

The rocket motor of the future “breathes” air like a jet engine

Enlarge / The air intake on Mountain Aerospace Research Solution's Fenris engine after its first hotfire last July. The lines around the cone feed kerosene and gaseous oxygen into a combustion chamber, where it is mixed with the air and ignited.

Aaron Davis | Mountain Aerospace Research Solutions

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There's a small airfield about a two-hour drive north of Los Angeles that sits on the edge of a vast expanse of desert and attracts aerospace mavericks like moths to a flame. The Mojave Air & Space Port is home to companies like Scaled Composites, the first to send a private astronaut to space, and Masten Space Systems, which is in the business of building lunar landers. It's the proving ground for America's most audacious space projects, and when Aaron Davis and Scott Stegman arrived at the hallowed tarmac last July, they knew they were in the right place.

The two men arrived at the airfield before dawn to set up the test stand for a prototype of their air-breathing rocket engine, a new kind of propulsion system that is a cross between a rocket motor and a jet engine. They call their unholy creation Fenris, and Davis believes that it's the only way to make getting to space cheap enough for the rest of us.

While a conventional rocket engine must carry giant tanks of fuel and oxidizer on its journey to space, an air-breathing rocket motor pulls most of its oxidizer directly from the atmosphere. This means that an air-breathing rocket can lift more stuff with less propellant and drastically lower the cost of space access—at least in theory.

The idea to combine the efficiency of a jet engine with the power of a rocket motor isn't new, but historically these systems have only been combined in stages. Virgin Galactic and Virgin Orbit, for example, use jet aircraft to carry conventional rockets several miles into the atmosphere before releasing them for the final leg of the journey to space. In other cases, the order is reversed. The fastest aircraft ever flown, NASA's X-43, used a rocket engine to provide an initial boost before an air-breathing hypersonic jet engine—known as a scramjet—took over and accelerated the vehicle to 7,300 mph, nearly 10 times the speed of sound.

But if these staged systems could be rolled up into one engine, the huge efficiency gains would dramatically lower the cost of getting to space. "The holy grail is a single-stage-to-orbit vehicle where you just take off from a runway, fly into space, and come back and reuse the system," says Christopher Goyne, director of the University of Virginia's Aerospace Research Laboratory and an expert in hypersonic flight.

The big challenge with a single-stage-to-orbit, or SSTO, rocket is that achieving the speeds necessary for orbit—around 17,000 mph—requires a lot of propellant. But adding more propellant makes a rocket heavier, which makes it harder to reach orbital velocity. This vicious circle is known as the "tyranny of the rocket equation," and is why it takes a two-stage rocket the size of an office building to launch a

satellite the size of a car. Staging a rocket helps because it can shed dead weight once the first stage's propellant is used up, but it's still pretty inefficient to have to burn all that propellant in the first place. This is where an SSTO rocket with air-breathing engines would provide a huge efficiency boost.

"The idea is to use air-breathing engines earlier in the launch to take advantage of efficiency gains from engines that don't have to carry their own oxidizer," says Goyne. "Once you get high enough in the atmosphere, you start to run out of air for the air-breathing system and you can use the rocket for that final boost to orbit."

Big money, big challenge

When Davis founded Mountain Aerospace Research Solutions in 2018, no one had ever made a working air-breathing rocket engine before. NASA and aerospace giants like Rolls-Royce had tried, and all the projects fizzled out due to soaring costs and major technological challenges. But Davis, a former Aviation Ordnance technician in the Marines, had an idea for an air-breathing engine of his own and couldn't shake the idea. "I hired Scott Stegman to prove to me it wouldn't work," Davis says. But Stegman, who previously worked as a mechanical engineer at Northrop Grumman, crunched the numbers and didn't find any showstoppers. As far as physics was concerned, Davis' engine seemed like it should work.

According to Stegman's calculations, a full-scale Fenris engine could reduce the amount of oxidizer a rocket needs to carry by around 20 percent. That's a huge efficiency gain, but first they had to demonstrate that Davis' design would work. Davis lacked the funds needed to run detailed fluid dynamics simulations to model the engine on a computer, so the duo decided to build a physical engine instead. "At the end of the day, you can make really pretty simulations and nobody's going

to believe you," Davis says. "It was cheaper to just go out and test whether my idea was valid or not."

