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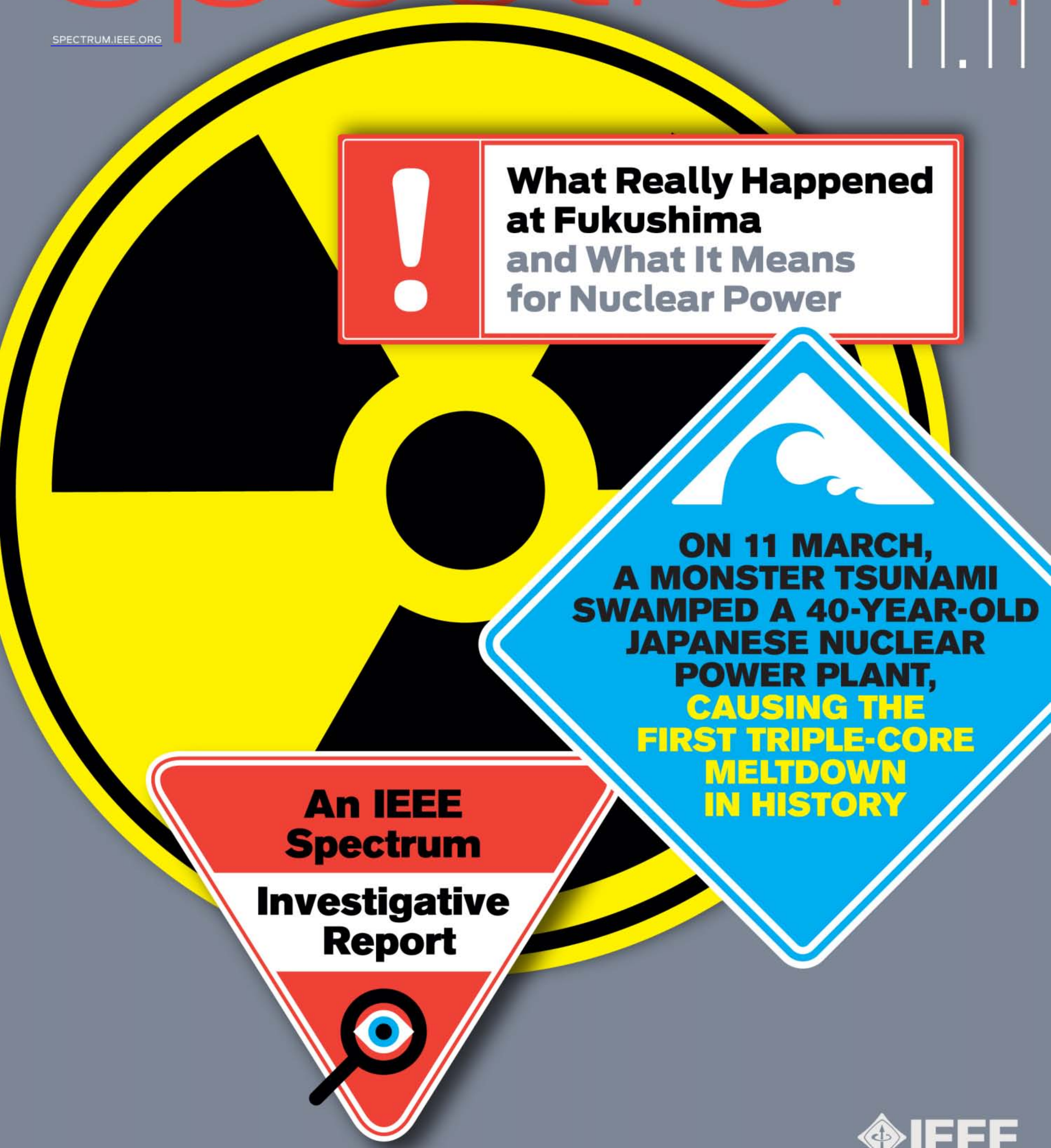

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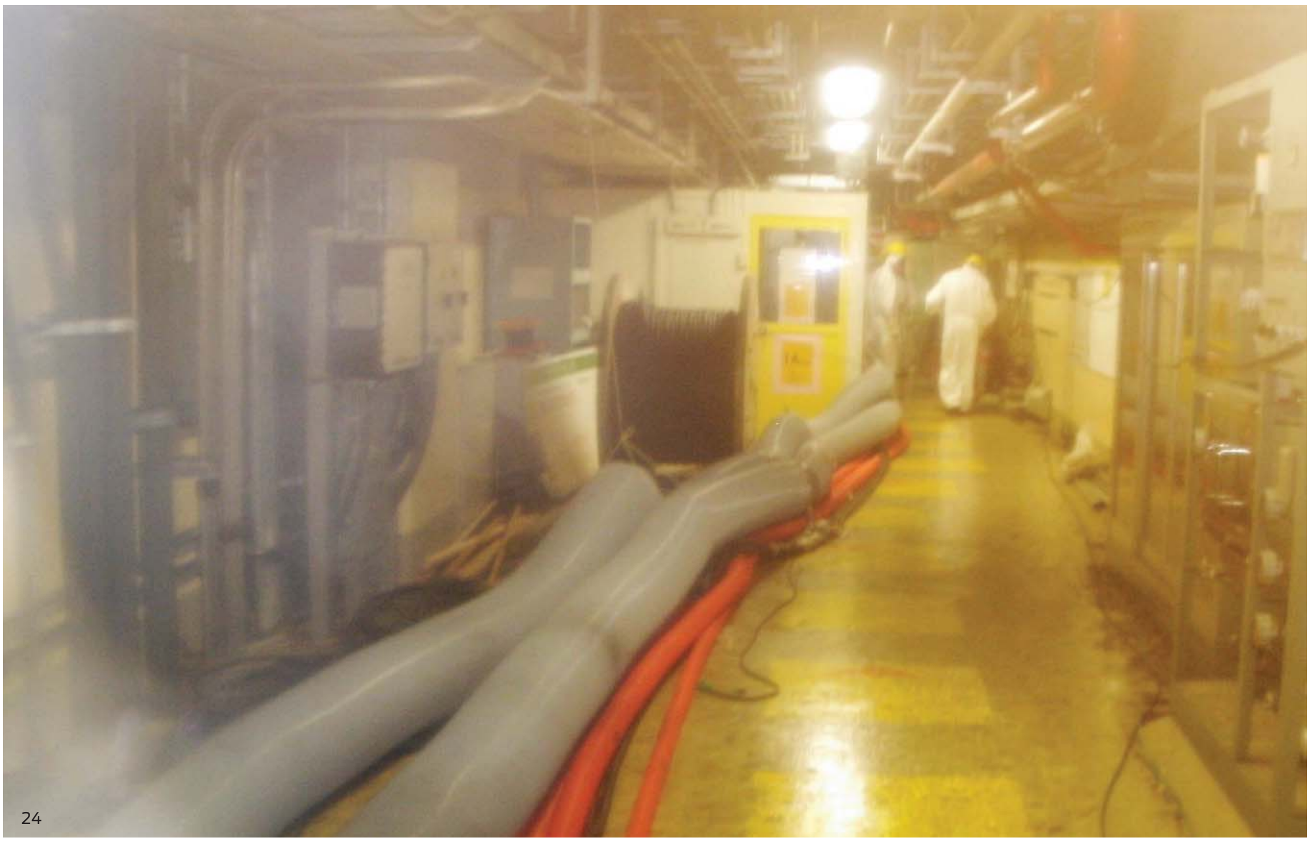
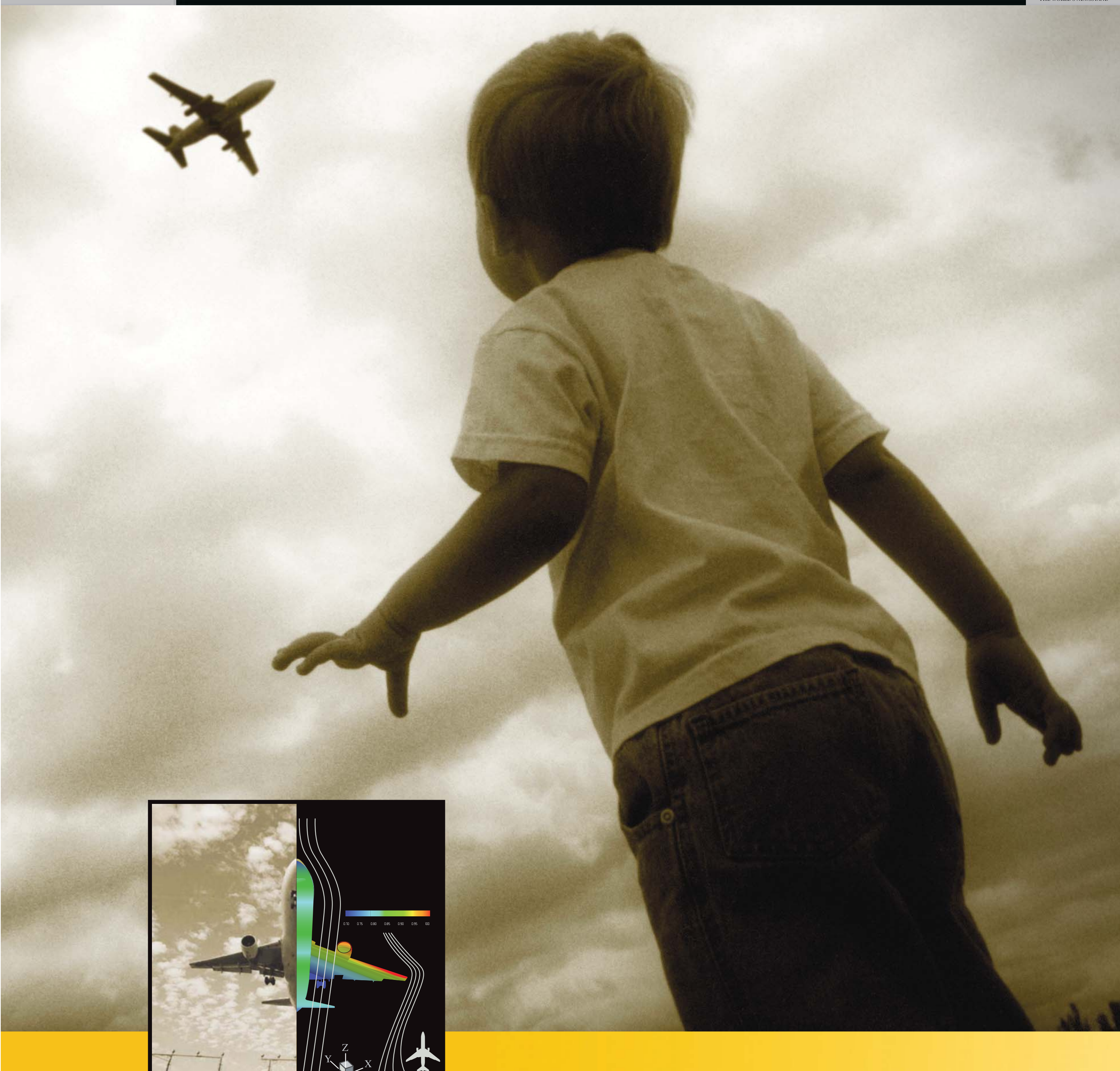


COPING WITH CATASTROPHE: Workers inside the Fukushima Dai-ichi nuclear power station labor to stabilize the ruined reactors.

COVER: CARL DETORRES

THIS PAGE: CLOCKWISE FROM TOP: TEPCO; DAVID PLUNKERT; ROLFE HORN



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UPDATE

OPINION

DEPARTMENTS

SPECTRUM.IEEE.ORG AVAILABLE 1 NOVEMBER

Fukushima: Measuring the Impact

The radiation released by Japan's nuclear disaster caused the government to evacuate towns and impose bans on fishing and agricultural exports. For an interactive map of the government's response, as well as a peek into the future of the Fukushima Dai-ichi site, go to http://spectrum.ieee.org/fukushima.

THEINSTITUTE.IEEE.ORG AVAILABLE 4 NOVEMBER

SATELLITE SERVICE EARNS MILESTONE
The world's first direct broadcast satellite service, which became available in 1984, is being honored with an IEEE Milestone this month. This service was the culmination of 18 years of research, which included the development of an inexpensive low-noise receiver and investigations of rain attenuation in the 12-gigahertz band.

FINANCING ENGINEERING EDUCATION
As most parents and students know, tuition at top engineering schools is not cheap. To help ease the financial burden, IEEE offers dozens of scholarships, fellowships, travel grants, and internships to engineering undergrads and grad students.

SIGNAL PROCESSING CONFERENCE
The IEEE International Conference on Emerging Signal Processing Applications, to be held from 12 to 14 January in Las Vegas, will cover 3-D technology for gaming, telepresence, gesture recognition for games and natural user interfaces, and more.

ONLINE WEBINARS & RESOURCES AVAILABLE AT http://spectrum.ieee.org/webinar

16 November: Big Demand Drives Small Solutions: Scalable Baseband Solutions

17 November: Electrostatic Actuation With COMSOL Multiphysics

Simulation of Vacuum Electronics Devices Using VORPAL

Constrained Optimization in MATLAB: A Framework for N-1-1 Contingency Analysis and Security Constrained Optimal Power Flow

The IEEE Emerging Technology Forum Series: Reinventing Infrastructure for High Speed Rail

Plasma Modeling With COMSOL Multiphysics

The IEEE Emerging Technology Forum Series: Silicon Valley's Impact on the Automotive Industry

Requirements Management's Key Role in the Nuclear Industry

Modeling and Simulation of HEV and EV Power Electronics

Teaching Control Systems to Future Engineers

Systems Engineering: Two Perspectives on a Domain That Is No Longer Optional

PMU Technology for Dynamic Conditions in Distribution

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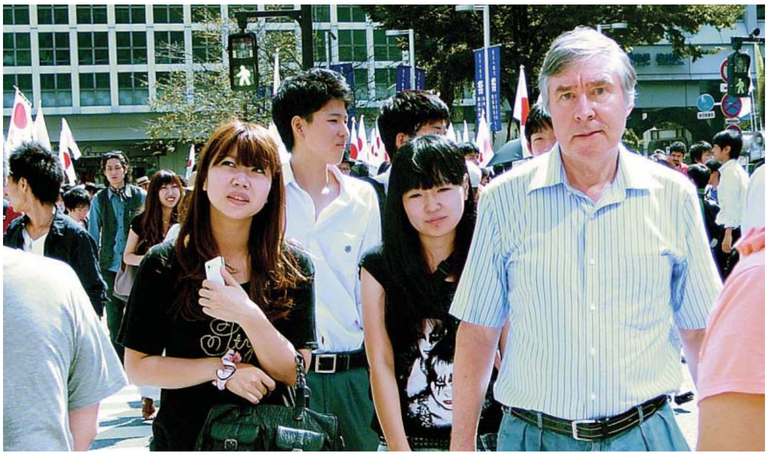
CLOCKWISE FROM TOP LEFT: DAN ISTITENE/GETTY IMAGES; YURIKO NAKAO/REUTERS; ISTOCKPHOTO

back story



Assignment: Fukushima

If you're a habitué of *IEEE Spectrum*'s website, then you've noticed that we've posted rather a lot of stories and updates on the disaster at the Fukushima Dai-ichi nuclear plant. Although nearly every *Spectrum* staffer has contributed to our coverage, it has been John Boyd [above], our man in Japan, whose reports have enabled us to break as many stories as we have.

You'll find his latest article on the effort to bring the Fukushima Dai-ichi reactors under control in the Update section of this issue. And behind that article are the more than 50 online reports he has filed since the crisis began on 11 March.

Born in England, Boyd arrived in Japan in 1972 during what was supposed to be an around-the-world hitchhike. He never left. Living in Japan for the past four decades has inured him to earthquakes. But he could tell that the one this past March was different.

"At first I thought it was a huge windstorm because the power lines were swinging so much," he says. The buildings in his neighborhood of greater Tokyo were shaking so violently that some people sought safety in a nearby field, only to discover that the field itself was bucking and heaving.

Amazingly, Boyd's apartment building withstood it all. After searching for a friend, he plunked down in front of the TV just in time to see a tsunami devour the northeast coast.

Although his own city was spared the tsunami's ravages, life was no picnic. "The first few weeks it was tough because there was a run on food, and bottled water wasn't available because of panic over radiation," he says. Train service was halted, aftershocks rattled coastal areas, and rolling blackouts stifled Tokyo. "But news was coming in all the time," Boyd marvels.

He says he wasn't immediately aware of the scope of this story. But when he filed his first report, he already seemed to know the direction it was going to take. It was prefaced by a note that "things are likely to get worse"—a true British understatement if ever there was one. ❑

ETSUKO YOKOYAMA

CITING ARTICLES IN IEEE SPECTRUM

IEEE Spectrum publishes two editions. In the international edition, the abbreviation INT appears at the foot of each page. The North American edition is identified with the letters NA. Both have the same editorial content, but because of differences in advertising, page numbers may differ. In citations, you should include the issue designation. For example, The Data is in *IEEE Spectrum*, Vol. 48, no. 11 (INT), November 2011, p. 64 or in *IEEE Spectrum*, Vol. 48, no. 11 (NA), November 2011, p. 92.

contributors

KHALED AHMED and **KLAUS SCHUEGRAF** write about the coming competition between thin-channel 3-D and 2-D transistors in “Transistor Wars” [p. 44]. Ahmed is an IEEE senior member and a technology strategist in the Silicon Systems Group at Applied Materials, where Schuegraf is chief technology officer. After years of working on ways to manufacture smaller and smaller bulk silicon transistors, both are excited about the rapid development of the new, thin-channel alternatives. “From a device physics perspective, thin is definitely in,” Ahmed says.

PETER FAIRLEY writes about energy as a contributing editor for *IEEE Spectrum*. Fairley, a world traveler who divides his time between Vancouver Island and Paris, has the international perspective *Spectrum* needed for articles about China’s nuclear-powered future [p. 40] and Germany’s nuclear-free future [p. 41]. “When it comes to energy, every country has its own unique set of political restraints and cultural hang-ups,” he says. “That’s what makes it interesting.”

DAVID KUSHNER wrote “Ticking to Eternity” [p. 50], about the effort to build a monumental clock that will tell time for 10 000 years. He wonders how people will view the clock millennia from now: “I keep picturing the Neanderthals in *2001: A Space Odyssey* discovering the monolith, stumbling on to this amazing thing.” A *Spectrum* contributing editor, Kushner has written three books, including *Levittown: Two Families, One Tycoon, and the Fight for Civil Rights in America’s Legendary Suburb.*

DAVE LEVITAN, a freelance journalist in New York City, is a contributor to *Spectrum*’s EnergyWise blog. He wrote “Prospects for an Artificial Leaf Are Growing” [p. 13] because “some of the best ideas for energy are already out there in nature,” he says. “We just have to adapt what exists.” A companion piece on how engineers are taking cues from whales and fish in designing wind farms is at http://spectrum.ieee.org/levitan0911.

HARRY TEASLEY has been developing video games for more than 20 years, and many of his games, like the massively multiplayer *Lord of the Rings* online, are supported by hyperspecialized computer mice. “I could open a museum of input devices, and most of them are total failures,” says Teasley, who writes about the Microsoft Touch Mouse in “Gestures Creep Into Mouse Interfaces” [p. 22]. But when you find a mouse that works well with a game, he says, “it’s a revelation.”

PAUL WALLICH took to his basement workshop in Vermont to test out a MakerBot 3-D printer for “Absolutely Fab” [p. 18]. There, he made a number of small plastic doodads, including a SpongeBob SquarePants figurine for his 6-year-old son. His 3-year-old isn’t so lucky, at least for now. “He’s being kept far away from this thing,” says Wallich, “considering that it’s squirting out plastic at 220 °C.”

CLOCKWISE FROM TOP RIGHT: DAVE LEVITAN; HARRY TEASLEY; JULIE ROBICHAUX; BETH KELLY; RANDI SILBERMAN KLETT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Area of Expertise
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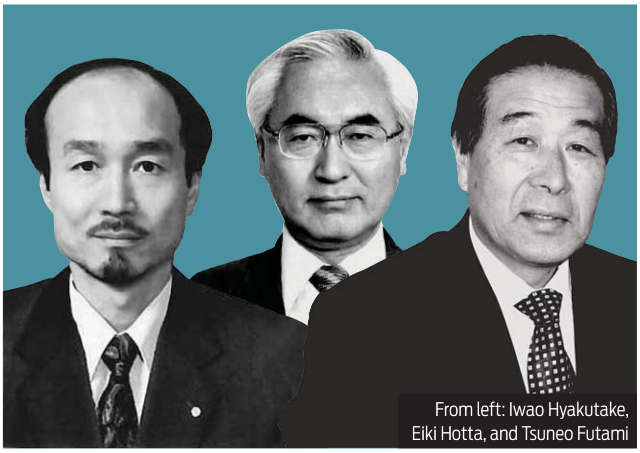
LabVIEW Helped Me
Analyze and visualize data interactively using custom algorithms
Latest Project
Mapping molecular structure changes during activation of the light receptor, rhodopsin
NI LabVIEW
LabVIEW makes me better because I can
PROGRAM
the way I think

spectral lines



From left: Iwao Hyakutake, Eiki Hotta, and Tsuneo Futami

Covering Fukushima With a Little Help From Our Friends

Journalism is about access—to people, places, documents, and other things. And here's why good journalism is hard: When a journalist most needs access to something is often the exact time it's hardest to get that access. The reason, of course, is that lots of journalists are all flocking to the same person or place, in response to the same news-making event. For example, everyone wants to talk to the cabinet minister the day after he resigns amid scandal.

And so it was with the Tokyo Electric Power Co., whose Fukushima Dai-ichi nuclear power plant suffered core meltdowns in three reactors in the days after an enormous tsunami inundated the plant. The world's journalists besieged TEPCO, which behaved in an all-too-predictable fashion: It hunkered down and gave terse and essentially useless updates about the unfolding disaster.

For us, perfunctory coverage of this calamity wasn't an option. IEEE members expect us to give them authoritative insights into engineering-related events. And the bigger the event, the greater the expectations. Besides, we had a reputation to live up to: *IEEE Spectrum* won its first National Magazine Award—the highest honor in U.S. magazine publishing—for a report published in 1979 on the Three Mile Island nuclear accident in Pennsylvania.

Immediately after the news of trouble at Fukushima broke, our Japan correspondent, John Boyd, began filing blog posts [see Back Story, this issue]. But we also needed a staffer in our New York City office to anchor our output, which was being directed by Samuel K. Moore, *Spectrum*'s news editor. Associate Editor Eliza Strickland accepted the challenge.

We had hired her to be our Asia editor, a newly created position, and her first day of work at *Spectrum* was Wednesday, 9 March. The Fukushima disaster began not quite two days later. For a true journalist, there's a kind of thrill, a mix of butterflies and fervor, that you feel when something huge occurs in your beat area. Strickland had never written on nuclear technology before, but she was well prepared to do so: She came to *Spectrum* from *Discover* magazine, where she had been a Web editor specializing in energy and environmental issues.

Over the next month she wrote or edited dozens of posts and stories, including ones on worst-case scenarios and a buoy-based tsunami warning system. She soon found that, in the endless quest for access, she had something important on her side: the global reach of IEEE. Strickland contacted Professor Eiki Hotta, chair of the Japan chapter of the IEEE Nuclear & Plasma Sciences Society (NPSS). He put her in touch with Professor Tsuneo Futami of the Tokyo Institute of Technology, who is a former superintendent of the Fukushima Dai-ichi plant. Professor Futami became Strickland's guide and champion, patiently answering her questions for two days at his Tokyo office and securing for her an exclusive interview at TEPCO headquarters.

