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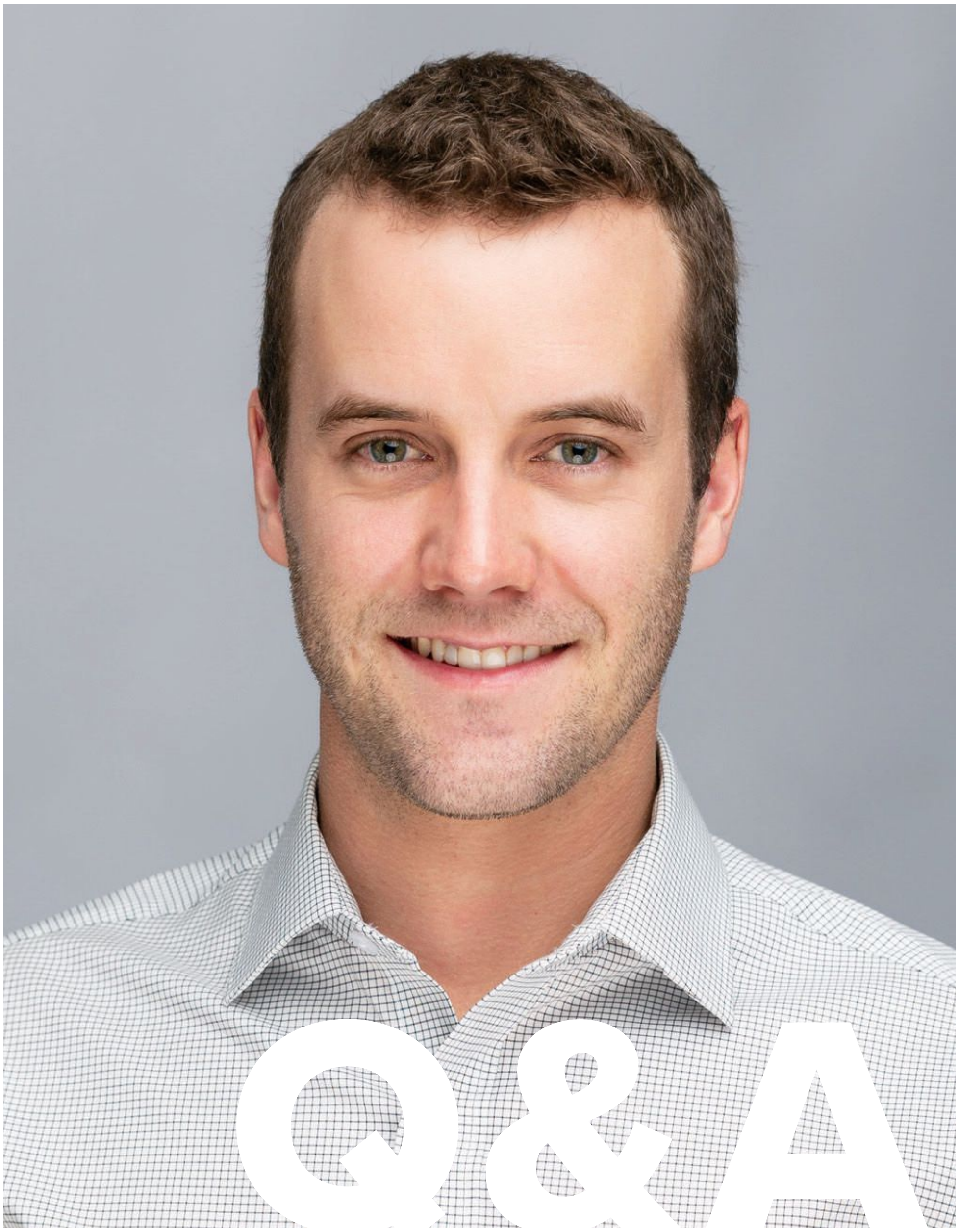


