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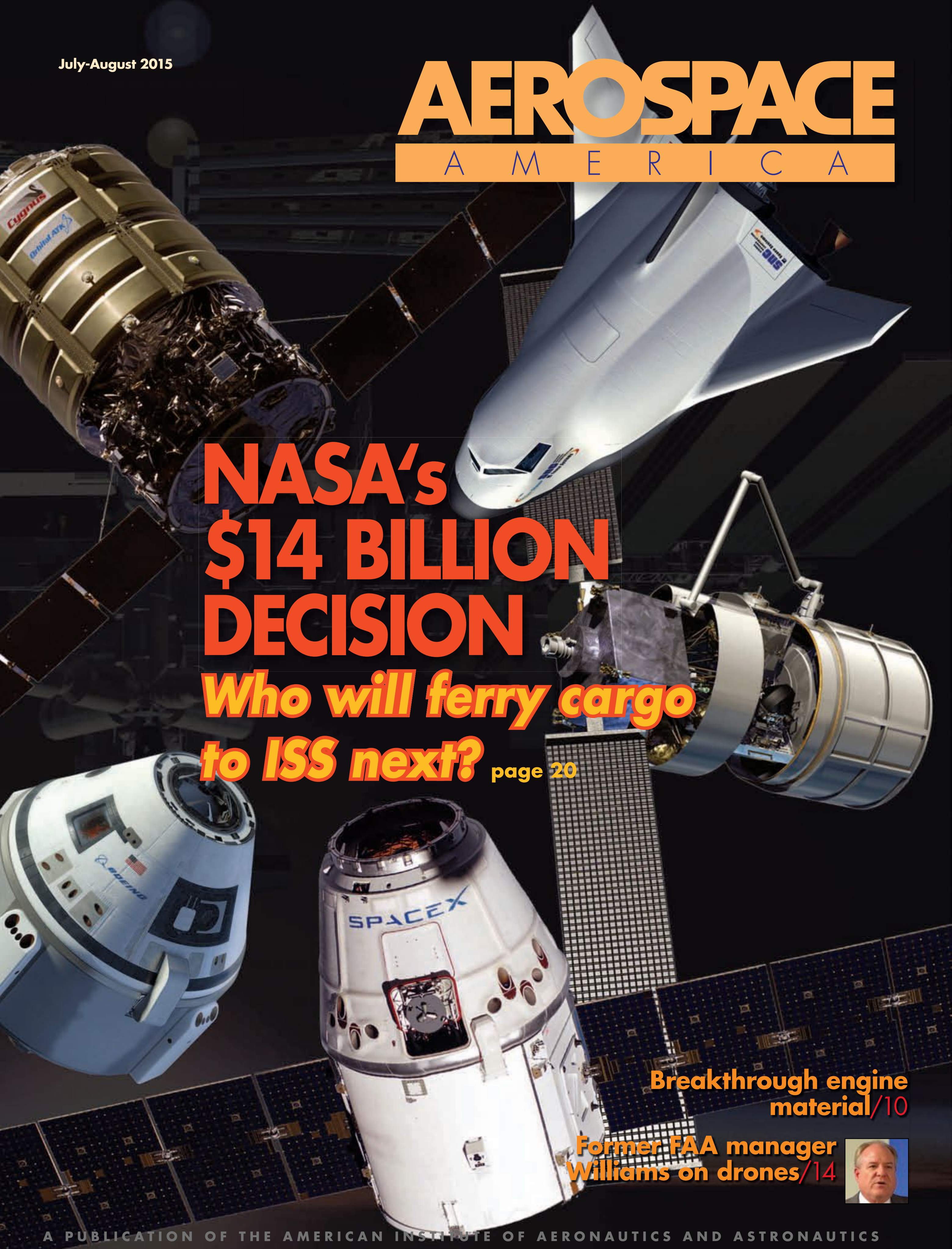

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TRU

3-D manufacturing’s Holy Grail

NASA

Additively made parts are being incorporated into rockets and spacecraft, but engineers are cautious about using the technique for such vital applications as the propellant tanks on spacecraft that must carry people or expensive communications and scientific equipment. Henry Kenyon interviewed experts at two companies that have different manufacturing approaches but a common goal: To convince customers to trust additively made components.

