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SHAPING THE FUTURE OF AEROSPACE

ICE BREAKER

NASA may be years away from taking up a mission to explore the subsurface oceans of the icy moons Enceladus or Europa, but it continues to fund research into promising technologies for getting under the ice. Engineers at a Texas engineering firm last year made a breakthrough on one of the biggest challenges. Keith Button takes us inside the laboratory and field tests.

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In this artist concept, a cryobot breaches the ice of the Jovian moon Europa and reaches its subsurface ocean. The yellow beam represents the notional field of view of a camera. Cyrobots could be equipped with cameras and other instruments to navigate and record their surroundings. NASA/JPL-Caltech

When it comes to the search for extraterrestrial life, astrobiologists consider any planetary body with liquid water the Holy Grail. As luck would have it, there are two such destinations relatively close by: Saturn's Enceladus and Jupiter's Europa, both of which are believed to host subsurface oceans. These icy moons are within 1 billion kilometers of Earth, reachable within several years by robotic landers, depending on the route.

So why isn't NASA developing such a lander? Among the reasons is that any microbes or other primitive lifeforms in the oceans are likely to be ensconced under sheets of ice up to 34 kilometers thick, equivalent to the height of nearly four Mount Everests. So for the past decade, the agency has funded preliminary research into different technologies for breaching the ice. One of the leading proposals is to equip a lander with one or multiple cryobots, cigar-shaped robots that would tunnel through the ice, perhaps by squirting jets of hot water from their nose cones to melt a path down to the liquid center of the ocean.

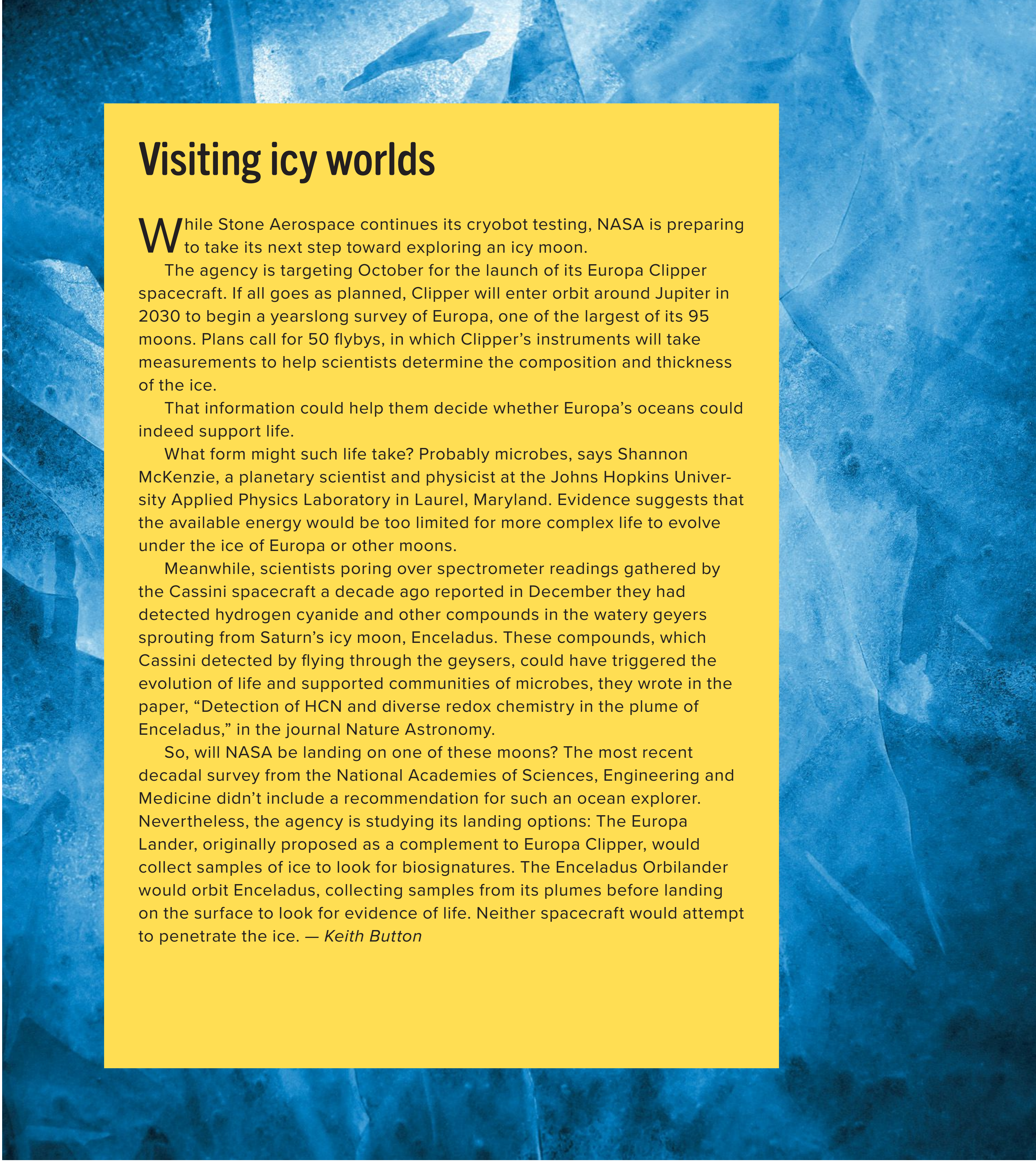
Technicians at Stone Aerospace, a small robotics company in Austin, Texas, are now working on one of the challenges such a future cryobot could encounter: descending through layers of asteroid gravel or other impurities in the ice.

