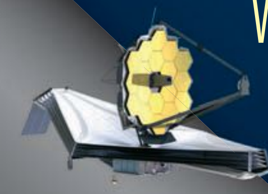


SHOWTIME FOR WEBB
PAGE 32

AEROSPACE AMERICA

SPACE RESCUE

Human spaceflight's Achilles' heel — stranding customers without a rescue plan PAGE 22

YOUR ARTEMIS I MISSION GUIDE

AIAA
SHAPING THE FUTURE OF AEROSPACE

NOVEMBER 2021 | A publication of the American Institute of Aeronautics and Astronautics | aerospaceamerica.aiaa.org

Preventing a bad day for SLS

High up the stack of NASA's first Space Launch System rocket is a component that will play a critical role in proving the rocket's safety during the upcoming Artemis I mission. This is its story as told by Keith Button.

▲ Technicians with Janicki Industries of Washington state piece together the composite layers of a dish-shaped barrier that must prevent propellant gases from collecting near the Orion capsule atop a Space Launch System rocket, posing an explosion hazard.

Janicki Industries

BY KEITH BUTTON | buttonkeith@gmail.com

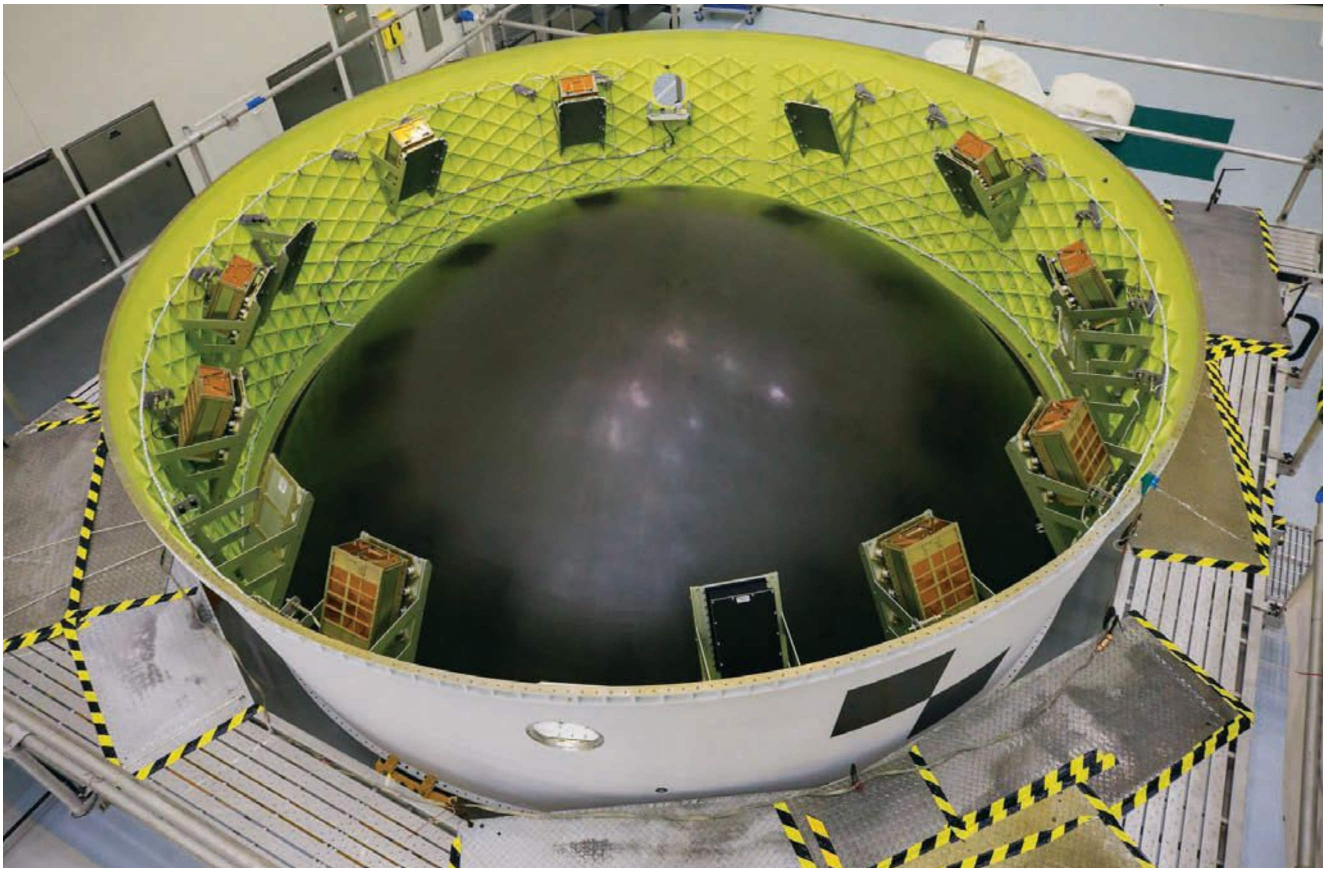
Engineers at NASA's Langley Research Center in Virginia received a challenging assignment in 2011: Design a barrier to keep propellant gases from accumulating near Orion astronauts before and during their ride atop a Space Launch System rocket.

