane to grab the stage skirt and lift it into a vertical position (Fig. 18). A forklift was used to provide skirt vertical stability. A swivel leveling mount is also threaded into the lower end of the shaft to enable vertical adjustment of the tank inside the skirt. The centering disk is then reattached to the aft boss to ensure the tank is concentric within the skirt inner diameter. Fig. 19 shows both the centering disk and the leveling mount.

The assembly shown in Fig. 19 is carefully positioned into the stage skirt. Fig. 20 illustrates the tank position before being lowered into the stage skirt. The clocking position of the tank relative to the skirt must be verified and locked into position. Shimming was necessary to ensure tank to skirt concentricity and to ensure an adequately uniform bond gap. A specially sized silicon tube was placed between the tank's lower dome and the skirt inner diameter to serve as a seal for the tank-to-skirt adhesive during cure.

3.8. Tank to skirt bond procedure

A Magnolia brand adhesive was chosen to bond the tank inside the skirt due to its shear strength, room temperature cure capability, and because of its low viscosity. Two experiments were conducted to mitigate the risk associated with the tank-to-skirt bond procedure. There were two concerns. The first was the adhesive's bond shear strength. The bond must be strong enough to withstand the shear stresses created by the stage engine thrust. The adhesive's shear strength was verified via a lap shear test. The skirt coupons are shown in Fig. 21 prior to pouring in the adhesive. The test results demonstrated that the adhesive had 25 times the necessary shear strength to keep the tank in position within the skirt. The second concern was that the adhesive would not flow uniformly throughout the bond and producing air gaps that would substantially reduce the bond's capability. To mitigate this risk, a subscale proof-of-concept hardware demonstration was set up (Fig. 22). A composite panel was laid up and bonded to an aluminum plate. The surface roughness of the laminate represented the tank's exterior surface. An acrylic sheet was used to represent the skirt's inner diameter. This surface texture was smooth since the skirt was wound on a relatively smooth mandrel. Shims were positioned between the laminate and the acrylic plate to produce the minimal bond gap allowable during the actual application. This was a worst-case scenario for

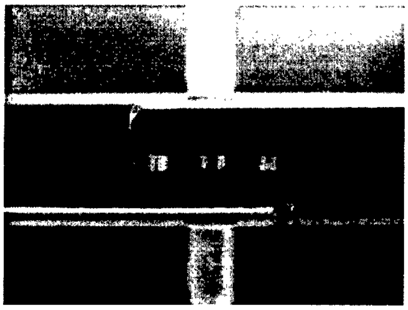

Fig. 21. Skirt coupon test prep.

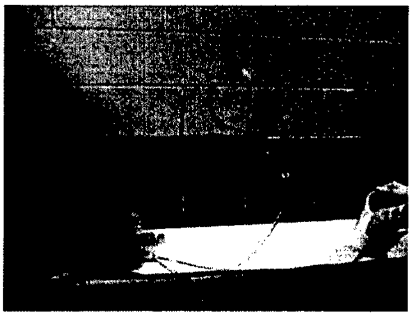

Fig. 22. Adhesive flow test.

the flow test. A peristaltic pump was used to deliver the adhesive to the bottom of the gap via "flattened" aluminum tubes. The test demonstrated that the Magnolia adhesive flowed very well within the gap and uniformly filled the gap to the top of the test setup. Fig. 16 illustrates the beginning of the test. Note the bell shaped flow of the adhesive as it enters the bond gap. Sixteen hours after the test had been completed, the adhesive level had dropped by 0.7 in., which meant that very small air bubbles (that could not be visually detected during the test) trapped within the adhesive, escaped or bled off, leaving a consolidated bond with little to no air pockets. Now we were confident our procedure would work.

For the flight unit application, the silicon tubes were positioned between the tank's lower dome and the skirt inner diameter, Magnolia adhesive was pumped into the tank-to-skirt gap in a manner consistent with our experiment. The gap was filled in 12 in. vertical increments to mitigate an exothermic adhesive reaction. Fortunately, there was no such reaction. We were happy to note that the silicon tube successfully contained the adhesive. The bond was allowed to cure for 3 days. The integral structure (tank/skirt structure) was now complete.

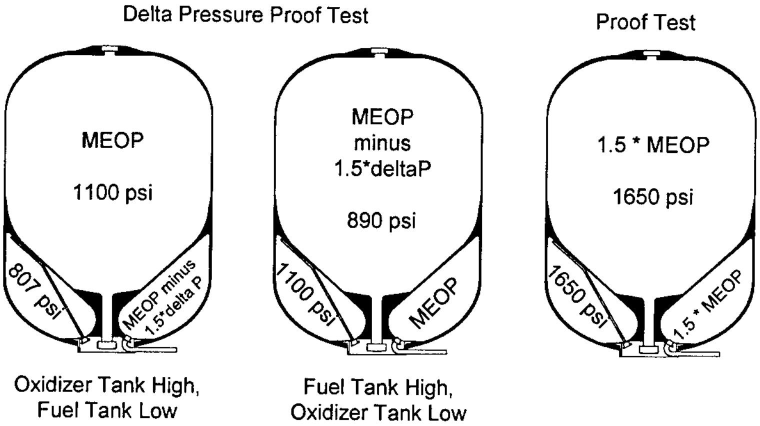

Fig. 23. Integral structure pressure testing (skirt no shown).