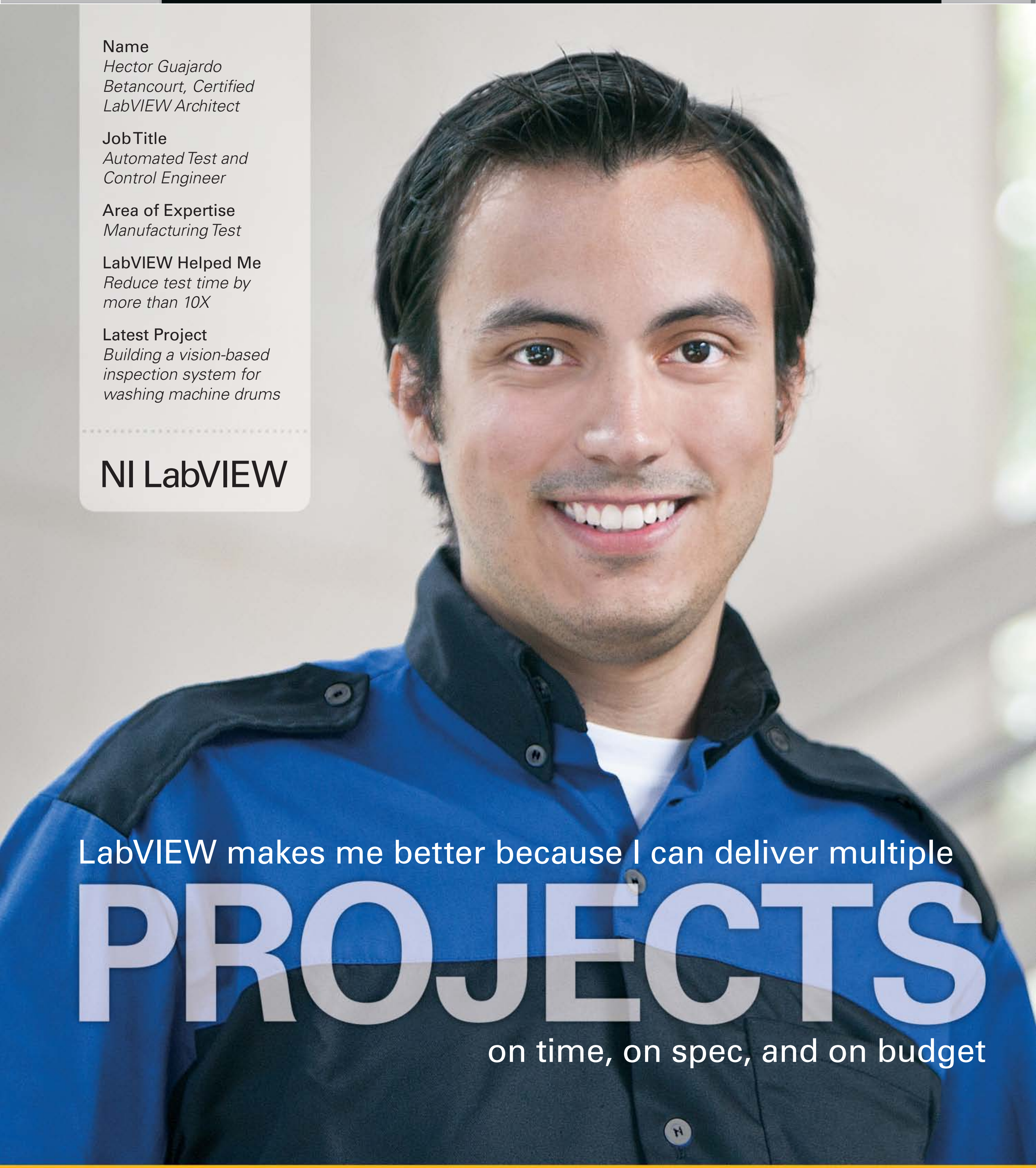
Although the executives at TEPCO didn't reveal much during the interview, the scene there was memorable. With summer coming on, the utility had embarked on a stringent energy conservation regime. So Strickland was startled on arriving to find TEPCO's senior management in suits and ties, rushing around dark, hot hallways as they grappled with the repercussions of the second-worst nuclear power plant accident in history. It was thanks to Professor Futami, too, that Strickland secured an interview with the officials at Japan's Nuclear and Industrial Safety Agency who oversaw the response to the Fukushima crisis. The vice-chair of the NPSS, Hiroshi Akatsuka, accompanied her to that interview.

IEEE's dynamic Japan organization helped at every turn. Just before Strickland left Tokyo to travel to the city of Aizu-Wakamatsu, she learned that her interpreter wouldn't be able to meet her there. The head of the IEEE Japan office, Iwao Hyakutake, wheeled into action and arranged for a replacement. In an empty school in Aizu-Wakamatsu, where Strickland interviewed the mayor of an evacuated town, she was touched by the sight of corridors lined with strings of paper cranes, sent by well-wishers from around the world.

We would like to thank Professor Futami, Professor Hotta, Professor Akatsuka, Mr. Hyakutake, and the many others who helped us with our report on Fukushima. By believing in what we do and by being generous with their time, they enabled us to start a discussion about exactly what happened at Fukushima and what it all means.

—Susan Hassler

FROM LEFT: IWAO HYAKUTAKE, EIKI HOTTA, TSUNEO FUTAMI



Name
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LabVIEW Helped Me
Reduce test time by more than 10X
Latest Project
Building a vision-based inspection system for washing machine drums
NI LabVIEW
LabVIEW makes me better because I can deliver multiple
PROJECTS
on time, on spec, and on budget

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The Future of Riots

Video surveillance of London's rioters points to the future of facial recognition

On 6 August, peaceful protests over the police shooting of a local man in London's Tottenham district exploded into full-blown riots. During four days of assaults, arson, and looting, some of London's thousands of closed-circuit TV cameras captured video of the violence.

In the aftermath of the unrest, police officials began poring over footage in an attempt to identify suspected rioters. They even employed a facial recognition system designed for use during the 2012 Olympic Games, in London. But they found traditional investigative techniques to be much more fruitful than software, in part because many of the rioters had obscured their faces with hoods or bandannas, and because other factors such as poor lighting made it difficult to identify people.

The presence of cameras was clearly not a deterrent to the London rioters. But will technological advances that seem poised to eliminate anonymity prevent civil unrest in the future?

"I don't think we'll ever be able to predict the behavior of crowds, because they're notoriously unpredictable," says James Orwell, of the computing and information systems department at London's Kingston University. Still, Orwell, who has been developing recognition and tracking systems, says that the proliferation of cameras and technologies that help authorities make more efficient use of the increasing volume of video may make an individual think twice.

Researchers working with Orwell and his colleague Sergio Velastin have developed software that allows for the automatic detection of objects or events in video footage, creating continuity

THE CLASH: A rioter throws a rock at police in London. Face recognition systems could probably tell you all about him.

PHOTO: DAN ISTITENE/ GETTY IMAGES

100 megabits per second The maximum data rate a new broadband technology allows over twisted pairs of copper wires. Alcatel-Lucent, the technology's developer, says it will give telecoms a cheaper option than running optical fiber.

update

between cameras that lets the police track someone's movements. The technology also makes it possible to search video for specific actions, such as people running or cars pulling over to a curb. "It can search content-based metadata such as 'guy in the red tracksuit,' to see if there is a better shot that lets his face be compared with those in online databases," explains Orwell.

Orwell's system can plow through video footage to retrace a person's movements, maybe even to his home. Still, Orwell is quick to issue this caveat: "If they're really intent on evading identification, there's no easy way around that."

The tracking software relies on video footage that's available only to authorities. The system may seem Orwellian, but because of a convergence of technological trends we're near the point where almost anyone can use facial recognition to pick you out of a crowd. And what they can do next is worrisome.

"Your face is a veritable conduit between the off-line and online worlds, and you can't change it," says Alessandro Acquisti, a professor of information technology and public policy at Carnegie Mellon University, in Pittsburgh.

In research presented just prior to the London riots, Acquisti's team used a combination of off-the-shelf face recognition software, cloud computing, and data publicly available from social networks to uncover information about people just from their photographs. His group was able to identify students on campus caught on a webcam and then use algorithms developed earlier to probabilistically infer such information as date and place of birth, as well as Social Security number and credit score.

"As photos become scannable and matchable against online databases, it is creating a form of identification that the person being identified doesn't control," says Marc Rotenberg, executive director of the Electronic Privacy Information Center.

This is not necessarily bad, Rotenberg says, pointing to the potential for identifying missing children or fugitives. But he is quick to turn to the flip side of the coin—a scenario in which people at a public demonstration expressing unpopular views are identified and subsequently harassed.

"I don't think the end of privacy is upon us," Rotenberg says. But he is concerned that as the ability to remain anonymous disappears, the rules governing interpersonal conduct and commerce may not change quickly enough to keep people from being exploited. —Willie D. Jones

Extraterrestrial Abode

If we ever get to Mars (or anywhere else in the solar system), we're going to need a place to live. In September, NASA tested its latest home away from home, the Habitat Demonstration Unit, or HDU. The agency set up this combination of solid and inflatable structures, air locks, ladders, and ramps in the desert and populated it with faux astronauts for testing. The newest additions to the HDU include a robotics workstation, where a person inside the habitat can teleoperate a robot rover out in the desert.

NASA

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15 meters The width a flying carpet would have to be to carry a human using existing materials and technologies. Engineers at Princeton built a 10-centimeter prototype that propels itself at 1 cm/s—but only near the surface.

JUAN ESTEY/ISTOCKPHOTO

Prospects for an Artificial Leaf Are Growing

Scientists design photosynthesis devices that could make hydrogen or other fuels

IF EVERY LEAF on the planet can do it, maybe we can too. Scientists have long tried to mimic photosynthesis as a way to harness the energy in sunlight and turn it into a usable fuel, just as plants do. There have been big technical challenges for just as long, and though researchers are far from the ultimate goal, last month two groups of scientists described some ways to hurdle those obstacles.

One of the groups, led by MIT chemistry professor Daniel Nocera, found a new way to reproduce part of the photosynthesis process, using light to split water molecules into oxygen and hydrogen. The gases can then be stored and used as a fuel.

Other groups have had some success with this process before, but there were always stumbling blocks that would make it hard to scale up or commercialize, such as extremely acidic or basic conditions, expensive catalytic materials, or both. However, Nocera's group managed to get artificial photosynthesis to work using benign conditions and cheap, abundant materials as catalysts.

Specifically, the team joined a commercially available triple-junction silicon solar cell to two catalysts: cobalt borate for splitting the water molecule and a nickel molybdenum zinc alloy to form the hydrogen gas. The water-splitting reaction achieved a sunlight-to-fuel conversion of 4.7 percent in one incarnation of the device and 2.5 percent in another. The difference between the two was that the more efficient device housed the hydrogen-generating alloy on a mesh wired to the solar cell. The less efficient version needed no wires, and the alloy was instead deposited onto the stainless-steel back of the solar cell.

It is the wireless possibility, where the entire device is self-contained, that researchers say is most exciting. "Because there are no wires, we are not limited by the size that the light-absorbing material has to be," says Steven Reece, a research scientist with Sun Catalytix (a company cofounded by Nocera) who worked on the discovery. "We can operate on the micro- or even nanoscale... so you can imagine micro- or nanoparticles, similar to the cells we've worked with here, dispersed in a solution." The final product could be much larger, too—a leaf-size stand-alone system, for instance. Whatever the size, the researchers believe such devices could help provide power in poor areas that lack consistent sources of electricity.

Sun Catalytix expects to be able to bring the device to the point where a kilogram of hydrogen could be produced for about US $3, according to its chief technology officer, Thomas Jarvi. Given that about 3.75 liters (1 gallon) of gasoline contains about the same amount of energy as 1 kilogram of hydrogen, the cost would compare favorably to gasoline, which is currently higher than $3 per gallon in the United States.

Daniel Gamelin, a professor of chemistry at the University of Washington, who works on related topics but was not involved with the new research, says the MIT and Sun Catalytix work represents an "impressive accomplishment." However, he says, it remains to be seen whether silicon is really the most desirable material to use. Something less susceptible to degrading by oxygen may be a better option, he says.

"For these specific devices, there remain open questions about their long-term stability," Gamelin says. "And their efficiencies would still need to be increased substantially to be commercially viable. But there is obviously potential for improvement on both fronts. In the bigger scheme, [this research] marks important progress toward the development of truly practical solar hydrogen technologies."

Separately, researchers in Illinois demonstrated a different part of the photosynthesis process—a step toward using sunlight to recycle carbon dioxide. In

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the natural world, the sun's energy extracts electrons from a water molecule. The electrons then reduce CO_2 into fuel (in plants, the fuel takes the form of carbohydrates). University of Illinois graduate student Brian Rosen and other scientists have invented a device that electroreduced CO_2 to carbon monoxide at a lower voltage than previously achieved. The high voltages usually required have been a major stumbling block in the past. Rosen's group brought the voltage down by using a combination of a silver cathode and an ionic liquid electrolyte that presumably stabilized the CO_2 ion. And, according to Rich Masel, who led the research and is CEO of Dioxide Materials, a company working on CO_2 electroreduction with the University of Illinois, this piece of the photosynthesis process could eventually lead to a way to turn captured CO_2 into "syngas"—a mixture of carbon monoxide and hydrogen used in the petrochemical industry to make gasoline and other fuels.

The experiment "shows that one can make syngas efficiently from any source of electricity," Masel says. However, large-scale versions of the device probably can't be cooked up until 2018. "Presently we have demonstrated the process on the 1-centimeter-squared scale. We need to go to the million cm^2 to make significant amounts of gasoline."

Work on artificial photosynthesis has ramped up considerably in recent years. In July 2010, the Department of Energy began funding the Joint Center for Artificial Photosynthesis to the tune of $122 million over five years. The center, with close to 200 members in universities and national laboratories across California, aims to build on nature's photosynthetic design, bridging all the disciplines required, from chemical engineering to applied physics.

In an interview earlier this year, the center's leader, Caltech professor Nate Lewis, told *IEEE Spectrum* that progress is certainly being made, but it isn't clear yet if the right combination of catalysts and light absorbers and everything else that goes into practical artificial photosynthetic devices has been found.

"We're seeing light in the tunnel," he said. "We don't know where the end of the tunnel is. It's a curved tunnel." —Dave Levitan

A version of this article appeared online in September.

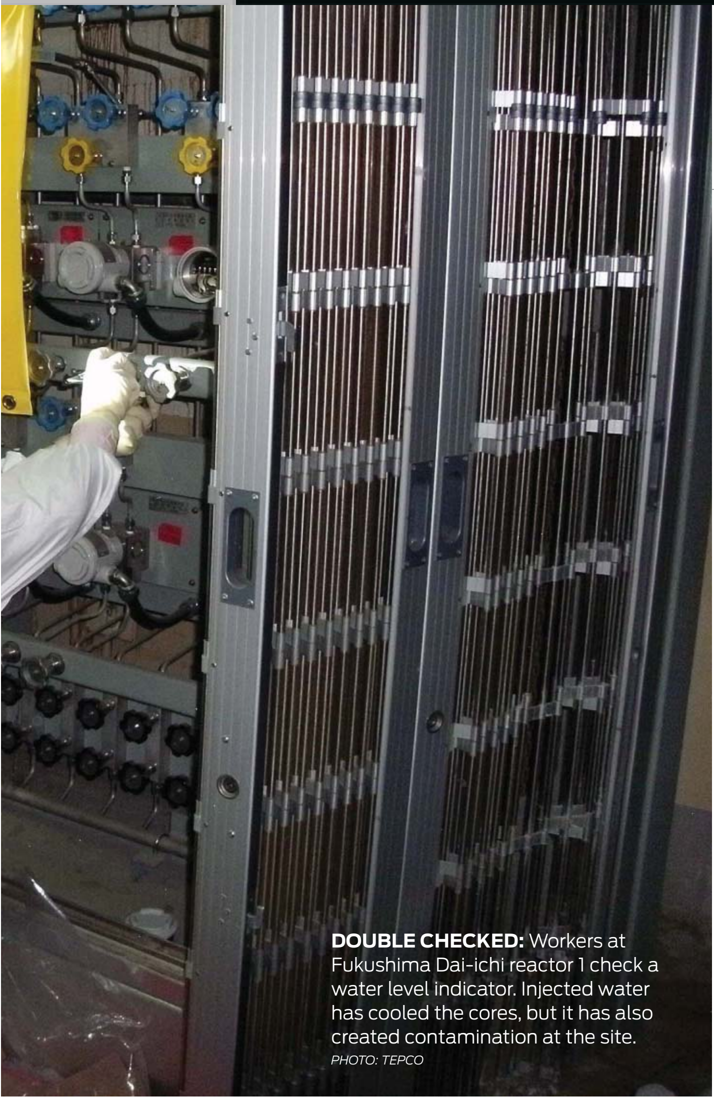
Shutdown of Fukushima Reactors Is Ahead of Schedule

Success in cooling the reactors suggests the plant could be stabilized by year's end

This past April, when the Japanese government and Tokyo Electric Power Co. (TEPCO) jointly unveiled their plan to bring the damaged reactors of the Fukushima Dai-ichi nuclear power plant to a cold shutdown and gain control of the release of radioactive materials, they set a tentative completion date for mid-January 2012.

And "tentative" had to be the operative word, for the obstacles TEPCO faced—and to some extent still does face—are challenging in the extreme. They include:

- ☐ Fuel rod meltdowns in reactors 1, 2, and 3 due to loss of cooling systems following the 11 March earthquake and tsunami;
- ☐ Severe damage to the upper levels of reactor buildings 1, 3, and 4 and slight damage to building 2, stemming from hydrogen explosions;
- ☐ High levels of radiation and contaminated rubble, making working conditions hazardous and difficult;
- ☐ Thousands of metric tons of contaminated water accumulating on the site and leaking out of the reactors.



DOUBLE CHECKED: Workers at Fukushima Dai-ichi reactor 1 check a water level indicator. Injected water has cooled the cores, but it has also created contamination at the site.
PHOTO: TEPCO

It appears, however, that the process is now ahead of schedule. Environment Minister Goshi Hosono, who is also in charge of the Fukushima nuclear accident recovery, told the International Atomic Energy Agency's annual general conference in Vienna on 19 September that Japan was now aiming to complete a cold shutdown of the Fukushima plant by December 2011, instead of mid-January 2012.

Progress was already evident in July, when Hosono announced that workers had completed step 1 of the two-step road map on schedule, reducing radioactive emissions and starting to bring down the core temperatures in reactors 1, 2, and 3.

Hosono attributed the success to the construction of a new cooling system, which had begun pumping water into all three damaged reactors. In addition to cooling, the system also decontaminates the water accumulating in the basements of the reactor and turbine buildings. The contamination is the result of injected water coming into contact with the molten fuel in the pressure vessels.

Critics, however, were quick to question the stability of the system and its ad hoc design. The combination of filtering and decontamination technologies—mainly from the French nuclear giant Areva and the U.S. nuclear waste management company Kurion—includes some 4 kilometers of piping.

The critics have a point. Even with the addition of a reportedly more robust system (to be used in parallel or as backup as needed) from Toshiba and IHI Corp., TEPCO admits the system underwent 39 disruptions between 10 July and 8 September. One consequence is that roughly 100 000 metric tons of water still need to be decontaminated.

Disruptions and remaining challenges notwithstanding, TEPCO has been making progress toward step 2 of the road map: a cold shutdown. According to TEPCO, that means achieving and maintaining a temperature of less than 100 °C as measured at the bottom of a reactor pressure vessel—the steel vessel containing the fuel rods—which itself is enclosed inside a protective containment vessel.

A major advance came at the beginning of September, when TEPCO was able to start up the core spray lines to cool reactors 1 and 3. The core spray lines apply water directly to the cores from above, while the system installed in July has been cooling the cores by injecting water from the bottom. TEPCO has also begun increasing the amount of water being injected into reactor 2. The core spray line could not be used until recently because TEPCO first had to survey the subsystem's piping and valves. Given the high radiation in the area, this was difficult, but workers completed the job in July and confirmed the system's operability in August.

By late September, as a result of these efforts, the temperatures in all three reactors had dropped below 100 °C for the first time since the accident. As of 29 September, the temperatures for reactors 1, 2, and 3, respectively, were 77.5 °C, 99.7 °C, and 78.7 °C.

"We are steadily bringing the postaccident situation under control," says Hosono. "To achieve step 2 this year, we'll move the schedule forward and do our best."

But Yoshinori Moriyama, deputy director-general of Japan's Nuclear and Industrial Safety Agency (NISA) is cautious. "We need to maintain this state over the midterm," he says. "Temporary lower temperatures and the nonrelease of radioactive substances do not immediately mean that this is a cold shutdown." In order for NISA to declare a cold shutdown, the temperatures must remain stable and below 100 °C into December. So NISA won't officially declare a cold shutdown until near the end of 2011.

Despite these positive developments, nuclear experts point out that achieving a cold shutdown does not make the troubled plant completely safe, given that even spent fuel continues to generate heat for years after use.

And upon achieving a cold shutdown, TEPCO must take on a new series of challenges. These include finding where the injected water is escaping, stopping those leaks, dealing with the accumulated contaminated water, removing and storing the thousands of spent fuel rods from the pools in reactors 1 to 4, and then figuring out a way to remove the melted fuel. The last is a task that could take a decade or more, according to experts.

—John Boyd

"When I pick a project on which to work, I don't generally look for a problem to solve. Rather, I look for a place to use something I can do very well."

—Wilson Greatbatch (1919–2011), inventor of the implantable pacemaker

update

Explaining LEDs' Diminishing Returns

New concept pulls popular theories together, drives researchers apart

The LED community is ensnared in a long-running and contentious debate over the origin of a phenomenon called droop, the decline in the efficiency of blue and white emitters as their current is cranked up. Solving this mystery will enable the design of droop-busting LED architectures that will make brighter, cheaper solid-state lighting.

The droop debate has recently heated up, with a handful of competing conjectures winning significant backing from groups of optoelectronics experts. Now a theorist at Sandia National Laboratories, in Albuquerque, has found a way to draw the models of light emission together. Weng Chow calculates the behavior of LEDs from their band structure, which specifies the energies that charge carriers can have within devices and the likelihood of finding carriers with those energies.

Every LED, regardless of its color, operates by injecting electrons into the device from one side and driving in their positive counterparts—holes—from the other. Both types of carriers meet in a narrow trench, known as a quantum well. Here they are trapped, bind together through electrostatic attraction, and recombine to emit light.

In red LEDs, these quantum wells are just like those in an elementary quantum-mechanics textbook, and the probability of finding electrons and holes in the trenches is very high. But blue and white LEDs are plagued by strong internal electric fields. Chow explains that when the current is merely trickling through the LED, electrons and holes rarely form the bound states needed for light emission: "The field just rips them off."

In one model, as you crank the current up, electron and hole populations rise, partially offsetting the internal electric field. However, even though most of the carriers are now in the well, droop sets in because the internal field is still strong enough to yank electrons to one side of the trench and holes to another, hampering light emission. Cranking the current even higher in this model negates the effects of the internal field, improving emission efficiency and leading to a recovery from droop, a phenomenon that contradicts what is seen in real LEDs.

Blue and white LEDs are riddled with defects in their crystal lattices, which are more prevalent in their indium gallium nitride quantum wells. When Chow includes this detail in his model, it can quash droop recovery and mimic the real behavior of these devices.

In this form, Chow's model unites two leading conjectures for the cause of LED droop—defects and inefficient carrier recombination in quantum wells. But, crucially, he took it one step further: Chow incorporated the most popular droop theory of all—Auger recombination, a non-light-emitting interaction of three charge carriers that propels either an electron or a hole to a higher energy state. With this addition, Chow's theoretical predictions for LED efficiency mirror the major trends seen in experimental results.

According to Ümit Özgür, from Virginia Commonwealth University, Chow's work warrants attention. He believes that one of its strengths is that it models real physical phenomena known to take place during light emission. A simpler, very widely used model to explain LED behavior and account for droop fails to do this. Özgür now wants Chow to fit experimental data from a range of real devices to his model.

Manos Kioupakis and Chris Van de Walle from the University of California, Santa Barbara, are more critical of Chow's work. They point out that in Chow's model, droop is sensitive to temperature and argue that this finding is inconsistent with experimental results.

The Sandia researcher counters by claiming this inconsistency does not exist, because his model is not as sensitive to temperature as the UCSB team suggests. He also points out that work by Jörg Hader and his colleagues from the University of Arizona can replicate LED behavior at various temperatures with a model, like Chow's, that includes defects.

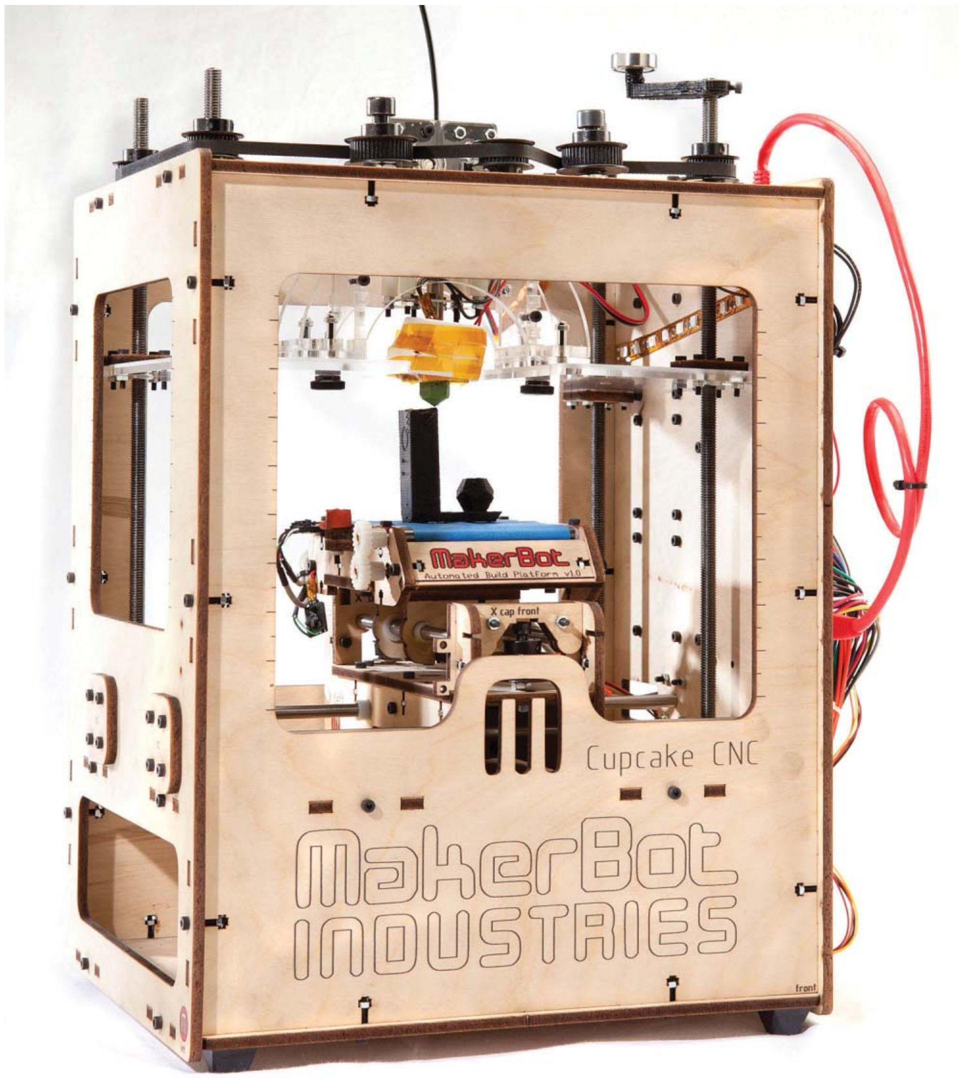
What is clear is that the droop debate shows no signs of abating. While Chow's work is drawing together several leading theories, it's failing to unite all the theorists responsible for them.