"The hope is that by developing this technology and showing that it's sufficiently mature, it could be considered as part of an ocean worlds lander in the next decade," says Benjamin Hockman, a robotics technologist at the NASA-funded Jet Propulsion Laboratory and the agency's liaison for Stone Aerospace's cryobot research projects.

For its proposed solution, Stone Aerospace returned to a discovery made a decade ago on Alaska's Matanuska Glacier. The company is one of about a dozen teams funded by NASA to examine aspects of cryobot technology, and under one such grant in 2014 and 2015, technicians were testing their Valkyrie cryobot, a hot-dog-shaped, 3.5-meter-long prototype built to demonstrate one method for drilling through ice. To

▲ Another option NASA is studying for exploring subsurface oceans is EELS, the Exobiology Exant Life Surveyor. Instead of tunneling through ice like a cryobot, this snake-like autonomous robot would burrow into existing crevices. In September, researchers from NASA's Jet Propulsion Laboratory conducted field tests with an EELS prototype at Athabasca Glacier in Alberta, Canada.

NASA/JPL-Caltech



Visiting icy worlds

While Stone Aerospace continues its cryobot testing, NASA is preparing to take its next step toward exploring an icy moon.

The agency is targeting October for the launch of its Europa Clipper spacecraft. If all goes as planned, Clipper will enter orbit around Jupiter in 2030 to begin a yearslong survey of Europa, one of the largest of its 95 moons. Plans call for 50 flybys, in which Clipper's instruments will take measurements to help scientists determine the composition and thickness of the ice.

That information could help them decide whether Europa's oceans could indeed support life.

What form might such life take? Probably microbes, says Shannon McKenzie, a planetary scientist and physicist at the Johns Hopkins University Applied Physics Laboratory in Laurel, Maryland. Evidence suggests that the available energy would be too limited for more complex life to evolve under the ice of Europa or other moons.

