In an underdog city, at an underdog NASA lab, researchers are thinking hard about an undeservedly neglected planet. Venus is Earth’s cousin, closest in composition and size, but for decades it has remained veiled. NASA hasn’t sent a mission there since 1989; more recent European and Japanese orbiters have made halting progress that stops largely at the planet’s thick sulfur clouds. No craft has touched down since 1985, when the last of a series of advanced Soviet landers clad in armored pressure vessels endured a couple hours before succumbing to the deep-ocean pressure and furnacelike temperature of the planet’s surface. The baleful conditions and lack of funding have made Venus, Earth’s closest neighbor, feel more distant than ever.

That is, except here.

In September, Phil Neudeck, an electrical engineer at NASA’s Glenn Research Center, a complex abutting the main airport in this Rust Belt city, sat watching purple and turquoise waveforms on a display. It was his window into the Venus next door. Behind sealed doors stood a 14-ton stainless steel tank, its massive ports sealed to hold pressures so high that the screws to secure its nuts have their own nuts. For 33 days, the Glenn Extreme Environments Rig (GEER) had run nonstop, simulating an atmosphere at 460°C and flooded with carbon dioxide at pressures that render it supercritical, both liquid and gas. Inside sat two microchips, pulsing with metronomic accuracy. Neudeck was running a clock on Venus, and it was keeping perfect time.

Neudeck and his Glenn colleagues are helping drive a technological leap that could transform the exploration of Venus, making it almost as accessible as Mars. Rather than barricading electronics within pressure vessels, by early next decade NASA may be able to land simple unprotected robots on Venus that can measure wind, temperature, chemistry, pressure, and seismic waves. And instead of running for a few hours, the landers could last for months. “We don’t have the world’s fastest chips,” Neudeck says. “We don’t have the world’s most complex chips. But in terms of Venus environment durability—that’s what we got.”

If the chips live up to their potential, scientists’ elusive dream of extended stays on Venus may at last be within reach. “The paradigm has been that long-term surface stuff is way down the road,” says Tibor Kremic, the scientist who has launched a push toward Venus at Glenn, a little-known NASA lab.

By Paul Voosen, in Cleveland, Ohio

Transistors that thrive on heat and pressure could take spacecraft to the surface of Venus

FEATURES

TOUGHER THAN HELL

Transistors that thrive on heat and pressure could take spacecraft to the surface of Venus

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When Neudeck joined Glenn in the early 1990s, Venus was far from his mind. He was chasing an earthly quarry: new semiconductors, materials that can deliver finely controlled doses of electric current. Under extreme heat, silicon, the backbone of modern electronics, becomes a pure conductor. That makes it useless for computing,

lab that has specialized in aviation. But early this decade, engineers here began to build heat-resistant electronics out of a new type of semiconductor, with an eye to placing sensors inside jet engines. Neudeck kept adding transistors to build more complex circuits. Meanwhile, at meetings, Russian researchers told Kremic they were seeking U.S. help in creating a pressure-vessel probe for a possible return-to-Venus mission called Venera-D. Kremic recalled Neudeck’s work and thought, “Maybe there’s another way to do this?”

Glenn’s campaign, if successful, could help revive interest in the planet. Once a primary target of planetary exploration, thanks especially to the brute-force Soviet campaign to land on its surface, Venus has long been overshadowed by missions to Mars, asteroids, and the outer planets and their moons. Early this year, missions to orbit Venus or dive into its atmosphere made up two of the five finalists for NASA’s latest Discovery mission—its line of $500 million planetary probes. The odds seemed good, but neither made the final cut (Science, 13 January, p. 116).

Later this year, the agency will announce finalists in the competition for its next billion-dollar New Frontiers mission; among the dozen candidates, three target Venus. But they face stiff competition—including a return to the saturnian moons Enceladus and Titan, which the Cassini mission showed have the potential for harboring life.

In the 1990s, NASA’s Magellan spacecraft used radar to penetrate Venus’s thick clouds and map its surface (bottom). But the only close-ups of the crushing inferno come from Soviet Venera and Vega landers, such as the one captured by Venera-13 in 1982 (top).

If Venus loses out again, Glenn’s innovations could be the best route back—not just to venusian orbit, but all the way to the surface. “The pie is finite,” says Bob Grimm, a geophysicist at the Southwest Research Institute in Boulder, Colorado, and chairman of NASA’s Venus Exploration Analysis Group. “If we want to improve Venus’s share, we have to have some kind of initial mission to get people excited again.” Ralph Harvey, a planetary scientist at Case Western Reserve University here, agrees: “This is the kind of technology development that could take a flagship kind of planetary mission and suddenly allow it to deliver a hell of a lot more.”

