Composite, Cryogenic, Conformal, Common Bulkhead, Aerogel-insulated Tank (CBAT)

Materials and Processing Methodologies

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ABSTRACT

The objective of the Composite, Cryogenic, Conformal, Common Bulkhead, Aerogel-insulated Tank (CBAT) Program is to evaluate the potential for using various new technologies in next generation Reusable Launch Vehicles (RLVs) through design, fabrication, and testing of a subscale system. The new technologies include polymer matrix composites (PMCs), conformal propellant storage, common bulkhead packaging, and aerogel insulation. The National Aeronautics and Space Administration (NASA) and Thiokol Propulsion from Cordant Technologies are working together to develop a design and the processing methodologies which will allow integration of these technologies into a single structural component assembly. Such integration will significantly decrease subsystem weight and reduce shape, volume, and placement restrictions, thereby enhancing overall launch system performance.

This paper/presentation focuses on the challenges related to materials and processes that were encountered and overcome during this program to date.

INTRODUCTION

One of the ongoing goals of the National Aeronautics and Space Administration (NASA) is to lower the cost of access to space. This objective is achieved through research and development into technologies that may be used to improve current and future space transportation systems. These technologies may result in improvements in safety, reliability, performance, cost, or operating efficiency. The Composite, Cryogenic, Conformal, Common Bulkhead, Aerogel-insulated Tank (CBAT) program has the potential to positively influence each of these areas.

What is CBAT? The name, CBAT or Composite, Cryogenic, Conformal, Common Bulkhead, Aerogel-insulated Tank, refers to the enabling technologies and/or the functionality desired in the end product. CBAT seeks to demonstrate and assess the potential for system improvements through the integration of various technologies. These technologies include polymer matrix composites (PMCs), conformal propellant storage, common bulkhead packaging, and aerogel insulation.

Evaluating the aspects of the system that the name suggests--Composite refers to the PMCs that will be used to fabricate the system. PMCs are the materials of choice for most of today's aerospace applications. They provide a unique combination of high strength and stiffness with low material density relative to metals. In addition, many properties of composite materials are anisotropic (directional). Therefore, these materials and their use may be tailored to a specific design. Other advantages of PMCs include their resistance to fracture, corrosion, and wear, ease of fabrication and assembly, ability to be fabricated to net shape, and capacity to facilitate component integration.

Cryogenic refers to the prospective propellants for use with the system. One of these propellants is liquid oxygen (LOX). LOX is a very harsh environment and hence presents many challenges to system designers. Two of its primary challenges are reactivity and low vaporization temperature. Some materials are susceptible to oxidation or combustion at standard atmospheric conditions. As oxygen concentration and pressure increases, the frequency and the severity of these reactions tend to increase, making a LOX environment very inhospitable to many materials. The other primary challenge, the low vaporization temperature of LOX (-297°F/-183°C), results in significant stresses and strains being induced simply due to thermal gradients and/or differences in coefficients of thermal expansion (CTEs). The materials have therefore been chosen with respect to the LOX environment. However, testing for this program will initially be performed using liquid nitrogen (LN_2, $T_{vap}(LN_2) = -320°F/-196°C$) to mitigate cost and safety issues.

Conformal refers to customizing the shape of the propellant storage system to the shape of the vehicle in which it will be used. . This customization provides two significant benefits. It allows a designer to maximize the amount of propellant storage within a given space in the vehicle. It also facilitates the integration of the tank structure into the vehicle structure. Overall, this ability reduces the restrictions placed on the vehicle designer.

Common bulkhead refers to the methodology for placing or packaging the propellant storage tanks within the vehicle, in this case, one adjacent to the other with a common interface in between. This ability removes additional constraints on tank shape and placement. For previous cryogenic propellant systems this arrangement has been very difficult to accomplish. Due to the high thermal conductivity of the materials used, and the difference in temperature between the propellants, freezing of one of the propellants would invariably become a serious concern.