AeroVironment

Martian aviator

Even before the now-famous Ingenuity helicopter made its first flight on Mars in 2021, Ben Pipenberg and his colleagues at drone maker AeroVironment began thinking about the next iteration of the aircraft whose airframe and rotor system they built. Knowing about the plan to bring samples of Mars back to Earth, they conceptualized and prototyped a helo with a gripper capable of grasping sample tubes, and demonstrated a model of this "advanced Mars Sample Fetch helicopter" to the NASA-funded Jet Propulsion Laboratory. The name was an obvious play on the NASA-European plan to send a Sample Fetch Rover to Mars, a plan that was abandoned last year in favor of sending two helos to Mars to retrieve the samples not collected by Perseverance. As of mid-December, NASA was assessing proposals. I reached Pipenberg by Zoom to discuss the company's concept. — *Paul Marks*

BEN PIPENBERG

POSITIONS: Since June, program chief engineer of AeroVironment's effort to create potentially multiple helos to retrieve some of the samples left on the surface of Mars by NASA's Perseverance rover; 2019-August 2022, chief engineer of a military drone program AeroVironment isn't permitted to name; 2017-October 2022, design lead and chief engineer for AeroVironment's fabrication of the rotor system and primary airframe structure for NASA's Ingenuity Mars Helicopter; 2014-2017, aeromechanical engineer at AeroVironment.

NOTABLE: Started his career at AeroVironment in 2009 as an engineering intern working on the Nano Hummingbird, later named one of TIME Magazine's 50 best inventions of 2011. Part of the NASA and Jet Propulsion Laboratory Ingenuity team that was awarded the 2021 Collier Trophy for demonstrating the first powered flight on Mars.

RESIDES: Los Angeles area

AGE: 33

EDUCATION: Bachelor of Science degree in aerospace engineering, Pennsylvania State University, 2011

Q: How long has AeroVironment been working on NASA's Mars helicopter program?

A: On Ingenuity, we started working with JPL very early on, initially in the late 1990s, early 2000s. There was some very initial, conceptual work that ended up not really going anywhere, but AeroVironment was involved in putting together some of the concepts for very early rotorcraft designs. And then, around 2012 or 2013, Bob Balaram, chief engineer for JPL's Ingenuity program, approached AeroVironment about starting work again on a small rotorcraft to demonstrate the utility of aerial robotics on Mars. And so, from pretty early on AeroVironment was doing the design and conceptual work on what would eventually become Ingenuity. After the early conceptual design work, AeroVironment was involved all the way through, designing, developing and building basically what we would call the airframe, the rotor system and the propulsion systems. That's Ingenuity's primary structure, the rotor blades, the landing gear system and the box on the bottom — that we call the helicopter's warm electronics box — plus the structure for the solar array, the propulsion motor, the servos and all the linkages and swash plates that control the rotors.

Q: What was it like to see the aircraft you built placed on the surface of Mars by the Perseverance rover in 2021?

A: It's pretty incredible. You go outside at night and you look up in the sky and you can see Mars, and you know, conceptually, that's a couple hundred million miles away. And then you go inside and you look at the images that are coming down from Ingenuity or of Ingenuity being taken by Perseverance, and it's really hard to wrap your brain around just how far away it is. We were working on the helicopter for years — we were all handling all of these pieces that have been in our labs, on our benches, so we're very familiar with it. Seeing it on the surface of Mars in this very, very alien environment is absolutely amazing.

Q: And what about when it spun up its rotors and flew on Mars for the first time?

A: In some ways, we had a lot of confidence. We had done an enormous amount of testing on this thing. This was basically the fourth helicopter that had flown in a Mars-like environment in the space simulator at JPL. So in some ways, it was completely unremarkable to us: It looked just like what we had been seeing. Except, of course, it's on Mars! It was pretty surreal, I think, for everybody. It was the culmination of years and years of work, and a lot of overtime, a lot of nights and weekends for everybody. So yeah, there were a lot of happy tears about that.