By the time Davis started the countdown at the Mojave Air & Space Port last July, he and Stegman had been working on the Fenris prototype for nearly a year and a half. Davis says he paid for the engine's development entirely out of pocket and estimates that he's spent about \$500,000 on the project so far. The hourglass-shaped engine isn't much larger than a toaster oven and is designed to passively pull in air from one end, combine the air with kerosene and some gaseous oxygen in a combustion chamber, and spit flames out the other end. And when Davis triggered the ignition last year, the Fenris engine worked.

Davis claims that test is the first and only time an air-breathing rocket motor has been successfully hotfired. It's a big assertion and it comes with an important caveat: The Fenris engine wasn't even close to powerful enough to send anything to space. The duo haven't released any data about the engine's performance, but in video of the engine firing it's clear that the exhaust lacks the ordered structure you'd expect to see in a high-performance rocket engine. In fairness, Davis and Stegman weren't trying to get to the final frontier. They just wanted to see if their engine could pull air in one end and belch flames out the other without blowing up. "It's literally a rocket engine with holes at both ends," Stegman says. "That's not normal and it's why we were really conservative for the first test."

Later this year, Davis and Stegman will run some more advanced engine tests in a decommissioned missile silo in Wyoming. Unlike the first test run, these will be all about pushing Fenris to its limits and extracting as much power as possible from the experimental engine. Based on his computer models, Davis says he expects to achieve over 600 seconds of specific impulse during the tests, which is a measure of how efficiently a rocket engine uses its propellant. This would be

a monumental achievement given that the world-record specific impulse—held by NASA—is 542 seconds, and most operating orbital rockets have specific impulses around 300 seconds. If the demos in Wyoming go well, the next big step would be to demonstrate the motor in flight. If he finds a launch partner, Davis says the Fenris engine could fly as soon as 2022.

Enlarge / The air intake on Mountain Aerospace Research Solution's Fenris engine after its first hotfire last July. The lines around the cone feed kerosene and gaseous oxygen into a combustion chamber, where it is mixed with the air and ignited.

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Historically speaking, Davis and Stegman are in good company. The birth of modern liquid-fueled rockets was driven by amateurs like Robert Goddard, Jack Parsons, and Werner von Braun who cleared the path for the massive state-run rocket programs that followed. But not everyone is convinced that Fenris is a game changer.

“I am skeptical of the entire concept,” says Dan Erwin, a professor of aerospace engineering at the University of Southern California and an expert in propulsion. One concern is that the atmosphere is mostly inert nitrogen—and in a rocket engine that nitrogen acts like a wet blanket. It gets heated by the combustion reaction between the oxygen and the kerosene without contributing to it, which lowers the combustion temperature and reduces thrust. And while nitrogen can contribute to an engine’s thrust—since it’s being heated in the combustion chamber and expelled through the nozzle—the exhaust speed must be greater than the spacecraft’s speed. Otherwise, Erwin says, the air is moving forward relative to the stationary atmosphere when it exits the engine, and this would detract from the rocket’s forward momentum. While such an engine isn’t impossible, it would have to be incredibly high performance.

Adonios Karpetsis, an aerospace engineer at Texas A&M University and an expert in high-speed combustion, also has qualms about the feasibility of the Fenris engine. He points out that although rockets spend most of their time moving at supersonic or hypersonic speeds, the combustion chamber itself

doesn't experience those conditions. This is not the case with hypersonic air-breathing engines, which experience hypersonic airflow in the engine itself. This has been a major technical challenge for companies building hypersonic scramjet engines and would also be faced by an air-breathing engine like Fenris during flight. "The one static fire test of the Fenris device took place at zero speed," says Karpetis. "What will happen when the Fenris device becomes truly supersonic and air is rushing into it through the inlet at high speeds? A simple guess would predict diminishing behavior, quickly reducing the 600 seconds specific impulse to some lesser value."