Lastly, aerogel-insulated refers to the use of a special class of materials, aerogels, between and around various portions of the system. Aerogels are some of the lightest solids ever produced. Highly porous and almost wispy in appearance (Figure 1), aerogels produced from such materials as silica, alumina, or zirconia can have densities as low as just three times that of air ($\rho_{aerogel} \sim 0.003$ g/cm^3). Another result of their highly porous nature is their low thermal conductivity. Aerogels can insulate almost 40X better than the best fiberglass insulations. This makes aerogels one of the best insulators available today (Figure 2).

Figure 1: The wispy, fragile appearance of an aerogel shown protecting a flower from being consumed by a burner.

Figure 2: Tom Tillotson, a chemist at Lawrence Livermore, applies a flame to the top of a 1-inch-thick silica aerogel brick. Even though a thermocouple placed on the aerogel's top surface reports a temperature of 2,108°F, his hand is totally unaffected by the heat.

Particulate/granular forms of these materials are also available. These forms trade off some of the density and thermal advantages for improvements in strength and ease of use.

The CBAT program will evaluate the potential for using and integrating these technologies through design, fabrication, and testing of a subscale system. This effort is considered critical to enabling development of the second generation of NASA RLV. The program is currently nearing the end of the design phase and the start of the fabrication phase.

The design created by NASA's George C. Marshall Space Flight Center (NASA/MSFC) and its industry partners incorporates each of the aforementioned technologies and functionality. This design is shown in Figures 3a through 3c. The design is based on a graphite/epoxy PMC. It will be fabricated by a combination of hand lay-up and filament winding, using both pre-impregnated (prepreg) fabric and tow/yarn. The system is designed for the LOX environment, and with some minor material/processing changes, may also be evaluated for use with hydrogen. The system and the tanks within the system have noncircular cross-sections. The shape is considered representative of one that would be used in conjunction with a lifting body-type RLV. The system also employs a common bulkhead between the two propellant tanks. The bulkhead functions in both structural and thermal capacities. The bulkhead utilizes graphite/epoxy and honeycomb to provide strength and aerogel-based material to provide insulation. A rapid prototype (RP) model of the system design was developed using the stereolithography apparatus (SLA) and laminated object manufacture (LOM). This model has been used to verify component form and fit.

This paper focuses on the challenges related to materials and processes that were encountered and overcome during this program to date.

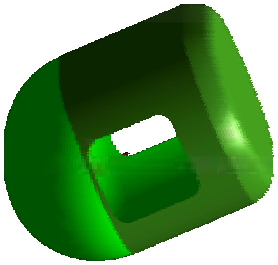
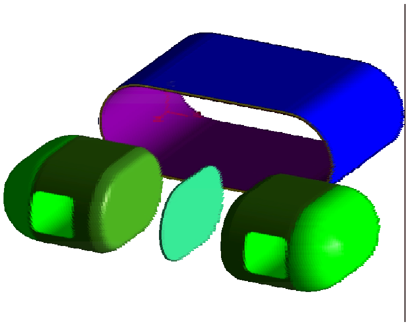


Figure 3a: CBAT propellant tank design. Cross-section is D-shaped in the plane perpendicular to the anticipated vehicle axis.

Figure 3b: Assembly of the CBAT propellant tanks around the bulkhead and insertion into the system skirt structure.



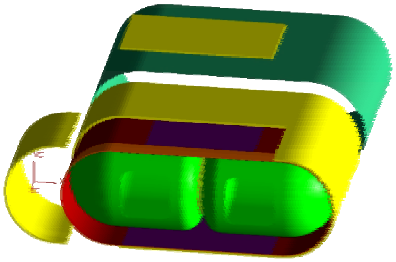


Figure 3c: Final assembly of the CBAT skirt sandwich structure. The skirt is composed of inner and outer graphite/epoxy skins bonded to a honeycomb core.

MATERIALS AND PROCESSES

At the beginning of any composite fabrication effort, potential fabrication methods must be evaluated. After the fabrication method is determined, the tooling and types of materials must be considered. For the CBAT propellant tank, the chosen method of fabrication is a combination of polar filament winding and hand lay-up. The tank material will be IM7/977-2 pre-impregnated filament winding tow and 5 harness satin (HS) cloth. The tooling will be a removable mandrel made from a sand replacement called Macrolite™. The following sections deal with the evaluation, selection, and development of the materials and processes for the fabrication of the CBAT system.