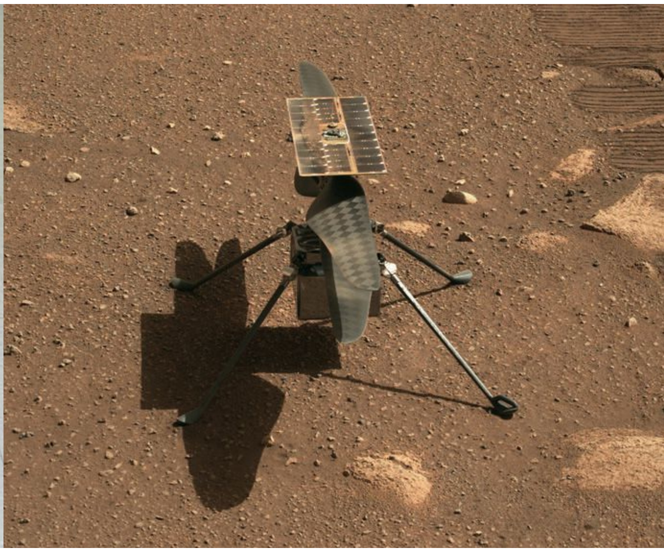
Q: What motivated your team to hatch the idea of the upgraded Ingenuity-class Mars helicopters for Mars Sample Return?

A: That concept was developed as a sort of tertiary backup. Perseverance, of course, is the primary means of getting samples to the Sample Retrieval Lander.

> *Plans call for Perseverance to backtrack to collect samples and deliver them to the Sample Retrieval Lander after its arrival in 2030 along with a Mars Ascent Vehicle. That rocket would boost the samples into orbit to rendezvous with the planned Earth Return Orbiter. The samples would land in Utah in 2033 (subject to ongoing back-contamination and environmental risk assessments). — PM*

The backup to that was the Sample Fetch Rover, the small European rover. And then we were looking at the recovery helicopter as sort of a tertiary backup, either deployed from the backshell [of the Retrieval Lander] during entry, or maybe stowed on the lander somewhere. Of course, the last eight months or so have kind of reordered things significantly. It's a single lander solution now when it had previously been two landers.

> "Precise positioning with just the aerial mobility system is likely possible, but it's pretty difficult. It's easier to develop a system which can very precisely position the vehicle down to millimeter kind of resolution on the surface, using a wheeled mobility system."



▲ In designing its sample recovery helicopter (an early model is shown at left), AeroVironment kept many of the design elements from the 1.8-kilogram Ingenuity helicopter, pictured at right on the surface of Mars days before its first flight in April 2021. The biggest changes are the addition of wheels for precise maneuvering up to caches of samples stowed on the Martian surface, and a robotic arm for retrieving multiple sample tubes, shown here stowed horizontally along the model.

AeroVironment

Q: What's the idea in giving the new helicopters motor-driven wheels?

A: Precise positioning with just the aerial mobility system is likely possible, but it's pretty difficult. It's easier to develop a system which can very precisely position the vehicle down to millimeter kind of resolution on the surface, using a wheeled mobility system. You can move much slower — and you can take your time to do that.

Q: What kind of sample tube pickup scenarios will that be useful for?

A: It's really just for the last meter or 2 meters — so in this case, you land near your sample, and then you drive right up to it. The other reason is so that we don't need to fly near the landed asset: the Sample Retrieval Lander with the MAV on it. We can land a couple of meters away and then drive up, which obviously is a much lower kinetic energy approach.

Q: Why stand off from those assets? Worried about damage to the MAV?

A: With Perseverance in particular, there's no good scientific reason for Ingenuity to ever come close to it. It's an unnecessary risk. And so with the Sample Retrieval Lander, that's not necessarily the case: We have to get the sample tubes right up to the lander so that the [lander's] sample transfer arm is able to pick those samples up off the ground and put them into the MAV. And so we do need to interact with the lander, but doing that in the safest way possible, of course, is desirable. And if we're on wheels, rather than spinning our rotor blades at 2,800 rpm, that's seen as a safer approach.

Q: It can be minus 60 degrees Celsius on Mars. What stops the motors from simply freezing up?

A: On Ingenuity, the primary propulsion motors were designed, developed and built at AeroVironment. The materials and the thermal design of the motor are pretty unusual. We use some exotic alloys in there, such as AlBeMet — an aluminum beryllium metal matrix — for the heatsink. The lubricants used are designed for very low temperature operation, with very low outgassing, which is really important for operation in a vacuum.

Q: That's way beyond conditions for unoccupied aerial vehicles on Earth. How did you predict what you'd need?

A: The motor design was pulled, indirectly, from AeroVironment's experience with very-high-altitude pseudo satellites — the HAPS programs everyone's working on. The atmospheric temperature on Mars is actually pretty similar to where, for example, Helios, an AeroVironment-designed aircraft, flew.