—Richard Stevenson

LUIS MOLINA/ISTOCKPHOTO

Absolutely Fab

Home fabrication for the fumble-fingered



I’VE BEEN building a 3-D printer from scratch for several years, but open-source hardware projects do not favor the leisurely. Between the time I first started ordering parts and when I was ready to assemble them, my controller circuits became antiques, and my ancient printed circuit boards are regarded by today’s software with the same sense of befuddlement my son had when looking at a vinyl record.

So when MakerBot Industries, one of the pioneers of prepackaged 3-D printer kits, announced that it was putting its iconic Cupcake CNC model on clearance sale, I decided that my customized version could wait while I built something that actually worked.

The Cupcake is a roughly cubical plywood frame that contains all the mechanical parts needed to extrude plastic (or some other materials) at arbitrary locations within a 100- by 100- by 130-millimeter build space. The device can make small model cars and airplanes, tableware, gear trains, clocks, and anything else that can be modeled as a set of 2-D slices at roughly a half-millimeter resolution. It has stepper motors and bearings to move the build platform and extruder; it also has a DC motor with a toothed pulley. Plastic filament is jammed through a melting chamber heated by a couple of power resistors and then through a 0.35-mm hole onto the build platform.

And it goes together in maybe a week’s worth of evenings, including soldering a handful of wires. Most of the work involves tightening nuts on the six or seven dozen 10-mm-long bolts that slide into ingenious slots in the laser-cut plywood sides to lock the whole thing together into a rigid framework.

Assembly was easy, but troubleshooting was hard, especially for a hobbyist with one antiquated multimeter. The build platform moved, the heaters ran right up to 220 °C, but the extruder did not extrude. After painstakingly disconnecting and reconnecting all the electronics, I discovered that the extruder motor had an intermittent short between two of its coils (not a rare problem, according to support forums). MakerBot sent out a replacement, but in the interim I foolishly decided to upgrade the firmware on the extruder board.

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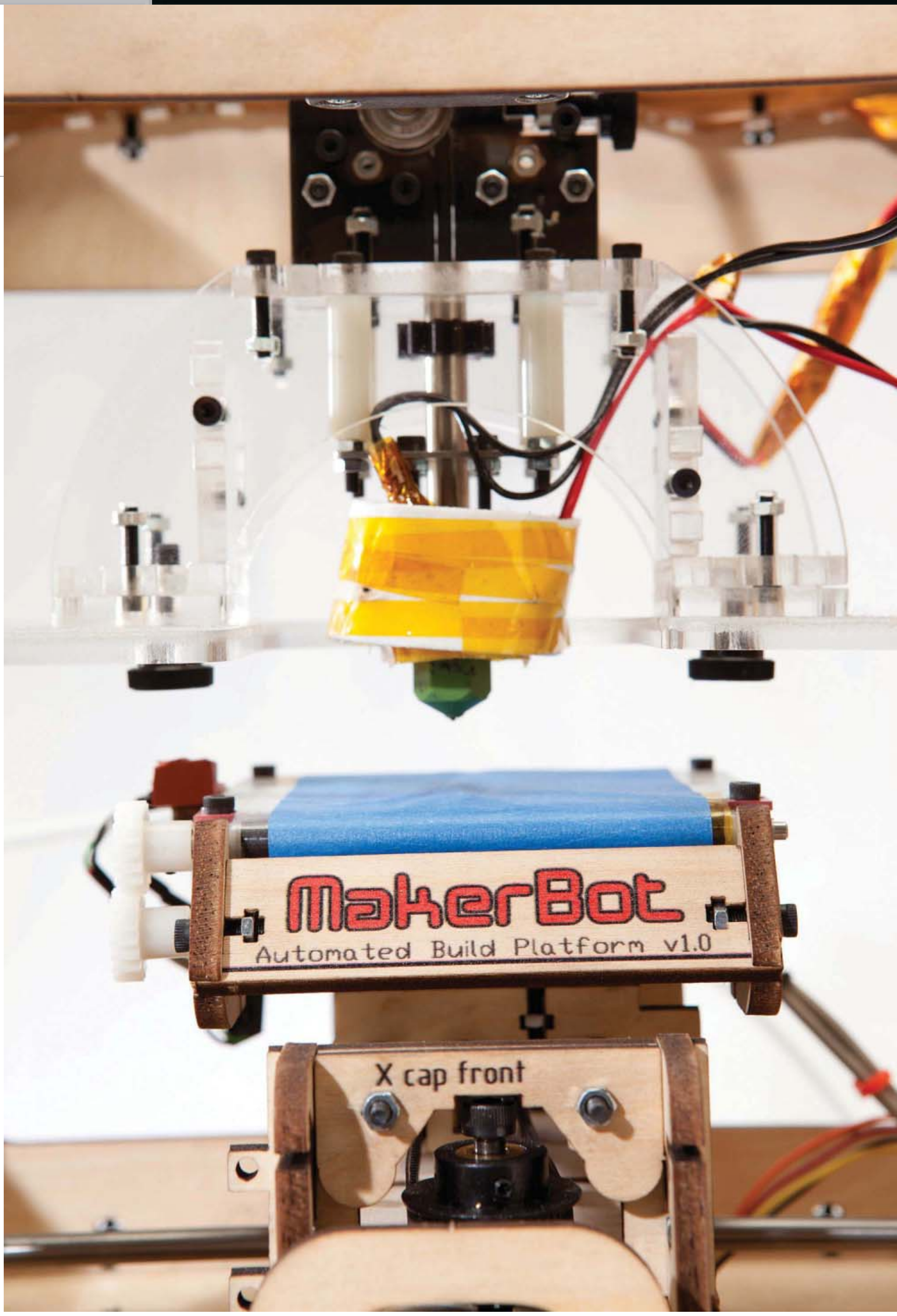

COPY THAT: When assembled, the Cupcake 3-D printer kit, from MakerBot, "photocopies" physical objects at a half-millimeter resolution.

PHOTOS: MAKERBOT

That sent me on a several-week detour in which I corrupted the old firmware, downloaded, compiled, and configured new software, ordered and assembled new microcontroller-programming hardware, learned about the secret Java USB library that actually works, then lost the controlling PC to a power surge and transferred its disk to a new one—all because (as I found out later) only an administrator can upload new firmware for my computer's configuration. Eventually, after I set the control program up to run as root, everything worked.

It's amazing. It's addictive. A tiny thread of molten plastic squirts out of the nozzle and solidifies into a spoon or a coat hook or a toy dump truck or a small wrench. The pieces are surprisingly strong. I now have a mile-long list of items to fab, including a shoehorn holder, customized Lego bricks, and a small statue of our cat. Yes, there's software out there to transform a set of photographs taken from different angles into a 3-D representation.

Oh, and—shades of the singularity, when sophisticated robots will manufacture even more sophisticated robots, ad infinitum—I also plan to make parts for an upgraded Cupcake, starting with a stepper-motor-based extruder. And parts for the original fabricator I was going to build before the Cupcake stepped in: mounting brackets, gear trains, maybe even some circuit boards laid out with etch-resist ink.

It's still not that easy, of course. I've already lowered the temperature setting a few degrees, but there are about a hundred other interacting settings—extrusion speed, wall thickness, turning radius, layer height, cooling time, and more—that can be tweaked for the best possible print. And then there's the interesting sensation when your PC loses contact with a machine that unconcernedly continues to spew out hot plastic.

There's also the minor detail that designing things in three dimensions is hard, and would be even if all the available software tools didn't have steep learning curves. On the other hand, OpenSCAD, one of the design programs I'm using, has a cone for a design primitive. That shoehorn holder will eventually be a perfect fit.

—Paul Wallich

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geek life

A TALE OF TWO MOVIES

Anonymous and *Iron Sky* take CGI in new and different directions

ONCE UPON a time, not so long ago, only big-budget movies could afford photorealistic computer-generated imagery (CGI), and even then only for selected scenes. Then again, musicians used to record things called "albums" in music studios that were so expensive they were rented by the hour.

Today, we have desktop machines that outperform the supercomputers of the *Terminator* 2 era. So just as your Mac laptop can replace an entire music studio, computers can render entire cities—such as Elizabethan London—that used to be shot on location. Meanwhile, one indie filmmaker has figured out how to do high-end CGI on a tight budget, by crowdsourcing some of the production.

Anonymous, which was scheduled to premiere on both sides of the Atlantic on 28 October, is a historical thriller set in the court of Queen Elizabeth I. A nobleman poet and playwright airs the court's dirty laundry via popular dramas like *Hamlet* and *Macbeth*, which are represented as coming from the pen of actor Will Shakespeare.

Director Roland Emmerich, a veteran of such special-effects blockbusters as *The Day After Tomorrow, The Patriot*, and *Independence Day*, spared no effort in making *Anonymous*, and although it features Vanessa Redgrave and Rhys Ifans, an unbilled star of the movie is the CGI. One stunning scene starts with a view of the whole city and then pans down to a massive crowd scene at the Globe Theatre. Although onscreen for just 12 seconds, the CGI involved thousands of individual layers.

"There's an enormous amount of detail, and the detail is what makes that shot," says one of *Anonymous*'s visual effects supervisors, Volker Engel. In it, the Globe Theatre audience is shown rowing small boats up the Thames, each with up to eight fully CGI-animated people. Little whitecaps appear on the tips of oars as they stroke through the water.

"Each one of those ships," Engel says, "though they're fairly small in-frame, has cloth animation, which means the sails are slightly billowing in the wind and the ropes are slightly moving." Flocks of birds come in different directions, thousands of chimneys belch smoke throughout the city, and yards are filled with pigs, chickens, and horses—"they're very tiny," Engel says, "but if they weren't there it would look very empty."

The buildings themselves were individually created by a 29-person visual effects team from a library of over 40 000 still photos that fellow visual effects supervisor Marc Weigert took of Tudor structures throughout England. The 2000 "people" in the shot are individual avatars animated by the same artificial-intelligence crowd-simulating software that Weta Digital used for the *Lord of the Rings* films' vast battle scenes. Giving the avatars Elizabethan-era wardrobes involved additional cloth simulations to show a dress or a doublet wrinkling and stretching with every motion.

Weigert and Engel would not disclose *Anonymous*'s budget. However, Terrence Masson—of Northeastern University, in Boston, and author of the industry textbook *CG101: A Computer Graphics Industry Reference*—said as a rule a shot like

GRAPHICALLY NOVEL: The new film *Anonymous* represents 16th-century London [top] with thousands of individual CGI layers. The low-budget *Iron Sky*'s graphics [bottom left and right] were generated in part by its 68 000 Facebook fans.

IMAGES: TOP, SONY PICTURES; BOTTOM: JUSSI LEHTINIEMI (2)

the Globe sequence eats up hundreds of thousands of dollars. "There's nothing breakthrough in these shots," he says. "But they're done so well. It's all about the spectacle. Nobody does it better than Roland [Emmerich]."

At the other end of the financial scale, Finnish indie director Timo Vuorensola is now wrapping production on *Iron Sky*, a satirical sci-fi thriller that imagines a team of German Nazis blasting off to the dark side of the moon at the end of World War II. In the ensuing decades the Nazis build a battle fleet on their remote lunar base; in 2018, they return to Earth with a vengeance.

In one sequence, four space zeppelins disgorge 1000 invading German "Valkyrie" fighters in low-Earth orbit. Visual effects supervisor Samuli Torssonen portioned out a US $1 million CGI budget across 500 shots by first digitally designing the zeppelin and Valkyrie prototypes. Stunning sequences can be made, he says, from many copies of these two carefully detailed CGI elements (which took three months each to create), a matte-painted Earth, and some good animation software. Torssonen outsourced other parts of the job, such as designing the ships of the 10 terrestrial nations defending the planet, to *Iron Sky*'s global fan base, including its 68 000 Facebook friends.

"You get 90 percent of the way there in 10 percent of the time," says Northeastern's Masson. "In Hollywood, it's all about that last 10 percent....You're zooming into each pixel on a giant plasma screen. That's what costs the big bucks."

—Mark Anderson

tools & toys

GESTURES CREEP INTO MOUSE INTERFACES

And the change isn't entirely for the better

THERE'S NO DENYING the evolution of electronic Muridae—computer mice, that is. Through the years we've seen third buttons, scroll wheels, Bluetooth wirelessness, foldability, and most recently, mice that have been turned into mobile track pads, with touch-sensitive surfaces. Apple started this latest mutation with the Magic Mouse, a sleek platform that enhances the appearance of any workstation, if not its functionality. With a hearty "challenge accepted," Microsoft created the Touch Mouse.

The Touch Mouse emulates the Magic Mouse's ability to capture gestures, not just clicks, while feeling much nicer in the hand. Microsoft, to its credit, never values aesthetics so highly as to impair function or comfort, which distinguishes its products from every mouse ever to emerge from Cupertino. And despite that commitment to function over form, Microsoft has created a graceful black teardrop of a mouse. Gridded on the front half to indicate the location of the tiny sensors that turn multitouch gestures into cursor actions, the Touch Mouse feels solid, and it glides nicely across any surface. Microsoft's BlueTrack technology lets it track more accurately than any other optical mouse I've used.

The Touch Mouse's packaging clearly says it's exclusively for Microsoft Windows 7. So the first thing I did was take the 2.4-gigahertz wireless nubbin of a transmitter out from the mouse's underbelly, where it is easily stored, and plugged it into my MacBook Air's USB socket. It worked right away as a simple two-button mouse—although it has no buttons, a subtle ridge down the middle distinguishes left from right. The real test came with my office workstation, a Dell. Inserting the transmitter brought up a driver installation dialogue in Windows 7, which quickly enabled the mouse's full potential.

Sweeping a single finger across the Touch Mouse scrolls the active window in the appropriate direction. Moving two fingers up or down maximizes or minimizes the active window, while going left or right snaps the window to the appropriate half of the screen. An upward sweep of three fingers shows all open windows; a downward sweep shows the desktop. And there are other shortcut gestures as well.

Microsoft Touch Mouse, US $80
http://www.microsoft.com/hardware/en-us/p/touch-mouse

It's all very nice, if you want to manipulate windows. But I have work to do, and that's where the Touch Mouse, like most mice these days, failed me. For a decade now, there have been no natural predators of three-button scroll mice, and as they proliferated, much software was written with them in mind. Despite the Touch Mouse's sophisticated sensor network, it does not have a middle-button function. (To be fair, Apple's Magic Mouse has this same problem.)

For example, Autodesk's Maya leans heavily on the middle mouse button for controlling viewport cameras and other things; without that button the software is effectively unusable. Similarly, in *World of Warcraft*, the scroll wheel dollies the camera in and out, changing the view of the game. The Touch Mouse scrolls, of course, but all too easily, like when I shift my grip. That doesn't render the game unplayable, but it can ruin a session.

This trend in mice is disturbing. Designers are discarding older, better functionality. In its place, they have introduced an element of uncertainty. Every interaction is fraught with a slight tension that I'll touch the mouse the wrong way. Nor can I reduce these missteps with new muscle habits—they're errors that can be avoided only with great vigilance. But that's just the opposite of what an input device should do—blend into invisibility as it enables my hand to manipulate objects in the virtual world.

Many, perhaps most, users will not care about the missing middle button, and as a way of controlling the size, shape, and location of windows on the screen, gestures are a welcome next step in the ongoing evolution of the electronic Muridae family. That we have to be Microsoft's and Apple's lab rats as they also take one step backward is unfortunate.

—HARRY TEASLEY

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 BY ROBERT W. LUCKY

GREG MABLY

The Advice Business

THROUGH THE YEARS I've had the privilege of serving on advisory boards and committees for government, academia, and industry. The work is unpaid, and sometimes there's a lot of it, but I've always gotten a great deal from it—working with the best and brightest is a crash course on important new technologies and strategies for using them. Sometimes, though, I wonder what's in it for the recipients of my advice. Are the benefits for them commensurate?

The answer depends a lot on their expectations, which often reflect a blend of objectives. If you're asked to join the board of the local opera, it's clear that you're expected to contribute personally, and they don't want you to tell them what to stage. But other charities may have goals that are less obvious, and while you may be assured that they're looking for expert advice, you may discover that donations are what they really expect.

A more common aim is the endorsement of existing plans. This is usually unspoken and subtle. When you are the advisee, as I have been on occasion, this aim is so natural that you may not even be aware of it yourself. Of course your distinguished advisors will find nothing wrong with your management or strategy except that the organization should receive more funding for its wonderful work. In such cases, the information conveyed to the advisory group is carefully crafted to lead to a rubber-stamp approval.

It takes a confident organization to reveal its problems to outsiders. I remember coming out of a board meeting and being intercepted in the hallway by an unknown employee. "You people don't know what's going on here," he whispered to me.

Before I could think of any reply, he was gone. Well, of course, he's right, I thought. We parachute in a couple of times a year to spend a day hearing hand-picked employees giving carefully rehearsed talks. How could we possibly know what is really going on? On the other hand, I might have said that while it was true that we didn't know what was really going on, neither did he. There are many views of an organization, depending on where you sit, and no one has a truly integrated understanding of such a complex maze of interactions.

Government advisory committees have a unique flavor. Most often the outside group is chartered to study a particular problem—one that is topical, thorny, and (for those to which I'm invited) at least partly technological. However, it's been my experience that technology is seldom either the problem or the solution. I look around at these meetings and see world-famous technical experts who presumably possess some secret knowledge that will solve the problem being studied. Alas, it seems never to be so.

Often, after much wordsmithing, a study is produced that reverts to generic conclusions: reorganize, appoint a czar, increase funding. It will refer to previous studies of the same problem that gave essentially the same recommendations. Indeed, some issues become perennials that are studied again and again, such as the federal acquisition system, which has been studied without noticeable effect for decades. In making these observations, I don't intend to slight the people involved. I've always found that they are dedicated and knowledgeable. It's just that we are all enmeshed in an infinitely complicated system of rules, laws, organizations, and legacy conditions. I'm amazed that it works at all.

Going back to my original question—that of benefits—I do believe in the value of advisory committees and boards. Sometimes we've given good advice, and sometimes I think back on a past report and cringe. But in any case, the existence of the outside group forces the inside group to study itself in its preparations and in the meetings themselves. Moreover, an honest endorsement of existing activities can be helpful and reassuring. Still, I often wish there was a good problem to be solved and that the solution involved a powerful new technology of which only our advisory group was aware. Maybe someday this will happen. ❑

フクシマ以後の原子力

SPECIAL REPORT

Nuclear Power After Fukushima

Never before in history has a nuclear power plant experienced a triple meltdown, with the simultaneous collapse of three reactor cores. Such a disaster was unimaginable—until it happened at Fukushima Dai-ichi. The nuclear industry now faces the hard questions of why this accident occurred and how such breakdowns can be prevented in the future. In this special report, *IEEE Spectrum* begins by explaining how Fukushima's nuclear tragedy unfolded, with a blow-by-blow account of the accident's first 24 hours. We then turn to the world's reaction to the catastrophe with a global survey of nuclear power policy responses and probe deeper with two case studies. Finally, we ask the experts how the nuclear industry can rebuild.

特別レポート

SPECIAL REPORT

RADIATION CHECK: About 80 000 people were evacuated because of radioactive emissions from the Fukushima Dai-ichi nuclear power station in the days after the accident. They have not yet returned to their homes. *PHOTO: CHRISTOPH BANGERT/LAIF/REDUX*

THE TSUNAMI'S TOLL: The deadly waves [top] that battered northeastern Japan obliterated coastal towns [bottom] and killed more than 15 000 people. The Japanese government has estimated rebuilding costs at US $220 billion. The tsunami also set in motion the nuclear disaster at the Fukushima Dai-ichi power station [opposite]. *PHOTOS, CLOCKWISE FROM TOP: JIJIPRESS/GETTY IMAGES; TEPCO; KAZUMA OBARA*

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特別レポート

SPECIAL REPORT


中温用

特別レポート

SPECIAL REPORT

福島の24時間

24 Hours at Fukushima

A blow-by-blow account of the worst nuclear accident since Chernobyl

BY ELIZA STRICKLAND

Sometimes it takes a disaster before we humans really figure out how to design something. In fact, sometimes it takes more than one.

Millions of people had to die on highways, for example, before governments forced auto companies to get serious about safety in the 1980s. But with nuclear power, learning by disaster has never really been an option. Or so it seemed, until officials found themselves grappling with the world's third major accident at a nuclear plant. On 11 March, a tidal wave set in motion a sequence of events that led to meltdowns in three reactors at the Fukushima Dai-ichi power station, 250 kilometers northeast of Tokyo.

AFTER THE DELUGE: A flooded equipment room at unit 3 of the Fukushima Dai-ichi nuclear power plant. *PHOTO: TEPCO*

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UNLIKE THE THREE MILE ISLAND accident in 1979 and Chernobyl in 1986, the chain of failures that led to disaster at Fukushima was caused by an extreme event. It was precisely the kind of occurrence that nuclear-plant designers strive to anticipate in their blueprints and emergency-response officials try to envision in their plans. The struggle to control the stricken plant, with its remarkable heroism, improvisational genius, and heartbreaking failure, will keep the experts busy for years to come. And in the end the calamity will undoubtedly improve nuclear plant design.

True, the antinuclear forces will find plenty in the Fukushima saga to bolster their arguments. The interlocked and cascading chain of mishaps seems to be a textbook validation of the "normal accidents" hypothesis developed by Charles Perrow after Three Mile Island. Perrow, a Yale University sociologist, identified the nuclear power plant as the canonical tightly coupled system, in which the occasional catastrophic failure is inevitable.

On the other hand, close study of the disaster's first 24 hours, before the cascade of failures carried reactor 1 beyond any hope of salvation, reveals clear inflection points where minor differences would have prevented events from spiraling out of control. Some of these are astonishingly simple: If the emergency generators had been installed on upper floors rather than in basements, for example, the disaster would have stopped before it began. And if workers had been able to vent gases in reactor 1 sooner, the rest of the plant's destruction might well have been averted.

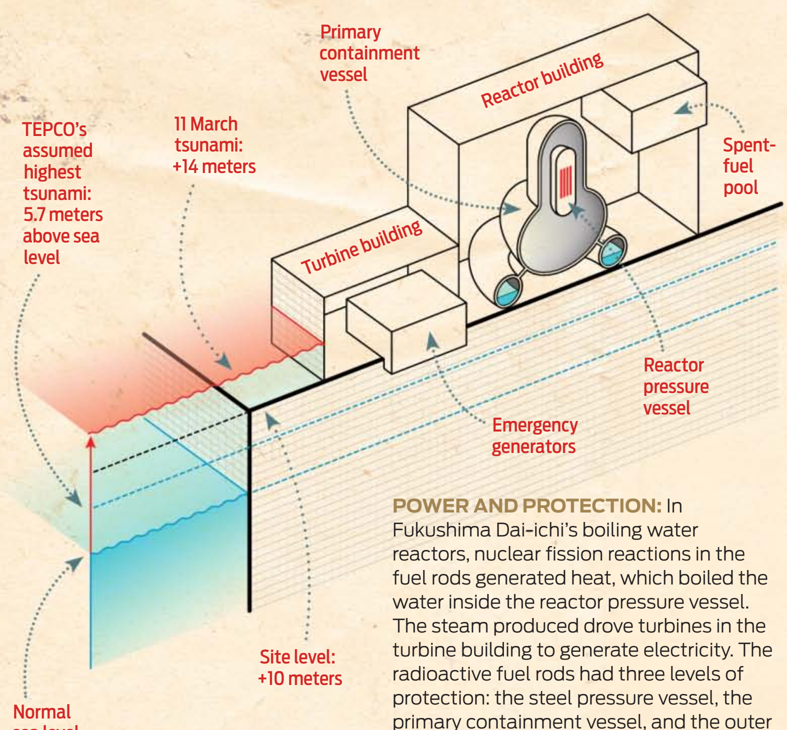
The world's three major nuclear accidents had very different causes, but they have one important thing in common: In each case, the company or government agency in charge withheld critical information from the public. And in the absence of information, the panicked public began to associate all nuclear power with horror and radiation nightmares. The owner of the Fukushima plant, the Tokyo Electric Power Co. (TEPCO), has only made the situation worse by presenting the Japanese and global public with obfuscations instead of a clear-eyed accounting.

Citing a government investigation, TEPCO has steadfastly refused to make workers available for interviews and is barely answering questions about the accident. By piecing together as best we can the story of what happened during the first 24 hours, when reactor 1 was spiraling toward catastrophe, we hope to facilitate the process of learning-by-disaster.

WHEN THE 9.0-MAGNITUDE earthquake struck off the east coast of Japan, at 2:46 p.m. on 11 March, the ground beneath the power plant shook and alarms blared. In quivering control rooms, ceiling panels fell open and dust floated down onto instrument panels like snow. Within 5 seconds, control rods thrust upward into the three operational reactors and stopped the fission reactions. It was a flawless automatic shutdown, but the radioactive by-products in the reactors' fuel rods continued to generate tremendous amounts of heat.

