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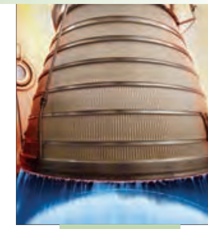


The new meaning of additive value

NASA GLENN'S SUCCESSFUL HOT-FIRE testing of an injector assembly designed and made by Aerojet Rocketdyne may well prove to be a significant milestone in the development of rocket engine manufacturing. In creating the assembly, the company had used an innovative 3D additive manufacturing technique.

The test demonstrated that one of the most critical and expensive components of a rocket engine could be built to the required standard much more quickly, simply, and cheaply with the additive manufacturing technique than with traditional methods.

By using selective laser melting and 3D fusing of a metallic-powder bed (in an inert gas environment to minimize the potential for oxidation of the powder), Aerojet Rocketdyne was able to manufacture two separate subassemblies. When joined, these structures created the entire center-core section of a full-scale injector that would represent a liquid oxygen-hydrogen RL10 engine.

Reducing complexity

With most conventional manufacturing techniques, the company would have to make more than 100 parts and then turn them into a finished injector using a combination of forging, plating, brazing, welding, and five-axis milling. Hundreds of holes and ports would have to be machined into the injector assembly to ensure that it would function as designed.

Tyler Hickman, NASA Glenn's hot-fire task lead for the Manufacturing Innovation Project (MIP), says a variety of "complicated flow passages" inside the RL10 injector "make it difficult to machine conventionally."

In a sizable rocket engine, the injector assembly usually is among the most expensive components, because its manufacture is extremely time- and labor-intensive. However, 3D additive manufacturing took no more than six days each for the test injector's two parts, says Jeff Haynes, Aerojet Rocketdyne's additive manufacturing program manager. The company paid for the manufacturing project entirely with internal funding.

Task lead Tyler Hickman, in red shirt, and technicians inspect the additively manufactured rocket injector assembly as it is installed in the Rocket Combustion Laboratory at NASA Glenn. Courtesy NASA.

Although each part required some postprocessing and heat treatment (both parts were treated at the same time), the finished injector core was available no more than eight weeks after manufacture began. Fabricating the injector core conventionally would have taken a year or more, says Haynes. For some parts of the injector, such as closed-die forgings, it would normally take six months of manufacturing lead time before they could be incorporated into a subassembly.

"We struggle to quantify the support cost" of labor and all the other factors implicit in a six-month lead time, says Haynes. "But if we can print a part in six days, we don't have that support cost."

That is one reason why Aerojet Rocketdyne selected the RL10 injector for its first major experiment, aimed at determining if additive manufacturing could cut the time and cost involved in rocket engine production.

In service for more than 50 years, the RL10 is one of the most widely used upper-stage engines in the history of space propulsion. It has helped place many military, government, and commercial satellites into orbit, and has powered space probe missions to nearly every planet in the solar system. RL10 missions included Juno to explore Jupiter; New Horizons, now en route to Pluto and the Kuiper Belt; the Solar Dynamic Observatory; Radiation Belt storm probes; and the Lunar Reconnaissance Orbiter.

More than 435 RL10 engines have flown in space. Today the engine continues as a reliable workhorse in the form of the RL10A-4-2, delivering 22,300 lb of thrust to power the upper stage of the Atlas V rocket; and the RL10B-2, with 24,750 lb of thrust powering the upper stage of the Delta IV.

The company sees the RL10 "as a good pull for this [additive manufacturing] technology and probably one of the lead programs to pull it in." If the experimental RL10-equivalent injector core's success is replicated in similar cost savings in future tests, then Aerojet could eventually use additive manufacturing routinely to fabricate complex RL10 assemblies.

The RL10-like injector center core tested by NASA used full-scale RL10 features "as a baseline," says Haynes.

However, the 3D manufacturing machine for which Aerojet Rocketdyne designed the part could produce parts measuring up to just 10 in. in any dimension. Since the production RL10 injector is 12 in. in maximum dimension, "we truncated" the design of the 3D part so it could be contained within a 10-in. cube, he says. However, its design faithfully replicated the LO_X post features of the RL10 injector.

In an RL10 engine, notes Haynes, "there is a very complex series of parts that bring the fluids together efficiently." If the injector is not manufactured or assembled to the sufficient standard, mixing of the fluids can create "very bad instability" when they are ignited in the combustor. The size, shape, and density of the spray cone of LO_X released into the combustor are particularly important.

Testing at Glenn

Before the full injector center-core assembly was sent to Glenn for testing (which NASA paid for under a nonreimbursable Space Act agreement as part of its MIP), the AFRL at Edwards AFB provided Aerojet Rocketdyne with pretest data on the LO_X-spray pattern of the test RL10 injector. AFRL tested the LO_X injector from the additively manufactured injector core in its high-pressure cold flow test facility, which is able to generate much higher fluid flow pressures than the company's own facilities, according to Haynes.