Helios was a remotely controlled, ultra-lightweight solar-electric flying wing built for NASA. Driven by 10 electric propellors, Helios was flown at high altitudes to test the use of unoccupied aircraft as communications platforms, and in one record-breaking flight in 2001 reached an altitude of 96,863 feet. Helios broke apart and crashed into the Pacific Ocean during a 2003 test flight due to turbulence. — PM

That flew at 99,000 feet above ground, and the atmospheric temperatures there are very similar to where Ingenuity actually operates on Mars. We fly at about minus 40 degrees C, and it's about one one-hundredth of the atmospheric density at sea level here. And so that's a pretty similar environment, actually, and we were able to pull lessons learned from the HAPS and Helios programs into the design of those motors.

▲ AeroVironment built this full-scale test article of its sample recovery helicopter and drove it over a sandbox filled with different sized rocks and dirt to help determine the best wheel design for maneuvering the Martian terrain. The company also prototyped various versions of a robotic arm, shown here clutching a representative sample tube. AeroVironment is designing the helicopter to carry up to four 70-gram sample tubes.

AeroVironment

Q: What do you need to do to keep Martian dust out of the wheel-drive motor at ground level?

A: All of the motor systems are either sealed or shielded. The primary propulsion motors have Teflon seals, the servo actuators that drive the swash plates have spring-energized Teflon seals. And those go through quite a bit of testing to make sure that they're robust to the dust environment.

Q: Moving on to the next amazing thing about the new helos: your addition of a robot arm and gripper to the helicopter. What engineering issues does this present?

A: First of all, AeroVironment has been working on this on our own internal research and development funding. But what that arm is going to look like, and who's going to be developing it for the Sample Recovery Helicopter, is still very much in the works.

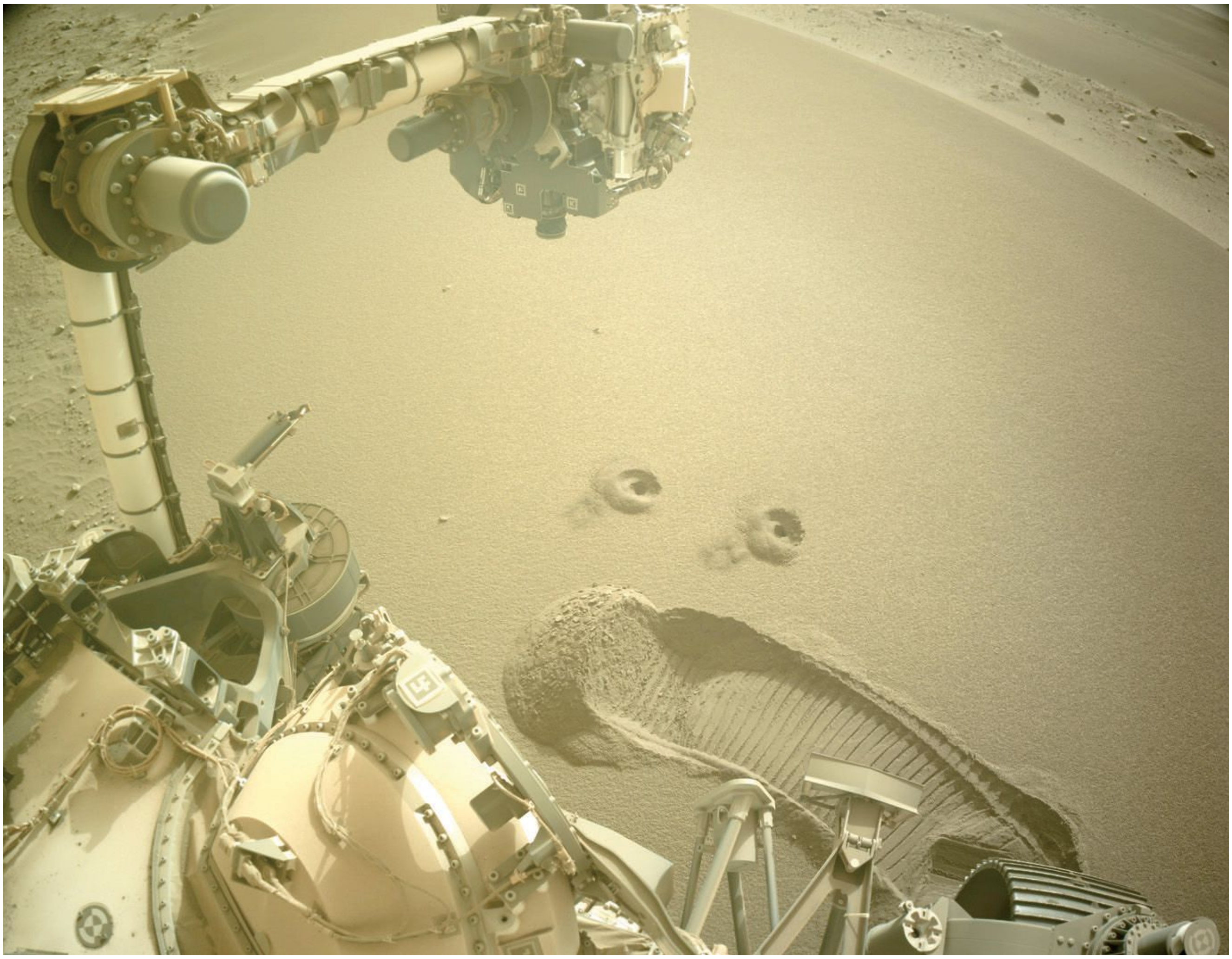
Q: So the robotic arm work could be performed by another contractor?

