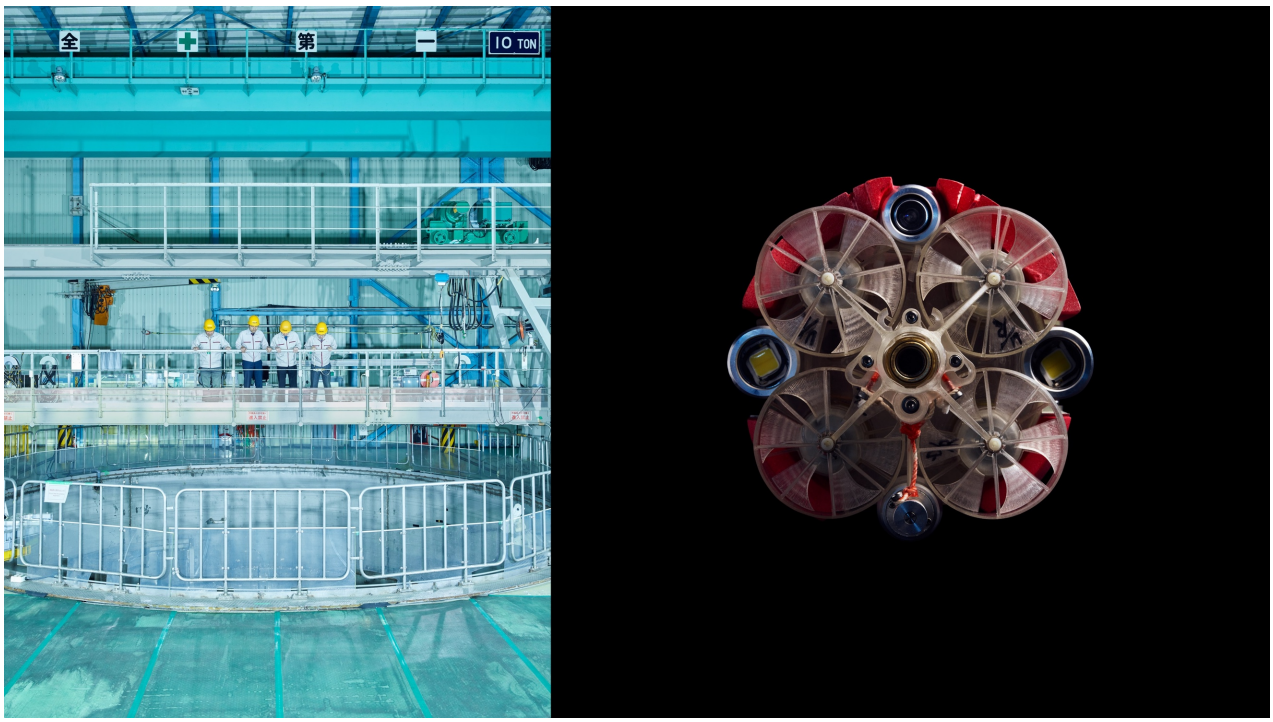


Inside Toshiba's research facility, engineers look into a pool (left) where robots like the Sunfish (right) are tested before being deployed in a nuclear reactor. Spencer Lowell

The Robot Assault On Fukushima

The 2011 earthquake and tsunami in Japan triggered a devastating catastrophe in one of the country's largest nuclear power plants. The cleanup will take decades, and it's no job for humans.

Author: Vince Beiser BY Vince Beiser, 04.26.18

The night before the mission, Kenji Matsuzaki could not sleep. For more than a year, Matsuzaki and a team of engineers had been developing their little robot—a bread-loaf-sized, red and white machine equipped with five propellers, a transparent dome, front and rear video cameras, and an array of lights and sensors. Nicknamed Little Sunfish, it was engineered to operate - underwater, in total darkness, amid intense radiation. And after three months of testing, training, and fine-tuning, it was deemed ready to fulfill its mission: to find and photograph the melted-down radioactive fuel that had gone missing inside the Fukushima Daiichi nuclear power plant.