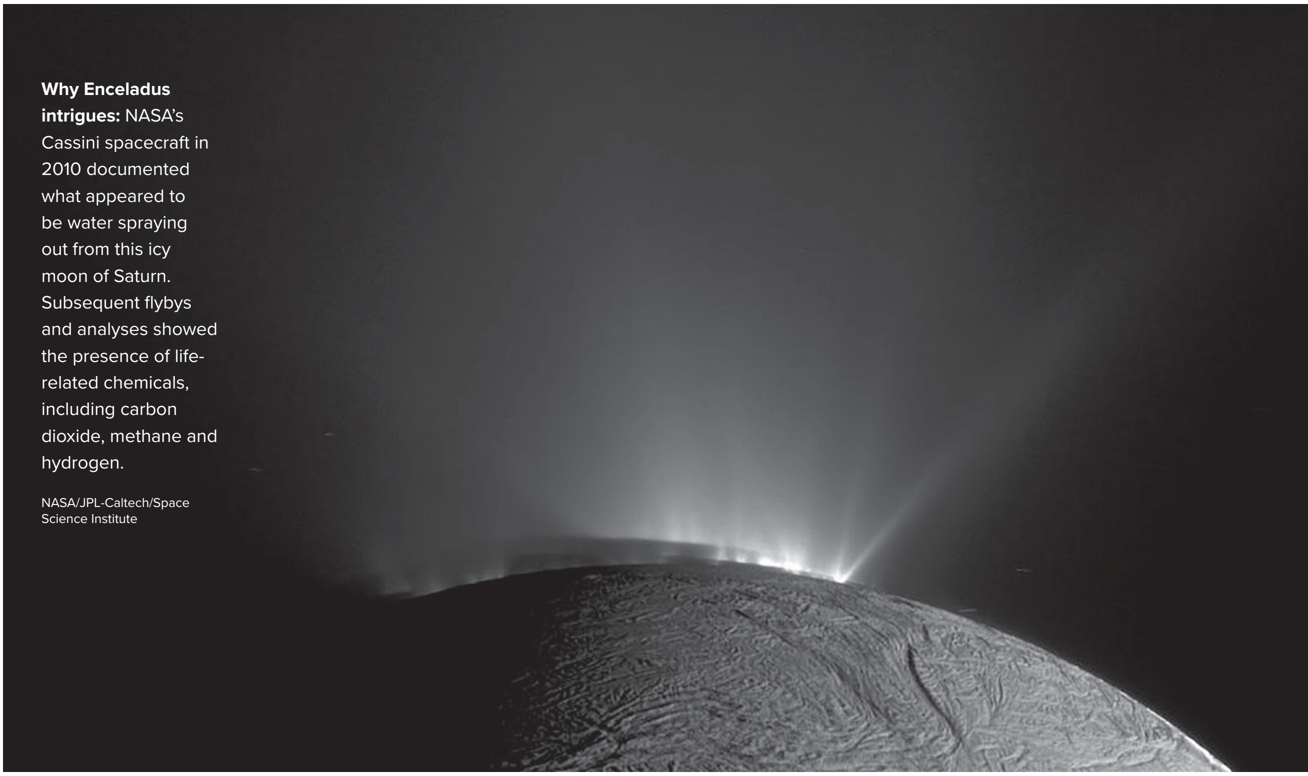
Meanwhile, scientists poring over spectrometer readings gathered by the Cassini spacecraft a decade ago reported in December they had detected hydrogen cyanide and other compounds in the watery geyers sprouting from Saturn's icy moon, Enceladus. These compounds, which Cassini detected by flying through the geysers, could have triggered the evolution of life and supported communities of microbes, they wrote in the paper, "Detection of HCN and diverse redox chemistry in the plume of Enceladus," in the journal Nature Astronomy.

So, will NASA be landing on one of these moons? The most recent decadal survey from the National Academies of Sciences, Engineering and Medicine didn't include a recommendation for such an ocean explorer. Nevertheless, the agency is studying its landing options: The Europa Lander, originally proposed as a complement to Europa Clipper, would collect samples of ice to look for biosignatures. The Enceladus Orbilander would orbit Enceladus, collecting samples from its plumes before landing on the surface to look for evidence of life. Neither spacecraft would attempt to penetrate the ice. — *Keith Button*

descend into the glacier, Valkyrie sprayed hot water through nozzles in its nose cone to melt the ice and then recirculated the meltwater into the cone to be heated and sprayed again.

On the glacier, they learned how they could maneuver Valkyrie as it descended to avoid potential obstacles farther down in the ice, like rocks detected via synthetic aperture radar, says Bill Stone, Stone Aerospace's founder and CEO.