A: It could, right. JPL is going to be leading the integration on that. We do not have a contract for that. But what I can say from our work on it over the last year and a half is that mass is always at a premium with these helicopters. They're extremely sensitive to carrying any dead weight, so they really need to be optimized for mass. And so these manipulators and the arms — what JPL is calling the placement mechanisms — are going to have to be extremely highly optimized. And in particular, the loads these things see are really pretty high due to launch on a rocket, something that you really don't think about.

Q: By "loads" do you mean pulling Gs on liftoff?

A: Yes, exactly. The loads that these [robotic arm] mechanisms see when the engines initially ignite. And the first couple of seconds when they're coming off of the pad are very, very high. Those are by far the highest loads that the gearboxes and actuators ever see. So it's kind of an unusual design for an arm: Not only does it need to work in the very austere Martian environment, but it needs to take these very rough loads during launch.

Q: Why is it such a complex arm? In your paper presented at the 2022 IEEE conference, it is shown with two elbow joints.



▲ NASA's Perseverance rover collects two samples of Martian rock and regolith in early December in this photo taken by one of the navigation cameras on the rover's mast. One of those samples, encased in a tube, may be left in a cache near the delta of Jezero Crater for retrieval later this decade by Perseverance or one of the Sample Recovery Helicopters NASA's Jet Propulsion Laboratory is developing.

NASA/JPL-Caltech

A: We worked on a handful of different versions of that arm. I believe the one that we showed there has two joints up at the shoulder. So there's kind of a rotation about the vertical axis of the helicopter, there's the up and down, and then there's the elbow, and then there's actually a wrist mode as well, so it can rotate down. So that one's a four-degree-of-freedom arm, and then the gripper is on the end of it. So this is picking up just the tubes that Perseverance drops onto the surface. In the IEEE paper, I showed a few pictures of it kind of putting the tube into a docking mechanism, where it can hold it securely during flight. And then the helicopter basically drives up to the lander, releases the tubes and places them on the ground in front of the lander.

Q: I understand the new helos will have different batteries. Was there something wrong with the one on Ingenuity?

A: It's kind of funny, but these science programs that we send to space, we have to baseline the technologies really pretty early on so they can go through the test campaigns, actually get fabricated into the helicopter, go through all of the integrated tests with the rest of the spacecraft system, and then actually launch to Mars. And so by the time it is actually operating on Mars, it's well out of date. And Ingenuity is using battery technology from almost 10 years ago. There have been significant advances in lithium batteries since.

Q: I'm surprised that you can use off-the-shelf technology at those super-frigid temperatures.

A: That whole box on the bottom of Ingenuity is heated with conventional Kapton resistive heaters at all times. A lot of the energy from the battery is actually just used to keep itself warm, overnight and during the day. That strange color on the box, that kind of grayish color, that's a very specifically tuned optical surface to collect solar energy to warm that battery and to prevent it from radiating heat. It's called a selective surface. So quite a bit of effort goes into making sure that we can keep those batteries warm at all times.