More than six years had passed since an earthquake and tsunami hammered northeastern Japan and reduced the Fukushima facility to radioactive ruin. In all that time, no one had been able to locate the hundreds of tons of fuel inside the three reactors that had suffered core meltdowns. The uranium fuel had overheated, turned into lava, and burned through its steel container. That much was known. What happened after that was the big question. Did all the fuel flow out of the reactors, or was some still inside? Did it pile up in a heap, spread out in a puddle, spatter on the walls? Without knowing the answers to those questions, it was nearly impossible to devise a plan to get rid of it. And getting rid of it is imperative. Every day, as much as 165 tons of groundwater seeps into the

reactors, becoming contaminated with radiation. And there's always the possibility that another earthquake or some other disaster could rupture the reactors again, sending radiation spilling out into the air, sea, or both.

Human beings couldn't go into the heart of Fukushima's reactors to find the missing fuel, though—at least not without absorbing a lethal dose of radiation. The job would have to be done by robots. But no robot had ever carried out such a mission before. Many had already tried and failed. Debris tripped them up. Yard-thick concrete walls threatened to block their wireless signals. Radiation fouled up their microprocessors and camera components. And so it fell to Matsuzaki, a shy-eyed , 41-year-old senior scientist with Toshiba's nuclear technology branch, to help build a machine that wouldn't end up as another one of the robot corpses already littering the reactors.

Just getting the Sunfish and its support gear into position inside the enormous concrete building that housed one of the crippled reactors took two days. Four separate teams took turns setting up the control panel, cable drum, and other equipment the robot would need to function. Even in full protective bodysuits, each group of workers could spend only a few minutes inside the structure, working by the light of portable electric lamps amid a thicket of machinery, pipes, and catwalks. When one team absorbed its maximum permitted daily dose of radiation, it was replaced by another group. Matsuzaki himself made two forays inside to put the final touches on the Sunfish, sweating inside his face mask and bodysuit in the summer heat, his nerves jumping each time his portable monitor dinged to indicate he'd received another increment of his allowable radiation dose.

The plan was for the Sunfish to spend three days mapping the debris and searching for signs of the missing fuel. Matsuzaki would monitor its progress from a control room about 500 yards away. He would be joined by a half-dozen top officials from his employer, Toshiba, and Tokyo Electric Power Company (Tepco), the mammoth utility that owns the plant. His success—or failure—would be broadcast daily around the world.

Beyond the immediate danger, cleaning up Fukushima remains critical to repairing the image of Japan's energy industry. In the wake of the disaster, Japan shut down every one of its dozens of nuclear plants, which had provided some 27 percent of the nation's power. To cover the loss, it had to massively increase imports of expensive fossil fuels. A few nuclear plants have since been permitted to restart, following years of safety upgrades, but Fukushima cost the industry much of its public support. Polls consistently show that a majority of the public opposes nuclear power. Two of Japan's former prime ministers, including the one in office at the time of the disaster, have flipped from supporting nuclear plants to calling for their elimination.

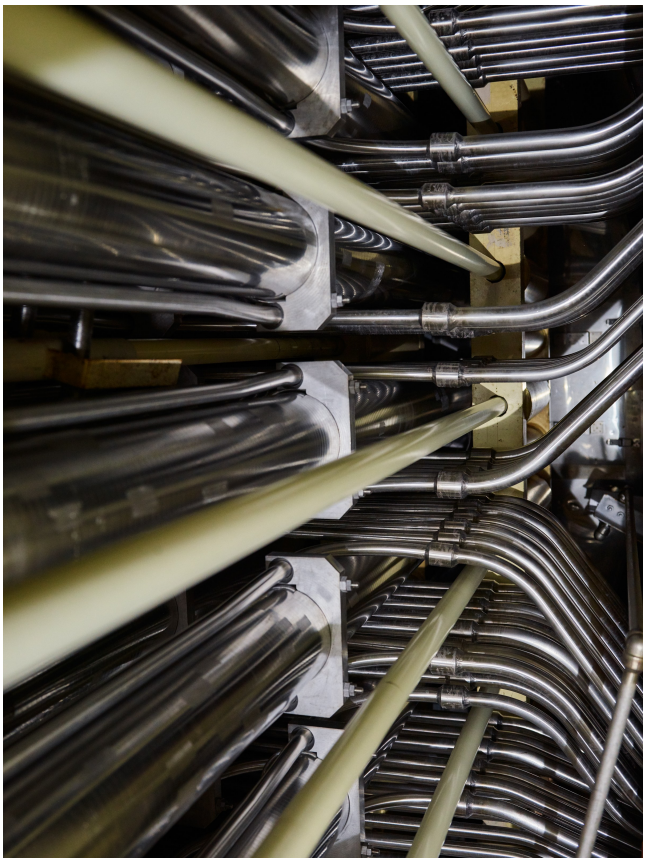
The disaster also dealt a severe blow to the global nuclear industry, which had been gaining favor even among some environmentalists as a carbon-free alternative to fossil fuels. In the aftermath of the meltdown, Germany announced it would phase out nuclear power altogether, Vietnam dropped plans to build reactors, and the whole industry was thrown on the defensive. Every proposed new reactor now has to answer the question: How do we know this won't be another Fukushima?