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When a NASA Orion capsule lifts off in 2018 for the program’s second unmanned test flight, the event won’t just mark the space agency’s return to human space flight after the retirement of the space shuttles. It will signal the beginning of a new way to build spacecraft. Fifteen percent of the components in the capsule will be made through additive manufacturing — metal and polymer structures and components constructed precisely, layer by layer from laser- or electron-beam welded powders, plastics and metals. Traditionally, everything from small parts, such as antenna brackets to propellant tanks rockets and satellites, have been made by technicians who machine away material from solid blocks of metal, using a variety of precision machine grinders. Making parts additively promises savings over traditional machining because fewer individual parts are needed to make a component, which saves weight and material and reduces the number of potential failure points.

For now, the 40 additively manufactured parts in Orion will be limited to non-mission critical components such as vents designed to equalize the pressure behind the capsule’s thermal protection system with the pressure in the rest of the cap-

At NASA Glenn Research Center's Rocket Combustion Laboratory in Cleveland, the agency tests a rocket engine with an additively manufactured gas injector assembly made by Aerojet Rocketdyne.

sule. These parts were flown on the December 2014 unmanned Orion test flight and eventually will be a part of manned missions, NASA says. Bigger savings will extend beyond Orion to the rocket it will ride on, NASA's Space Launch System, as the agency plans to make titanium propulsion tanks and entire rocket engines with additive manufacturing technology.

The Orion plan reflects an industry-wide trend of cautiously incorporating such parts into spacecraft and rockets, the ultimate goal being to convince customers that they can trust additive manufacturing with the lives of astronauts and the fate of multibillion-dollar communication satellites and space probes.

BIG METAL, SMALL METAL

Additive manufacturing is so new that leading manufacturers of rockets and satellites are still figuring out the best techniques to make metal structures capable of withstanding the rigors of launch and the harsh vacuum environment of space. Such is the case with Aerojet Rocketdyne and Lockheed Martin.

Both companies rely on a powder-based process to build smaller components. A robotic arm lays down layers of metal powder that are fused into shape by a laser, and the arm then deposits another layer of powder to be fused. But their techniques diverge when it comes to making large components. Aerojet Rocketdyne uses a scaled-up version of the powder-based method to manufacture rocket engines, while Lockheed Martin builds big parts like propellant tanks from large strands of titanium wire welded into shape with a high-energy beam.

Slade Gardner, a Lockheed Martin fellow focusing on advanced manufacturing and materials, refers to the powder bed method as "small metal," because it typically is used to make such parts as mounting brackets for communications antennas. He calls the alternative wire-fusing process "big metal," and his company hopes to someday make tanks that way for Orion and other spacecraft.

Aerojet Rocketdyne, by contrast, likes the powder-based system even for large items, such as nozzles, fuel injectors and ultimately entire engines.

Lockheed Martin

The Sciaky electron beam additive manufacturing machine is the largest 3-D printer in use at Lockheed Martin Space Systems in Denver.

Despite the differences, the companies have similar construction setups, with clusters of computer-controlled additive manufacturing machines working in concert to make parts. At Lockheed Martin, the big metal construction gear consists of a large vacuum chamber containing a robotic arm from Chicago-based Sciaky, Inc. It has an attached feeder containing a 100-pound spool of titanium wire and an electron gun. A vacuum is necessary for the electron gun to fuse the wire into shape. The arm moves along ceiling-mounted slides that allow it to move back and forth, left to right in what resembles a very large version of a desktop fabrication device, Gardner explains. The working chamber also contains a table that can tilt and move side to side, permitting the arm to build complex shapes.

When the electron gun fuses the titanium wire, it creates a bead of metal. As layers of wire are put down, the resulting surface is rough and much thicker than the target width of what will be a lightweight structure. A second robotic arm trims away the excess metal and machines the walls down to their proper thickness.

"Inherently it's still a welding process. If you imagine the way that really beautiful weld beads look, they have some flow to them. We cannot achieve smooth wall surfaces using this deposition process," Gardner says.