Q: Have the seasons on Mars affected Ingenuity's ability to keep its electronics warm enough?

A: What's been happening is that because it's winter and there's a lot of dust in the atmosphere, the [solar] energy on Mars has been so low and the temperatures have been so cold at night that we are not able to keep Ingenuity warm overnight. It actually does get cold and so cold that the helicopter shuts down every single night and then restarts the next morning. And we've been operating like that continuously now since early May.

Q: How long does the solar-powered restart take?

A: It's a couple of hours. By about noon, things are warm enough that we can communicate with the helicopter, and it wakes up again. But that is not standard operation, right? We never intended for Ingenuity to operate in winter; it was originally designed for 30 days of operation from April 2021. And so we're kind of as shocked as anybody that it's been able to survive in this in this very, very low power state and that it's still able to operate.

Q: Ingenuity is called a helicopter and not a drone because it has rotors with both collective and cyclic control. Will the Sample Recovery Helicopters operate similarly?

A: Yes, that is likely going to be the case. In the IEEE paper, we were proposing putting just collective on one of the two rotors and cyclic on only one.

> *Collective pitch control means the rotor blades can be angled equally and simultaneously to produce vertical up/down motion; cyclic blade pitch control angles blades individually for forward/backward, nose up/down and roll control. — PM*

Actually, the first full-sized helicopter that we flew in May 2016 in the space simulator at JPL only had collective on one rotor and collective and cyclic on the other. It was being proposed in that paper as a mass saving.

Q: Because you'd need less metal to manipulate the rotors?

A: Yeah. Basically, we now have a lot of information about flying on Mars. And so that was one of the things that we're proposing, but it's not clear whether or not that's going to happen. There's a bit of an argument, at all times, between control margin and mass: If you can reduce mass, you can carry more other stuff, like make the [robot] arm heavier or whatever. But of course, control margin is important for just the basic stability when you have any kind of a disturbance, like wind or anything like that. And so what we're saying is that we only need collective on the upper rotor, we don't need cyclic, but that's TBD.

Q: Whatever happens, will the motors spinning those rotors be any different on the new helos?

A: Absolutely. These motors are a little bit unusual. Our flight time is relatively short: Three minutes lets us do what we need to do. But the environment on Mars, that very low atmospheric density, means that we don't get very effective cooling. In fact, we're assuming that we don't get any cooling at all, because we have these motors sealed against dust. It's a very strange operating condition because with Ingenuity, the maximum flight time was actually limited by overheating the motors. We're starting with these motors very cold, well below freezing. But by the end of the flight, they're hotter than 100 degrees C. And so in the case of the Sample Recovery Helicopter, the motors are being redesigned to accommodate that higher mass [of wheels and a robot arm] and still maintain about a three-minute flight time. So the motors are larger, the motors are slightly heavier, they're going to be more efficient and we're likely going to be using some different materials to improve the thermal properties.

Q: What kind of materials might you change?

A: In particular, we're going to be looking at higher thermal conductivity in the adhesives. We know that was one of the limiting issues for us with Ingenuity. Otherwise, they're going to be very similar. We're trying to maintain flight heritage from Ingenuity so that we aren't going way outside of our current experience with flight on Mars.

Q: What about the composite rotors? Is there anything different you'll do there?

A: We're potentially going to be trying to make those lighter. One of the limiting issues with those rotors is how much we can lift with them and how fast we can spin them. We have a fundamental limit just due to the speed of sound. We don't want to get too close to supersonic at the rotor tips. If it did, it'd create quite a bit of drag and vibration and pretty negative structural impacts on the system. Wave drag [an opposing force caused by shockwaves] is a big one as well. And so in the case of Ingenuity, we kind of limit the rpm to about 2,800 — we've never actually needed to fly at that full 2,800 rpm. But as we make the helicopter heavier, we think that we can increase the rpm somewhat without having a significant performance hit. We think that we can go to a slightly higher tip Mach number. But to do that, if you spin those blades faster, the centrifugal forces go up, of course. And so all of the loads on the structure go up, unless you make the blades lighter. We think that we can take just a couple of grams more out of those rotor blades. They already only weigh 1 ounce each. ★