Without adequate cooling, those rods would become hot enough to melt through the steel pressure vessel, and then through the steel containment vessel. That would result in the dreaded core-meltdown scenario, which could lead to the release of clouds of radioactivity that would be carried by winds to sicken or kill masses of people.

But the heat wouldn't be a problem so long as Fukushima Dai-ichi had power to run the pumps that circulate water from the reactor cores through heat-removal systems. The mighty earthquake had toppled power transmission towers and jumbled equipment at nearby substations, but the interruption in power to the plant was negligible: Within 10 seconds, the plant's emergency power system kicked in. Twelve diesel generators, most of them installed in basement areas below the turbines, were now responsible for the integrity of the plant's reactors—and the well-being of its workers.



POWER AND PROTECTION: In Fukushima Dai-ichi's boiling water reactors, nuclear fission reactions in the fuel rods generated heat, which boiled the water inside the reactor pressure vessel. The steam produced drove turbines in the turbine building to generate electricity. The radioactive fuel rods had three levels of protection: the steel pressure vessel, the primary containment vessel, and the outer reactor building.

EMILY COOPER

SYSTEM FAILURE: On 11 March, a TEPCO worker photographed the tsunami sweeping into the Fukushima Dai-ichi power station [top] and submerging tanks and cars [bottom]. After the plant lost electric power, operators could read instruments only by plugging in temporary batteries [left]. PHOTOS: TEPCO (3)

At the time of the earthquake, three of the power station's six reactors were operating; the other three were down for scheduled maintenance. In the control rooms governing the active reactors—units 1, 2, and 3—the staff checked the cooling systems that remove residual heat from the reactor cores by cycling water through heat exchangers filled with seawater. Everything seemed under control. Water also filled the spent-fuel pools on the top floors of all six reactor buildings to prevent the pools from overheating.

At 2:52 p.m., the shift supervisor overseeing the plant's oldest reactor, the 40-year-old unit 1, confirmed that a backup cooling system called an isolation condenser (IC) had started up automatically. This system didn't need electric power to cycle steam through a cold-water tank on a higher floor, or to let the resulting water drop back down to the pressure vessel. But operators soon noticed that the IC was cooling the core too quickly, which could stress the steel walls of the pressure vessel. So they shut the system down. It was a by-the-book decision, but the book wasn't written for the extraordinary events of 11 March.

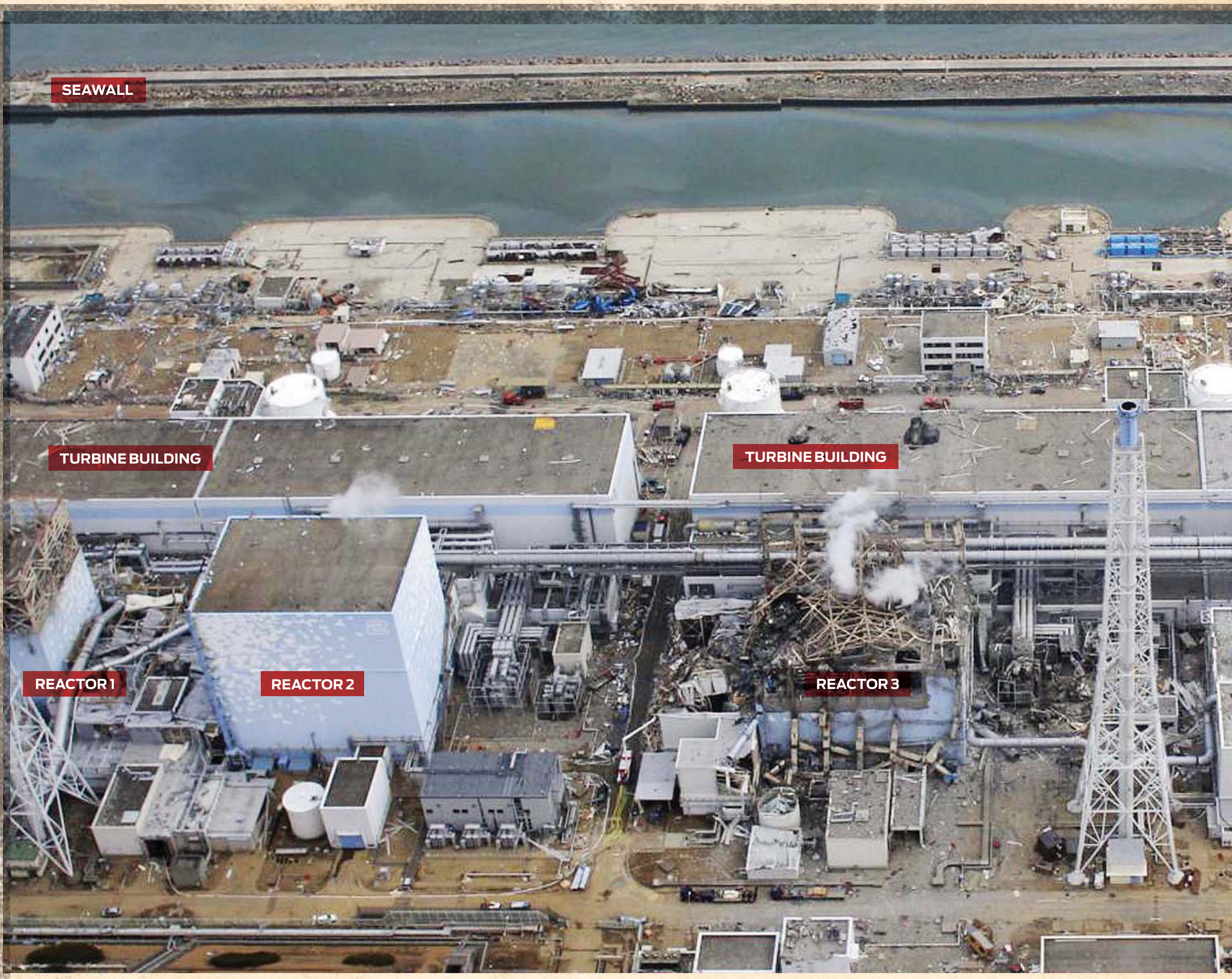
This report is based on interviews with officials from the Tokyo Electric Power Co. (TEPCO), Japan's Nuclear and Industrial Safety Agency, the U.S. Nuclear Regulatory Commission, the International Atomic Energy Agency, local governments, and with other experts in nuclear engineering, as well as a review of hundreds of pages of official reports.

Tsunami alerts flashed on TV screens, predicting a 3-meter-high tsunami for Fukushima prefecture. Although the coastal Fukushima Dai-ichi plant was 10 meters above sea level, nonessential personnel followed procedure and began evacuating the site.

At 3:27 p.m. the first tsunami wave surged into the man-made harbor protecting Fukushima Dai-ichi, rushing past a tidal gauge that measured a water height of 4 meters above normal. At 3:35 another set of much higher waves rolled in and obliterated the gauge. The water rushed over the seawalls and swept toward the plant. It smashed into the seawater pumps used in the heat-removal systems, then burst open the large doors on the turbine buildings and submerged power panels that controlled the operation of pumps, valves, and other equipment. Weeks later, TEPCO employees would measure the water stains on the buildings and estimate the monstrous tsunami's height at 14 meters.

In the basements of turbine and reactor buildings, 6 of the 12 diesel generators shuddered to a halt as the floodwaters inundated them. Five other generators cut out when their power distribution panels were drenched. Only one generator, on the first floor of a building near unit 6, kept going; unlike the others, all of its equipment was above the water line. Reactor 6 and its sister unit, reactor 5, would weather the crisis without serious damage, thanks in part to that generator.

The rest of Fukushima Dai-ichi now faced a cataclysmic scenario that nuclear power plant operators have long feared but never experienced: a complete station blackout.



IN THE CONTROL ROOM where operators managed reactor 1, the alarms went silent. The overhead lights blinked off, and the indicator lights on the instrument panels faded away. The floodwaters had even knocked out the control room's batteries, the power source of last resort. The operators would have to respond to the emergency without working instruments.

With the power out, the pumps were no longer channeling water from unit 1's pressure vessel through the cooling system's heat exchangers, and the ferociously hot fuel rods were boiling the water into steam. The water level in the nuclear core was dropping, but, lacking power for their instruments, the plant operators could only guess at how fast the water was boiling away.

The isolation condenser, which relied on convection and gravity to perform its cooling function, should have helped keep the water level high in unit 1's core through the crisis. But operators had turned off the system just before the tsunami by closing its valves—and there was no electric power to reopen them and let steam and water flow. Workers struggled to manually open the valves on the IC system, but experts believe the IC provided no help after the tsunami struck.

LESSON 1

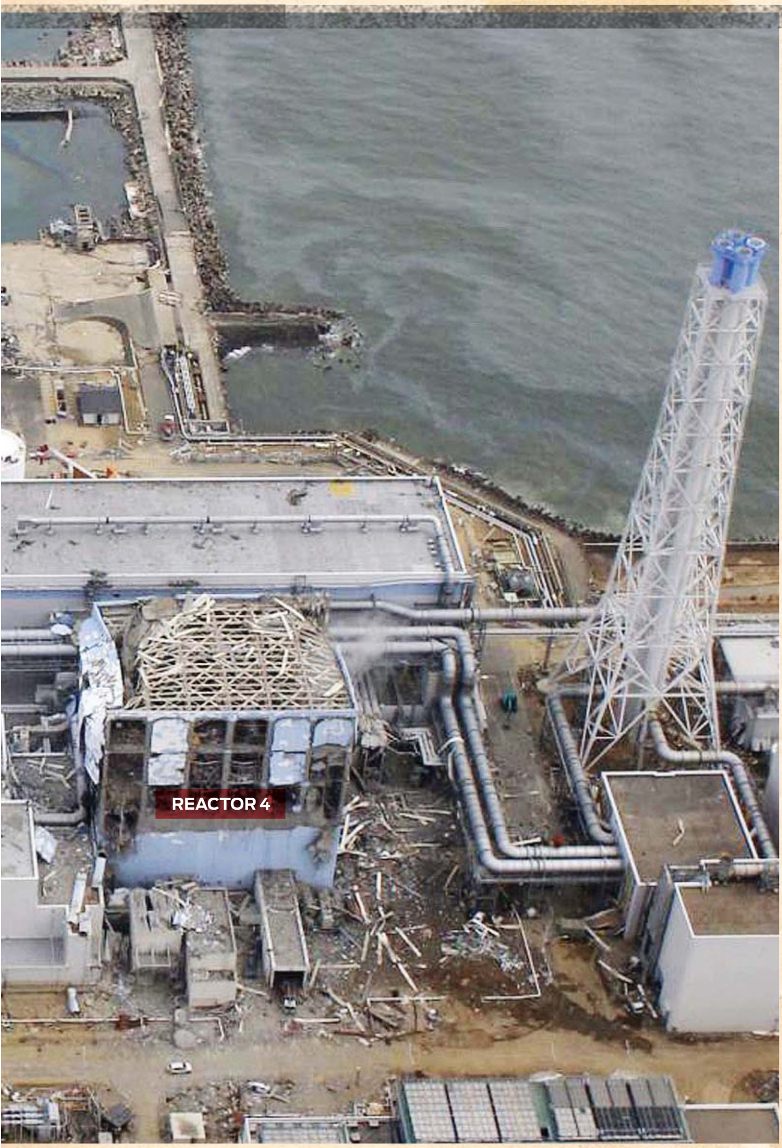
Emergency generators should be installed at high elevations or in watertight chambers.

LESSON 2

If a cooling system is intended to operate without power, make sure all of its parts can be manipulated without power.

As the operators surveyed the damage, they quickly realized that the diesel generators couldn't be salvaged and that external power wouldn't be restored anytime soon. In the plant's parking lots, workers raised car hoods, grabbed the batteries, and lugged them back to the control rooms. They found cables in storage rooms and studied diagrams. If they could connect the batteries to the instrument panels, they could at least determine the water levels in the pressure vessels.

TEPCO did have a backup for the emergency generators: power supply trucks outfitted with high-voltage dynamos. That afternoon, emergency managers at TEPCO's Tokyo headquarters sent 11 power supply trucks racing toward Fukushima Dai-ichi, 250 km away. They promptly got stuck in traffic. The roads that hadn't been damaged by the earthquake or tsunami were clogged with residents fleeing the disaster sites.



THE DAMAGE: In the days following the tsunami, explosions tore the roofs off reactors 1, 3, and 4, and an interior detonation is thought to have damaged reactor 2.
PHOTO: GAMMA/GETTY IMAGES

But TEPCO's later analysis found that the gauges were wrong. Months later, calculations would show that the superheated water inside the reactor 1 pressure vessel had dropped all the way below the bottom of the uranium fuel rods shortly before operators checked the gauge, leaving the reactor core completely uncovered. Heat pulsed through the exposed rods. When temperatures passed 1300 °C, the fuel rods' protective zirconium cladding began to react with the steam inside the vessel, producing highly volatile hydrogen gas. And the uranium inside the fuel rods began to melt, slump, and sag.

THROUGHOUT THE NIGHT of 11 March, radiation levels rose around the plant. At 9:51 p.m. managers prohibited entry into the unit 1 reactor building.

It was a wise decision, because in the bowels of the reactor, the meltdown had already begun. In the reactors used at Fukushima, the control rods thrust up into the pressure vessel from below, and the housings around each control rod's entry point were essentially weak spots. When the melted fuel began to pool at the bottom of the pressure vessel, it likely melted through those vulnerable seams. TEPCO's later analysis found that the pressure vessel was damaged by 11 p.m., allowing highly radioactive water and gases to leak into the primary containment vessel.

The containment vessel, which surrounds the pressure vessel, is a crucial line of defense: It's a thick steel hull meant to hold in any tainted materials that have escaped from the inner vessel. At 11:50 p.m. operators in the control room finally connected car batteries to the pressure gauge for the primary containment vessel. But the gauge revealed that the containment vessel had already exceeded its maximum operating pressure, increasing the likelihood that it would leak, crack, or even explode.

As 11 March turned into 12 March, TEPCO headquarters told the sleepless operators that they must bring down the pressure by venting the containment vessel. A venting operation would jet the vessel's radioactive gases into the air; Fukushima Dai-ichi's nightmare would soon spread across the countryside.

That night, the desperate struggle to contain the peril at reactor 1 diverged into three responses. Besides the team making preparations to vent the containment vessel, there was also a group getting ready to receive the power supply trucks, which were still making their way to the plant. On arrival, they would supply electricity to restart the pumps and reestablish steady water circulation through the pressure vessel. The third team focused on another, short-term plan for cooling the core: fire trucks, which could inject water from emergency tanks into one of the reactor's cooling systems.

At 4:36 p.m., TEPCO officially informed the Japanese government about the increasingly dire situation at reactor 1. The company declared that it "could not confirm" that any water was being injected into the reactor's core. The situation was better at the slightly more modern reactors 2 and 3, where emergency cooling systems were operating, driven by the steam from the reactors themselves. And the idled reactors 4, 5, and 6 didn't pose an immediate threat.

At 5:41, the sun set over the pools of seawater and the mounds of debris scattered around the power station. Work crews picked their way through the gloom by flashlight.

At around 9 p.m., operators finally plugged the car batteries they'd collected into the instrument panels and got a vital piece of information—the water level in reactor 1. The information seemed reassuring. The gauge registered a water level of 550 millimeters above the top of the fuel assembly, which, while far below normal safety standards, was enough to assure the operators that no fuel had melted yet.

LESSON 3
Keep power trucks on or very close to the power plant site.

LESSON 4
Install independent and secure battery systems to power crucial instruments during emergencies.

It was after midnight when the first power supply trucks began to arrive at the site, creeping along cracked roads. The trucks parked outside the unit 2 turbine building, adjacent to the troubled unit 1, where workers had found one undamaged power control panel. In the darkness, they began snaking a 200-meter-long power cable through the mud-caked building in order to connect it to the power control panel. Usually trucks are used to lay such a cable, which weighed more than a ton, but that night 40 workers did the job by hand. It took them 5 hours.

Work continued at the power control panel all morning and into the afternoon of 12 March. Finally, at 3:30 p.m., everything was ready. Current flowed from a power supply truck through the cable to the panel, which was ready to switch on the pumps for a backup cooling system inside the reactor 1 building. Workers prepared to start the flow of freshwater into the pressure vessel, knowing that they were about to take a crucial step toward stabilizing the plant.

Meanwhile, the fire engine team had been grappling with difficult logistics all through the early morning hours. Of the three fire engines on site, one had been wrecked by the tsunami; another was stuck near reactors 5 and 6, trapped by damaged roads. That left one fire engine to cool the overheating reactor 1. This truck was the best hope for getting water into the pressure vessel quickly, but it took hours to maneuver it through the plant's wreckage. Finally the workers smashed a lock on an electronic gate and drove the fire engine through.

In their initial, improvised response, the fire crew pumped water into the truck's storage tanks, then drove close to the side of the reactor building and injected the water into the fire protection system's intake lines. It was 5:46 a.m. on 12 March when the first drops of water sprayed across the molten fuel. Then the workers drove back to the water tanks and began the slow, arduous operation all over again. Eventually workers managed to use the fire engine's hoses to connect the water tanks directly to the intake lines and established a steady flow of water. By midafternoon, they had injected 80 000 liters of water into the pressure vessel using this makeshift system. But it was too little, too late.

At 2:54 p.m., with freshwater supplies running short, TEPCO headquarters ordered the fire truck crews to inject seawater into the pressure vessel through the fire protection line. Under normal conditions, saltwater is never allowed in a reactor pressure vessel because it would corrode the vessel's protective steel walls and leave a mineral residue on the fuel rods. The decision was an admission that saving the reactor was no longer an option and that operators could only hope to prevent a wide-scale disaster. Fukushima Dai-ichi was now beyond the point of no return.

Workers stretched long fire hoses from a seaside pit that had been filled with seawater by the tsunami; three newly arrived fire engines lined up to pump the water through. They connected the hose to the fire protection system's intake line, and around 3:30 on 12 March they prepared to blast the reactor with seawater.

LESSON 5

Ensure that catalytic hydrogen recombiners (power-free devices that turn dangerous hydrogen gas back into steam) are positioned at the tops of reactor buildings where gas would most likely collect.

It had been 24 hours since the tsunami roared into the harbor, and the desperate efforts of both the power crew and the fire truck crew were about to pay off. It must have seemed that their exhaustion and terror were nearly at an end.

THE ORDER TO VENT the containment vessel had come at midnight. But without power to remotely operate the vent system's valves, it wouldn't be a simple task.

And whether the workers knew it or not, time was of the essence. While the venting team prepared for action during the early morning hours of 12 March, gases were building up inside the primary containment vessel and pushing on its weakest points, its gaskets and seals, and they were starting to give. Hydrogen gas hissed through the breaches and drifted up to the top of the building. Hour by hour, the gas collected there until it formed a layer of pure combustible menace.

The workers in charge of the venting operation took iodine tablets. It was a feeble attempt at protection against the radiation they'd soon encounter, but it was better than nothing. They gathered protective head-to-toe suits and face masks connected to air tanks. At 3:45 a.m., the vent crew tried to measure the radiation dose inside the reactor building, which had been off limits for 6 hours. Armed with handheld dosimeters, they opened the air lock, only to find a malevolent white cloud of some "gaseous substance" billowing toward them. Fearing a radiation steam bath, they slammed the door shut. They didn't get their reading, but they had a good indication that things had already gone seriously wrong inside the reactor.

If they could have looked inside the reactor pressure vessel at around 6:30 a.m. on the morning of 12 March, they would have seen a nuclear core transformed into molten sludge. The melted mixture of uranium, zirconium, and other metals had oozed to the bottom of the reactor pressure vessel, where it was gradually eating through the steel floor.

But as the morning ticked on, the vent crew were forced to sit and wait; they were standing by for word that residents had been evacuated and that it was safe to release the radioactive gases into the air. The government had issued an evacuation order for residents living within 3 km the night before; in the early morning hours officials announced that everyone within a 10 km radius of the plant should pack up and go. Residents who had lived their whole lives in the shadow of the Fukushima Dai-ichi plant boarded buses, expecting to be gone for a couple of days at most.

At 9:03 a.m. the message came: The last buses had departed. At 9:04 workers set out for the reactor building to open the valves that would allow gas to flow out of the primary containment vessel. They entered the reactor building and began a long, dark trek around the periphery of the primary containment vessel, guided only by flashlight beams. As they walked, their handheld dosimeters flashed troubling numbers. In normal conditions, a nuclear plant employee's radiation limit is

IN THE RUINS: The explosions during the first days of the accident scattered radioactive rubble around the site. This patch of debris [top] has a radiation level of 1000 millisieverts per hour; under normal conditions, a nuclear worker's radiation limit is 50 mSv per year. The dangerous conditions at the power station made robots [bottom] a necessary addition to cleanup crews. *PHOTOS: TEPCO (2)*

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50 millisieverts per year; in an emergency situation it is 100 mSv. The workers had covered about half the distance to the valve when they realized they had to turn back—if they continued, they would exceed the 100 mSv dose. They returned to the control room at 9:30. They had failed.

Over the next hours the operators scrambled to find another way to open the valves; finally they decided to blast the valve open with air. They used a crane truck to haul a portable air compressor, the kind typically used at construction sites, to the crucial valve's location. At 2:00 p.m. the vent crew switched the compressor on, while workers in the control room nervously watched the gauge.

By 3:30 p.m. on 12 March, it seemed that the venting had worked and that the worst was over. The pressure had dropped significantly in unit 1's primary containment vessel, suggesting that the valve had opened and that gases had rushed through the pipes to the ventilation stack near the reactor building. The workers must have felt that the danger was ebbing. They had no idea that leaks from the vent lines had added even more hydrogen to the gas collected below the ceiling of unit 1's outer building—and it was now ready to blow.

LESSON 6

Install power-free filters on vent lines to remove radioactive materials and allow for venting that won't harm nearby residents.

BROKEN SHELL: The unit 4 reactor building was wrecked by an explosion and a fire.
PHOTO: TEPCO

AT 3:36 P.M., a spark flashed in the darkness of the reactor building, and hydrogen gas ignited. With a roar, the top of the reactor building exploded.

The roof shattered and the walls splintered; fragments of the building flew through the air. Chunks of rubble cut into the cable leading from the power truck, and the flow of current stopped; now the pumps could not be turned on, and freshwater could not cascade into the core. Other pieces of debris sliced into the fire engine hoses leading from the seawater pit. Smoke billowed upward, radiation levels soared, and the workers fled Fukushima's first radioactive ruin. It wouldn't be the last: The battle to contain the catastrophe during the first 24 hours was lost, and the explosions would keep coming.

The failure of reactor 1 made efforts to stabilize the other reactors exponentially more difficult: Now workers would be laboring in a radioactive hot zone littered with debris. In addition, when work crews returned to the power truck sometime after the explosion, they couldn't get the power flowing. So the disaster continued. At reactors 2 and 3, emergency cooling systems functioned for several days. When reactor 3's overtaxed system failed on 13 March, workers struggled to connect alternate water supplies and to vent the primary containment vessel. But work was slow, and soon reactor 3 followed reactor 1's example. Leaking gas collected at the top of the building, and it exploded on the morning of 14 March.

That blast further impeded recovery efforts at reactor 2, and on the morning of 15 March some still-obscure explosive noise resonated inside the unit 2 reactor building. On that same day, an explosion tore the roof off reactor building 4 and a fire broke out inside. TEPCO reports say the problems in reactor 4 were probably due to hydrogen gas that leaked in from reactor 3; despite early reports to the contrary, the spent fuel rods stored in pools in reactors 4, 5, and 6 were covered with water throughout the accident and never posed a threat.

Each detonation made the effort to stabilize the plant more hopeless. It is clear that if workers had been able to gain control of reactor 1, the whole terrible sequence of events would have been different. But could the workers have done anything differently to speed up their response? Could the full scope of the catastrophe have been averted? So far, TEPCO management hasn't answered those questions.