"We said, 'Can we steer the vehicle as it goes down?' Because we had a hot water drill, and we had pressurized jets," Stone says. "And the answer is, 'Yes, you can.'" To do so, they added some jets on the nose cone that pointed laterally. When the lateral jets were turned on in one direction, they would cut a pocket in the ice — a cavity larger in diameter than the cryobot to the side and just below its nose — that the cryobot would then fall into. Repeating this process



Why Enceladus intrigues: NASA's Cassini spacecraft in 2010 documented what appeared to be water spraying out from this icy moon of Saturn. Subsequent flybys and analyses showed the presence of life-related chemicals, including carbon dioxide, methane and hydrogen.

NASA/JPL-Caltech/Space Science Institute

created cavities in a descending stairlike pattern through the ice, through which Valkyrie progressed deeper into the glacier.

This steering technique led to another discovery, Stone says. "We were seeing insoluble glacier material collecting at the bottom of the hole. But when we did these lateral cuts, it disappeared." They found that the sediment was falling into the lateral pockets they were creating for steering.

"That was the experimental kind of 'aha,'" he says. If a cryobot could sense that its rate of descent was slowing because of sediment building up in front of it, it could create a side pocket in the ice to move the sediment out of the way. Then, the cryobot could direct its nozzle downward to continue the path straight down into the ice.

Shortly after these tests, Stone put the side-pocket technique for removing sediment on hold for eight years as the team built and experimented with a series of cryobot prototypes in the lab to test for other icy moon challenges. They built and tested the full-scale, 4-meter-long Thor — large enough to carry a miniature nuclear reactor or decaying plutonium device to power a cryobot. They also tested 30-centimeter-long cryobots in a cryovacuum chamber to simulate the temperatures on the icy surfaces of Enceladus and Europa — promising targets not only for their oceans but also because they likely have rocky seabeds with the chemicals and energy to foster life.

In July, the Stone team received an additional Small Business Innovation Research grant from NASA to revisit the side-pocket sediment removal concept. They named the project Mjolnir, after the hammer of Thor, the Norse god of thunder.

As a starting point, they estimated that a cryobot equipped with a miniature nuclear reactor could cut through a 24-km ice shelf in about 300 days. If the cryobot were to encounter sediment in the ice — from asteroids or accumulations of insoluble salts, for instance — more and more detritus would accumulate in the pocket of meltwater below the nose as the bot descended.

▶▶ To observe how a cryobot might burrow its way through ice on frozen moons, researchers from Stone Aerospace tunneled into the clear block of ice shown on the next page with a model cryobot nose cone. They then filled the hole with plaster of Paris (the white cast at center) to document the size and shape of the pocket created.

Stone Aerospace

◀ Jets of hot water would be sprayed through the holes of a cryobot's nose cone (left) to descend through solid ice.