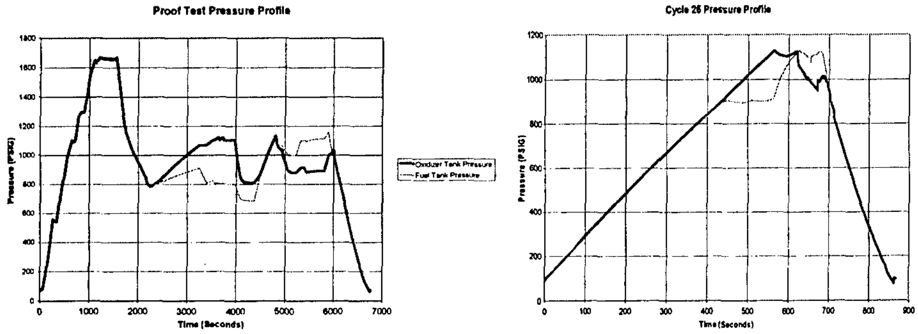

Fig. 24. Test pressure cycling to MEOP.

4. Pressure testing the integral flight structure

To satisfy range safety requirements, the integral structure was subjected to a hydrostatic proof and cycle test. The test was conducted April 15-17, 2003 at Orbital Sciences Corporation's Chandler, Arizona facility. Fig. 23 shows the various pressures that the integral structure was subjected to during the test.

The proof test involved pressurizing both propellant tanks to 150% of maximum expected operating pressure (MEOP). MEOP is 1100 PSIA. During the proof test, a delta-P was also applied across the tanks' common bulkhead. The applied delta-P was equivalent to 150% of the maximum expected delta-P. The maximum expected delta-P across the bulkhead is 195 PSID when the oxidizer tank pressure is higher than the fuel tank pressure. When the fuel tank pressure is higher than the oxidizer tank pressure, the maximum expected delta-P across the bulkhead is 140 PSID.

After the proof test, the integral structure was subjected to 50 pressure cycles with both propellant tanks pressurized to MEOP. During each cycle, the maximum expected delta-P was also applied across the bulkhead in both directions. Fig. 24 illustrates pressure cycling test results.

Strain gauges were installed on the oxidizer tank dome, fuel tank dome, and outside diameter of the skirt. The figures below show the tank pressure profile during the proof test and during cycle 25 (typical of cycles 1–50).

Tables 2–4 summarize strain data acquired during the test. During the proof test, tank pressures and strains held steady throughout the 5-minute hold period. In general, strains were consistent from one cycle to the next. No visible leakage was detected during, or after, the proof and cycle test. Measured strain levels at 100% of MEOP were less than 1/2 of the material allowables.

Table 2
Proof test strain results

Proof test strain results	
Strain gage location	Max. actual value (micro-strain)
Fuel dome meridonal $R = 13.5$ in.	4700
Fuel dome meridonal $R = 21$ in.	4300
Fuel dome hoop $R = 13.5$ in.	4500
Fuel dome hoop $R = 21$ in.	7900
Oxid. dome meridonal $R = 19.5$ in.	4800
Oxid. dome hoop $R = 19.5$ in.	8100
Skirt axial sta = 106.7 in.	230
Skirt axial sta = 116.2 in.	620
Skirt hoop sta = 106.7 in.	4600
Skirt hoop sta = 116.2 in.	3300
Skirt hoop sta = 121.1 in.	3500

Table 3
Cycle test results

Cycle test strain results			
Strain gage location	Cycle 1 max. micro-strain	Cycle 25 max. micro-strain	Cycle 50 max. micro-strain
Fuel dome meridonal $R = 13.5$ in.	2700	2700	2800
Fuel dome meridonal $R = 21$ in.	3000	2800	3000
Fuel dome hoop $R = 13.5$ in.	3200	2900	3100
Fuel dome hoop $R = 21$ in.	5400	5200	5200
Oxid. dome meridonal $R = 19.5$ in.	3200	3200	3300
Oxid. dome hoop $R = 19.5$ in.	4800	4700	4900
Skirt axial sta = 106.7 in.	200	270	100
Skirt axial sta = 116.2 in.	970	1000	450
Skirt hoop sta = 106.7 in.	3000	3000	3200
Skirt hoop sta = 116.2 in.	2200	2200	2300
Skirt hoop sta = 121.1 in.	1300	1300	1350

Table 4
Strain design allowables comparison

Comparison of test data to material allowables		
Location	Max. allowable tensile strain (in./in.)	Max. measured strain at 100% MEOP (in./in.)
Tank	0.015	0.0054
Skirt	0.0082	0.0032

Based on these results, the USFE integral structure successfully passed the hydrostatic proof and cycle test.

5. Conclusions

To summarize, the USFE tank development effort was a major success because it validated not only the innovative design, but it also developed the necessary manufacturing techniques that enables the tank's fabrication. One way to improve the fabrication procedure would be wind the composite tank first, then size the inner diameter of the stage skirt afterwards. This would eliminate problems associated with the tank-to-skirt bond gap due to tolerance error associated with the fabrication procedure. Too much or too little gap can substantially degrade the adhesive's sheer strength and could cause a catastrophic failure during the stage operations. Another lesson learned is to pick a better material for the skirt mandrel. The mandrel would grown considerably during the curing process. Finally, it is very important to fabricate both the fuel liner and the oxidizer liner with as tight a tolerance as possible. Therefore, it is very important to pick a liner vendor with previous experience in aerospace applications. Machined mold tooling tends to be much better in terms of precision relative to cast mold tooling.

Reference

[1] Crockett D et al. Volume optimized composite propellant tanks for hydrogen peroxide/kerosene propulsion applications. In: Proceedigns of the 5th International H_2O_2 Conference; 2002.