Small wonder that in the nights leading up to the mission, Matsuzaki was feeling the pressure. "I've been having nightmares about failing," he confessed to his boss, Akira Tsuyuki. "Me too," Tsuyuki said. Late at night on July 18, 2017, the mission start time just a few hours away, Matsuzaki lay awake, wondering whether his team's technology would be any match for Fukushima.

1/6 The exteriors of Units 1 and 2, two of Fukushima Daiichi's six reactors. SPENCER LOWELL

2/6 The outside of the Unit 1 turbine building. Spencer Lowell

3/6 Irradiated groundwater tanks being measured for radiation at Fukushima Daiichi. Spencer Lowell



4/6 Pipes inside Unit 5. Spencer Lowell

5/6 Ice wall control room at Fukushima Daiichi. Spencer Lowell

1/6 The exteriors of Units 1 and 2, two of Fukushima Daiichi's six reactors. SPENCER LOWELL

The earthquake on March 11, 2011, was the biggest ever recorded in Japanese history, a 9.0 monster that devastated northeastern Japan and triggered a series of tsunamis that slammed into the coast, killing nearly 16,000 people. The tsunamis also knocked out power to the Fukushima Daiichi plant, shutting down the pumps needed to keep cooling water circulating in the reactor cores. Over the next several days, as Tepco engineers worked by flashlight to regain control, the fuel in three of the plant's six reactors—Units 1, 2, and 3—melted down. Gases unleashed by the damage exploded, sending plumes of radioactive particles like iodine, cesium, and plutonium into the atmosphere. The government ordered everyone within a 12-mile radius to evacuate, with about 165,000 people eventually displaced.

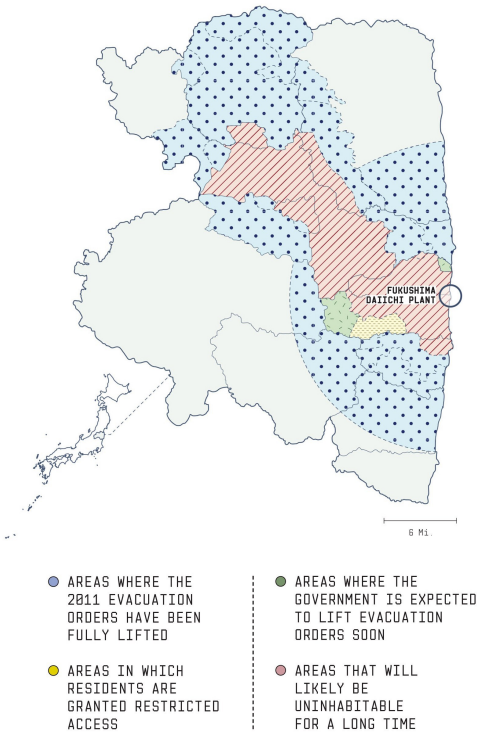
Government officials originally estimated it would take about 40 years and $50 billion to clean up the plant, decontaminate the surrounding area, and compensate the disaster's victims. In December 2016, they more than tripled that estimate to $188 billion. "We have never experienced a disaster as big as Fukushima," Hiroshige Seko, the head of Japan's Ministry of Economy, Trade, and Industry, told reporters at the time, according to Bloomberg. "With our limited knowledge, it was very difficult to make the previous forecast."

The Fukushima cleanup is a project far bigger and more complex than those of even the world's worst previous nuclear catastrophes. Chernobyl was literally covered up: The Soviets simply encased the whole thing in concrete and steel. Three Mile Island was tiny by comparison. Only a single reactor melted down, and none of its fuel escaped. "Fukushima is orders of magnitude more difficult," says Lake Barrett, an American who oversaw the cleanup of Three Mile Island and who signed on as a consultant to Tepco and the Japanese government in 2013.