Stone Aerospace

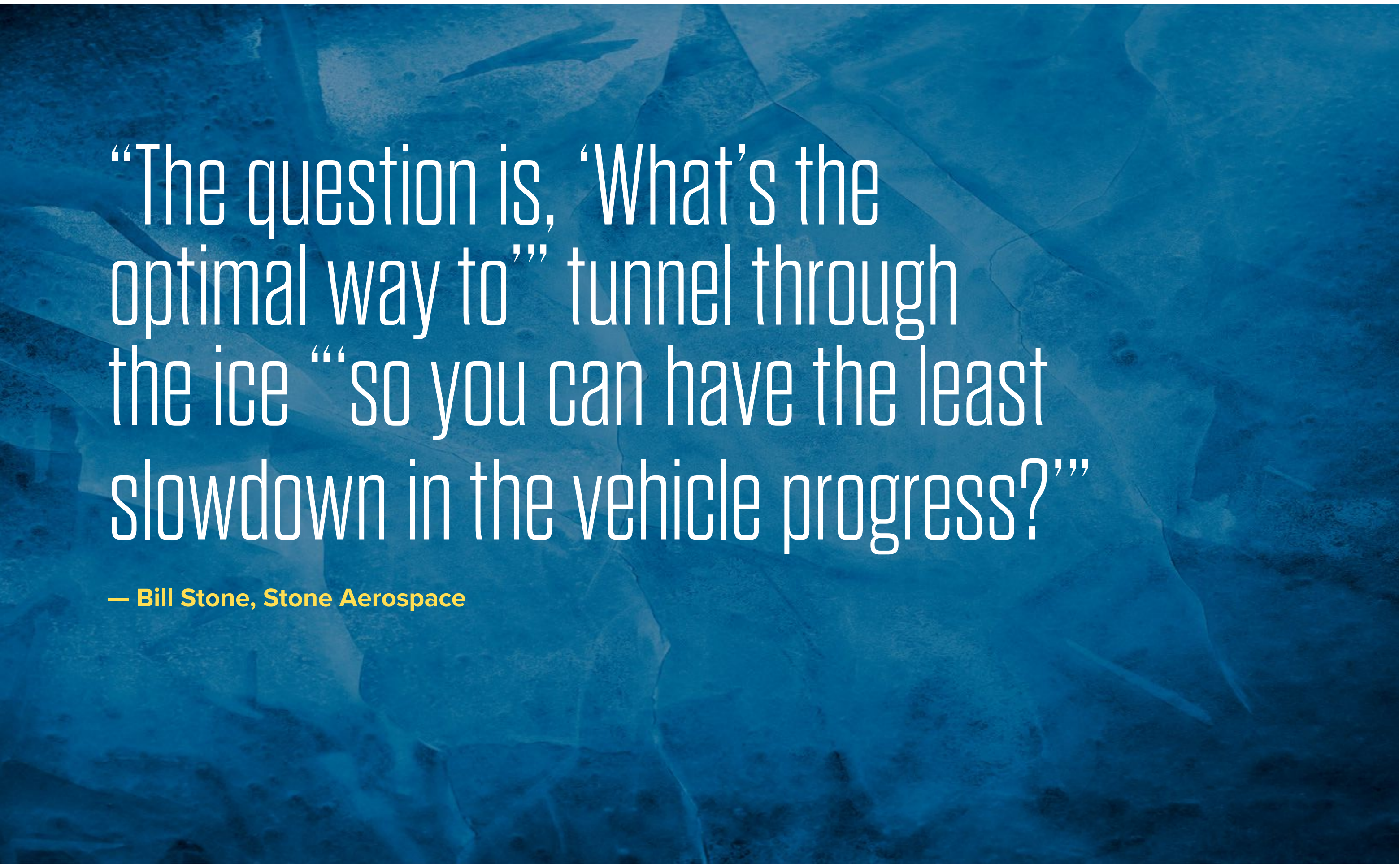
NASA is preparing to launch its Europa Clipper spacecraft in October. Pictured here being assembled at the Jet Propulsion Laboratory in late 2023, Clipper is to fly past Europa, one of Jupiter's 95 moons, dozens of times to help scientists determine whether the moon's icy subsurface ocean has the conditions to support life.

NASA/JPL-Caltech

"As it collects, it becomes an insulator, and it will stall out your forward progress," Stone says.

To advance the side-pocket concept so it could be applied to an icy moon cryobot, they needed to determine the most efficient way of creating the ice pockets for the sediment to fall into or be pushed into. How should the lateral cutting water jets be shaped? What angle, temperature and pressure should they operate at, and for how long?

"The question is, 'What's the optimal way to do it so you can have the least slowdown in the vehicle progress?'" Stone says. "It's going to take almost a year to get through [the ice]; you don't want to be doubling that because you've got this problem that's recurrent."



First, they modeled on a computer how the ice-cutting hot water flows would interact with sediment particles and how that would change with variable levels of gravity. Europa's gravity is about one-sixth that of Earth's; Enceladus' gravity is even less.