We've learned a great deal about the Fukushima accident in the past seven months. But the nuclear industry's trial-and-error learning process is a dreadful thing: The rare catastrophes advance the science of nuclear power but also destroy lives and render entire towns uninhabitable. Three Mile Island left the public terrified of nuclear power; Chernobyl scattered fallout across vast swaths of Eastern Europe and is estimated to have caused thousands of cancer deaths. So far, the cost of Fukushima is a dozen dead towns ringing the broken power station, more than 80 000 refugees, and a traumatized Japan. We will learn even more as TEPCO releases more details of what went wrong in the first days of the accident. But as we go forward, we will also live with the knowledge that some future catastrophe will have yet more lessons to teach us. ❑

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ポスト・フクシマの世界

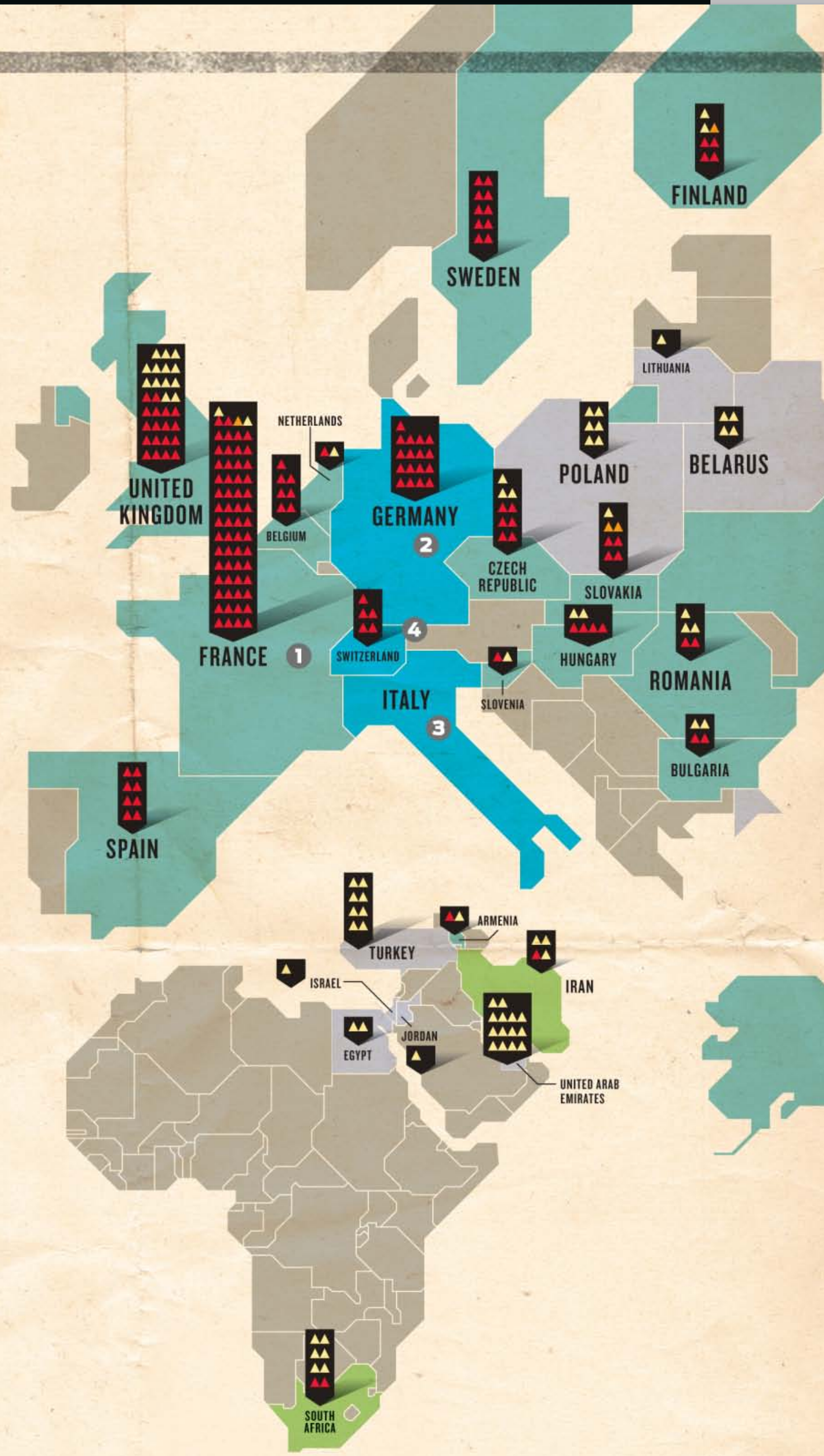
The Post-Fukushima World

The meltdowns have provoked policy changes around the planet

By Ritchie S. King Graphic by Carl DeTorres

The nuclear disaster at Fukushima Dai-ichi shocked the world. As radioactive particles floated into the air, a troubling question floated into people's minds: If such a disaster could happen in technologically advanced and cautious Japan, were their own countries packed with accidents waiting to happen?

In the months since, governments have embarked on a variety of safety assessments and policy reappraisals. But so far, only two countries with active reactors have committed to leaving the nuclear power club—and a good number of countries are still eager to join.



LEGEND

- Countries with operational reactors that have announced no safety reviews or policy changes
- Countries that are reviewing their existing reactors
- Countries conducting wider appraisals of reactors and nuclear safety standards
- Countries that are ending their nuclear power programs
- Countries with their first reactors in planning or proposal stages; some of these countries have not yet declared whether they'll follow through with their nuclear plans

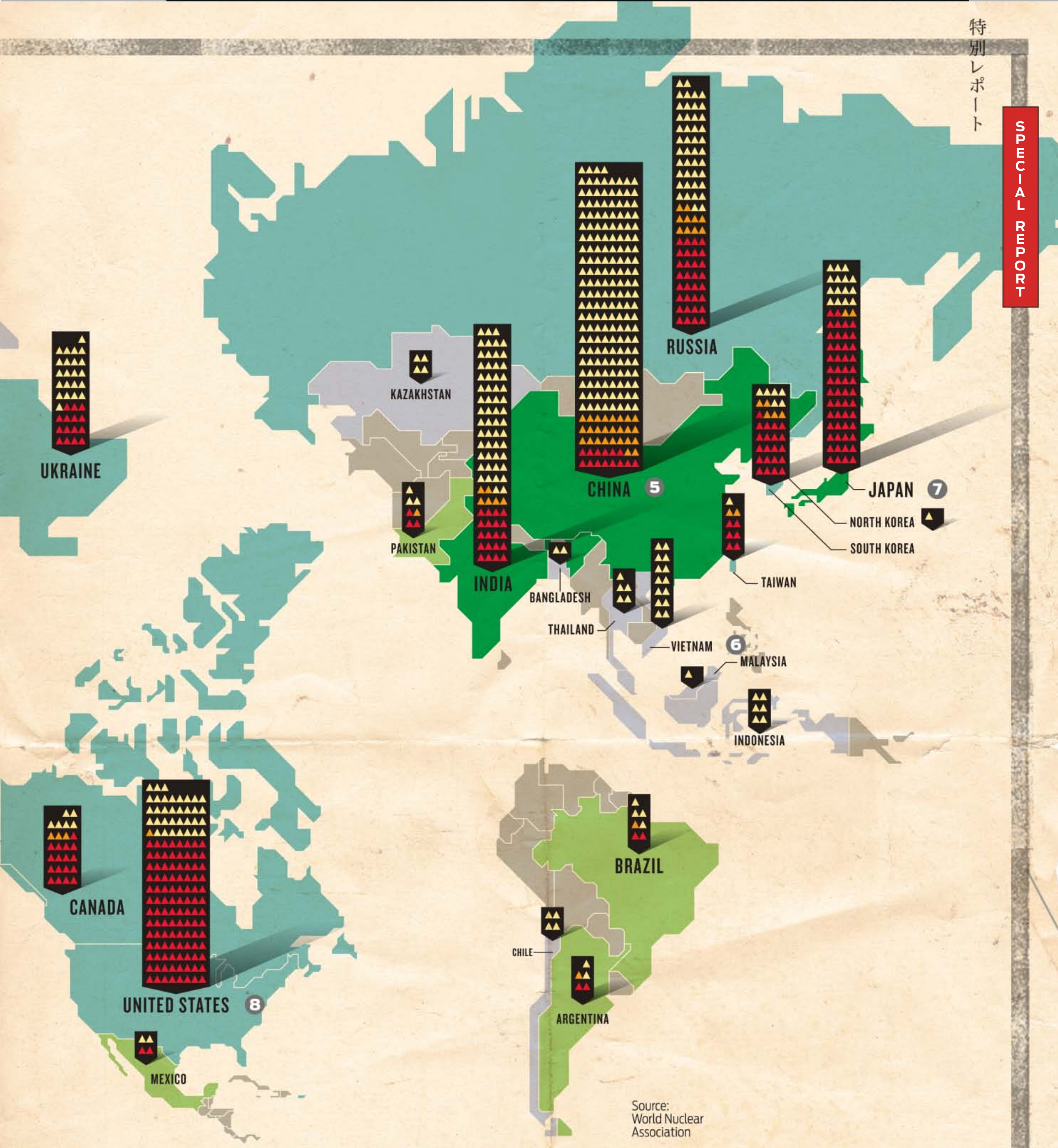
- Reactors in use
- Reactors under construction
- Reactors planned/proposed

1. FRANCE
The French government has ordered safety inspections of its 58 nuclear reactors. But France confirmed its commitment to nuclear power by dedicating €1 billion to nuclear research in June and by approving a 10-year license extension for its oldest reactor in July.

2. GERMANY
On 15 March, Germany halted operations at eight of its oldest reactors. Two months later Chancellor Angela Merkel announced the end of the country's nuclear program: All of the country's reactors will shut down by 2022.

3. ITALY
Italy has no operating reactors; its nuclear program was ended by referendum in 1987. In 2008 the government reversed that decision and began planning new nuclear construction. But on 13 June a referendum to bury the nuclear program once again passed, with 94 percent of voters in favor.

4. SWITZERLAND
On 14 March, the Swiss government froze the licensing process for three new reactors intended to replace aging units. Then, on 25 May, the cabinet decided that the replacements would not be built at all, effectively ending the country's nuclear program by 2034.



5. CHINA
On 16 March, the Chinese government declared it would issue no permits for new nuclear power plants until it updates its safety standards. The government also ordered inspections of all existing plants and reviews of all new construction.

6. VIETNAM
Vietnam is counting on nuclear power to keep its growing economy humming in the coming decades. In September, a government official said that a new nuclear feasibility study shows "Vietnam's determination to develop nuclear power, especially in the face of global economic difficulties and after the incident at Japan's Fukushima plant."

7. JAPAN
As of early September, only 11 of the country's 54 reactors were running. Reactors currently off-line due to routine maintenance or tsunami damage must pass stress tests before they can restart operations. Regulators are also assessing the safety of the entire nuclear program. The prime minister supports bringing idled reactors back online but has suggested that Japan should gradually phase out nuclear power.

8. UNITED STATES
In March, the U.S. Nuclear Regulatory Commission began a safety review of the country's 104 reactors. It was determined that all of them could be safely turned off in a severe flood or earthquake. However, the commission is still considering updating its regulations to require more safeguards.

中国の原子力への決意

China Doubles Down

Beijing presses forward with its reactor building boom

BY PETER FAIRLEY

CHINA'S SURGING ECONOMY runs mostly on coal, which slakes four-fifths of the country's thirst for electricity. And all over China, the consequences of that dependence are apparent: Its major cities are swathed in deadly smog, regional blackouts ensue when coal trains bog down on clogged rail networks, and coal mining routinely kills more than 2000 people a year. China desperately needs alternatives to coal-fired power.

So Beijing has launched an aggressive plan to decarbonize China's economy by pushing nuclear and renewable energy to 15 percent of energy consumption by 2020, up from 9.5 percent last year. Nuclear generating capacity would rise to over 80 gigawatts from the 11.3 GW currently in place. As a result, analysts expect China to meet its environmental goal for 2020: to reduce carbon emissions per yuan of economic output by 40 percent compared with 2005 levels.

To meet its nuclear numbers, China has embarked on the world's biggest reactor building program. Beijing has standardized its nuclear juggernaut around two pressurized water reactor designs: the Chinese/French CPR-1000, designed in the 1990s, and Westinghouse Electric's AP1000, designed in the 2000s. The country is turning both types out at high speed. According to the World Nuclear Association, 14 reactors were operating as of September, and 26 more were under construction. China's Ministry of Environmental Protection has said that 100 reactors may be feeding the grid by 2020.

"They are not just building nuclear power plants. They are building an entire industry," says Chi-Jen Yang, a technology policy expert at Duke University's Center on Global Change.

Nevertheless, the Fukushima disaster has highlighted the risks of China's aggressive nuclear build-out. In Fukushima's wake Chinese leaders put new reactor projects on hold while they reviewed the safety of existing ones. Officials concerned by a potential shortfall of trained reactor operators and inspectors suggested trimming China's 2020 goal for more than 80 GW nuclear capacity by 10 GW or so. Experts also worry that corrupt management of the build-out could affect the safety of China's reactors. As Yang puts it: "If everything is done well, the risks should be low. But we don't know if everything is done correctly."

China may well resume all of its planned projects once the post-Fukushima reviews are complete. But Yang says that safety concerns may cause China to focus its efforts on the Westinghouse AP1000 instead of the CPR-1000. Modest cost made the CPR-1000 attractive, but like Fukushima's second-generation reactors, its emergency cooling systems require electricity. The third-generation AP1000 reactor, in contrast, has a passive cooling system: water stored atop the plant's pressure vessel, ready to be gravity-fed to the reactor core below.

Meanwhile China's state-owned utilities have raced far ahead of Beijing's official goals for renewable energy. More than 40 GW of wind power was installed by the end of 2010, smashing the 5 GW target set by Beijing three years earlier.

China's investments could transform the country by midcentury. A Lawrence Berkeley National Laboratory report projects that China could install as much as 550 GW of nuclear capacity and 970 GW of wind, hydro, and solar power by 2050. Combined with energy efficiency upgrades, that surge of low-carbon electricity would slash China's annual CO_2 emissions from power generation to nearly one-fifth their current level.

Yang sees a possibility that China's central planners could build enough momentum within a decade to leave the United States behind if Washington doesn't adopt carbon-reduction measures to drive its economy off coal. "If the U.S. policymakers continue to postpone," says Yang, "the U.S. may someday find itself unable to catch up." ❑

GROWTH INDUSTRY: Work is under way on 26 new reactors in China, including this pressurized water reactor in Fujian province. PHOTO: ZHANG GUOJUN/XINHUA/REDUX

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原子力と決別するドイツ

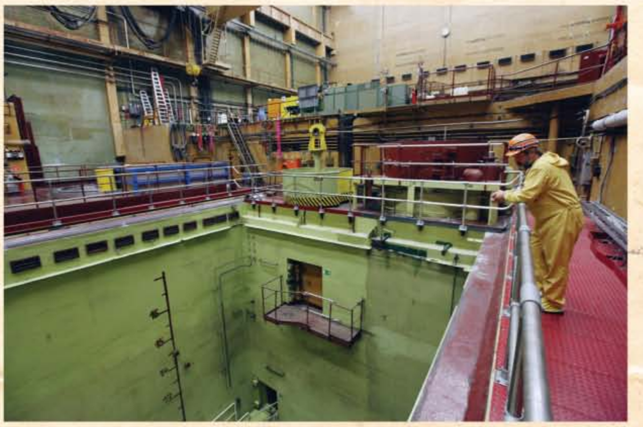
Germany Folds

Berlin's decision to shut down reactors means tough energy choices ahead

BY PETER FAIRLEY

AMONG MAJOR INDUSTRIALIZED NATIONS, Germany has long stood out for its deep ambivalence about nuclear power. So it wasn't much of a surprise when, two months after the Fukushima crisis began, Environment Minister Norbert Rottgen announced that Germany would shut down all its nuclear plants by 2022. And the phaseout began immediately: Rottgen declared that eight of the country's oldest reactors, seven of which had been idled after Fukushima, would never go online again.

So what now? Germany's 17 reactors had provided 28 percent of its power. To make up for the energy shortfall, officials named some of the usual suspects: offshore wind farms, coal-fired power plants fitted with carbon sequestration technology, and additional transmission lines to accommodate added renewable generation. But all of those options have provoked intense opposition in Germany. The upshot is that many analysts expect Germany's nuclear shutdown to collide headlong with its long-standing goal to cut greenhouse gases.



SHUTTING DOWN: A worker looks over a partially dismantled nuclear plant in Germany. *PHOTO: SEAN GALLUP/GETTY IMAGES*

Germany has pledged to slash its carbon emissions by 2020, to 40 percent below 1990 levels. But Claudia Kemfert, head of the energy, transportation, and environment department at the German Institute for Economic Research, says the country will probably fail to reach that goal. "It's easy to say we'll phase out nuclear power," Kemfert says. The difficult part will be doing so without resorting to greater dependence on fossil fuels, such as lignite and hard coal, which currently account for 40 percent of power production. That, she says, will require a fundamental restructuring of the nation's energy infrastructure. "The question is how to change the whole electricity system," she explains.

Lawmakers have already started the transition. The law that finalized the nuclear phaseout includes provisions that support the expansion of renewable generation to meet at least 35 percent of the country's power consumption by 2020—more than double its share in 2010. Parliament also approved laws to accelerate grid upgrades and allow carbon sequestration.

Germany is already a world leader in the installation of solar panels and wind turbines, thanks to its existing energy policies. But to reach the new 2020 target for renewable generation, the country must solve problems that have bedeviled it in the past. Offshore wind farms proposed over the last decade have run into stiff resistance from wildlife conservationists; that opposition has pushed the development zone farther out to sea and driven up costs. Germany's first commercial-scale offshore wind project, the 400-megawatt Bard 1, will stand some 112 kilometers from shore. By the project's completion in 2012, construction costs are expected to total €1.9 billion (US $2.6 billion)—40 percent more per megawatt than offshore wind farms in the United Kingdom.

The new transmission-planning law, meanwhile, is intended to deliver the 3600 km of added high-voltage lines that grid operators need to integrate new power from anticipated renewable installations. Legislators hope that by streamlining the approvals process and compensating affected communities, the law can resolve persistent conflicts and thus cut four to six years off the 10 currently required to build new lines.

Most energy analysts agree that Germany will also need new fossil-fueled power plants to meet its energy demands, if only to replace aging and inefficient coal-fired stations. Kemfert predicts many of these will be fueled by natural gas, because German policymakers have lost patience with coal's heavy carbon footprint and they aren't sold on carbon sequestration as a large-scale solution. (The July 2011 law authorizing sequestration gave German states veto power over local projects, and Kemfert has no doubt they will use it.)

Though natural gas supplied just 14 percent of Germany's electric power last year and delivers costlier power than coal, Kemfert believes it's a good fit for the country. Gas-fired plants currently produce one-half to one-third the greenhouse-gas emissions of coal plants and could even become renewable generators, thanks to Germany's increasing production of biogas from animal waste.

However, all these solutions will take time to implement, and Germany will need energy to keep the lights on in the meantime. One possible, ironic source of that energy: nuclear power imported from France and the Czech Republic. ❑

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原子力の将来

What Next for Nuclear?

We asked the experts how to build a safer and stronger nuclear industry

Q: Can the nuclear industry regain the public trust after the Fukushima Dai-ichi accident?

A: Our June 2011 survey found that support from people who live closest to U.S. reactors is still very strong: Eighty percent favor the use of nuclear energy. These people typically have a stronger knowledge base, and the trend we've always seen in our industry is that the more people know about nuclear energy, the more they support it.

The polling data show that we have lost some support for nuclear power, but it hasn't gone to the opposition—it's gone to neutral. Many people are doing a reassessment of nuclear energy. So the industry has to be as forthcoming and transparent as possible in providing information that will help people with that assessment.
—J. SCOTT PETERSON, *senior vice president of communications at the Nuclear Energy Institute*

Q: Are sweeping new regulations required to keep nuclear plants safe?

A: The more urgent need is for the United States Nuclear Regulatory Commission (NRC) to strictly enforce existing safety regulations. Two examples are rules governing fire protection and releases of radioactively contaminated liquids. The NRC has a list of 47 nuclear power reactors in the United States that do not meet fire protection regulations. The agency doesn't care. The NRC has a list of even more nuclear power reactors that have illegally leaked radioactively contaminated liquids. The agency has done nothing about it. The NRC cannot watch plant owners limbo beneath its safety bar until Americans die. The NRC must enforce regulations now to prevent that future disaster.
—DAVE LOCHBAUM, *director of the Nuclear Safety Project at the Union of Concerned Scientists*

Q: Is there one action governments can take now to make new reactors financially viable?

A: If we want to limit CO_2 emissions in this country, then the government should introduce a price for carbon. That would drive up the cost of burning natural gas and might end up stimulating demand for nuclear power plants, because they're the largest source of carbon-free electricity we have. The United States should do away with all the Department of Energy loan guarantees for nuclear, provide a very clear policy regarding the price of carbon, and then let the utility industry decide how to adapt.
—CHRIS GADOMSKI, *analyst at Bloomberg New Energy Finance*

Q: What are nuclear regulators' top priorities following Fukushima?

A: We're focusing on things we can do in the near term to make physical improvements at the plants. We're likely to upgrade seismic and flood protections. And there may also be new requirements in response to the issue that was at the heart of what happened at Fukushima: There was a very long time period without any on-site or off-site electrical power. You need to have an electrical power system that's designed to withstand a very large event caused by natural forces. All U.S. plants are now capable of operating between 4 and 8 hours without any off-site power supply, but we want to be sure they're capable of operating for much longer periods of time.
—MARTIN VIRGILIO, *deputy executive director for reactor preparedness programs at the NRC*

Q: If governments demand safety upgrades for new nuclear plants, will utilities still find it economically viable to build them?

A: I don't think regulatory requirements are going to have an impact on new nuclear construction—I think it depends more on the price of natural gas. A lot of utilities that were eager to enter the nuclear field five years ago are now looking at natural gas prices and asking, "Is nuclear the right way to go at this point in time?" Those decisions really depend on the economics around other alternatives for generating power.
—MARTIN VIRGILIO, *deputy executive director for reactor preparedness programs at the U.S. Nuclear Regulatory Commission (NRC)*

ICONS: CARL DeTORRES

Q: How can international entities ensure safety in countries that plan to join the nuclear power club soon?

A: For operators that are moving toward fuel loading in their first reactor, the World Association of Nuclear Operators offers pre-start-up peer reviews. This effort is focused particularly on countries without previous nuclear power experience. The transition between construction and operation at a nuclear power plant is a delicate period, and many incidents (most notably, Three Mile Island) occur during the early months of plant operation.

—JOHN RITCH, *director general of the World Nuclear Association (WNA)*

Q: In the United States, there's already talk of extending plants' operating licenses to 80 years. What are the challenges in renewing the licenses of aging plants?

A: There are many technical issues to examine in determining whether a second license extension is safe and economically feasible. Decisions will have to made, for example, on which pieces of equipment have to be replaced, which can be upgraded, and which can continue operating. You can replace many things in a nuclear power station—pumps, motors, valves, pipe work. The concrete containment, however, is pretty tough to replace. So we're working to understand the aging mechanisms of concrete and what the degradation process may be, and then, if necessary, we can develop inspection techniques. So far, we haven't found anything that would be a technical showstopper.

—NEIL WILMSHURST, *vice president of the nuclear sector at the Electric Power Research Institute (EPRI)*

Q: Will the Fukushima accident cause companies to reevaluate their newest reactor designs? Is there a new urgency to develop advanced, Generation IV reactors?

A: The entire nuclear industry is evaluating the impact of the Fukushima event on reactor designs. Westinghouse will incorporate lessons learned into its AP1000 design (a Generation III+ reactor design) when an industry consensus is achieved. There will be no significant change in our direction and no new urgency to pursue development of Generation IV designs. These Generation IV designs are typically considered to be advanced reactors that use either gas or liquid metals as reactor coolant instead of water. The commercialization of these Generation IV reactors is not feasible in the near term, as many technical challenges need to be addressed.

—ED CUMMINS, *vice president of new plant technology for Westinghouse Electric Co.*

Q: How have the industry's R&D priorities changed after Fukushima?

A: One area that clearly needs attention involves the industry's understanding of external events that impact more than one reactor on a site, and the consequences of those events. Fukushima was a clear demonstration that you can't always rely on equipment and functionality from a neighboring unit to support the unit in trouble.

—NEIL WILMSHURST, *vice president of the nuclear sector at EPRI*

Q: What about ensuring nuclear safety in China, which is building reactors at a rapid rate?

A: It would be a mistake to assume that China is less concerned about nuclear safety than are other nations. China's emphasis on safety was illustrated by the government's immediate response to Fukushima: Five days after the Fukushima accident began, the State Council of the People's Republic of China announced that it would suspend approvals for new nuclear power stations and conduct comprehensive safety checks of all nuclear projects.

Last year the International Atomic Energy Agency carried out a two-week review of China's regulatory framework for nuclear safety. The IAEA made a number of recommendations but concluded that the review had provided "confidence in the effectiveness of the Chinese safety regulatory system and the future safety of the vast expanding nuclear industry."

—JOHN RITCH, *director general of the WNA*

Q: What's the best solution to the nuclear waste problem?

A: Compared to keeping waste on the surface indefinitely, putting it 500 meters underground is much more safe. Establishing a permanent repository is more a political than a technical problem. Congress tried to force a spent-fuel repository on Nevada, but forcing a host community has not worked in any democracy. As the Blue Ribbon Commission on America's Nuclear Future has observed in its draft report, "a new consent-based approach to siting" is required. This approach has been adopted successfully by Sweden and Finland and is quickly becoming the standard approach.

—FRANK VON HIPPEL, *codirector of the program on science and global security at Princeton University*

TRANSISTOR WARS

RIVAL ARCHITECTURES FACE OFF IN A BID TO KEEP MOORE'S LAW ALIVE

BY KHALED AHMED & KLAUS SCHUEGRAF

In May, Intel announced the most dramatic change to the architecture of the transistor since the device was invented. The company will henceforth build its transistors in three dimensions, a shift that—if all goes well—should add at least a half dozen years to the life of Moore's Law, the biennial doubling in transistor density that has driven the chip industry for decades.

But Intel's big announcement was notable for another reason: It signaled the start of a growing schism among chipmakers. Despite all the great advantages of going 3-D, a simpler alternative design is also nearing production. Although it's not yet clear which device architecture will win out, what is certain is that the complementary metal-oxide semiconductor (CMOS) field-effect transistor (FET)—the centerpiece of computer processors since the 1980s—will get an entirely new look. And the change is more than cosmetic; these designs will help open up a new world of low-power mobile electronics with fantastic capabilities.

There's a simple reason everyone's contemplating a redesign: The smaller you make a CMOS transistor, the more current it leaks when it's switched off. This leakage arises from the device's geometry. A standard CMOS transistor has four parts: a source, a drain, a channel that connects the two, and a gate on top to control the channel. When the gate is turned on, it creates a conductive path that allows electrons or holes to move from the source to the drain. When the gate is switched off, this conductive path is supposed to disappear. But as engineers have shrunk the distance between the source and drain, the gate's control over the transistor channel has gotten weaker. Current sneaks through the part of the channel that's farthest from the gate and also through the underlying silicon substrate. The only way to cut down on leaks is to find a way to remove all that excess silicon.

