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Composite tanks promise major savings

Rocket engineers have long been enthralled by the idea of storing liquid hydrogen in cryogenic tanks made from graphite composite. These would weigh an estimated 40% less than the cryogenic tanks used today, which are made of aluminum or higher strength aluminum lithium alloy. Automated manufacturing also could make the composite tanks 20% less expensive than metal versions.

The shift to composite cryogenic tanks has not happened yet, largely because of a composite tank failure that occurred at NASA Marshall over a decade ago. Late in the afternoon of November 3, 1999, a ragged crack of broken graphite fibers appeared along the circumference of a hydrogen tank that was in testing for use on NASA's X-33 reusable launch vehicle demonstrator. The tank broke the very first time it was subjected to external loads.

The failure was not very dramatic, producing no flames, explosions, or bursting. But the damage was real. The X-33 program was cancelled and NASA's rocket plans were thrown into years of disarray. The agency had been counting on the X-33 to pave the way for a space shuttle replacement.

Fast forward 14 years, and NASA is back in the composite tank business, ground testing versions specifically designed to avoid the X-33 pitfalls. NASA aims to use the new tank for expendable rockets, including the forthcoming Space Launch System to be used for launching astronauts to Mars or to asteroids. Boeing is making the tanks under NASA's Game Changing Technology Initiative, having beaten Lockheed Martin (the X-33 contractor) and Northrop Grumman for the $24-million contract in 2011.

The work is starting to get interesting, with a 2.4-m-diam. version passing pressure tests at Marshall, according to a preliminary report, and a 5.5-m version now in development at Boeing's Tukwila, Washington, facility. The bigger tank is supposed to prove the feasibility of making an 8.4-m composite tank for NASA's Space Launch System.

Changing the game

Liquid hydrogen propellant is typically stored inside cryogenic pressure vessels that are nearly spherical. In what's known as an integral tank design, the pressure vessels are bonded to a section of the launch vehicle's outer

A robotic arm applies composite laminate to Boeing's 2.4-m-diam. pressure vessel at Boeing's Tukwila, Washington, facility. Credit: Boeing.

shell—a cylinder in the case of an expandable rocket.

NASA thinks one of the X-33's two tanks broke because tiny amounts of hydrogen gas seeped into the honeycomb core of the tank wall. The wall was a sandwich composite consisting of a honeycomb core with facesheets bonded on the outside and inside of the core. Gas seeped in through microscopic cracks in the interior facesheet and produced "higher than expected core pressures" that caused the core to debond from the outer facesheet, according to the investigation report.

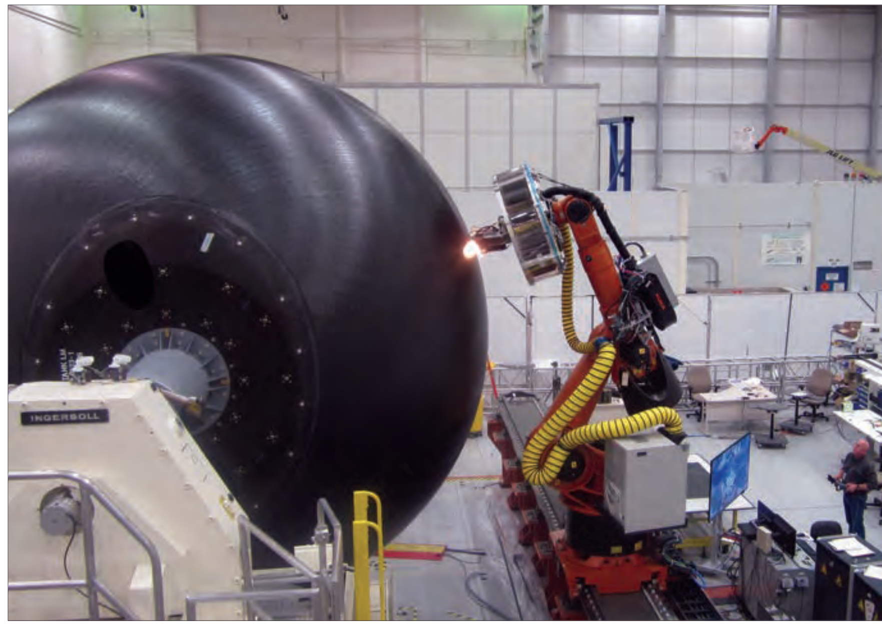
Boeing has come up with a tank design that shifts to an entirely new lamination technique for the pressure vessel and does away with the honeycombs in the core of the cylinder wall.

A 5.5-m tank assembly is scheduled to arrive at Marshall next April inside NASA's Super Guppy plane. Boeing and NASA engineers say the tank is big enough to test the design and manufacturing processes for the larger version that would be needed for the Space Launch System.

The first thing the new tank team did was to look closely at the history of the X-33 program, including a May 2000 investigative report describing the failure. The investigators cited not only technical flaws but also poor communications among engineers and managers: "A design of this complexity requires high levels of communication, both internal and external to the involved organizations; such communication did not occur in this case," the investigators said.

The Boeing-NASA team appears to have taken that criticism to heart. NASA project manager John Vickers says "a very close working relationship" has been established among engineers from Boeing and the Marshall, Glenn, and Langley centers. "We've got this small, passionate engineering team of government engineers and industry engineers working," he says.