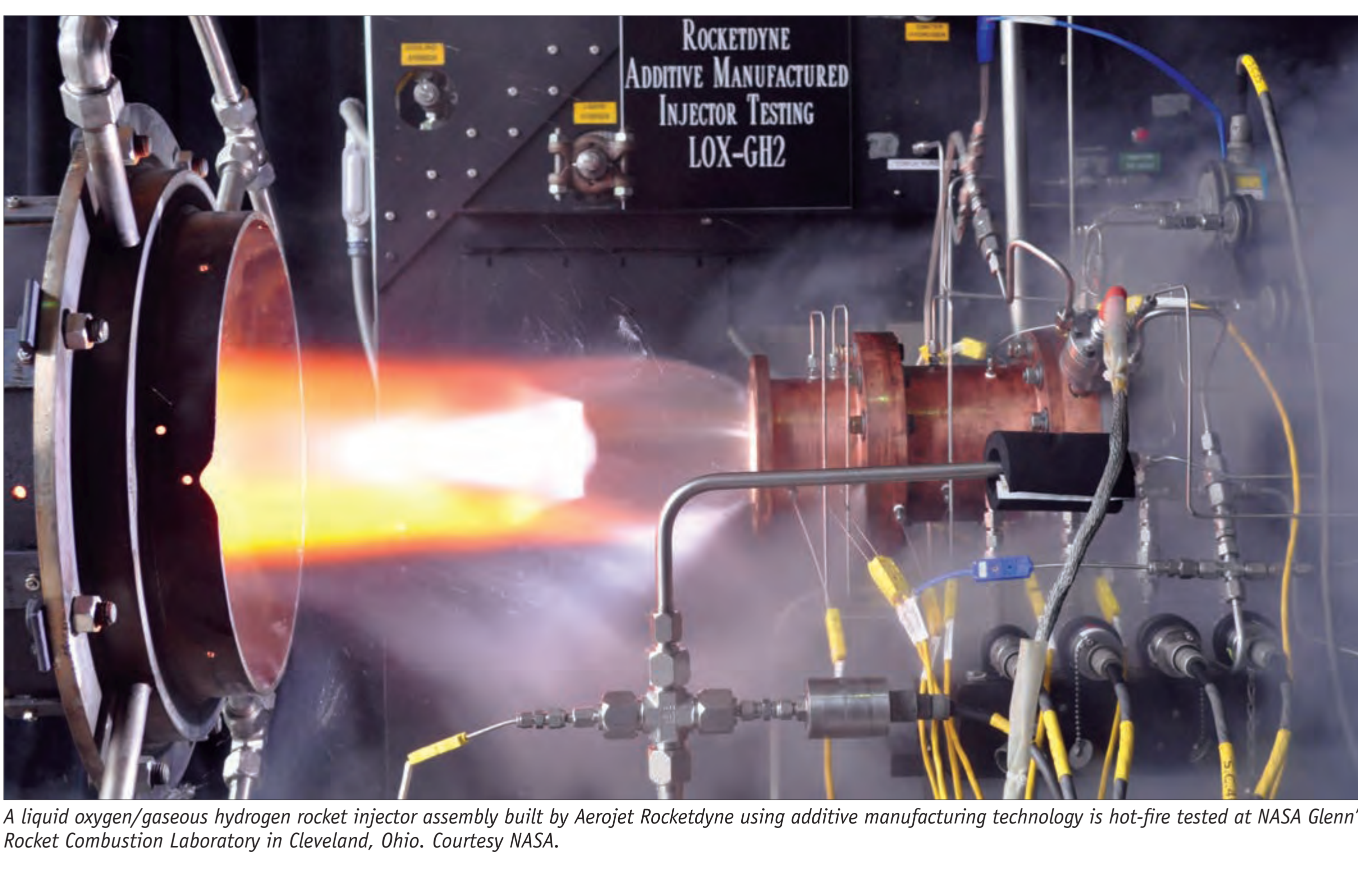
Reviewing the AFRL data gave the company "a lot of confidence" that the LO_X spray from the specially made injector would be "within the variability" needed to perform like a production RL10 in NASA Glenn's hot-fire testing, according to Haynes.

AFRL's offer to participate provided an "excellent" opportunity for Aerojet Rocketdyne and NASA to extend the government-industry partnership and the cost-sharing collaboration associated with the tests. Carol Tolbert, project manager for the MIP at Glenn, says AFRL funded the cold flow pretesting of the LO_X injector, maximizing the benefit of the funds that Aerojet Rocketdyne and NASA had made available for their parts of the effort. (NASA Langley and NASA Marshall are also involved in the MIP, each with its own research projects.)