The Hot Zone

Following the meltdown, nearly 165,000 people had to evacuate the area surrounding the

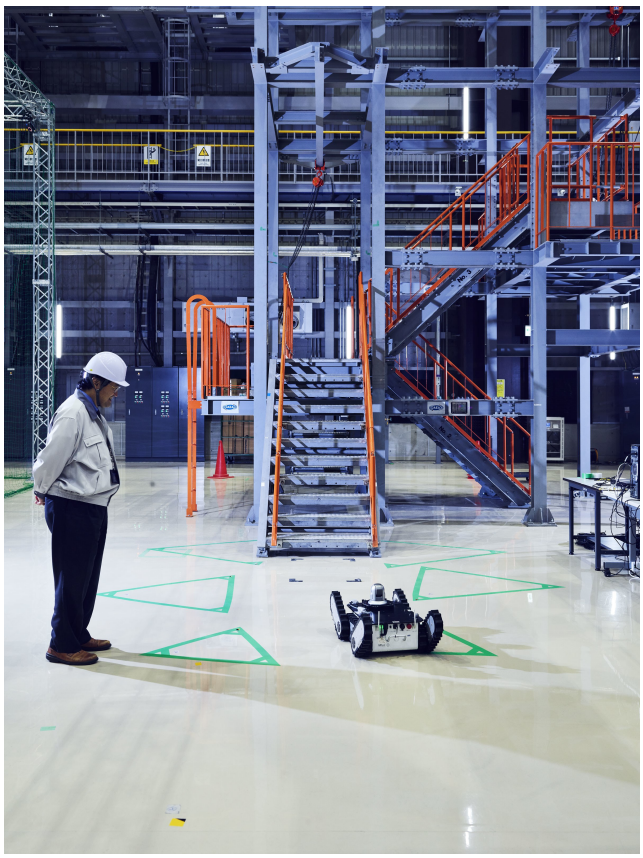
Fukushima plant to avoid radioactive exposure. Today, even after extensive cleanup efforts, 50,000 people still can't go home.



In the first chaotic weeks after the meltdown, with radiation levels far too intense for anyone to work inside the reactors, Tepco scrambled to deploy robots to assess and contain the damage. Tractor-treaded bots from iRobot, drones from Honeywell, and a prototype disaster-response mech from Tohoku University scouted the rubble-strewn facility and tried to measure the intensity of the radiation. A remote-controlled concrete pumping truck was adapted so that its extendable spout could pour water into the reactors, cooling and stabilizing the overheated chambers.

In the months and years that followed, Fukushima became both a market and a proving ground for ever-advancing robot technologies designed to operate in hazardous conditions. Remote-controlled front-end loaders, backhoes, and other heavy equipment were put to work breaking up radioactive debris and loading it onto remote-controlled dump trucks. A four-legged walking robot investigated the reactor buildings. Robots with 3-D scanners were sent in to gather imagery and map radiation levels. Swimming robots inspected pools where spent fuel rods were stored, taking pictures.

But none of these robots were capable of penetrating the innermost areas of the reactors. In August 2013, the Japanese government assembled a consortium of public utilities and private companies, including Mitsubishi, Hitachi, and Toshiba, to create robots specifically for the most challenging environments. Dubbed the International Research Institute for Nuclear Decommissioning, it has developed some 20 machines that have been deployed onsite. Their ranks include a snakelike bot that crawled through a tiny accessway into Unit 1, then bent itself into a more stable U-shape to explore inside. Then there was the Scorpion, a tank-tread-driven machine with a camera mounted on an elevating "tail" that was sent into Unit 2. The Japanese government is bankrolling a $100 million, state-of-the-art R&D center near the nuclear plant where robot operators train on digital models of the reactors in a giant 3-D Holo Stage and on life-size physical mock-ups.



A robot undergoes testing at the government's new $100 million R&D center near the nuclear plant. Spencer Lowell