To build a propellant tank, a satellite or rocket, the Sciaky wire-deposition gear builds two domes and a central "barrel" section. A grinder mounted on a robotic arm then machines the three parts to remove excess material and to achieve the desired thickness of .02 to .04 inch before they are welded together.

So far, Lockheed Martin has built a 16-inch diameter prototype propellant tank, as well as parts for a 33-inch diameter tank. The prototype tanks are built to the requirements of the company's A2100 communications satellite frames. It takes about 15 hours to get a tank to its basic shape, with each dome and barrel requiring roughly three hours to construct. The entire process from construction to machining, welding, and final testing takes roughly a month, Gardner says. This is a great improvement over the traditional method of making a tank, which required forging a mushroom-shaped dome of titanium and machining it down to size. The forging process requires a lengthy lead time, up to 12 months and tank sizes are limited to less than 50 inches in diameter due to the cost and expense of making the dies and presses. Plus, with additive manufacturing, engineers can change a product by adjusting the digital blueprint that the robotic equipment follows, rather than having to make new dies and presses. Additive manufacturing eliminates the long wait times and the size limitations for making titanium propellant tanks, because it's easier to adjust robotic arms in the chamber than to adjust conventional tools to make a new component. "You can build a bigger vacuum chamber for a lot less money than building a bigger forging press," Gardner says.

Aerojet Rocketdyne's powder-bed deposition process chamber resembles a large sandbox, but the sand is a specific mix of metal powders that are fused with a laser into the desired shape, explains Jay Littles, director of advanced launch programs at Aerojet Rocketdyne in Huntsville, Alabama. Depending on the component, the powder can be titanium or nickel alloys such as Inconel, or copper. Construction takes place in a vacuum chamber or one filled with an inert gas, using a machine provided by Concept Laser Inc. of Grapevine, Texas, the U.S. subsidiary of the German additive equipment company.

A turning point for Aerojet Rocketdyne came in 2014 when it test fired a subscale version of its RS-88 Bantam engine on the ground. Whereas the Baby Bantam generated 5,000 pounds of thrust, Aerojet Rocketdyne has now additively built a 30,000-pound thrust, regeneratively cooled version of the Bantam. The company has also manufactured a full-scale integrated injector assembly for possible use on its RL10 engines. Rocketdyne has also manufactured a full-scale regeneratively cooled copper chamber for an 18,000-pound thrust liquid oxygen/liquid hydrogen upper stage engine and is preparing to demonstrate a slightly larger additively manufactured engine in the 25,000 to 35,000 pound thrust range, Littles says.

ALMOST READY FOR FLIGHT

Aerojet Rocketdyne and Lockheed Martin are working on incorporating more additively manufactured parts in current and upcoming satellite and rocket projects. This will be a gradual process, say Littles and Lockheed Martin's Brynn Watson, vice president of engineering operations in Sunnyvale, California. Beyond making more parts for spacecraft, manufacturers are looking at redesigning their entire industrial processes. Lockheed Martin has an integrated design-to-construction process called the digital tapestry that combines rapid software-based testing and modeling with 3-D printed prototypes and parts. The company is also considering investing in "clusters" of additive manufacturing robots to speed production with the long-term goal of being able to essentially print an entire spacecraft. "Our 3-D printing capability is evolving," Gardner says. "We're starting with propulsion tanks and will progress onto other elements. We eventually plan to include other parts and systems, like the structure for heat shields."

Lockheed Martin

A Sciaky 3-D manufacturing machine, located at the Lockheed Martin Space Systems plant in Denver, makes a propellant tank for a satellite. The machine unspools titanium wire, which is then welded into shape with an electron beam.

Lockheed Martin expects to fly its first additively manufactured large components, such as propulsion tanks, within five years.

Aerojet Rocketdyne is also restructuring its design and construction processes. The company has spent the last half decade investing in 3-D construction techniques for developing components for rocket engines and other spacecraft parts. This process is now poised to begin moving to operational missions. "We are at the point to really start reaping the benefits of the significant investments we've made over the past four or five years," Little says.