Filament Winding

Polar winding was chosen as part of the fabrication of the CBAT propellant tanks to minimize the amount of fiber build-up in the dome regions. A 16 by 22-inch portion of the dome region will be cut out for the manhole door. Excessive build-up in this region would create mating problems for the door and the tank. Polar winding will alleviate this issue because no crossovers will occur in the filament winding pattern in the dome. Helical winding would create a greater thickness build-up in the dome region because of the crossovers that occur in a helical pattern. Polar winding creates a build-up directly adjacent to the polar boss but that area will be removed for door installation.

Since the CBAT propellant tanks have a flat portion in the common bulkhead region, filament winding will be challenging because of the changing contour. The filament winding program that controls the machine motion will be generated for a 60 inch diameter cylinder, but the tank shape creates a variation in diameter from 60 inches to 36 inches with a flat side. This will obviously lead to tow overlaps and potential tow slippage in some areas of the barrel sections of the propellant tanks. The greatest potential for tow slippage occurs in the transition from the cylindrical sections to the flat sections of the tanks.

One-fifth scale models were wound using a polar pattern to determine if these issues would be insurmountable. Both slippage and overlaps occurred in initial trials. A layer of film adhesive was then applied to the mandrel to give a tacky surface for the tow to grab. This was successful in minimizing slipping on the small-scale model. A higher resin content; i.e., tackier, version of the IM7/977-2 was also ordered for the full-scale tanks to further alleviate any problems with slipping. Issues associated with the transition regions will also be reduced upon scale-up to the full-sized tank. This effect will be due to the reduction in the size of the tow relative to the geometric features of the tank and the winding pattern. For example, overlaps will occur, but these should be less prominent on the full-scale tank because they will be spread over a larger area. To illustrate the differences between polar and helical patterns, figure 4a shows a one-fifth scale model that was wound with a polar pattern, and figure 4b shows a one-fifth scale model that was wound with a helical pattern. Notice the crossovers in the dome of the helical wound model.

Figure 4a: Polar wound one-fifth scale model of a CBAT Propellant Tank. Polar winding minimizes build up in the domes due to fewer crossovers. The non-cylindrical shape creates fiber tow overlaps in the flat regions.

Figure 4b: Helical wound one-fifth scale model of a CBAT Propellant Tank (before cure). Helical winding causes more build up in the domes regions because of the crossovers.

Hand Lay-up

Pre-impregnated IM7-977-2/5HS cloth will be hand laid, as the design requires, over the three regions of the propellant tanks. The hoop region will require 16 plies, the dome regions will require 10 plies and the door build-ups will require 20 plies. Laying the hoop plies and the door build-up plies should be relatively typical. The dome regions will require more attention.

The issue involved with the cloth lay-up on the domes is the challenge of getting a flat piece of cloth to conform to an 18-inch spherical surface. Obviously the fiber pattern in the cloth material will distort. NASA/MSFC Structures and Design personnel used PATRAN® Laminate Modeler to simulate how much fiber distortion would occur as the cloth was draped over the spherical dome regions. Also, a drape test was conducted with 5HS cloth to determine the degree of ply distortion that would occur. Figure 5 shows the result of the drape test. The dashed tracer lines follow individual tows within the 5HS cloth and show the distortion as the ply is wrapped around the dome. Figure 6 is the result of the modeling that was done to simulate the fiber distortion in the cloth. The model shown in Figure 6 accurately predicted the results of the actual drape test.

Figure 5: The results of the 5HS cloth drape test on a 36 inch diameter dome. The dashed tracer lines follow individual tows within the cloth. The solid line represents the centerline of the dome.