Hickman coordinated the test activities at Glenn and led the design team that produced the supporting hardware for the injector test. He says Glenn first performed a series of cold-flow tests using nonreacting fluids to characterize the pressure drop in the system, refine the abort limits, and perfect the valve timing for the first ignition attempt.

Valuable data

Although the injector Glenn tested was not quite a full-size RL10 injector, Hickman says the hot-fire test data NASA obtained was significant. The exercise demonstrated that the addi-



A liquid oxygen/gaseous hydrogen rocket injector assembly built by Aerojet Rocketdyne using additive manufacturing technology is hot-fire tested at NASA Glenn's Rocket Combustion Laboratory in Cleveland, Ohio. Courtesy NASA.

tively manufactured assembly was able to withstand intense cold (in the form of LO_X); intense heat from combustion in the chamber, just downstream of the injector; and high pressures, since the pressure of the thrust chamber was significantly higher than the pressure of the external environment.

The test data will help NASA and Aerojet Rocketdyne to scale additive manufacturing and testing of components to a larger engine. Indeed, both groups are already looking ahead to more tests. The RL10 injector-core test was "the first of many hot-fire tests" NASA is planning "for infusing this technology," says Hickman.

A production RL10 engine awaits testing. Courtesy: Aerojet Rocketdyne.

The organizations continue to look at other engine parts that might benefit from additive manufacturing. "It may not be the whole engine, but it could be some of the most expensive parts," says Tolbert.

Other possibilities

NASA and Aerojet Rocketdyne have already tested two components of the J-2X engine for the Earth departure stage of NASA's planned Space Launch System: a workhorse gas generator duct in a rig test, and a fuel maintenance port cover in a full engine test. Neither has the complexity of an injector, but both tests provided exposure to combustion environments. Tolbert says NASA is also looking at how—in the longer term—astronauts might additively manufacture components and equipment in space, or on the surface of Mars.

Haynes notes powder-bed melting would not be a suitable additive manufacturing technique for space, because "zero *g* would wreak havoc on the powder." Laser melting of metal powder beds may also be a challenging technique for very large engine parts: A machine capable of making a part eight times the volume of a 10-in. cube would have to manipulate more than a ton of metal powder, a very difficult task. This machine exists today, but it is still being evaluated for the larger scale capability.

Other additive manufacturing techniques might be able to take up the slack. For instance, electron beam freeform fabrication (EBF3) uses a wire feed rather than powder. A potential disadvantage is that to be effective, the electron beams that melt the metal need a vacuum in order to operate. For in-space applications, however, EBF3 is ideal.

Additive manufacturing potentially could be used to 'print' an entire in-space thruster that is small, pressure-fed, and has no turbomachinery, according to Haynes. He says that the approach would be particularly suitable for rocket engine parts that require no postprocessing.

Haynes says such techniques would not be applicable to building an entire large engine like the space shuttle main engine, which would be "too big and complex." They could, however, be used to manufacture complex subassemblies quickly and cheaply. Now that a powder-bed additive manufacturing machine is available that can 3D manufacture a component the size of a 15-in. cube, this could "potentially support [production of] an entire injector."

Future outlook

Haynes and Hickman believe that routine production of small, simple rocket engine parts such as brackets and fittings might be only a couple of years away. Hickman estimates that the hot-fire test of the RL10 injector assembly took the technology readiness level (TRL) of additive manufacturing for rocket engine parts from TRL3 to TRL4 or even TRL5 (TRL6 represents a wholly production-ready technology).

However, routine use of this technology for production of complex rocket engine assemblies is still four or five years away, in their opinion. The reason is that although an additively manufactured part may appear to be exactly the same as an identical-looking part made using traditional methods, it is not the same.

"We're treating [additive manufacturing] as a new product," Haynes says. "We're having to define that and get the data we need" to show adequate manufacturing repeatability, to define and maintain the range of acceptable variability among parts, and to discover the limits of the process.

Theoretically, a component manufactured additively using powder-metal melting and deposition should demonstrate more repeatability and less variability in its properties than a part made by working sheet metal. First, however, manufacturers such as Aerojet Rocketdyne must do a lot of design, manufacturing, and testing work to demonstrate that this is indeed the case. This requires development of new design data that takes the new manufacturing method into account. That in turn means creating a new design and product definition process.

"We spent over a year building and developing design data," Haynes says. "To print out highly valuable equipment such as rocket engines, it is key to have specific design data for it in order to have your customers recognize it as production-ready technology."

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