The scientific case for Venus is strong. No planet has more to say about how Earth came to be. Mars is tiny and frozen, its heat and atmosphere largely lost to space long ago. “In terms of Earth-sized terrestrial planets, it’s really Venus,” says Colin Wilson, a planetary scientist at the University of Oxford in the United Kingdom. “Venus is all we got.” The planet could host active volcanoes, and it may have once featured oceans and continents, which are critical to the evolution of life. Plate tectonics roughly like Earth’s might have held sway there, or might be starting today, hidden under the clouds. Venus also proves by example that orbiting within a star’s “habitable zone” doesn’t guarantee that a planet is suitable for life. Understanding how Venus’s atmosphere went bad and turned into a runaway greenhouse, boiling away any oceans and baking the surface, could help astronomers studying other solar systems distinguish truly Earth-like exoplanets from our evil twins.
because stopping and starting the flow of electricity is how zeroes turn into ones.

Neudeck had his eye on silicon carbide, a hybrid of silicon and carbon commonly used as an abrasive in sandpaper and for growing fake diamonds. Silicon carbide has a bigger bandgap than silicon, which means its electrons can absorb much more energy before it becomes a conductor. As a result, it functions as a semiconductor at much higher temperatures. But it is difficult to work with. Because silicon carbide doesn't melt, the techniques used to produce large silicon wafers break down. When researchers managed to grow wafers by vaporizing the material and depositing it on a seed crystal, the resulting films were riddled with impurities that made them unreliable.

**“Being able to rove or explore the surface of Venus is within the future horizon.”**

Lori Glaze, Goddard Space Flight Center

The allure of high-temperature electronics was too great to ignore, however. Slowly, with the support of NASA and the Office of Naval Research, researchers, led especially by Cree, an upstart electronics company, devised ways to grow usable silicon carbide crystals more than 150 millimeters in diameter. The power industry is now harnessing the material to build smaller transformers and more efficient power plants, Neudeck says.

He and his colleagues set out to turn the material into full-fledged computer circuits, assembling more and more complex chips in their clean room. The biggest breakthrough came 4 years ago, when they figured out how to create layered chips that allow electrical signals to crisscross, rapidly increasing potential complexity. “We’re really trying to recreate Moore’s law, but to do it for high temperature,” Neudeck says. In 1 year, they increased the number of transistors on their silicon carbide chips 10-fold.

Pentiums these are not. A modern silicon chip can contain 7 billion transistors; each of the chips running in the Venus chamber has 175. Neudeck also uses an old-school transistor design, long since abandoned in conventional microelectronics. It’s basically a hyperexpensive, obtuse pocket calculator. But a pocket calculator running on Venus could be valuable indeed. “This is already the complexity of many of the early scientific missions flown back in the ’60s and ’70s,” Neudeck says, and more powerful than the chips on Apollo flight computers. “You really can do science.”

Still, Neudeck’s team’s work would have been a sideshow unless he had a way to prove his chips’ endurance. Last year, that’s exactly what the team did.

**YOU COULD BE FORGIVEN** for not knowing that Glenn even exists. It has never become a scientific hotbed like the Jet Propulsion Laboratory (JPL) in Pasadena, California, the leader in robotic space exploration. Several times, past NASA administrators or Congress have considered closing it.

The Venus chamber started as another failed dream. NASA planned to test efficient nuclear-fueled engines called Stirling generators that could have driven refrigerators to keep traditional silicon-based electronics cool. Glenn’s experience in simulating the extreme environments inside jet and rocket engines made it a natural home for the chamber. “The mantra of our branch is small, smart, and rugged,” says Glenn engineer Gary Hunter, who had developed basic chemical sensors for the Venus environment. But the agency canceled the program in 2013, leaving the stainless steel vessel and its gas-mixing apparatus gathering dust.

Kremic, who had spent some time at NASA headquarters in Washington, D.C., in planetary science before returning to Glenn, saw an opportunity. In fits and starts, he cobbled together money to create the largest and most advanced facility for simulating the surface of Venus. The minivan-size chamber was rebuilt and upgraded last year. Now, besides simply running large volumes of gas at high temperature and pressures of 90 bars or more, the GEER can mix eight different gases to create a Venus-like atmosphere, and it can inject water and other liquids into the cauldron. “The end result is we’re much more likely to understand more fully what Venus will be like when we get there,” Harvey says.