Over the past few decades, two very different solutions to this problem have emerged. One approach is to make the silicon channel of the traditional planar transistor as thin as possible, by eliminating the silicon substrate and instead building the channel on top of insulating material. The other scheme is to turn this channel on its side, popping it out of the transistor plane to create a 3-D device. Each approach comes with its own set of merits and manufacturing challenges, and chipmakers are now working out the best way to catch up with Intel's leap forward. The next few years will see dramatic upheaval in an already fast-moving industry.

CHANGE IS NOTHING NEW to CMOS transistors, but the pace has been accelerating. When the first CMOS devices entered mass production in the 1980s, the path to further miniaturization seemed straightforward. Back in 1974, engineers at the IBM T. J. Watson Research Center in Yorktown Heights, N.Y., led by Robert Dennard, had already sketched out the ideal progression. The team described how steadily reducing gate length, gate insulator thickness, and other feature dimensions could simultaneously improve switching speed, power consumption, and transistor density.

But this set of rules, known as Dennard's scaling law, hasn't been followed for some time. During the 1990s boom in personal computing, the demand for faster microprocessors drove down transistor gate length faster than Dennard's law called for. Shrinking transistors boosted speeds, but engineers found that as they did so, they couldn't reduce the voltage across the devices to improve power consumption. So much current was being lost when the transistor was off that a strong voltage—applied on the drain to pull charge carriers through the channel—was needed to make sure the device switched as quickly as possible to avoid losing power in the switching process.

By 2001, the leakage power was fast approaching the amount of power needed to switch a transistor out of its "off" state. This was a warning sign for the industry. The trend promised chips that would consume the same amount of energy regardless of whether they were in use or not. Chipmakers needed to find new ways to boost transistor density. In 2003, as the length of transistor channels dropped to 45 nanometers, Intel debuted chips bearing devices made with strain engineering. These transistors boasted silicon channels that had been physically squeezed or pulled to boost speed and reduce the power lost due to resistance. By the next "node"—industry lingo for a transistor density milestone—companies had stopped shrinking transistor dimensions and instead began just squeezing transistors closer together. And in 2007, Intel bought Moore's Law a few more years by introducing the first big materials change, replacing the ever-thinning silicon oxide insulator that sits between a transistor's gate and channel with hafnium oxide.

This better-insulating material helped stanch a main source of leakage current—the tunneling of electrons between the gate and the channel. But leakage from the source to the drain was still a huge problem. As companies faced the prospect of creating even denser chips with features approaching 20 nm, it became increasingly clear that squeezing together traditional planar transistors or shrinking them even further would be impossible with existing technology. Swapping in a new insulator or adding more strain wouldn't cut it. Driving down power consumption and saving Moore's Law would require a fundamental change to transistor structure—a new design that could maximize the gate's control over the channel.

FORTUNATELY, over the course of more than 20 years of research, transistor designers have found two very powerful ways to boost the effectiveness of the transistor gate. As the gate itself can't get much stronger, these schemes focus on making the channel easier to control. One approach replaces the bulk silicon of a normal transistor with a thin layer of silicon built on an insulating layer, creating a device that is often called an ultrathin body silicon-on-insulator, or UTB SOI, also known as a fully depleted SOI.

PREVIOUS PAGE: ILLUSTRATION: DAVID PLUNKERT; RIGHT: EMILY COOPER

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A second strategy turns the thin silicon channel by 90 degrees, creating a "fin" that juts out of the plane of the device. The transistor gate is then draped over the top of the channel like an upside-down U, bracketing it on three sides and giving the gate almost complete control of the channel. While conventional CMOS devices are largely flat, save for a thin insulating layer and the gate, these FinFETs—or Tri-Gate transistors, as Intel has named its three-sided devices—are decidedly 3-D. All the main components of the transistor—source, drain, channel, and gate—sit on top of the device's substrate.

Both schemes offer the same basic advantage: By thinning the channel, they bring the gate closer to the drain. When a transistor is off, the drain's electric field can take one of two paths inside the channel to zero-voltage destinations. It can propagate all the way across the channel to the source, or it can terminate at the transistor's gate. If the field gets to the source, it can lower the energy barrier that keeps charge carriers in the source from entering the channel. But if the gate is close enough to the drain, it can act as a lightning rod, diverting field lines away from the source. This cuts down on leakage, and it also means that field lines don't penetrate very far into the channel, dissipating even more energy by tugging on any stray carriers.

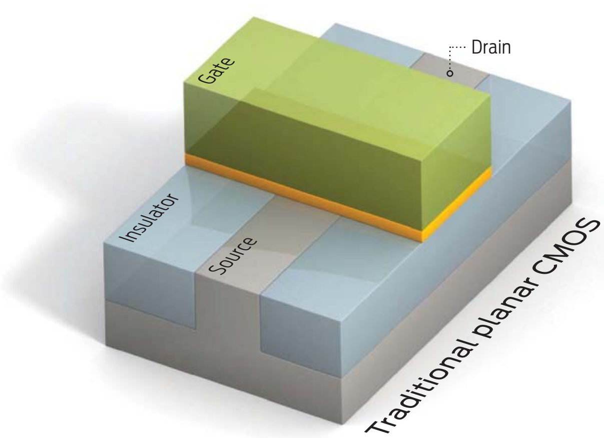
The first 3-D transistor was sketched out by Digh Hisamoto and others at Hitachi, who presented the design for a device dubbed a Delta at a conference in 1989. The UTB SOI's roots extend even further back; they are a natural extension of early SOI channel research, which began in the 1980s when researchers started experimenting with transistors built with 200-nm thick, undoped silicon channels on insulating material.

But the promise of both of these thin-channel approaches wasn't fully appreciated until 1996, when Chenming Hu and his colleagues at the University of California, Berkeley, began an ambitious study, funded by the U.S. Defense Advanced Research Projects Agency, to see how far these designs could go. At the time, the industry was producing 250-nm transistors, and no one knew whether the devices could be scaled below 100 nm. Hu's team showed that the two alternate architectures could solve the power consumption problems of planar CMOS transistors and that they could operate with gate lengths of 20 nm—and later, even less.

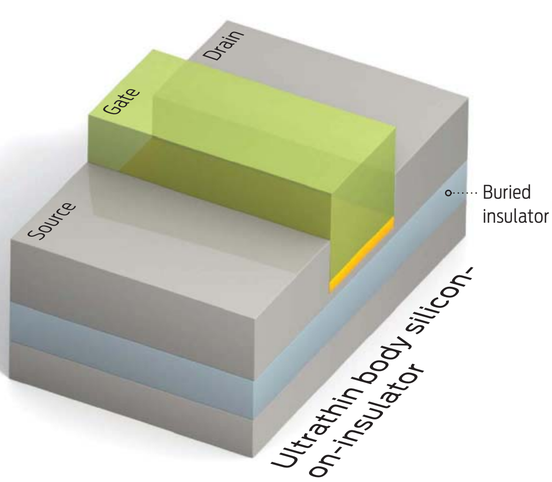
The FinFET and the UTB SOI both offer big gains in power consumption. Logic chip designs typically require that a transistor in its on state draw at least 10 000 times as much current as the device leaks in its off state. For 30-nm transistors—about the size that most chipmakers are currently aiming for—this design spec means devices should leak no more than a few nanoamperes of current when they're off. While 30-nm planar CMOS devices leak about 50 times that amount, both thin-channel designs hit the target quite easily.

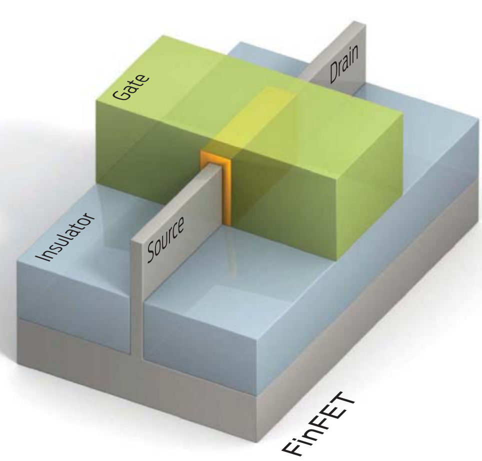
But the two architectures aren't entirely equal. To get the best performance, the channel of a UTB SOI should be no more than about one-fourth as thick as the length of the gate. Because a FinFET's gate brackets the channel on three sides, the 3-D transistors can achieve the same level of control with a channel—or fin—that's as much as half as thick as the length of the transistor gate.

This bigger channel volume gives FinFETs a distinct advantage when it comes to current-carrying capacity. The best R&D results suggest that a 25-nm FinFET can carry



ELIMINATING EXCESS: In the next few years, traditional planar CMOS field-effect transistors [left] will be replaced by alternate architectures that boost the gate's control of the channel. The UTB SOI [bottom left] replaces the bulk silicon channel with a thin layer of silicon mounted on insulator. The FinFET [bottom right] turns the transistor channel on its side and wraps the gate around three sides.





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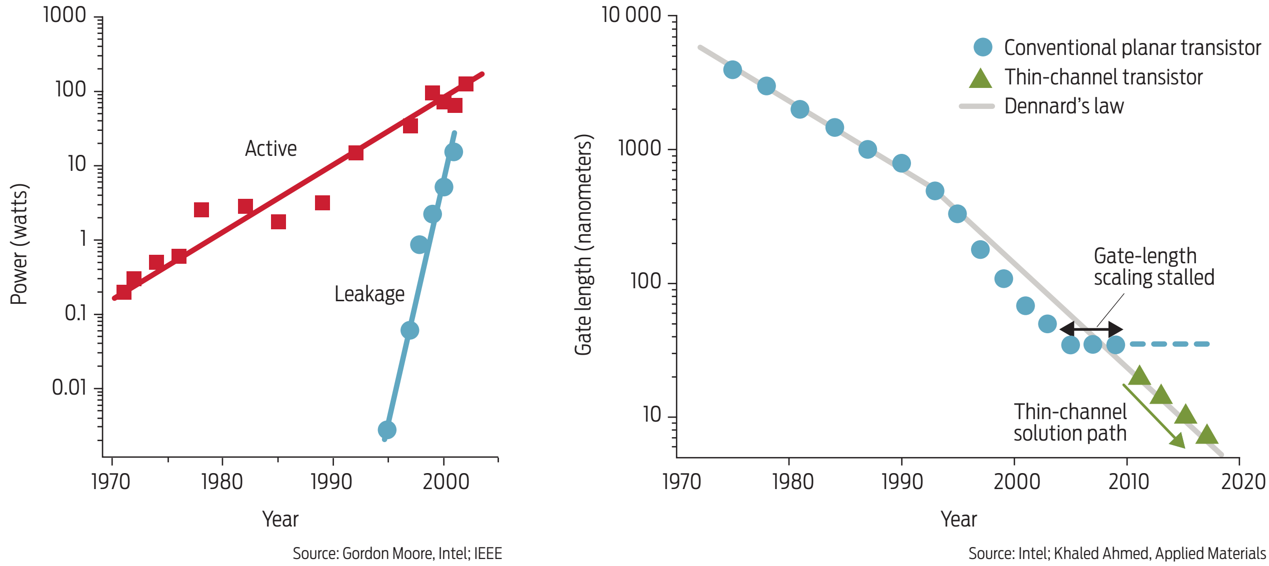


SHRINKING RETURNS: As transistors got smaller, their power demands grew. By 2001, the power that leaked through a transistor when it was off was fast approaching the amount of power needed to turn the transistor on [left], a warning sign for the chip industry. As these Intel data show, the leakage problem eventually put a halt to the transistor scaling [right], a progression called Dennard's law. Switching to alternate architectures will allow chipmakers to shrink transistors again, boosting transistor density and performance.

about 25 percent more current than a UTB SOI. This current boost doesn't matter much if you have only a single transistor, but in an IC, it means you can charge capacitors 25 percent faster, making for much speedier chips. Faster chips obviously mean a lot to a microprocessor manufacturer like Intel. The question is whether other chipmakers will find the faster speeds meaningful enough to switch to FinFETs, a prospect that requires a big up-front investment and an entirely new set of manufacturing challenges.

The single biggest hurdle in making FinFETs is manufacturing the fins so that they're both narrow and uniform. For a 20-nm transistor—roughly the same size as the one that Intel is putting into production in 2012—the fin must be about 10 nm wide and 25 nm high; it must also deviate by no more than half a nanometer—just a few atomic layers—in any given direction. Over the course of production, manufacturers must control all sources of variation, limiting it to no more than 1 nm in a 300-millimeter-wide wafer.

This precision is needed not only to manufacture the fin; it must also be maintained for the rest of the manufacturing process, including thermal treatment, doping, and the multiple film deposition and removal steps needed to build the transistor's gate insulator and gate. As an added complication, the gate oxide and the gate must be deposited so that they follow the contours of the fin. Any process that damages the fin could affect how the device performs. The resultant variation in device quality would force engineers to operate circuits at a higher power than they're designed for, eliminating any gains in power efficiency.

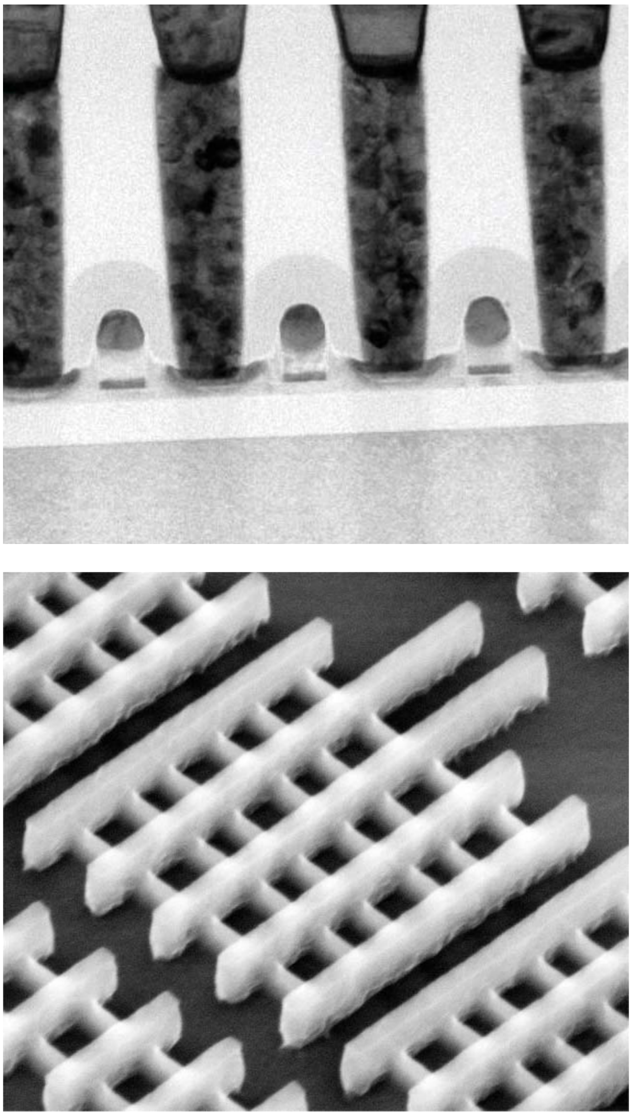
The unusual geometry of the FinFET also poses challenges for doping, which isn't required but can help cut down on leakage current. FinFET channels need two kinds of dopants: One is deposited underneath the gate and the other into the parts of the channel that extend on either side of the gate, helping mate the channel to the source and drain. Manufacturers currently dope channels by shooting ions straight down into the material. But that approach won't work for FinFETs. The devices need dopants to be distributed evenly through the top of the fin and the side walls; any unevenness in concentration will cause a pileup of charges, boosting the device's resistance and wasting power.

Doping will get only more difficult in the future. As FinFETs shrink, they'll get so close together that they will cast "shadows" on one another, preventing dopants from permeating every part of every fin. At Applied Materials' Silicon Systems Group, we've been working on one possible fix: immersing fins in plasma so that dopants can migrate directly into the material, no matter what its shape is.

Because UTB SOI devices are quite similar to conventional planar CMOS transistors, they are easier to manufacture than FinFETs. Most existing designs and manufacturing techniques will work just as well with the new thin-silicon transistors as they do with the traditional variety. And in some ways, UTB SOIs are easier to produce than present-day transistors. The devices don't need doped channels, a simplification that can save planar CMOS manufacturers some 20 to 30 steps out of roughly 400 in the wafer production process.

But the UTB SOI comes with its own challenges, chiefly the thin channel. The requirement that UTB SOI channels be half as thick as comparable FinFET fins makes any variations in thickness even more critical for these devices. A firm called Soitec, headquartered in Bernin, France, which has been leading the charge in manufacturing ultrathin silicon-on-insulator wafers, is currently demonstrating 10-nm-thick silicon layers that vary by just 0.5 nm in thickness. That's an impressive achievement for wafers that measure 300 mm across, but it will need to be improved as transistors shrink. And it's not clear how precise Soitec's technique—which involves splitting a wafer to create an ultrathin silicon layer—can ultimately be made.

Another key stumbling block for UTB SOI adoption is the supply chain. At the moment, there are few potential provid-



DOWN AND UP: A cross section of UTB SOI transistors [top] and a micrograph of an array of FinFET transistors [bottom]. *PHOTOS: TOP, STMICROELECTRONICS; BOTTOM, INTEL*

ers of ultrathin SOI wafers, which could ultimately make manufacturers of UTB SOI chips dependent on a handful of sources. Intel's Mark Bohr says the hard-to-find wafers could add 10 percent to the cost of a finished wafer, compared to 2 to 3 percent for wafers bearing 3-D transistors (an estimate from the SOI Industry Consortium suggests that finished UTB SOI wafers will actually be less expensive).

Going forward, we expect that chipmakers will split into two camps. Those interested in the speediest transistors will move toward FinFETs. Others who don't want to invest as much in a switch will find UTB SOIs more attractive.

UTB SOI transistors have an additional feature that makes them particularly appealing for low-power applications: A small voltage can easily be applied to the very bottom of a chip full of UTB SOI devices. This small bias voltage alters the channel properties, reducing the electrical barrier that stops current flowing from the source to the drain. As a result, less voltage needs to be applied to the transistor gates to turn the devices on. When the transistors aren't needed, this bias voltage can be removed, which restores the electrical barrier, reducing the amount of current that leaks through the device when it's off. As Thomas Skotnicki of STMicroelectronics has long argued, this sort of dynamic switching saves power, making the devices particularly attractive for chips in smartphones and other mobile gadgets. Skotnicki says the company expects to release its first UTB SOI chip, which will use 28-nm transistors to power a mobile multimedia processor, by the end of 2012.

That said, few companies have committed to one technology or the other. STMicroelectronics—as well as firms such as GlobalFoundries and Samsung—is part of the International Semiconductor Development Alliance, which supports and benefits from device research at IBM and is investing in both FinFETs and UTB SOIs. Exactly how the industry will split up and which design will come to dominate will depend on decisions made by the biggest foundries and how quickly standards are developed. Reports suggest that Taiwan Semiconductor Manufacturing Co., which dominates bespoke manufacturing in the chip industry, will begin making 14-nm FinFETs in 2015, but it's not clear whether the company will also support UTB SOI production. Switching to FinFET production requires a substantial investment, and whichever way TSMC swings, it will put pressure on other manufacturers, such as GlobalFoundries, United Microelectronics Corp., and newcomers to the foundry business such as Samsung, to choose a direction.

Also still unclear is how far each technology can be extended. Right now it looks like both FinFETs and UTB SOIs should be able to cover the next three generations of transistors. But UTB SOI transistors may not evolve much below 7 nm, because at that point, their gate oxide would need an effective thickness of 0.7 nm, which would require significant materials innovation. FinFETs may have a similar limit. In 2006, a team at the Korea Advanced Institute of Science and Technology used electron-beam lithography to build 3-nm FinFETs. But crafting a single device isn't quite the same as packing millions together to make a microprocessor; when transistors are that close to each other, parasitic capacitances and resistances will draw current away from each switch. Some projections suggest that when FinFETs are scaled down to 7 nm or so, they will perform no better than planar devices.

Meanwhile, researchers are already trying to figure out what devices might succeed FinFETs and UTB SOIs, to continue Moore's Law scaling. One possibility is to extrapolate the FinFET concept by using a nanowire device that is completely surrounded by a cylindrical gate. Another idea is to exploit quantum tunneling to create switches that can't leak current when they're not switched on. We don't know what will come next. The emergence of FinFETs and UTB SOIs clearly shows that the days of simple transistor scaling are long behind us. But the switch to these new designs also offers a clear demonstration of how creative thinking and a good amount of competition can help us push Moore's Law to its ultimate limit—whatever that might be. ❑

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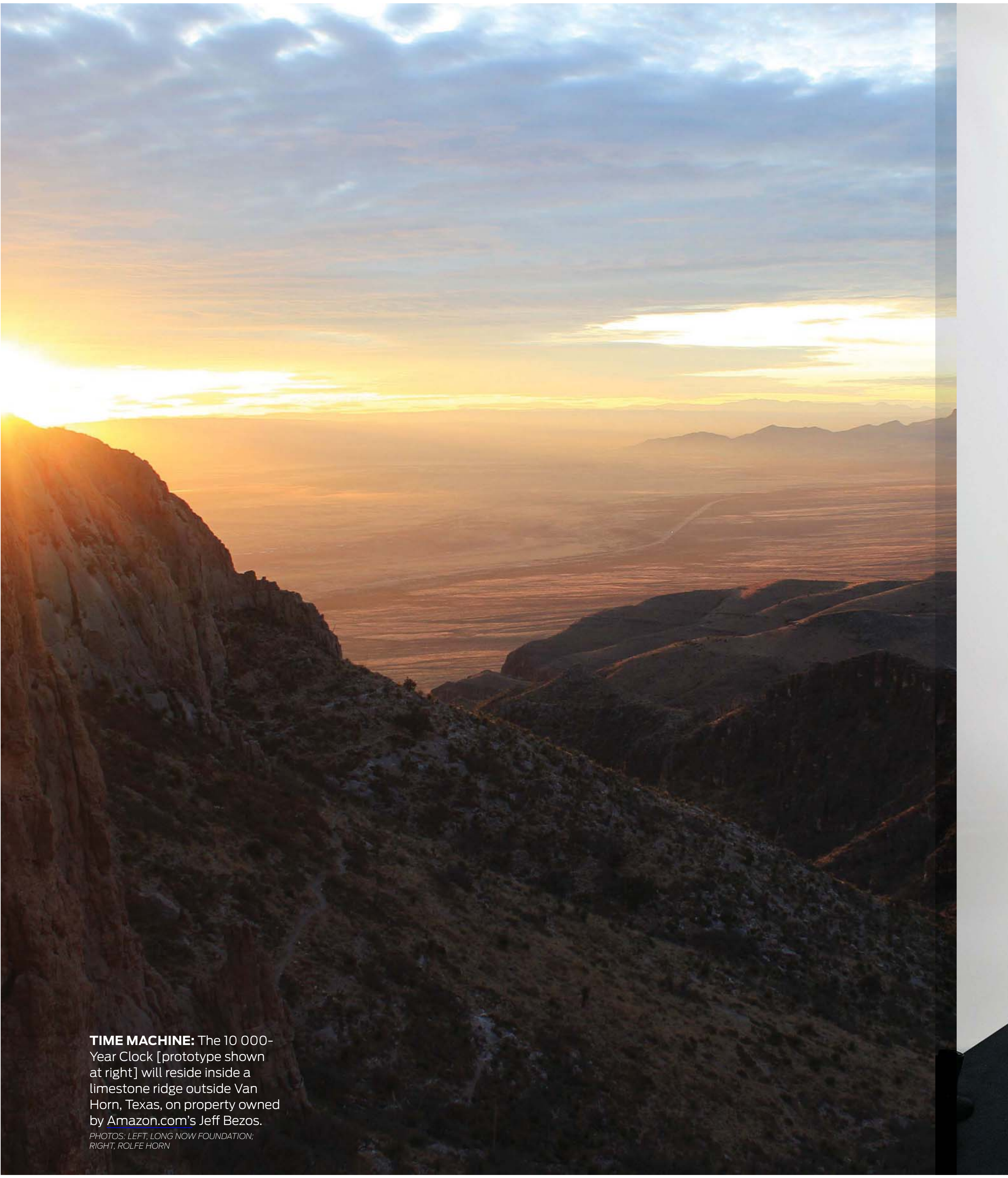

TIME MACHINE: The 10 000-Year Clock [prototype shown at right] will reside inside a limestone ridge outside Van Horn, Texas, on property owned by Amazon.com's Jeff Bezos.
PHOTOS: LEFT, LONG NOW FOUNDATION; RIGHT, ROLFE HORN

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Ticking to Eternity

How do you design a clock to tell time for 10 000 years?