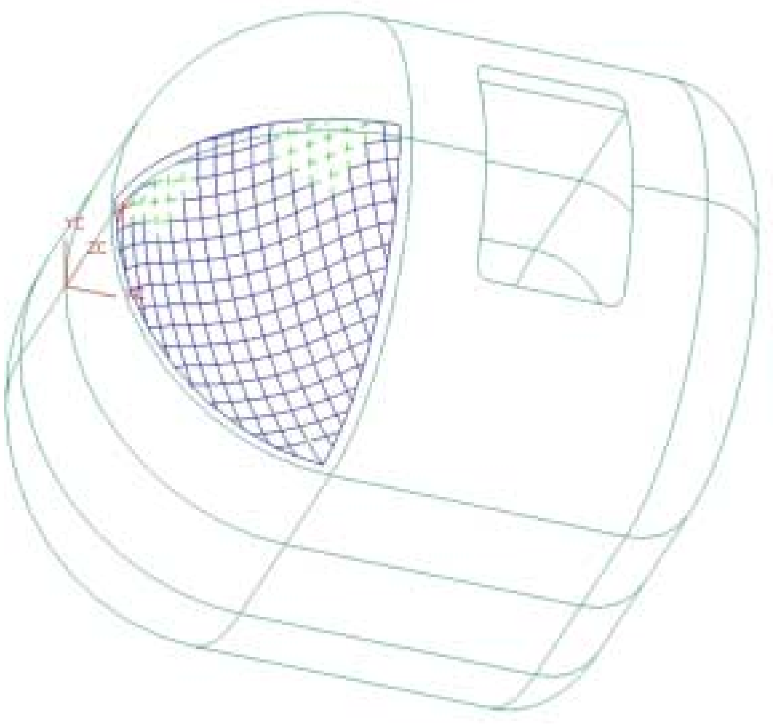


Figure 6: PATRAN® Laminate Modeler software was used by the MSFC Structures and Design Group to predict the fiber distortion as the cloth draped on the 36 inch domes. The image shown is from Unigraphics/FiberSIM.

Tooling

The major parameters for selection of the mandrels for fabrication of the propellant tanks were weight, ease of removal, and dimensional stability. Sand mandrels are typically a first choice because of their ease of fabrication, ease of removal, and low cost. The mandrels for the CBAT propellant tanks will each be 48 cubic feet. A sand mandrel would weigh approximately 4000 pounds. Urethane foam was another option that was considered. Foam is lightweight and could be machined to the proper tank dimensions. Foam was eliminated as an option for the CBAT propellant tank mandrels because of the lack of dimensional stability. Since the foam has a high expansion rate and the CBAT mandrels will not be cylindrical, the expansion in the different regions of the tank would be difficult to predict. After considering the options, a lightweight ceramic material, Macrolite™, was chosen for the CBAT propellant tank mandrels.

Macrolite™ is actually a water filtration media that consists of various sizes of ceramic spheres (see Figure 7). Macrolite™ is used for tooling by some composite manufacturers including Thiokol Propulsion in Brigham City, Utah. The M&P Composites group at Thiokol-Utah researched various combinations of the different size and density Macrolite™ particles (Table 1) (Yorgason). These particles were mixed with alumina microspheres and a binder, polyvinyl alcohol (PVA). An optimized mix was used to fabricate a 97-inch diameter 110-inch long mandrel. The information from this research was used to begin the development of a Macrolite™ mandrel for the CBAT propellant tanks.

Material	Density (lbs./cu.ft.)
Macrolite™ M357	21
Macrolite™ M714	25
Macrolite™ M1430	28
Macrolite™ M3050	30
Macrolite™ M4060	56
Macrolite™ M7080	60
Sand	95

Table 1: Densities for all the Macrolite™ particles and sand. The M4060 and M7080 particles were deleted from the final mix and replaced with sand.

The cure of the 977-2 epoxy resin used in tank fabrication will take place at 350°F (177°C). However, PVA tends to react adversely at such temperatures and produce mandrels with significantly lower solubility. For this reason sodium silicate was substituted as the binder in the CBAT program. Unfortunately, using sodium silicate as a binder with the Macrolite™ particle mix developed at Thiokol-Utah also created relatively insoluble mandrels. After discussions with the sodium silicate vendor, PQ Corporation, and many trials, a successful mixture was tested. This mixture included a reduction in the percentage of binder used from 10% to 8%, and elimination of the smallest Macrolite™ particles (M4060 and M7080) and alumina microspheres. These particles were replaced with sand. The difficulties that were encountered are thought to have been the result of the high surface area associated with the fine Macrolite™ particles. This leads to greater wetting and absorption of the binder by the Macrolite™. These fine particles also pack together better, thus eliminating porosity and preventing the water from penetrating the mandrel during washout. The addition of sand allowed the hot water to penetrate through the mandrel more readily, and therefore break down/dissolve the sodium silicate binder at a faster rate. The Macrolite™ mix reduces mandrel weight by 70% when compared to sand. The addition of the sand led to a Macrolite™ mix that was 3% heavier than the mix established by Thiokol-Utah.