The chamber quickly proved its worth both for stress tests and for basic science. “It was kind of heaven,” says Harvey, who has pushed the GEER to run for a record 80 days in two “cook and look” experiments to see how different volcanic rocks would react with the venusian atmosphere—long a matter of debate among planetary scientists.

The chamber’s marquee moment came last year, when the previous, 24-transistor generation of Neudeck’s chip survived 21 days in the GEER—an ordeal that may have changed the course of Venus exploration. Since then, NASA has funded Kremic’s team to explore three different concepts for long-lived landers. Across the country, a team at JPL, led by mechatronics engineer Jonathan Sauder, had been exploring a clockwork rover, virtually free of electron-
Into the hot zone

The few brave robots that have pierced Venus's thick clouds to reach the surface did not last long in the scorching temperatures (460°C) and overwhelming pressures (90 bars). Researchers at NASA's Glenn Research Center in Cleveland, Ohio, and the Jet Propulsion Laboratory in Pasadena, California, are developing concepts for landers and rovers that could last months rather than hours. They would depend on silicon carbide circuitry that can handle the extreme environment.

Automaton Rover for Extreme Environments (AREE)
The AREE strives to be mechanical rather than electrical. With no memory or centralized digital brain, the AREE could rove for months, using preprogrammed behaviors to avoid obstacles.

Duration: >120 days
Status: Prototype tested under venusian conditions by 2019.

1. Sample collection tool: Collects and deposits rock samples for chemical analysis.
2. Radar reflectors: Rotating shutters reveal reflectors to an orbiter. The semaphores could transmit 1000 bits a day.
3. Turbine: A double-cupped turbine gathers wind energy and stores it in a spiral-shaped clockspring.
4. Tank tread: Inspired by World War I tanks, the caterpillar track provides a ramp for surmounting obstacles.

Long-Life In-Situ Solar System Explorer (LLISSE)
By surviving at least 60 days, the LLISSE could gather data across at least one night-day transition of Venus’s 117-Earth-day-long day.

Duration: >60 days
Status: Prototype tested under venusian conditions by 2021.

1. Drag plates: Like feathers on a shuttlecock, plates help keep the lander oriented during descent through the thick atmosphere.
2. Turbine: Dual turbine contains inner cups and outer blades to maximize energy collection from slow surface winds.
3. Electronics: High-temperature circuits eliminate the need for a heavy, pressurized container.
4. Radio antenna: Planar antenna transmits data at tens of bits per second.

Chip shot
Researchers have turned to silicon carbide, an unreactive semiconductor increasingly used in modern power converter circuits. Silicon loses its semiconductor behavior above 300°C, whereas silicon carbide maintains it above 900°C.

Built to last
Chips are fixed within stable ceramics instead of polymers. Glenn researchers baked chips inside a chamber that mimics venusian conditions.

Outdoing Apollo
Modern chips contain billions of transistors. But this silicon carbide circuit has 175 transistors—more than the chips on the Apollo spacecraft.

Etched for success
Crosscrossed metal layers increase circuit density. Silicon carbide junction gates are used instead of modern chips’ metal oxide gates.
ics, that could explore the surface of Venus. When they caught wind of the developments at Glenn, they began to think about how their mechanical designs could supplement the high-temperature chips. “We’re starting to get into a different realm,” says Lori Glaze, who is based at NASA’s Goddard Space Flight Center in Greenbelt, Maryland, and is leading one of the proposed billion-dollar New Frontiers missions to Venus (all of which rely on conventional silicon chips). “I definitely think that being able to rove or explore the surface of Venus is within the future horizon.”

THAT SURFACE COULD PROVE a lot more active than planetary scientists thought just a few years ago. In the 1990s, cloud-penetrating radar aboard NASA’s Magellan orbiter showed relatively few craters, distributed seemingly at random. Some 500 million years ago, researchers theorized, a catastrophic event—perhaps a vast flood of magma—wiped the surface clean, like a planet-size slate, smoothing any possibility of volcanoes or plate tectonics beneath a thick, cold crust. And Venus has been pretty much dead ever since.

In the late 2000s, however, the European Venus Express orbiter began to sketch a much livelier picture. Tracking the atmosphere, it saw what appeared to be a fourfold spike in sulfur dioxide that lasted about a year—perhaps the sign of a large, Mount Pinatubo–style volcanic eruption. Peering through the clouds in specific wavelengths of light, Venus Express seemed to discern unusually dark terrain near volcanic features—what fresh lava might look like on Earth. And near the end of its mission, in a rift on the side of a volcano, it saw what seemed to be a spike in temperatures of several hundred degrees. “This really makes us think Venus should be active,” Wilson says.