By David Kushner

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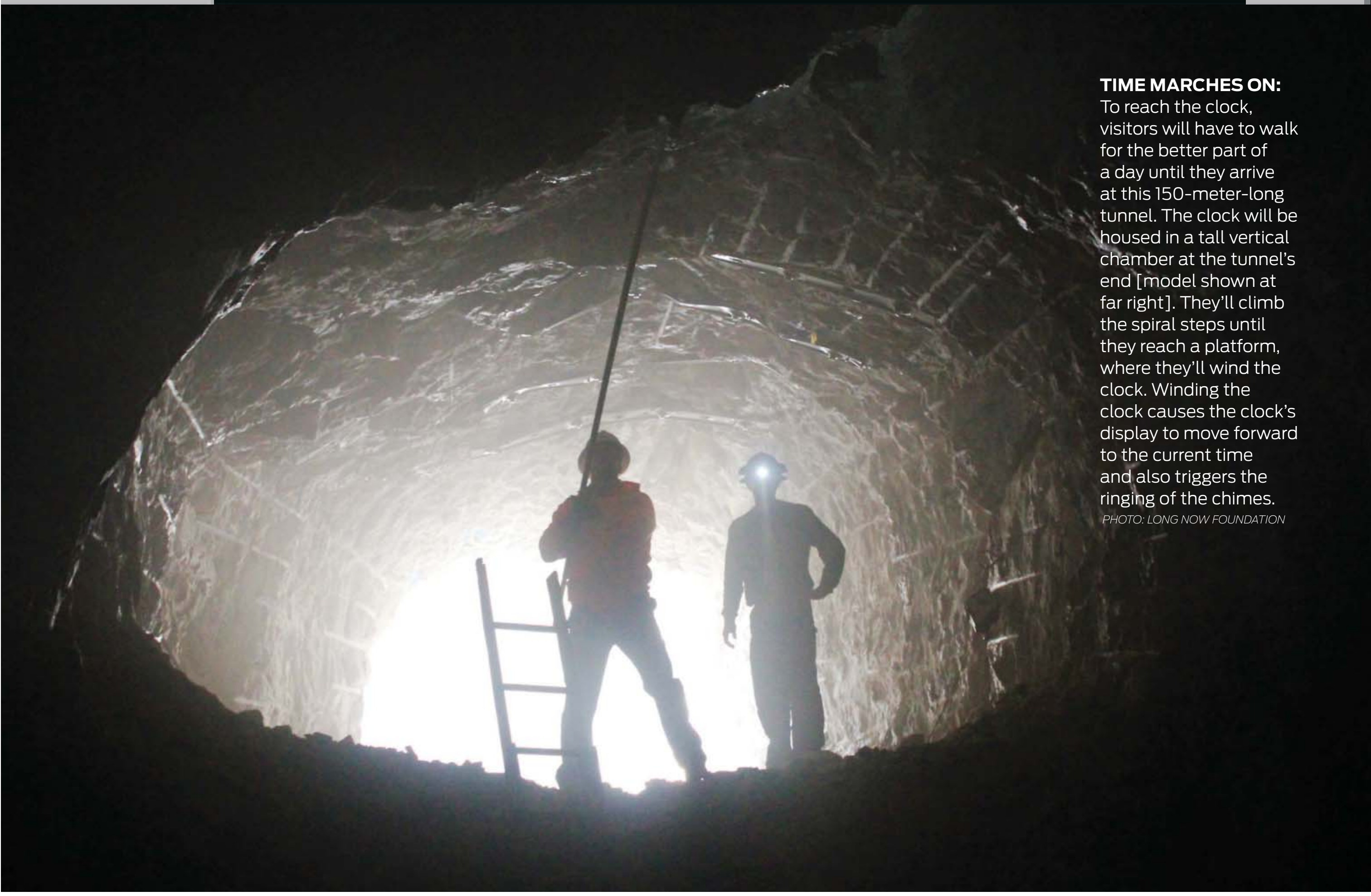

TIME MARCHES ON: To reach the clock, visitors will have to walk for the better part of a day until they arrive at this 150-meter-long tunnel. The clock will be housed in a tall vertical chamber at the tunnel's end [model shown at far right]. They'll climb the spiral steps until they reach a platform, where they'll wind the clock. Winding the clock causes the clock's display to move forward to the current time and also triggers the ringing of the chimes.
PHOTO: LONG NOW FOUNDATION

THE YEAR IS 12011. TWO HIKERS CUT THROUGH A STRETCH OF CACTUS-FILLED DESERT OUTSIDE WHAT WAS ONCE THE SMALL TOWN OF VAN HORN, NEAR THE MEXICAN BORDER, IN WEST TEXAS. AFTER WALKING FOR THE BETTER PART OF A DAY UNDER A RELENTLESS SUN, THEY STRUGGLE UP A CRAGGY LIMESTONE RIDGE. FINALLY THEY COME TO AN OPENING IN THE ROCK, THE MOUTH OF WHAT APPEARS TO BE A LONG, DEEP TUNNEL.

AS THEY HEAD INTO THE SHADOWS, not quite knowing where the tunnel will lead, the sudden darkness and the drop in temperature startle their senses. After a few minutes the hikers reach a cool chamber dimly lit from above. A tall column of strange shiny metal gears and rods rises hundreds of meters above them. Steps cut into the walls spiral upward, and the hikers ascend until they reach a platform. A black globe suspended above depicts the night sky, encircled by metal disks that indicate the year and the century.

A giant metal wheel sits in the middle of the platform, and the visitors each grasp a handle that juts out from its smooth edges. For the next several hours, they push and walk and push and walk in a circle, methodically, silently, until the wheel will turn no further. Exhausted, they rest on the platform and drift off to sleep. At noon the next day, they're suddenly awakened by the ethereal tones of chiming bells.

It sounds like science fiction, but this is the real vision for the 10 000-Year Clock, a monument-size mechanical clock designed to measure time for 10 millennia. Danny Hillis, an electrical engineer with three degrees from MIT who pioneered parallel supercomputers at Thinking Machines Corp., worked for Walt Disney Imagineering, and then cofounded the consultancy Applied Minds, dreamed up the project in 1995 to get people thinking more about the distant future. But the clock is no longer just a thought experiment. In a cluttered machine shop near a Starbucks in San Rafael, Calif., it's finally ticking to life.

This clock, the flagship project of Hillis's Long Now Foundation, is a wonder of mechanical engineering. Over the course of its 10 000-year life span, it will be able to power itself enough to keep time, synchronize that timekeeping with the sun, and randomly generate unique melodies on its chimes so that visitors will never hear the same tune twice. And it will do so entirely without electricity. Think of it as "the slowest computer in the world," says project manager Alexander Rose.

With funding from Jeff Bezos, the billionaire founder of Amazon.com, three teams of engineers in San Francisco, Seattle,

TIMEKEEPERS: Parallel computing pioneer Danny Hillis [right] dreamed up the 10 000-Year Clock as a way to encourage long-range thinking. He and Alexander Rose [left] are now leading the clock's design and engineering team. "Building a big physical thing is just cool," Rose says. *PHOTOS: ABOVE, QUINN NORTON; RIGHT, STEVE HOGE*

and Texas have been working through the complexities of the design, including how to keep the clock ticking and how to ensure that its components will hold up through the millennia. Meanwhile, a construction crew in Texas has been blasting and digging through limestone to create the tunnel. In Washington state, engineers at Seattle Solstice are refining a giant stone-cutting robot that will eventually be shipped to Texas and deployed inside the mountain, to etch the spiral staircase directly into the rock. "This is a project of a bunch of engineers," says Rose. "And building a big physical thing is just cool."

Still, the designers believe there's much more to the project than just geek chic. A clock that's meant to last for 10 000 years poses a fundamental challenge for a speed-obsessed age: How do you engineer something for the very distant future and get people to care about it today?

ON A BRIGHT BLUE MORNING in February, I drove to the San Rafael shop with Rose to see the first assembled piece of the clock in action: several 2.4-meter-wide gears for the chime generator, one of the largest and most complex parts of the clock. Over the lifetime of the clock, the chime generator will ring a series of 10 bells in a different arrangement each time.

"I haven't seen it turn on yet," says Rose, tall and chrome-domed, dressed in a black polo shirt and khaki pants. "Baptism by fire." He flips a switch, and he and I watch the giant stainless-steel gears spin silently. I picture those future hikers deep inside the mountain, waking up to the sound of bells.

But what's the point of building something to last 10 000 years? Hillis says he chose that time span because that's about how long human technology has been around. One inspiration came from a possibly apocryphal tale of a forward-looking architect. According to the myth, back in 1386, the builder of the University of Oxford's New College planted some oak trees. The purpose was to have wood that could be used to replace the oak beams of the college's great dining hall hundreds of years in the future.

For an engineer who had built his career on making fast machines, Hillis found this story of forethought striking. Living in an increasingly accelerated culture, he thought, was eroding our ability to think concretely about the future. "Why bother making plans when everything will change?" he wrote in a 1995 manifesto. Building an ageless clock, Hillis suggested, was a way to bring really long-term thinking back.

He took his idea to a private mailing list that included future-minded thinkers such as Stewart Brand, founder of the WELL (the Whole Earth 'Lectronic Link) online community, and electronic musician Brian Eno. The idea captivated the group, and Hillis began to consider more seriously how his clock might actually get built. In 1997, after starting the Long Now Foundation, he began to work on the clock in earnest with Rose, a Carnegie Mellon–educated industrial designer whose eclectic résumé includes stints as artist in residence at Silicon Graphics and designer of championship combat robots.

Like Hillis, Rose saw the urgency of the idea. Society needs to think long term or risk failing to appreciate such century-spanning problems as climate change and deforestation, Rose told me. The basic notion may have been a quick sell, but actually building the clock, he and Hillis knew, would be immensely difficult. As Hillis wrote in his essay, "My engineering friends worry about the power source: solar, water, nuclear, geothermal, diffusion, or tidal? My entrepreneurial friends muse about how to make it financially self-sustaining."

The money turned out to be the easy part, because the clock had attracted a formidable believer: Amazon's Bezos, who calls himself "the first steward" of the project. Bezos was struck by the clock's big idea. "If you read my 1997 shareholder letter [the year Amazon.com went public], it's all about the long term," Bezos tells me. "And so this philosophy, this ability to use long-term thinking to accomplish important things, is a common thread in everything I'm involved in." This includes Blue Origin, his private spaceflight company. The clock is being built on a ridge that overlooks Blue Origin's headquarters.

Bezos, who got his undergraduate degree in electrical engineering and computer science from Princeton, was also drawn to the project by the sheer geeky quality of the thing.

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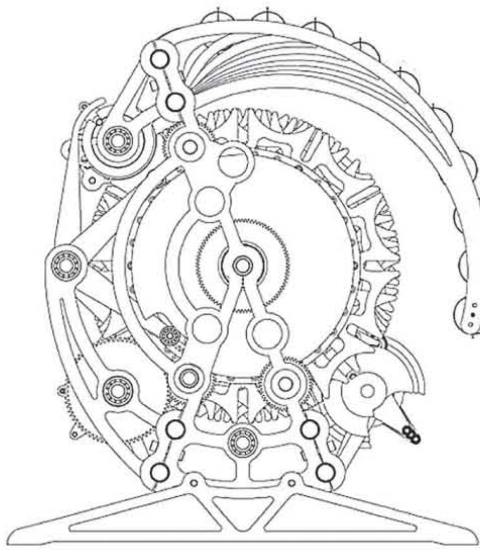

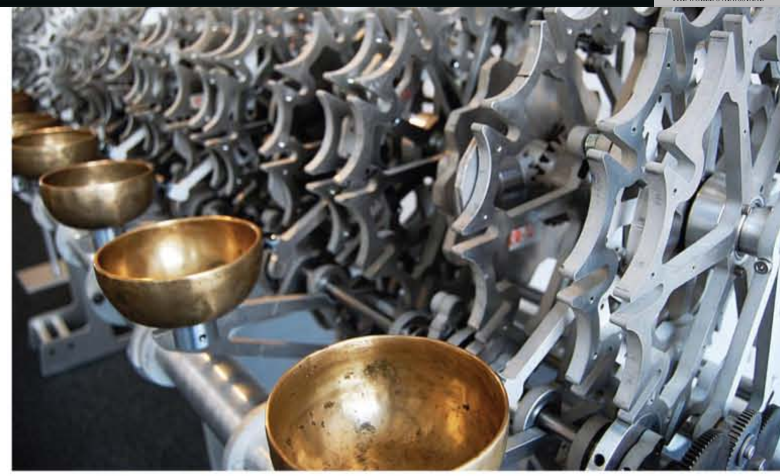

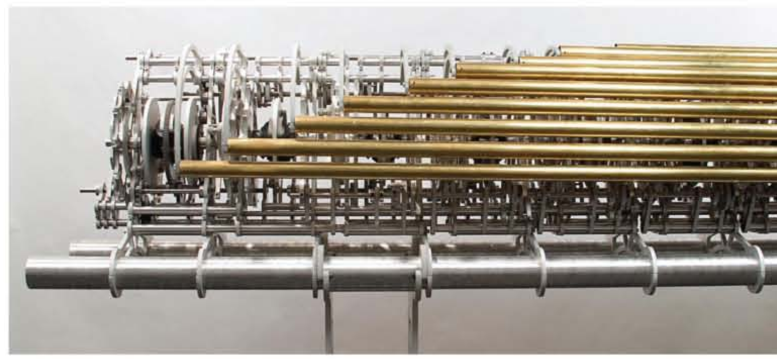

CHIME TIME: The clock's digital mechanical computer [drawing above, prototypes at right] is a complex system of gears, pins, and rollers that generates a unique sequence of chimes each time it's played.

IMAGES: CLOCKWISE FROM LEFT, LONG NOW FOUNDATION (2); NICHOLAS CHATFIELD-TAYLOR

"It's a challenging engineering problem and so fun in its own right," he says.

Bezos is footing the bill for the clock's installation near the tiny town of Van Horn. Hillis and Rose hope this clock will be the first of several at different sites. (Small-scale prototypes of the clock already exist, including one that's now housed at the Science Museum in London.) Although the budget for the Texas project has not been officially disclosed, a recent article in *Wired* put it at US $42 million. Given the highly skilled staff, the high-tech construction and machining equipment, and the rarefied raw materials involved, that seems about right. But Bezos bristles at the notion that his investment might be perceived as frivolous. "Symbols are important," he says.

IF YOU ACCEPT THAT PREMISE, then you'll understand why Hillis and Rose's first concern wasn't sketching out the clock's innards. Instead, they obsessed over how people would experience the clock. They wanted it to be as engaging as possible, "to make someone care about it in 10 000 years," Hillis says.

"We spent more time debating the aesthetics of a given part and how humans will interact with it than any other thing," says Rose. "What is the day like as they walk through this architectural-scale clock mechanism?"

For inspiration, the team looked backward—to enduring ancient monuments like the Egyptian pyramids and Stonehenge. They also looked to the present—to theme park rides, such as those Hillis designed during his time as vice president of R&D for Walt Disney Imagineering. They realized that what each of these very different entities has in common is that the visitor experiences it as a rite of passage.

Hillis has spent the past seven years working with Rose and other members of the team to design what he calls the "plotline" of the clock. First, they wanted to ensure that visitors would be vested in the journey. That meant building the clock in a faraway, hard-to-reach place, somewhere requiring a real commitment to visit. (The site they chose indeed qualifies—for now. But it's anyone's guess what this place will be like in 10 000 years.)

Even after the intrepid explorers of the future reach the site, the drama of their journey would continue to unfold as they enter the mountain, snake through tunnels, and climb up the spiral steps past the clock gears. Finally, they would arrive at the chosen spot, where they would wind the chime generator and hear the bells ring.

But what if you were the first person to visit the clock in centuries, or even millennia? Given the vagaries of human history, it's reasonable to expect that people might one day forget the clock even exists. So for the sake of the wayward traveler who just happens upon the clock by accident, the operation had to be obvious just from looking at it.

"Someone who looks at a part must be able to figure out what to do," Rose says. "People need to be able to stumble across it and understand how it works and how to maintain it." He and Hillis call this quality "transparency."

An electronic clock was therefore out of the question: It wasn't sufficiently transparent. Instead, they decided to make the clock entirely mechanical—even the digital computer that generates the melody of the clock's 10 chimes. The chime-generating computer uses a phased series of twenty 2.4-meter-diameter gears, called Geneva wheels, to produce up to 3.5 million unique sequences of chimes.

Although much of the clockwork is similar to the workings of a standard grandfather clock, it differs from an ordinary analog gear-driven clock in a few key ways. For one thing, it will be the largest clock ever built. And instead of having a pendulum that counts off each second, the clock's pendulum has a base of 10 seconds. So it will tick at one-tenth the speed of a regular clock, which should help its gears, bearings, and other components last

HARD TIME: Stuart Kendall of Seattle Solstice designed this stone-cutting robotic arm to create the spiral steps that will line the limestone walls of the clock chamber.
PHOTO: JIM MERITHEW/WIRED.COM/ CONDÉ NAST PUBLICATIONS

at least 10 times as long. And rather than having a 12-hour face, the clock will display the positions of the stars on a black globe, surrounded by dials showing the year, the positions of the sun and moon, and other astronomical data.

The clock is being designed modularly, so visitors will be able to see how the various parts go together. Working in modules has the added advantage of letting the engineers tweak different elements of the design without having to start from scratch each time. They are also discussing the possibility of including some kind of instruction manual, likely in the form of photographs or diagrams. They haven't yet decided, though, where to put the instructions or even how to alert people 10 000 years from now that the clock exists.

ONCE THEY'D SETTLED on the narrative arc of the clock experience, Hillis says, "then it's just a lot of engineering." Despite his flip response, the clock's design has been about as thoroughly thought out as that of a Formula One race car.

Hillis and Rose could find no precedents for what they wanted to do. "Nothing else is built to last this long," Rose told me. He had just returned from the Svalbard Global Seed Vault, in Norway, where millions of seeds from around the world are now being stored in a remote, highly protected underground bunker as a hedge against climate change and human conflict. Rose also considered the design of nuclear-waste storage facilities, which are built to last for centuries or longer. But neither of these constructs is a working machine, he explains.

Even seemingly simple questions proved difficult to answer, such as: What should the clock be made of? The team needed materials that could stand up to thousands of years of wear and tear, yet few studies could shed light on the matter. For insights, they looked at the 11 000-year-old tower of Jericho, believed to be the oldest existing building in the world. They discovered that the mortar's high silica content contributed to its longevity. The team is now culling similar material from a marble mine in Texas.

For the clock's components, the team has been selecting durable materials such as stainless steel, titanium, and ceramic, whose longevity can be gauged through high-temperature testing. "How they behave at a high temperature is a good indication of how they will perform over a long period of time," Hillis says.

Consider the chime generator. The gears are made of type 316L stainless steel, a marine-grade alloy that is extremely resistant to corrosion. "It has been tested in saltwater environments and accelerated aging systems for almost a century now," explains Rose. "Like all things it will eventually oxidize, but it does so at a known rate that is within our parameters."

There was a concern, however, that over the centuries the clock's components might weld together if everything were made from the same material. So most of the pinion gears, as well as the pendulum and encasement, will be made of titanium. Many of the bearings, meanwhile, will be made from silicon nitride, a ceramic.

The bearings will have unusually rigorous demands placed on them: Although they'll be protected by dust shields, they'll still have to hold up for 10 million slow speed cycles without lubrication. The closest real-life parallel is the bearings in satellites, says Rose, and those have only a 20-year operational life. So far, the group's testing shows that the gears won't gum up from extended use. But 10 000 years is a long time.

"No one has tested them the way we need them tested," Rose says with a sigh. "No one has used titanium against stainless steel for such long periods of time."

SELECTING THE RIGHT MATERIALS is only one piece of the puzzle. There's also the matter of keeping the clock ticking and telling the correct time. Because, really, what's the point of a clock if it can't tell time?

SHOW TIME: Although the clock will keep time internally, It will display only the year, and its display will update only when visitors wind the clock. *PHOTO: SETH McANESPIE*

To maintain the clock's accuracy, Hillis and Rose had to figure out a way to somehow sync their clock, buried deep within a mountain, with the outside world. In earlier designs, they considered a solar synchronizer: A beam of sunlight would pass through a slot in the top of the clock at noon, heating up and contracting a piece of nickel titanium shape-memory wire; the wire would act as a mechanical trigger, resetting any error that had crept into the timekeeping since the previous day.

It's a clever idea, one of many the team has devised. In total, they have 10 U.S. patents on the clock, including the winding tower, the clock face, and the solar-triggering mechanism. "We're probably the only ones patenting weird clock esoterica," Rose says.

The problem with memory wire, as with the use of electronics, was the lack of transparency. "Nickel titanium can last, but it's effectively a magic material," Rose says. "It would be difficult to replicate it in the future if someone needed to remake that part."

Instead, the sun could be exploited in two different ways. "The most promising design we're looking at uses two tanks of air: one near the surface of the mountain where the sun can heat it up and another that is kept cool inside the mountain," says Rose. The difference in temperature, amounting to tens of degrees, causes air to move from the hot tank to the cool one during the day; when the surface tank cools down at night, the airflow reverses. The movement of air will drive a piston or a bellows, which will ratchet up the clock's 4.5-metric-ton weights. The weights will then have enough potential energy to keep the 136-kilogram pendulum swinging for the next day.

To recalibrate the clock, the current plan is to use a titanium box that pops out one normally concave side when the air inside heats and expands at around solar noon. This will trigger a correction in the pendulum if it's swinging too quickly or too slowly.

Using these mechanisms, the clock will be able to keep track of the time. But displaying the current time, the team decided, will require visitors to wind the clock—yet another way to give the visitor's experience meaning. How long you spend winding the clock will depend on how long it has been since the last person visited: Winding it fully will take three people about 8 hours. Of course, that's assuming people 10 000 years from now will still be able to perform manual labor.

POST YOUR COMMENTS *online at* http://spectrum.ieee.org/10kclock

THE CHALLENGE DIDN'T END with designing the clock. The question was also where to put it. The team knew they wanted somewhere remote, to enhance the experience and because cities are so vulnerable to the ravages of war. They also figured it needed to be underground to have a shot at lasting for millennia, but not so far down that it would be below the water table. This meant putting it inside a mountain. But what kind of rock? Granite is difficult to cut, so they settled on limestone—soft, but not so soft as to easily fall apart.

The search was then on for a dry desert region with limestone mountains. They needed a cliff that was fracture free, so they could dig the tunnel, and also south facing, for solar-power generation. Sites from South America to the Middle East were considered. In 1999, the Long Now Foundation purchased some land in eastern Nevada as a possible home for the clock.

Ultimately, though, a patch of land owned by Bezos outside Van Horn, Texas, was chosen for the first clock installation. The monument will sit between two cliffs on either side of the mountain. With 150 meters of tunnels and shafts to excavate, the construction crew is using high-precision blasting and robotic mining equipment. Eventually, the clock's components will be shipped to Texas and reassembled inside the mountain. Although the project was originally slated to finish in 2001, these days there is no official schedule for completion, and the team estimates at least a few more years of construction lie ahead before the clock will be completed and opened to the public.

For all the creative deliberation, hard work, and long-term planning, there's one thought that continues to haunt these engineers. "My biggest fear is that people will destroy it on purpose," Rose says.

To help it survive, the team is making it as tamperproof as possible. Rose compares the overall design to "a ship in a bottle. Once it's built it will be hard to get it out of the space it's in." They also plan to store spare parts nearby. "We're building it to withstand being broken," he says. But even a broken clock will change the way people think, Rose adds. He recalls a recent encounter with a skeptic, who predicted that the machine would eventually be rendered inoperable "when the blood of future human sacrifices stops up the gears."

"That might be," Rose told the man. "But before you walked into this room, you weren't thinking 3000 years ahead. So it's already worked. By you and I having this conversation, it achieved its goal—and it's not even built yet." ❑

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APPLICATIONS DUE FEBRUARY 1

EPFL
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Faculty Position in Mechanical Design

at the Ecole Polytechnique Fédérale de Lausanne (EPFL)

The School of Engineering at EPFL invites applications for the position of **tenured full or associate professor.** Applications are encouraged within the broad area of **advanced mechanical design,** with the emphasis on ultra-fast mechanisms, mechatronics, computer aided engineering, advanced structures, manufacturing, etc.

Particular application areas of interest include, but are not limited to, high precision manipulators and robotics for extreme environments (e.g. ultra-high vacuum, cryogenic or high temperatures, heavy vibrations and radiation, highly corrosive environments) and critical mechanisms requiring high-precision machining (e.g. for aerospace mechanisms, energy systems, ultra-light structures, high specific power machines, machine tools, biomechanical devices).

A doctoral degree in engineering with evidence of strong research and teaching capabilities and experience with industrial collaborations are expected.

As a faculty member of the School of Engineering, the successful candidate will be expected to initiate independent, creative research programs and participate in undergraduate and graduate teaching. In particular, he/she will be responsible for the design teaching laboratories, integrating the support to cover teaching requirements in design for the Mechanical and Microengineering curricula. Internationally competitive salaries, start-up resources and benefits are offered.

The EPFL, located in Lausanne, Switzerland, is a dynamically growing and well-funded institution fostering excellence and diversity. It has a highly international campus at an exceptionally attractive location boasting first-class infrastructure. As a technical university covering computer & communication sciences, engineering, environment, basic and life sciences, management of technology and financial engineering, EPFL offers a fertile environment for research cooperation between different disciplines. The EPFL environment is multi-lingual and multi-cultural, with English often serving as a common interface.

Applications should include a curriculum vitae with a list of publications, a concise statement of research and teaching interests, and the names of at least five referees. Applications should be uploaded in PDF format to the recruitment web site: **design-search11.epfl.ch**

Formal evaluation of candidates will begin on **15 December 2011** and will continue until the position is filled.

Enquiries can be addressed to:
Prof. Demetri Psaltis
Search Chairman
e-mail: **design-search@epfl.ch**

For additional information on EPFL, please consult the web sites: **www.epfl.ch**, **sti.epfl.ch**, **igm.epfl.ch** and **imt.epfl.ch**.

EPFL is committed to increasing the diversity of its faculty, and strongly encourages women to apply.