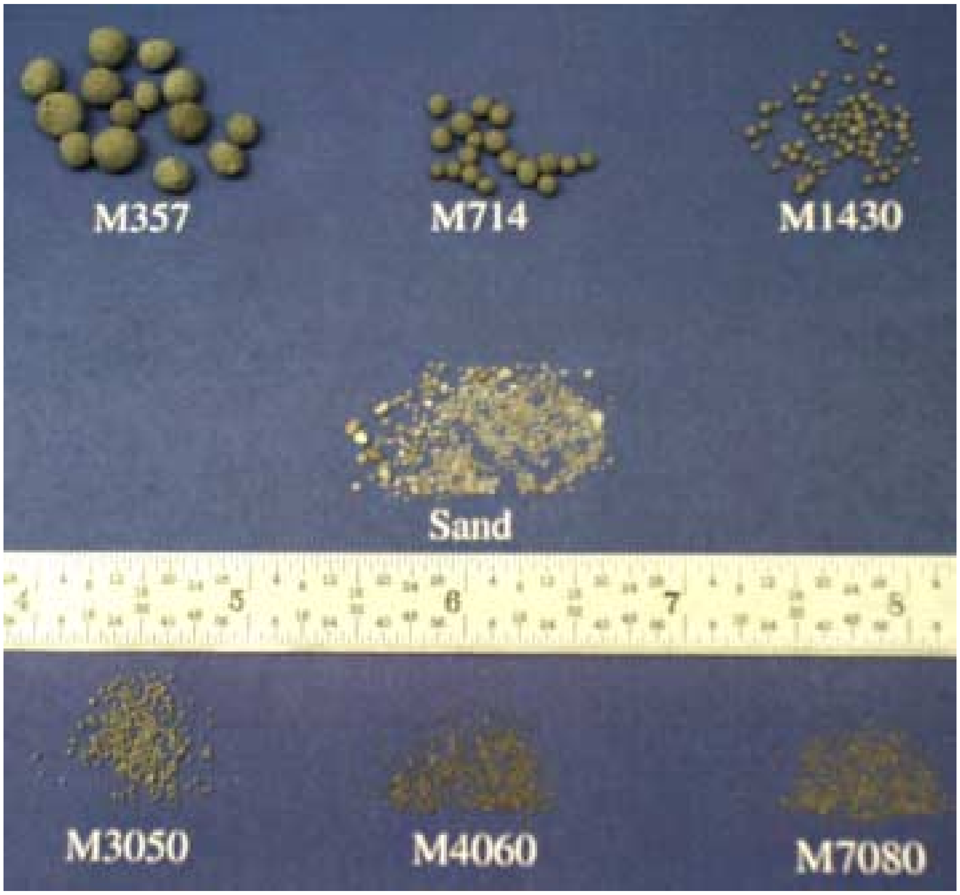


Figure 7: A photograph of the various Macrolite™ particles alongside sand. Notice the different size particles within the sand while the Macrolite™ particles are relatively consistent especially in the smaller sizes.

SUMMARY

The CBAT program will evaluate the potential for building a conformal composite tank system that integrates a common bulkhead with aerogel insulation to reduce subsystem weight and volume, thereby enhancing the performance of future reusable launch vehicles. Although in the early stages, the CBAT fabrication effort has encountered and overcome several obstacles. The issues associated with filament winding a non-cylindrical shape, while not proven on a large scale, have been minimized through material selection and proper fabrication sequence. The hand laying of cloth onto the dome sections has been successfully tested to allow integration into the design models. Lastly, a lightweight mandrel material has been tailored to meet the specific requirements of the CBAT program.

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