Scientists would love to find out. Missions such as NASA’s three New Frontiers candidates, however, focus more on the planet’s distant past. Two of them—one led by Glaze, the other by Larry Esposito, a planetary scientist at the University of Colorado in Boulder—would be short-lived. Each would drop a pressure vessel into the atmosphere, which would measure atmospheric chemistry on the way down and spend its few hours of life on the surface sampling rocks with either lasers or a drill. Analyzing isotopes of non-reactive noble gases in the atmosphere could give scientists a window into whether Venus started with as much water as Earth did—and whether it might still be hiding water, the lubricant of plate tectonics, deep in its interior. Probing the rock composition could reveal whether, as some researchers suspect, the slightly elevated regions called tesserae are remnants of continents.

The third New Frontiers mission, proposed by JPL research scientist Suzanne Smrekar, would take a more unconventional approach: using orbiting radar and spectrometers to probe the surface’s composition while a small probe swoops in and out of the atmosphere to capture air for isotope analysis. The high-resolution radar could reveal surface features lost in the noise of old measurements, Smrekar says: perhaps chasms that resemble Earth’s midocean ridges, or the details of mysterious oval-shaped features called coronae, which could mark where plumes of hot material from Venus’s mantle are causing parts of the crust to sink under others. Smrekar suspects Venus is a good analog for the time when plate tectonics began on Earth. Its greenhouse-heated surface is cooling much more slowly than Earth’s, and may only now be starting to crack into plates. “We may be seeing evidence for the process of subduction starting on Venus today,” she says.

To know for sure, however, researchers need to measure what’s happening in Venus’s interior today. That information can come only with sustained listening—exactly what Glenn’s landers propose to provide.

Each of them, Kremic says, was designed to be small enough to hitch a ride on other missions—either one of the New Frontiers spacecraft, Venera-D, or spacecraft that could swoop by Venus en route to other destinations. The first proposal, called the Long-Life In-Situ Solar System Explorer (LLISSE), was modest: a glorified cube of the size of a car battery that would drop from a balloon or larger probe and record temperature, pressure, wind speed, and a few specific chemicals for 60 Earth days. Because silicon carbide isn’t good for storing data, the LLISSE would stream its observations either up to an orbiter or straight to Earth. The readings would provide ground truth for circulation models of the planet’s atmosphere, and they would help researchers estimate how mass is distributed throughout the planet—one fundamental mystery that a short-term mission could not answer.

A slightly larger design, the Seismic and Atmospheric Exploration of Venus, unveiled this month at a Venus meeting at the Johns Hopkins University Applied Physics Laboratory in Laurel, Maryland, could add a seismometer, a heat flux gauge, possibly even a camera, all for $100 million. Such a seismometer would be the killer app for long-lived landers. “The ultimate goal is to have seismometers on Venus,” Smrekar says. Nothing can tell you more about the interior structure of a planet. By listening to the ground over a long span of time, Wilson says, you might hear the crust stretching or cracking from tectonic processes, including “Venusquakes,” or hear the rumbling of distant volcanoes. Such a mission could quickly answer the fundamental question: Is Venus dead or alive?

Another test of Glenn’s silicon carbide electronics could potentially come quite soon: a proposal called Venus Bridge Orbiter and Surface Science (V-BOSS), one of two candidates for a quick-to-fly, low-cost (less than $200 million) “Venus Bridge” mission that NASA’s associate administrator for science, Thomas Zurbuchen, asked Venus scientists to prepare in the wake of the failed Discovery round. While details of the V-BOSS won’t be set until early next year, it would build off of the LLISSE and add an orbiter to relay lander data back to Earth.

Some researchers, blindsided by the brisk progress in high-temperature electronics, worry that the Glenn and Venus Bridge landers could outcompete more conventional missions such as New Frontiers. That would be a loss to science, Esposito says, because the cut-rate landers can’t match sophisticated sensors, such as mass spectrometers and radar, for answering key questions. “There’s not a cheap way to find out the dominant mineral on the surface of Venus,” he says. But Harvey says Glenn-style electronics could make even more ambitious future Venus probes—such as a long-delayed potential multibillion-dollar flagship mission—vastly more productive.

Meanwhile, back here in Cleveland, the latest endurance test has wound up. Neudeck reports that his microchips worked the whole way through, and could have run longer. One day, he is confident, devices like these will brave the hellish surface of Venus. Until they are ready, he will keep putting them through their paces, marking time in the little hell next door.
Tougher than hell
Paul Voosen

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