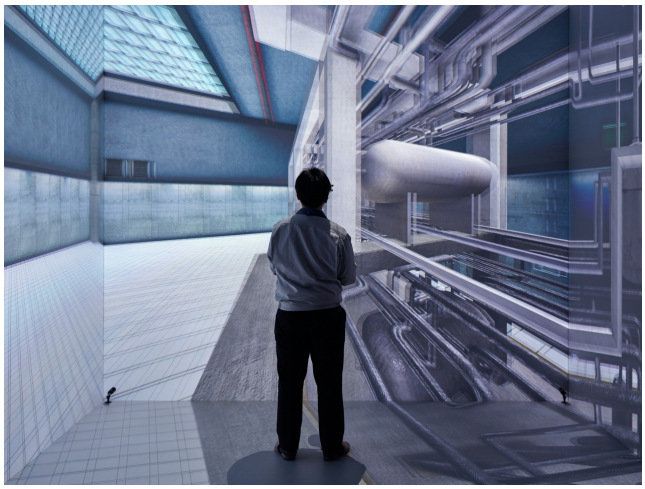
But even with the massive government investment, many of the new robots still couldn't hack it inside the reactors. The camera on one of them, sent to clear a path for the Scorpion, was shut down by radiation; the Scorpion itself got tripped up by fallen debris. The first version of the snakelike bot got stuck; the second did better but failed to find any melted fuel. "It's very difficult to design a robot to operate in an unknown environment," says Hajime Asama, a professor at the University of Tokyo who was one of the first roboticists the government turned to for help. "Until we send the bot in, we don't know what the conditions are. And after it's sent, we can't change it."

Kenji Matsuzaki has worked in Toshiba's nuclear technology branch for more than 10 years, and by May 2016, when he was assigned to the team developing a robot to explore inside Unit 3 of Fukushima, he was familiar with the plant's basic architecture. All six of its reactors are boiling-water reactors, a type designed in the late 1960s and early 1970s and found all over the world, including in the United States. They generate electricity by circulating water through their infernally hot cores, converting it to steam that is used to turn turbine generators. Each reactor has three containers set one inside another like Russian nesting dolls. The smallest container, a steel capsule about the length of a tennis court, is called the reactor pressure vessel. That's where the nuclear fission reaction takes place, powered by fuel composed of uranium dioxide baked into ceramic pellets. This capsule is enclosed inside a primary containment vessel, a concrete and steel structure shaped like a massive light bulb, designed to capture any radiation that might accidentally escape. The containment vessel in turn is housed inside the reactor building, a concrete and metal rectangle that offers only minimal protection from radiation.

Technicians in protective gear can work for short periods inside the reactor building, but they can't enter the far more radioactive containment vessel, which is where they were likely to find at least some of the missing fuel. Building a robot that could get inside and maneuver around the containment vessel presented several unique challenges. First, the containment vessel was only practically accessible through a 5.5-inch circular maintenance opening about 8 feet above the floor of the reactor building, so the robot would have to be small. Second, because the containment vessel had been pumped full of water to cool it down, the robot would have to be able to swim. Third, since the water and thick walls would defeat wireless signals, this small, swimming robot would need to be powerful enough to move underwater while dragging as much as 65 yards of electric cable behind it.

It took months of research, experimentation, and testing in Toshiba's labs and in an enormous

simulation tank at the government-run Port and Airport Research Institute to balance all these capabilities inside the little machine. Matsuzaki's team had to try different configurations of propellers, cameras, and sensors, boost the power of the propeller motors, develop a new type of coating to make the cable move more smoothly, and ensure the whole package could withstand a blistering level of radiation.



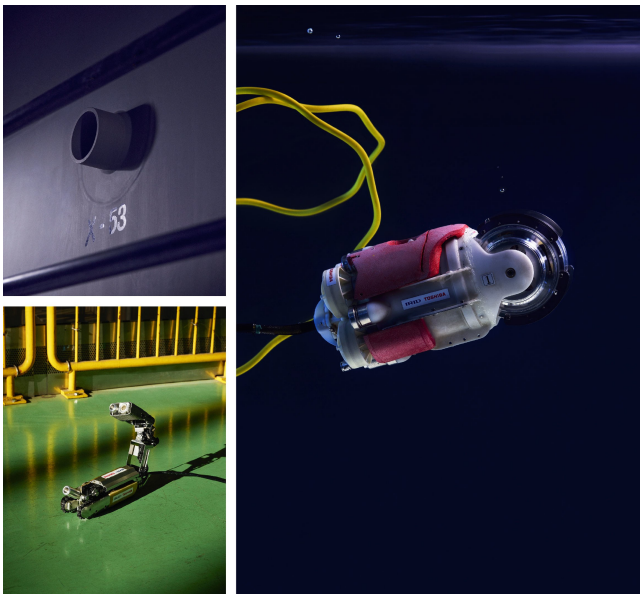
Simulation facility at the Naraha Remote Technology Development Center.