Tufts UNIVERSITY

Faculty Position in Electrical and Computer Engineering

The Department of Electrical and Computer Engineering at Tufts University seeks a junior tenure-track faculty member at the level of Assistant or Associate Professor. Truly exceptional senior candidates may also be considered at the level of Full Professor. The department is particularly interested in attracting an individual with expertise in the field of Signals and Systems. Particular subfields of interest include statistical and wireless communications with an emphasis on physical-layer communications and network information theory including the study of network coding, co-operative communications, and security and secrecy in information and communication systems. The ideal candidate will have two to three years of postdoctoral experience that includes a strong publication record, supervision of graduate students, and substantive interaction with funding agencies. Primary evaluation criteria will include an ability to build and sustain cross-disciplinary research programs, the potential for developing collaborations with current faculty, and a strong desire to inclusively mentor both graduate and undergraduate students. It is anticipated that the successful candidate will also contribute to one or more of the School's three strategic focal areas: Engineering for Human Health, Engineering for Sustainability, and Engineering the Human-Computer Interface.

The past seven years have been a period of extraordinary growth for Tufts' School of Engineering, witnessing recruitment of over half of its current tenured and tenure-track faculty members and close to a three-fold increase in research expenditures. The SOE distinguishes itself by the interdisciplinary and integrative nature of its engineering education and research programs within the environment of both a "Research Class 1" University and a top-ranked undergraduate institution. We offer the best of a liberal arts college atmosphere, coupled with the intellectual and technological resources of a major research university. As home to seven graduate and professional schools across three campuses, Tufts University prides itself on its culture of cross-School partnerships. Located on Tufts' Medford/Somerville campus, only six miles from historic downtown Boston, SOE faculty members have extensive opportunities for academic and industrial collaboration, as well as participation in the rich intellectual life of the region.

Candidates should possess an earned doctorate in Electrical Engineering or a closely related discipline. The applicant should clearly describe a research and teaching plan that builds on existing strengths and focal areas within the ECE Department and the School of Engineering. Candidates should upload a letter of application, research and educational plans, curriculum vitae, and the names and contact information for three references to **academicjobsonline.org**. Review of applications will begin immediately and will continue until the position is filled. Tufts University is an Affirmative Action / Equal Opportunity Employer. We are committed to increasing the diversity of our faculty. Women and members of underrepresented groups are strongly encouraged to apply.

Faculty positions at the Université catholique de Louvain, Louvain la Neuve, Belgium

UCL Université catholique de Louvain

The Louvain School of Engineering, the Institute of Information and Communication Technologies, Electronics and Applied Mathematics (ICTEAM) and the Institute of Mechanics, Materials and Civil Engineering (IMMC) invite applications for tenure track positions of **Professors** in the fields of

1. Electronic circuits and systems **2. Electrical energy**

The successful candidates are expected to have a strong scientific record in relation to the position applied for. They will have to initiate and lead research programs in the respective fields, and to teach at graduate and undergraduate levels. They are expected to be leaders in their fields and to cooperate with other teams of the School and of the Institute(s).

For position 1, research interests include but are not limited to biomedical circuits and systems, design of mixed (analog-digital) circuits and systems. Cooperation is expected with the communications, signal and image and mechatronics research teams.

For position 2, research interests include but are not limited to systems or components for the production and/or conversion and/or management of electrical energy; at small scale in mobile and/or autonomous systems (cars, planes, robots, satellites, ...), or at large scale in power plants and in distribution networks. Systems for energy storage and energy harvesting are also concerned. Cooperation is expected with research teams in energy, electronics and mechatronics.

More information about the teams can be found at **http://www.uclouvain.be/en-icteam.html** and **http://www.uclouvain.be/en-immc**.

The information about the elements to be sent for application can be obtained from the main page of the university website: **http://www.uclouvain.be/**.

The application deadline is December 15, 2011.

Information can be obtained from Prof. F. Delannay, Dean of Louvain School of Engineering (francis.delannay@uclouvain.be).

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Max Planck Institute for Informatics

max planck institut informatik

Federal Ministry of Education and Research

The Max Planck Institute for Informatics, as the coordinator of the Max Planck Center for Visual Computing and Communication (MPC-VCC), invites applications for

Junior Research Group Leaders

in the Max Planck Center for Visual Computing and Communication

The Max Planck Center for Visual Computing and Communications offers young scientists in information technology the opportunity to develop their own research program addressing important problems in areas such as

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- visual media security.

The center includes an outstanding group of faculty members at Stanford's Computer Science and Electrical Engineering Departments, the Max Planck Institute for Informatics, and Saarland University.

The program begins with a preparatory 1-2 year postdoc phase (**Phase P**) at the Max Planck Institute for Informatics, followed by a two-year appointment at Stanford University (**Phase I**) as a visiting assistant professor, and then a position at the Max Planck Institute for Informatics as a junior research group leader (**Phase II**). However, the program can be entered flexibly at each phase, commensurate with the experience of the applicant.

Applicants to the program must have completed an outstanding PhD. Exact duration of the preparatory postdoc phase is flexible, but we typically expect this to be about 1-2 years. Applicants who completed their PhD in Germany may enter Phase I of the program directly. Applicants for Phase II are expected to have completed a postdoc stay abroad and must have demonstrated their outstanding research potential and ability to successfully lead a research group.

Reviewing of applications will commence on **November 1, 2011**. The final deadline is **December 31, 2011**. Applicants should submit their CV, copies of their school and university reports, list of publications, reprints of five selected publications, names of references, a brief description of their previous research and a detailed description of the proposed research project (including possible opportunities for collaboration with existing research groups at Saarbrücken and Stanford) to:

Prof. Dr. Hans-Peter Seidel
Max Planck Institute for Informatics,
Campus E1 4, 66123 Saarbrücken, Germany
Email: **mpc-vcc@mpi-inf.mpg.de**

The Max Planck Center is an equal opportunity employer and women are encouraged to apply.

Additional information is available on the website **http://www.mpc-vcc.de**

ASSOCIATE PROFESSOR
in Electronics Systems

The position is in the Division of Electronics Systems at the Department of Electrical Engineering (ISY), Linköping University, Sweden. A strong teaching commitment on both bachelor and master level is expected. The research background and interests should be within the broader area of Electronics Systems. A track record of attracting competitive funding and a strong publication record in the subject area are expected.

The application deadline is Dec. 2. For more information about the position, visit "Prospective employees" at **liu.se**.

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THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

FACULTY POSITIONS IN Electronic and Computer Engineering

The Department of Electronic and Computer Engineering at the Hong Kong University of Science and Technology invites applications for faculty positions at the rank of Assistant Professor, Associate Professor and Professor.

Applicants for faculty positions at the rank of Assistant Professor should have a PhD with demonstrated strength in research, a commitment to teaching and a desire to link with industry in the region. We are interested in qualified applicants with relevant research experience in areas relating to systems and particularly smart grid systems, bio-informatics, financial engineering, internet-of-things, cyber physical systems or social networking.

Applicants for faculty positions at the rank of Professor will be jointly appointed with the School of Engineering and should have a PhD with an outstanding international track record in research, a commitment to teaching and a desire to link with industry in the region. In addition the successful candidate should have demonstrated leadership skills and experience in leading large interdisciplinary projects funded by both government and industry. We are particularly interested in qualified applicants with relevant research experience in interdisciplinary areas related to energy and that bridge Electronic and Computer Engineering with Mechanical Engineering and/or Chemical Engineering and/or Industrial Engineering and/or Civil Engineering.

The Hong Kong University of Science and Technology is a truly international university in Asia's world city, Hong Kong, and its Engineering School has been consistently ranked among the world's top 25 since 2004. The high quality of our faculty, students and facilities provides outstanding opportunities for faculty to develop highly visible research programs. All formal instruction is given in English and all faculty members are expected to conduct research and teach both undergraduate and graduate courses. The Department has excellent computing resources, state-of-the-art teaching and research laboratories and currently has about 40 faculty members, 800 undergraduate students and 350 postgraduate students. The Department is also an equal opportunity employer.

Starting rank and salary will depend on qualifications and experience. Fringe benefits including medical and dental benefits, annual leave and housing will be provided where applicable. Initial appointment at Associate Professor and Assistant Professor ranks will normally be on a three-year contract. A gratuity will be payable upon successful completion of contract. Re-appointment will be subject to mutual agreement.

Applications including full curriculum vitae, list of publications, names of five referees addressed to: Professor Vincent Lau, Chair of Search Committee and should be sent by email to **eesearch@ust.hk**. Applications will be considered until all the positions are filled.

More information about the Department is available on the website **http://www.ece.ust.hk/**.

(Information provided by applicants will be used for recruitment and other employment-related purposes.)

MARQUETTE UNIVERSITY

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V. Clayton Lafferty Endowed Chair in Electrical Engineering

The Lafferty Endowed Chair focuses on Smart Sensor Systems. Smart sensor systems is a major research thrust that supports other college research thrust areas in secure and renewable energy, water resources and water quality, and human performance and neurosystems. Strengthening our research capability in smart sensor systems will have a significant impact on a broad range of practical applications such as homeland security, healthcare, the environment, and transportation. The Lafferty Endowed Chair is expected to lead multi-disciplinary research cluster activities in smart sensor systems; lead associated faculty efforts in recruiting and mentoring students; and lead the establishment of world class laboratories to support smart sensor systems research efforts in the new Engineering Hall.

Thomas H. and Suzanne M. Werner Endowed Chair in Secure and Renewable Energy Systems

The Werner Endowed Chair focuses on secure and renewable energy systems. Renewable energy is a major research thrust area in the College of Engineering. The Werner Endowed Chair is expected to lead with a systemic vision to plan, develop and deploy improvements of a multi-disciplinary curriculum and research involving energy generation and storage, integration of distributed and intermittent energy sources to the electric grid, design of the smart grid, secure supply of energy, and efficient use of energy while enhancing our traditional strengths in diagnostics, prognostics and mitigation of faults in electric energy generation and utilization systems. The Werner Chair is expected to play a major role in the Wisconsin Energy Research Consortium of which the college is an active participant.

Applications are invited for the V. Clayton Lafferty Endowed Chair in Electrical Engineering and the Thomas H. and Suzanne M. Werner Endowed Chair in Secure and Renewable Energy Systems in the Department of Electrical and Computer Engineering in the College of Engineering at Marquette University. The two endowed chairs will have access to significant laboratory and research space within the new Engineering Hall (**http://www.marquette.edu/engineering-hall/**), a new concept in higher education allowing students and faculty to tackle global challenges in a setting that will educate and inspire. For both endowed positions, the qualifications include a Ph.D. in Electrical Engineering or other related engineering; a level of professional accomplishment in research, teaching and service that merits appointment at a tenure-track full professor; an international reputation as a scholar; an ability to build a coherent interdisciplinary research program and demonstrated ability to build an international network of research collaboration.

For further information and application go to: **http://www.marquette.edu/careers/**

Marquette University is an Equal Opportunity Employer; women and minorities are encouraged to apply.

Massachusetts Institute of Technology

FACULTY POSITIONS

The Department of Electrical Engineering and Computer Science (EECS) seeks candidates for faculty positions starting in September 2012. Appointment will be at the assistant or untenured associate professor level. In special cases, a senior faculty appointment may be possible. Faculty duties include teaching at the graduate and undergraduate levels, research, and supervision of student research. We will consider candidates with backgrounds and interests in any area of electrical engineering and computer science. Faculty appointments will commence after completion of a doctoral degree.

Candidates must register with the EECS search website at

https://eecs-search.eecs.mit.edu,

and must submit application materials electronically to this website. Candidate applications should include a description of professional interests and goals in both teaching and research. Each application should include a curriculum vita and the names and addresses of three or more individuals who will provide letters of recommendation. Letter writers should submit their letters directly to MIT, preferably on the website or by mailing to the address below. Please submit a complete application by December 15, 2011.

Send all materials not submitted on the website to:
Professor Anantha Chandrakassan
Department Head, Electrical Engineering and Computer Science
Massachusetts Institute of Technology
Room 38-401
77 Massachusetts Avenue
Cambridge, MA 02139

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the data

Three Mile Island, Chernobyl, and Fukushima

A COMPARISON OF THREE NUCLEAR REACTOR CALAMITIES REVEALS SOME KEY DIFFERENCES

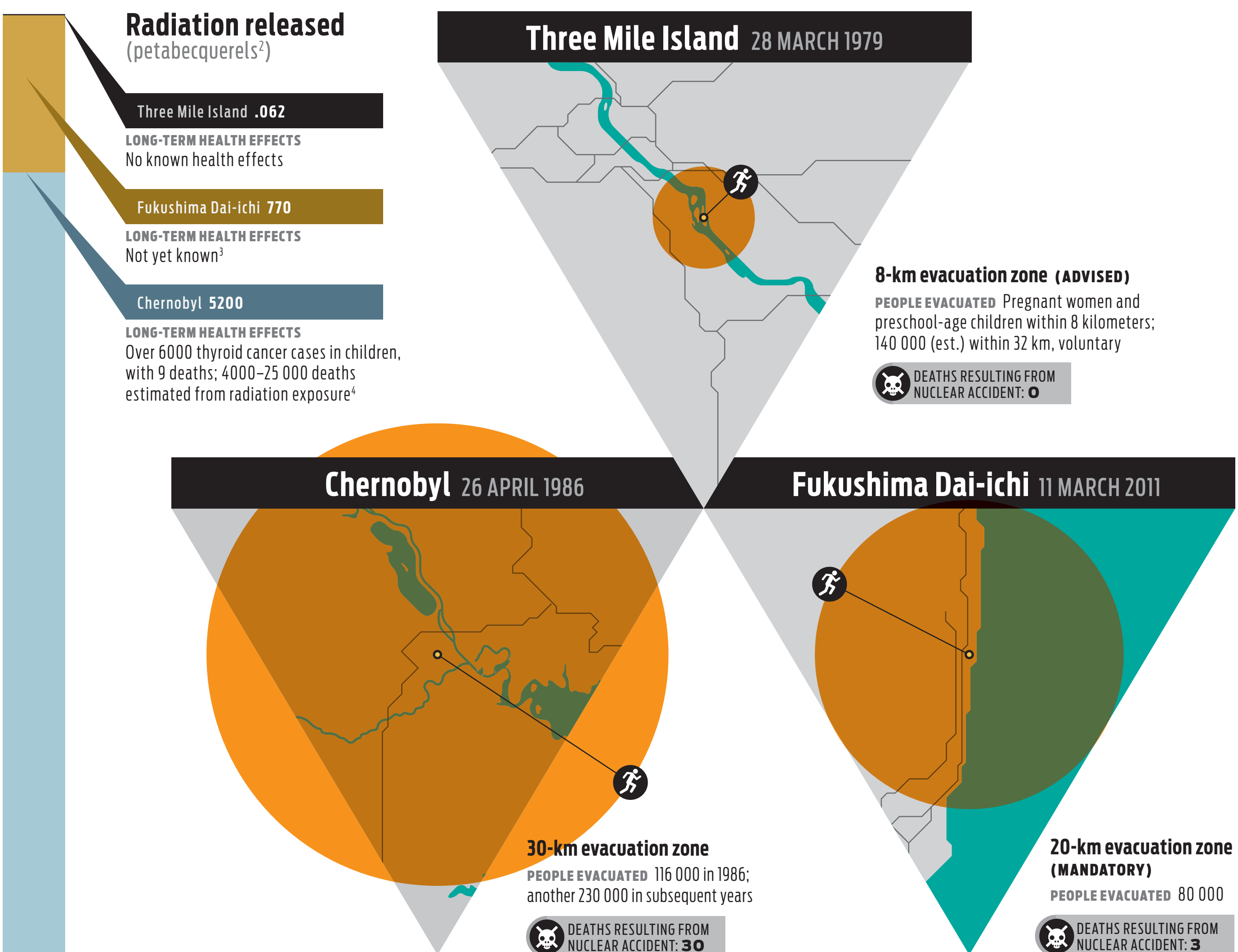
NEARLY 25 years after the Chernobyl catastrophe, the Fukushima Dai-ichi crisis became the only other civilian nuclear accident to warrant the highest possible rating of 7 on the International Nuclear Event Scale (INES). The scale judges the severity of nuclear events by their impact on people and the environment.

By contrast, Three Mile Island, another incident seared in memory as a reminder of what can go wrong with nuclear power generation, rated a 5 on the INES. The scale is logarithmic—meaning the U.S. event was roughly one one-hundredth as serious—and is self-defined (in the case of Fukushima, by Japan's Nuclear and Industrial Safety Agency).

While Fukushima and Chernobyl received equally high ratings, it's not obvious they were equivalent in severity.

When the reactor exploded at Chernobyl, there were 600 workers at the plant. Two died as a result of the explosion, and of the 134 who acquired acute radiation sickness, 28 died within weeks. The lack of a containment vessel around the reactor and a graphite fire that burned for 10 days led to radiation spreading high and wide.

By contrast, no deaths have resulted from the Fukushima accident's radiation release, although three workers died in mishaps. The amount of harmful iodine-131 equivalent[1] radiation released was about one-seventh the amount dispersed at Chernobyl. Of course, it's too early to estimate Fukushima's full health and ecological impact. *—Prachi Patel*



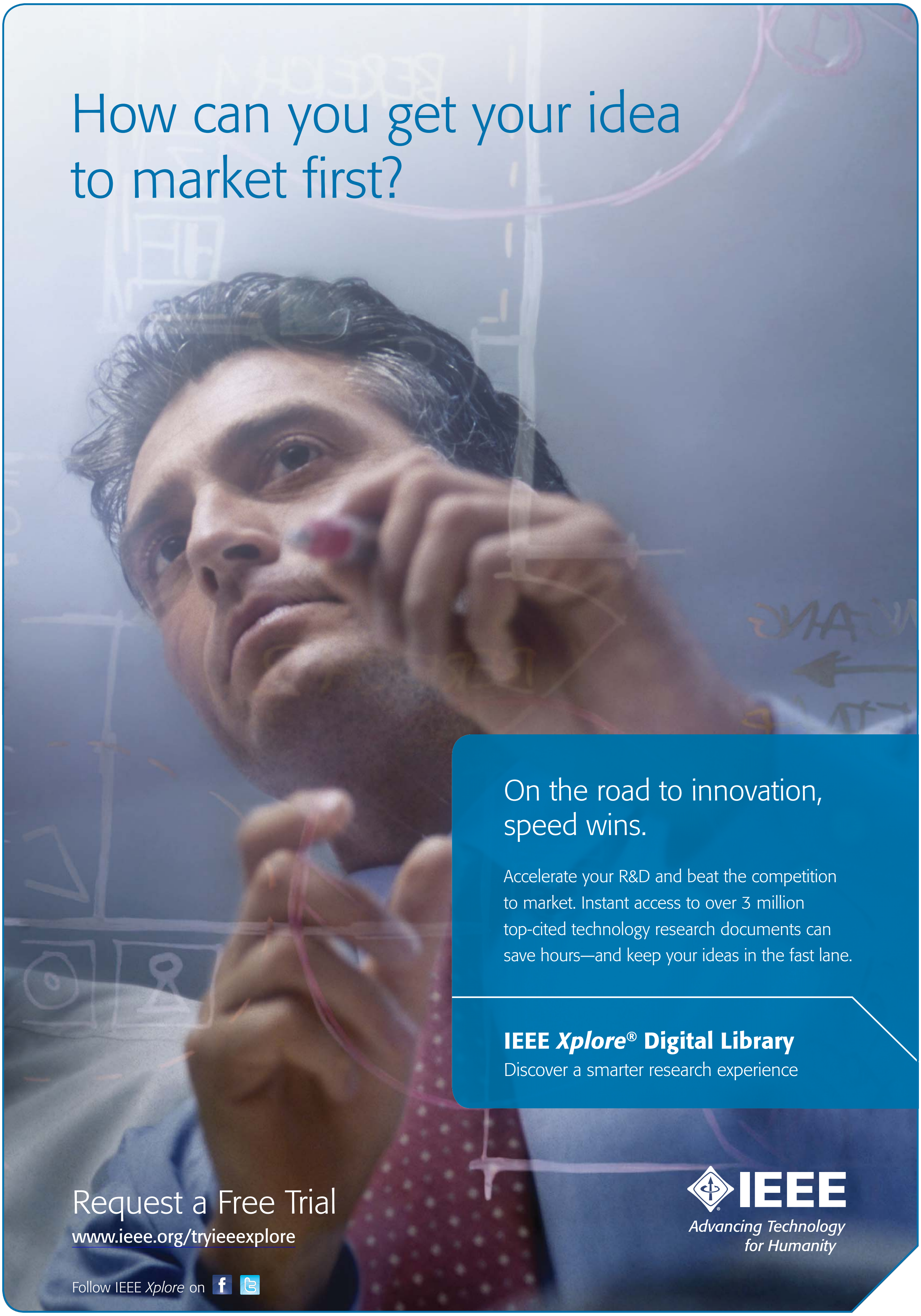
NOTES:
1. That is, radiation "equivalent...to the natural background radiation during one year." (World Health Organization)

2. A becquerel is "a unit of radio-activity equal to one disintegration per second." (*Webster's Third New International Dictionary*, 2002)

3. The *Bulletin of the Atomic Scientists* estimates deaths "on the order of 1000."

4. Four thousand deaths: The International Atomic Energy Agency/U.N. Chernobyl Forum; 16 000 deaths: *Bulletin of the Atomic Scientists*; 25 000 deaths: The Union of Concerned Scientists. Note that a Russian study, "Chernobyl: Consequences of the Catastrophe for People and the Environment," estimates the number of radiation-caused deaths to be 985 000.

SOURCES:
Bulletin of the Atomic Scientists; IAEA/U.N. Chernobyl Forum, Public Broadcasting Service, Union of Concerned Scientists, United Nations Scientific Committee on the Effects of Atomic Radiation, U.S. Nuclear Regulatory Commission, Wikipedia, World Health Organization, World Nuclear Association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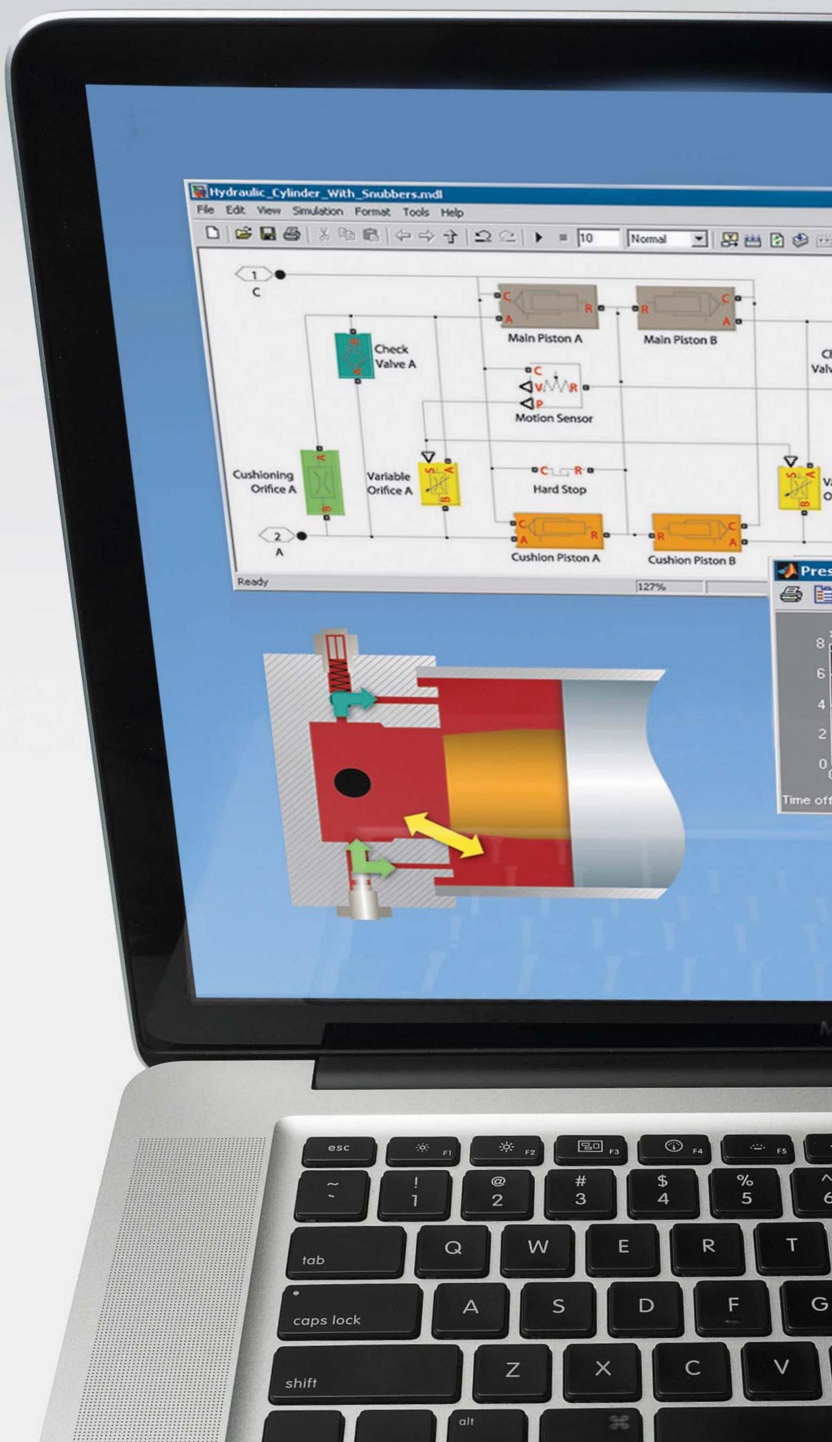

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