Job number one was to address the permeation of hydrogen out of the pressure vessel. Boeing came up with



A robotic arm applies composite laminate to Boeing's 5.5-m-diam. composite propellant vessel at Boeing's Tukwila, Washington, facility. The light at the tip of the arm provides heat to soften the ribbon and make it adhere. Credit: Boeing.

a new lamination technique for the vessel wall. An undisclosed number of thin plies of graphite composite are surrounded by standard thickness plies. This hybrid laminate sounds like a small change but is supposed to have a big effect.

"We've incorporated thin composite plies into the laminate to not only mitigate, but the hope is to eliminate, permeability of the hydrogen from inside the tank," says Vickers. "The thin plies are the keys to eliminating the permeability, and they're really half the thickness of a typical ply material," he notes. Specifically, each layer is 2.5 mm wide, compared to the standard 5.5 mm.

What if the engineers are wrong about the impermeability of the new laminate? The Boeing-NASA team had to be sure that the tank's cylindrical outer wall would not soak up any hydrogen that might escape, so they found a way to eliminate the honeycombs in the core of the outer shell. For the X-33, those honeycombs were supposed to add strength when sandwiched between carbon-fiber facesheets, but they became the program's Achilles' heel. In the new design, "You don't get a trapped gas, and it's the trapped gas that contributed to X-33 failure," says mechanical engineer Dan Rivera, Boeing's project manager.

Instead of honeycombs, the core of the outer shell will be formed from hollow tubes called flutes. These run along the axis of the cylinder from end to end. "If you do have any sort of permeation from the tank wall, if it gets into the core, those flutes can very easily exhaust to the air, the ambient environment," Rivera explains.

Engineers know they must keep the voids of any composite sandwich empty and clean. Hydrogen from the tank is one threat, but so is moisture. It can freeze and expand, pulling the tips of the honeycomb away from the facesheet that forms the surface, weakening the whole sandwich structure. The flutes give engineers a way to address that problem too.

"The hollow tube provides the ability for us to very easily purge and vent the core. That is very challenging in a honeycomb structure. You have to machine in vent paths and things

Boeing's 2.4-m-diam. pressure vessel is bonded inside a composite cylinder that would form a segment of an expendable rocket. The tank assembly is pictured in a clean room in Marshall's advanced manufacturing facility. Credit: NASA.

like that," Rivera says. "Our core naturally provides those vent paths, so we can keep the air in those flutes very dry," he says.

An inert gas is run through the core, he explains.

Cue the robots

NASA and Boeing know that a stronger, lighter tank won't be a game changer if no one can afford it. Consider the pressure vessel. It requires wrapping ribbons of composite fiber material around a mandrel made from epoxy cured into the shape of the vessel. Doing the wrapping by hand would be time consuming and expensive, if it were possible at all. Engineers have chosen an intricate spiral application to maximize the strength of the vessel and minimize its weight. The job will be especially difficult for the 5.5-m pressure vessel or the 8.4-m version for the Space Launch System.

Instead of laying the ribbons by hand, Boeing took a commercially available, robotic manufacturing arm and designed a fiber placement head for it. The head provides heat to soften the ribbon and make it adhere. That's necessary because Boeing procures the ribbons as "pre-preg," a stiff material pre-impregnated with epoxy.

"The angle of that spiral wrap is key to the performance and weight savings of the tank, and so you can only really do that with this very sophisticated robotic, fiber placement capability," Vickers says. "It continually goes around the tank in this spiral pattern until it completely covers the tank, and then it'll do that for another layer."

Not everything is left to the robots, though. Once the vessel is done, the mandrel must be removed a section at a time. For a big vessel like the 5.5-m version, someone actually climbs in the mandrel and uses a crane and other lifting devices to remove the mandrel a section at a time. The mandrel is coated with a chemical release agent before the ribbons are applied, so that that they won't get stuck on it. "It's much like a wax," Vickers says.

First of a kind

Composite structures need to be cured, and doing that for a large structure like the 5.5-m tank posed what may be the biggest challenge for the team. Composite aerospace structures are typically cured in pressure chambers called autoclaves. As far as the Boeing-NASA team knows, there simply is no autoclave large enough to fit an 8.4-m-wide cylinder and pressure vessel. A structure that size will need to be cured in a giant oven—something that does exist, because it's easier to produce heat on that scale than pressure.

"The alternative would be you would have to go design, build, and purchase the world's largest autoclave to fit an 8.4-m tank," says Rivera.

The 5.5-m tank must prove the feasibility of oven curing for such a large structure. "It's the first time ever for a tank this large to be cured in an oven as opposed to an autoclave," Vickers says.

For the material, Boeing chose a commercial resin dubbed 5320, plus IM7 carbon fibers. "The 5320-IM7 has been developed for out of autoclave operations," Rivera explains.

NASA and Boeing conducted numerous tests to qualify the material for use in the 5.5-m tank. The real proof will come when the tank arrives at Marshall for installation on the test stand that the agency has begun setting up to accommodate it. The tank will be filled with liquid hydrogen and hooked up to a tank farm that adds pressure by pumping more liquid hydrogen into it. Those tests will simulate the pressures and structural loads the tank would experience inside a launch vehicle.

These tests will be tougher than those performed on the 2.4-m tank: "We did not test the 2.4-m with those structural loads," Vickers cautions. "The 5.5-m is really the biggest milestone we have for the project."

Space applications might not be all that's at stake in the composite tank program. If a giant, composite tank can be cured without an autoclave, engineers might be able to do the same with windmill parts or fuel storage tanks.

"Composites really are the materials of the future, and if we can build these structures outside the autoclave, that opens it up to many, many more companies" that otherwise could not produce the parts, "because autoclaves are very large capital investments," Vickers says.

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