Spencer Lowell

At midnight on July 19, the day the Sunfish was scheduled to make its first foray into the reactor, Matsuzaki's alarm went off in his hotel room. He and his team were staying in Iwaki, the closest habitable city with a hotel, about an hour south of the plant. Starting their day in the dark of night was the only way to have enough time to drive to the plant, suit up in protective gear, and hold a last round of meetings before their start time. That would give them about eight hours; by noon it would be too hot inside the reactor building for the technicians monitoring the robot to do their jobs.

At about 4:30 am, a group of Toshiba techs in full protective gear darted into the reactor building. They fast-walked to the outer wall of the containment vessel and climbed a step ladder up to the opening where the Sunfish and its equipment had been pre-positioned. They unsealed the valve over the opening, then pushed in a heavy guiding pipe, with the Sunfish at its tip, all the way through to the other side. Slowly and carefully, they angled the pipe until the bot slid into the water below.

Inside, it was completely dark. On their monitors in the control room, Matsuzaki's team, connected to the Sunfish's controls via the electric cable, could see only a narrow swath cut through the turbid water by the Sunfish's lights. Seated at a long table, one technician "drove" the Sunfish with a videogame-type controller. Another reeled its cable in and out, keeping it taut so it wouldn't get tangled as the bot swam this way and that. A third did his best to estimate the machine's position using a 3-D software model of the containment vessel. Matsuzaki oversaw them all, trying to forget about the platoon of corporate officials watching over his shoulder.



The Sunfish had to be able to swim (right), fit into the small opening of the containment vessel (top left), and withstand challenges that crippled an earlier robot, the Scorpion (bottom left).

Spencer Lowell

The first day, the Sunfish spent most of its time reconnoitering. The damage inside the containment vessel was worse than expected. Unidentifiable clumps of pebble-sized debris and

pieces of half-destroyed equipment littered the floor. But there was no sign of the fuel, and after eight hours of searching, the team pulled the Sunfish back to the surface. They gave it a rest the next day while they discussed their findings and strategized their next steps.

The following morning, they sent the Sunfish back into the water. The team drove it slowly and carefully, but time after time, the bot's powerful propellers would stir up a blinding cloud of sediment, forcing them to wait until the water cleared again. After several hours of maneuvering, and with the noon deadline looming, Matsuzaki was growing nervous. Then, something startling appeared on the monitors.

"What is that?" said Matsuzaki.

Everyone began talking at once and pointing to what they saw on the screens: murky glimpses of what appeared to be stalactites of something dripping like candle wax from the bottom of the reactor pressure vessel. They'd found the first signs of the missing fuel.

They maneuvered the Sunfish around the area, documenting as much as possible, before pulling the bot out. When Matsuzaki declared the mission complete, the control room burst into applause.

Kenji Matsuzaki, the lead scientist behind Little Sunfish. Spencer Lowell

By now, much of Fukushima Daiichi itself, an expansive complex covering some 860 acres, is a lot safer than you'd expect. Most areas have been decontaminated to the point where full bodysuits are no longer required. The 5,000-plus workers tasked with cleaning the place up have cut down hundreds of the cherry trees that used to enliven the grounds, torn up and paved over once-grassy open areas, and scrubbed down buildings. They have covered the seafloor just off the coast with clay to seal in cesium that seeped into the mud after the disaster. Using an enormous, purpose-built fuel-handling machine, they have removed the hundreds of spent uranium fuel rods from Unit 4, a reactor that was damaged by an explosion but did not melt down.

Still, when I visited the site last December with Lake Barrett, Tepco's American consultant, we had to put on gloves, safety glasses, surgical masks, three pairs of socks, and plastic booties

over our shoes, as well as a personal radiation detector, before being allowed inside the facility.

At 72, Barrett is tall, fit, and astonishingly energetic. I first met him at the Narita airport outside Tokyo, where he bounced right off a 20-hour trip from his home in Florida, joined me in a car without stopping for so much as a cup of coffee, and talked cheerily for the entire two-hour drive to Fukushima prefecture.

When Barrett heard the first news reports about the disaster, he "didn't think much of it," he says. "There's always so much hype around these things." Then he saw the picture of Unit 1 exploding. "I said, 'Holy shit. I know exactly what that was.' I knew they were in deep doo-doo." When the call came to help out, he didn't hesitate. "It's personal for me," he says. "Japan was the only country that helped us at Three Mile Island. We owe Japan."