Now, a decade later, an updated version of this Langley design is poised to be demonstrated on an SLS rocket for the first time in the uncrewed Artemis I mission scheduled for February 2022. Once NASA begins crewed Artemis flights, the barrier's role will be one of life and death, and its development story is fittingly complex given those stakes.

The story begins with the hydrogen and oxygen propellant gases that, as with other rockets, must be vented off SLS on the launch pad and during the first seconds of liftoff. This venting avoids overpressurization of the propellant tanks in the core and upper stages given that some of the propellant inside them inevitably warms and turns to gas.

Without a barrier above the upper stage, called the Interim Cryogenic Propulsion Stage, any gas from below that was not vented off board could leak into the sections above. Those sections are the Orion Stage Adapter cylinder that joins the core and upper stages to the Orion service module and Orion crew spacecraft. Even separately, oxygen or hydrogen gases present a fire or explosion hazard, but if they mix together they're a particularly combustible brew.

The dome-shaped barrier — known as the Orion Stage Adapter diaphragm — creates a space within the adapter that will be purged of gases by blowing nitrogen gas into it. Were it not for this purging, in essence, "You're making fuel there, and you don't want that in a closed space like the adapter," says Robert Parker, who headed the



Langley team that designed the first version of the barrier. "It's like carrying a can of gas in your trunk: It's not going to start a fire by itself, but you get all those vapors in your trunk, that's a bomb waiting to happen."

Confident in the design

Engineers at NASA's Marshall Space Flight Center in Alabama who adopted the project in 2013 stuck largely to the design crafted at Langley and tested in 2014 during the uncrewed Exploration Flight Test-1 mission in which a Delta IV rocket sent an Orion spacecraft up for two orbits of Earth culminating in a splashdown off the California coast.

They knew that some strengthening would be required to launch the diaphragm on SLS with its 8.8 million pounds of thrust compared to 2.1 million pounds for the Delta IV.

But the 2014 launch left them confident in the basic design begun three years earlier at Langley. At that time, the Langley team's orders from the Spacecraft Payload Integration and Evolution Office at Marshall were to create a vapor barrier to trap gases in a void above the interim stage that could be purged. Initially, Parker and his team weren't told the dimensions or weight requirement for what would become the diaphragm, but they knew the basic shape would probably be similar to the dome structures that had served a similar function on United Launch Alliance rockets.

The team came up with 11 options for the diaphragm, including a welded metal structure, an inflatable barrier, metal structures shaped by bending and riveting, stamped metal, spun metal, structures made from other metal fabrication methods and a carbon-fiber composite structure. The inflatable option was ruled out because the structure would have to be rigid to withstand a pressure differential between the Orion Stage Adapter and the section above it.

Not long after they made this list, word came down from the Marshall payload office that the barrier would need to weigh no more than 180 kilograms. That ruled out the metal options, the lightest of which weighed 340 kilograms. That left only one option: the composite structure, and this became the material for the diaphragm.

They were also given instructions about the geometry for the barrier. It had to be 5 meters in diameter to fit over the cryogenic tank that rides below the stage adapter. So they decided a dome design, and one that is the largest government-furnished composite structure ever on a NASA spacecraft, according to Parker.

The next step was to choose the specific composite material. Some composites had properties that matched those they needed for the diaphragm, such

▲ The black dome is a protective diaphragm inside the Orion Stage Adapter. Both are now on the Space Launch System rocket that's being readied for the Artemis I mission, the SLS debut from Kennedy Space Center in Florida. Some of the 10 cubesats that will be released are visible along the periphery of the adapter.

NASA

Barrier against explosive gases

The Orion Stage Adapter with its internal diaphragm will ride on top of the Interim Cryogen Propulsion Stage and beneath the Orion Multi-purpose Crew Vehicle on the first Space Launch System rocket.

NASA

as adequate tensile and shear strengths over the required temperature range.

But the problem with these well-understood composites was that they either required a long lead time for ordering, because they were in high demand for military projects, or a large autoclave for curing, and the engineers weren't sure they could access one.

As an alternative, the team chose NB321, a composite that was readily available and due to its use in aircraft had well-established properties at temperatures close to what the engineers needed for the diaphragm. But they had to test the material to make sure it would be reliably strong enough at the lower temperatures.