Next, they needed to test the water-cutting parameters in the lab, including the side angle, temperature, pressure and length of time to create a pocket. Plans called for running the initial tests with 1-meter-tall slabs of ice at minus 30 degrees Celsius, close to the estimated temperatures deep in Europa's ice.

They needed clear ice without any bubbles so they could observe and record video of the ice-cutting and sediment movement, so they made their 1-meter-tall block in a machine that froze the ice from the bottom up while vibrating the water to eliminate any bubbles, similar to the "shot block" machines used by bars to make clear ice for cocktails. Each block took about two days to make in a walk-in freezer at Stone's Austin lab. They also had to transfer the ice slowly from the machine to the lab, allowing the exterior to slowly warm to the ambient temperature of the lab before moving the block so it wouldn't crack.

The next step was 3D printing a 7-cm-diameter scale model of the cryobot nose cone — one-fifth the expected size of the notional operational cryobot nose. They drilled a hole vertically down into the ice bock, filled it with water and dropped in the scale-model cryobot nose cone.

Then they started the experiment, turning on the water-cutting jet in the nose cone for the predetermined angle and other characteristics to be tested. Instead of recirculating the water, as a cryobot would do on Enceladus or Europa, they simplified the lab setup: A collar sealed the top of the hole, and the excess water was drawn off through the top. For each test, the cutting jet was turned on for up to 10 minutes.

Another problem they encountered was how to document the size and shape of the pocket to correlate with the water jet characteristics tested on the block. For about a month, they tried pouring in various types of epoxies and plasters to create casts of the cavity after the water jet was turned off. In the end, plaster of Paris was the best option.

"We went through a long road of trying everything under the sun, but the kindergarten solution won out," says Vickie Siegel, chief operating officer of Stone Aerospace.

But there was another obstacle: Each time they tried to make a cast, the pocket would continue to melt

▲ Stone Aerospace's Valkyrie prototype burrowed its way through layers of ice in 2014 and 2015 at the Matanuska Glacier in Alaska. Valkyrie traveled about 30 meters, melting the ice with hot water jets in its nose. The engineers observed that sediment often fell into the lateral holes that Valkyrie created for steering through the ice.

Stone Aerospace

before the cast could set up.

"This was a big issue until one of our lab techs came up with a super clever idea," Stone says: After the pocket was formed, they pulled out the nose cone and dumped the water. Instead of trying to make a cast in the lab, they immediately placed the ice block in their industrial freezer at minus 30 Celsius to prevent any further melting. Then, in the freezer, they filled the pocket with plaster of Paris. Once the material hardened, they took the block outside to melt in the Texas sun. They 3D-scanned the solid shape left behind and logged the shape into their digital archives.

From this testing, Stone will have a catalog of results showing how altering the angle and other characteristics of the water-cutting jet affected the size and shape of the side pocket. Next, they plan to test and catalog how much sediment the water jet can push into the pockets by employing blocks of ice with various types of sediment frozen in them. From these results, they want to narrow in on the sediment removal techniques that are fastest and that require the least energy to execute. The next slate of activity is scheduled for July, when they plan to test techniques on ice frozen to minus 190 C — roughly the equivalent of the surface temperatures of the icy moons.

"It'll be incredibly valuable to analytical models for predicting how to come up with the best design for a cryobot," Stone says.

For now, preliminary results from the ice block tests indicate that the best technique is to cut a side pocket at least twice the width of the cryobot with jets of hot water that also push the sediment over. Then, by turning off the jets and letting the cryobot simply melt its way downward via the heat of the nose cone, the cryobot would avoid the risk of slicing a hole in the pocket, which could let sediment fall into the cavity in front of the nose cone again.

The discovery of that technique a decade ago on Matanuska Glacier illustrates the importance of field work, Siegel says. In the lab, a researcher can get tunnel vision trying to solve for the daunting task of drilling through a massive ice shelf, but the natural world reveals challenges that the researcher might not consider, she says.

"You're so focused on the ice, and maybe you don't think about it when you go out onto an actual glacier," Siegel says. "Getting out in the field and watching these things occur in nature really kind of highlights elements that you wouldn't even have thought you needed to design to." ★