Inside the Fukushima plant, each of these blue towers holds 100 personal radiation detectors.

Spencer Lowell

From atop a small hill, once covered with grass and now encased in concrete, Barrett and I survey the trio of hulking buildings outlined against the blues of the winter sky and the Pacific Ocean behind them. Remotely operated orange-and-white cranes lean over them like reverent metal giraffes. These are the reactor buildings: the intractable core of the disaster zone, the radioactive redoubts the robots must penetrate.

Each poses a unique challenge. The amount and type of damage inflicted on each is different, as is the depth of the water flooding their bases. Of course, at the heart of each is a mess of melted fuel, presumed to have flowed in different ways to different places.

Less than half a mile from these three reactors sits Unit 5, one of the three other reactors that had been shut down for regular maintenance when the tsunami hit. Since it escaped largely unscathed and is nearly identical to the damaged reactors, Tepco engineers use it to plan robot missions. Inside is a baffling maze of machines, ducts, cables, and catwalks. "You can see how hard it is to run the robots around in here," Barrett says.

We navigate our way through the building to the containment vessel. "That's just like where the Sunfish went in," he says, pointing up to an unassuming circular opening in the wall of the vessel.

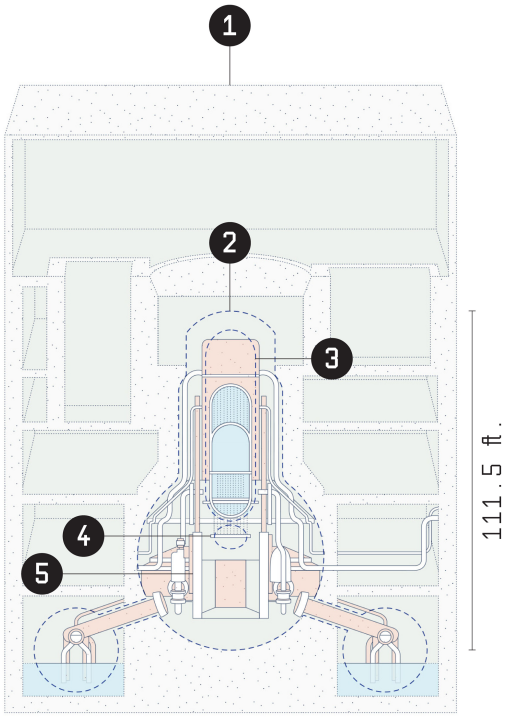
We enter the containment vessel and make our way through a narrow doorway into a chamber below the reactor pressure vessel. Control rod assemblies stud the reactor vessel's underside; we have to crouch to avoid bumping our heads on them. Pointing out key areas and components, Barrett walks me through the current theories on what happened to the fuel in each of the meltdown units. "No one knows if the lava made a nice neat vertical pile or whether it flowed sideways," he says. "Hot molten fuel could have fallen into the water and caused a steam explosion that would have blown it everywhere."

In Unit 3, at least, thanks to the Sunfish, Tepco is relatively certain about a few things. The pictures it took show that the control-rod mechanisms at the bottom of the reactor vessel disintegrated. Molten fuel mixed with melted metal dripped down through the openings they left behind, presumably creating the stalactites seen in the

videos. The lava-like mixture burned through both the steel grate beneath the reactor pressure vessel and a refrigerator-sized machine used to insert the control rods, and some of it dripped down to the floor of the containment vessel. There also appear to be chunks of fuel on the vessel's walls.

Inside Unit 3

Each reactor is made up of three containers, one set inside another, that hold critical equipment.



1. Reactor Building: A large concrete and steel structure that acts as the last line of defense to keep radiation from escaping into the outside world. **2. Primary Containment Vessel:** An airtight enclosure made of steel and concrete. **3. Reactor Pressure Vessel:** A thick steel container that holds the uranium fuel, which powers the nuclear reactor. **4. Control-Rod Drive:** A mechanical system that uses thin rods to speed up or slow down a nuclear fission reaction. The rods work by absorbing the stray neutrons that trigger a chain reaction. **5. Pedestal:** A circular concrete structure that holds up the reactor. From inside, workers can access the control-rod drive.