Material testing

To make samples of the composite for testing, the engineers laid out the woven carbon fiber — pre-impregnated with resin — in layers, placed the material in plastic bags with ports to vacuum the air out and heated the material to cure it in ovens at Langley. They repeated the process to make sure their testing results were consistent through several bagging and baking sequences, and through more than one purchase of the material from the supplier.

For strength testing, they bent cured samples by placing cylinders of metal spaced at certain points below and on top of the sample, then compressed the sample to see if it would shear. For tensile strength testing, they clamped the sides of a sample and pulled to see if it would pull apart.

To determine if the fibers and the resin had melded together properly, the engineers cut and polished samples and examined them under a microscope, looking for voids in the microstructure. They also sent out samples for chemical analysis to see if the fibers and resin had meshed properly during the curing process.

In addition to strength testing, Parker and his team tested the composite for how much it expanded or contracted at different temperatures. These thermal characteristics were important because the metal ring that the diaphragm would be bolted to in the stage adapter would also expand and contract with temperature changes. The engineers had to factor into their design the structural stress caused by these differences in expansion and contraction rates.

With the strength and thermal testing results in hand, the engineers knew how many layers of the composite they would need at the areas of the diaphragm that required the most strength. Where the structure required the most strength — along the bottom ring where it bolts to the stage adapter — their design called for 35 layers; where it needed the least strength, at the top of the dome, only 19 layers.

Under pressure

The team calculated that the biggest structural stress the diaphragm could face would be a pressure differential that increases as the launch vehicle rapidly gains altitude, Parkers says. As the atmospheric

> "It's like carrying a can of gas in your trunk: It's not going to start a fire by itself, but you get all those vapors in your trunk, that's a bomb waiting to happen."
>
> — Robert Parker, NASA

pressure drops, each section of the rocket — except for the pressurized crew module — must let the air inside escape to the outside to prevent internal pressure from building up. However, if the sections above and below the diaphragm vent at different rates, then the barrier could experience structural stress.

With the design ready, NASA contracted the composites engineering firm, Janicki Industries in Hamilton, Washington, to construct the diaphragm for EFT-1.

A hurdle was the lack of prototype to run past the breaking point in ground testing.

"Ideally you're building prototypes and then you're testing with huge loads," Parker says. His team would have to test EFT-1 flight hardware with a smaller, but adequate, load number.

To find the right number, they calculated the largest potential air pressure differential that the diaphragm could experience due to the large volume of air space inside the rocket above the diaphragm and the small volume of air space below it. To provide a safe margin, they calculated that they should test to 1.2 times this maximum. They sent the diaphragm to Marshall, where the stage adapter was being assembled for EFT-1. Technicians sealed the diaphragm's bottom ring onto a floor and vacuumed out air until the pressure difference was 1.2 times the maximum. They monitored the walls of the diaphragm with strain gauges to check for buckling potential, and the structure held up.

As planned, the diaphragm that Parker and his team designed was launched with Exploration Flight Test-1 and burned up with the stage adapter as it reentered the atmosphere. After the flight, engineers confirmed from instrumentation data taken near the diaphragm that it performed as expected.

Tweaking the design

With the basic design proven, next came the effort by engineers at Marshall to strengthen the version for Artemis I, the SLS debut launch.

The Marshall team added more layers of composite material to the diaphragm design, but they discovered an issue that they thought might call for a more extensive design overhaul.

To maximize the strength of a composite material, typically the directions of the swaths of woven carbon fiber are at 90 and 45 degrees to each other as the layers are stacked in a layout, before curing. But as the Marshall engineers were building the diaphragm for Artemis I, they discovered that the 90- and 45-degree angling method was thrown off because of the dome shape, especially along the walls of the dome, which would make the structure weaker than what its designers had predicted with a consistent 90-45 layout method.

"We were partway through the build before we stumbled upon this issue," says Allyson Thomas, who led Marshall's 2013 design team for the diaphragm. Thomas and her team considered cutting smaller pieces of the woven carbon fiber for the layout, which could have adhered better to a 90- and 45-degree layout pattern. But they decided against it because smaller pieces would have introduced other problems, such as more joints in the structure, creating points of weakness.

After updating their computer models to revise their analysis of the "as-built" diaphragm without the consistent 90-45 layout pattern, the engineers found that the structure was strong enough where it needed to be, says Thomas, who is now deputy lead for the section of the rocket between the Orion spacecraft and the core stage. They made no changes beyond adding more layers.

NASA was confident enough in Parker's Orion-related work, including the initial design of the diaphragm, to present him with a Silver Snoopy Award for going above a normal day's work to "ensure flight safety." The agency is counting on the diaphragm to perform just as well on Artemis I as it did on EFT-1.★