It ain't easy

There is a long history of organizations with lots of money and plenty of expertise that struggled to bring air-breathing rocket engines to life. In the 1980s, NASA and a partnership of British aerospace companies were both pursuing concepts for SSTO air-breathing space planes that could replace the space shuttle. NASA's vehicle, known as the National Aero Space Plane, was designed to use an air-breathing scramjet to accelerate to 25 times the speed of sound [PDF] and reach orbit without a rocket engine. The British vehicle, called Horizontal Take-Off and Landing (or Hotol), was meant to have a hybrid engine that combined aspects of a jet engine and a rocket motor.

Budget constraints killed both spaceplane programs before they were ever built, but Alan Bond, one of Hotol's lead engineers, couldn't quit the idea. In 1989, Bond founded Reaction Engines to build a new air-breathing rocket engine based on Hotol's designs. He envisioned using the engine on a conceptual space plane he called Skylon, which looks like a rocket outfitted with an air-breathing engine at the tips of its two narrow wings. Skylon's engine is known as the Synergetic Air Breathing Rocket Engine, or Sabre, and although the spaceplane is still little more than a concept, the engine is very real.

The idea behind Sabre is to use the engine's air-breathing mode to whip a spacecraft up to hypersonic speeds in the lower atmosphere and then switch to a full rocket mode at the edge of space. It's conceptually simple, but the devil is in the details. For example, as the engine works the aircraft up to hypersonic speeds at low altitudes, the air temperature approaches 1,800 degrees Fahrenheit, which is hot enough to melt engine components. To overcome this challenge, Sabre uses a precooler to lower the air temperature by circulating hydrogen fuel through the engine. This lowers the air to ambient temperatures at altitude, which are around -200 degrees Fahrenheit. "Effectively the core engine does not know it is flying hypersonically," says Shaun Driscoll, the programs director at Reaction Engines. "The precooler takes care of that."

Once the air is lowered to a manageable temperature, it's passed to a compressor to raise the gas pressure, much like in a conventional jet engine. Then it's routed to a rocket combustion chamber where it is mixed with liquid hydrogen fuel and ignited to produce thrust. By the time the vehicle reaches hypersonic speeds, the atmosphere is too thin for an air-breathing engine and the system switches to its onboard oxidizer tank for the final leg of the journey to space.

Bond retired from Reaction Engines in 2017, but work on the Sabre engine continues apace. Over the past four years, the company has raised over \$100 million to develop Sabre, and shortly after Bond stepped back from the company, Reaction Engines contracted with Darpa to develop a test facility for the engine's precooler in Colorado. Late last year, the company demonstrated that its precooler could handle the extreme heat generated under hypersonic conditions, a major milestone on its path to a full engine demonstration. Around the same time, the European Space Agency concluded its design review of the engine and gave the company the green light to start testing its engine core.

Reaction Engines CEO Mark Thomas says the company expects to begin these tests next year. The Sabre engine core is the air-breathing heart of the propulsion system stripped of its exhaust nozzle and the precooler. "These tests will take place during next year and will be a significant step towards the world's first air-breathing engine capable of accelerating from zero to Mach 5," says Thomas. If these tests go well, Thomas says the next big step will be to integrate all the engine components and perform a high-speed flight demonstration with a custom airframe. Thomas says he anticipates the first demo flight to happen by the mid-2020s.

"In recent years commercial launch companies have delivered significant advances in reusability and reductions in launch costs, however, their approach is essentially utilizing existing chemical rocket technology that has been used for over 70 years," Thomas says. "Only an air-breathing system will deliver a further quantum reduction in launch costs and reliability."

Sabre is the culmination of more than 40 years of research and development backed by millions of dollars in government and industry funding. It's about as far as you can get from two guys juicing a small prototype rocket engine in the desert, but Davis isn't phased by the long odds. "This matters more than anything," he says. "Only 600 people have ever been to outer space and I'm not going to quit until I've realized that ability for everybody."

This story originally appeared on wired.com.

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