That still leaves an awful lot unknown. At the end of the day, "how much did we learn from the Sunfish mission?" Barrett asks. "It was a step, not a leap. We're getting closer and closer, but we have a long, long way to go." Tepco is continuing its efforts to scout the inside of the reactors. In January, a robotic probe using a remote-controlled camera mounted on a long pole spotted for the first time what appears to be melted fuel inside Unit 2. There may be another Sunfish mission, though it won't be the same robot that found the fuel in Unit 3. Despite emerging from the reactor undamaged, it had still absorbed a dangerous amount of radioactivity. Tepco engineers sealed it in a steel cask and interred it with other radioactive waste on the plant site.

Limited and uncertain as the Sunfish's findings are, they have helped move the ball forward. Engineers have now begun thinking about how to build the next generation of robots that will have to carry out the most complicated undertaking of all: removing the melted fuel.

Their first challenge will be enabling the bots to reach their target. "These are cramped spaces filled with huge pieces of equipment that weigh many tons. You have to cut them up in pieces and pull them out," Barrett says. One idea currently in favor is to build a massive 20-foot robot arm that would enter the reactor building on rails, reach into the reactor pressure vessel, and scoop up the fuel. Another is to send in a bot the size of a small refrigerator on tractor treads, equipped with cutting and gripping tools to wrangle debris. A second robot would lift the detritus into containers, seal it, and put it on a conveyor belt to the outside.

Either system will take years to develop. Either or both might fail. Tepco has pegged 2021 as the

target year to begin removing fuel debris. How long might the entire Fukushima cleanup take? "Good question. Nobody knows. No one in human history has experience with this," says Naoaki Okuzumi, a senior manager with the decommissioning institute. "The government says 30 to 40 years. I think that is optimistic."

While the robots' work inside Fukushima Daiichi drags on, human beings who once lived near the plant are waiting to go home. The national government has decontaminated several towns and urged residents to return. At the time of my visit in December, though, roughly 130 square miles of land was still off-limits, including the better part of a town called Okuma, perched in the hills a few miles from the plant.

Yoshihiro Takada, a former resident who now works with the local government agency in charge of rebuilding, agreed to show me around. Takada spent almost his entire life in Okuma and had to escape with his wife, child, and parents when the disaster hit. They've relocated to another town 65 miles away.

I met up with Takada in a parking lot just outside the exclusion zone, where we put on full-body Tyvek suits, face masks, gloves, socks, and booties over our shoes to protect us from the particles of cesium and strontium. Inhaling even a dust speck of one of those isotopes can be dangerous. That's part of what makes radiation so terrifying: You can't feel it, see it, or smell it. It can kill you without you ever knowing you encountered it.

A few miles from the Fukushima plant, in the town of Okuma, visitors must wear full-body Tyvek suits, face masks, gloves, socks, and booties when walking along the abandoned streets. Spencer Lowell

The desolation of the exclusion zone, in the town of Okuma. Spencer Lowell

There was no one in the train station, the barbershop, the restaurants, or the stores. The modest houses and apartment buildings on the residential streets were all empty. The only sound I heard as we walked down the middle of the deserted main street was the chirping of clueless birds who didn't realize they'd chosen to nest in a radioactive hot zone.

"I remember this place—their pizza was so good," Takada says, gesturing at a shuttered restaurant as we walk through town. Several shop windows have been smashed by wild boar that have come down from the hills to ransack the deserted town for food. Cars sit in driveways half-hidden by overgrown weeds. Takada only occasionally checks in on his own house. "Rats are running all over it inside. There are droppings and garbage all over," he says.

The area around Fukushima is mostly scenic farmland fringed with thickly wooded hills. But drive along practically any road and you pass fields filled with rows and rows of boulder-sized, black polypropylene bags. They are filled with contaminated earth; as part of the cleanup, a layer of topsoil is being scraped up from gardens, schoolyards, and fields all across the region. Roughly 20 million of the bags are scattered around the prefecture. Many of them will eventually be moved to the outskirts of Fukushima Daiichi itself for indefinite storage, along with an ever-growing array of tanks holding the radioactive water Tepco continues to pump out of the reactors.

Ultimately, there is no technology that can simply fix what happened at Fukushima. The only certainty is that it will be a slow, incremental, frustrating process that may not even be completed in Kenji Matsuzaki's lifetime. For now, all the scientists, engineers, and their allies can do is keep the radioactivity under control, track down its source, and try to capture it. But first, they need to create the robots to do it.

Radioactive waste at the Tomioka contaminated waste facility. It will be buried for 200 years. Spencer Lowell

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Vince Beiser *(@vincelb) is the author of* The World in a Grain, *to be published in August.*