FEATURES

REKINDLING THE FLAME

After decades of decline, the U.S. government's fusion lab seeks a rebirth

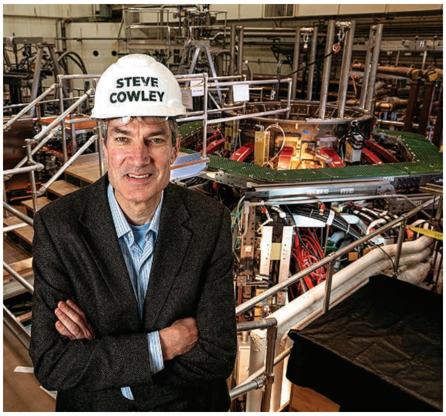
By **Adrian Cho**, *in Princeton, New Jersey*

Joseph Winston, a technician here at the Princeton Plasma Physics Laboratory (PPPL), knew something was wrong with the fusion reactor just by listening. In 2016, PPPL physicists had restarted their National Spherical Torus Experiment (NSTX), after a 5-year, $94 million upgrade. During one of the machine's runs, which last just seconds, millions of amps course through NSTX's magnet coils, creating fields that squeeze an ionized gas so tightly that atomic nuclei can fuse. The currents also stress the coils, which emit a groan loud enough to be heard through more than a meter of concrete. But the sound was petering out prematurely, Winston recalls.

When Winston and his team traced the problem to a short in one coil, the 50-year PPPL veteran knew the reactor, or tokamak, would be down for a long time. The machine is "like a one-way street," he says. "If anything happens to these coils, the whole thing has to come apart just to get to it." After running for just 10 weeks, NSTX was shut down again.

It was a body blow to a lab that was already staggering. In the 1980s, PPPL ran multiple machines, employed nearly 1300 people, and led the worldwide quest to harness fusion, the energy source of the Sun. "The action was almost frantic," says Dale Meade, a PPPL physicist emeritus. "We were taking risks, building one thing before the other was finished." In 1994, PPPL's largest machine ever, the Tokamak Fusion Test Reactor (TFTR), briefly generated 10.7 megawatts of power, still the record for U.S. efforts.

The good times didn't last. Within years, Congress had slashed the Department of Energy's (DOE's) fusion budget and shut down TFTR. In 2003, the United States joined the effort to build ITER, the giant international reactor under construction near Cadarache in France—a commitment that squeezed fusion research at home even harder. In 2008, DOE canceled another unfinished fusion reactor at PPPL, leading to a reshuffling of lab leadership. Now, PPPL employs 560 people. Its one large machine, NSTX, sits idle 3 years after breaking down.



PPPL director Steven Cowley wants to grow the lab. His first task is to repair its main fusion reactor.

PHOTO: ELLE STARKMAN/PRINCETON PLASMA PHYSICS LABORATORY

Yet things may be looking up for the lab. After years of DOE reviews, PPPL researchers expect to start to rebuild NSTX in April. And a year ago, a report from the National Academies of Sciences, Engineering, and Medicine (NASEM) urged the United States not only to stick with ITER—which is hugely overbudget and behind schedule—but also to prepare to build the machine after it (*Science*, 21 December 2018, p. 1343). This would be a prototype power plant, smaller and cheaper than ITER, and PPPL would likely play a leading role in building it.

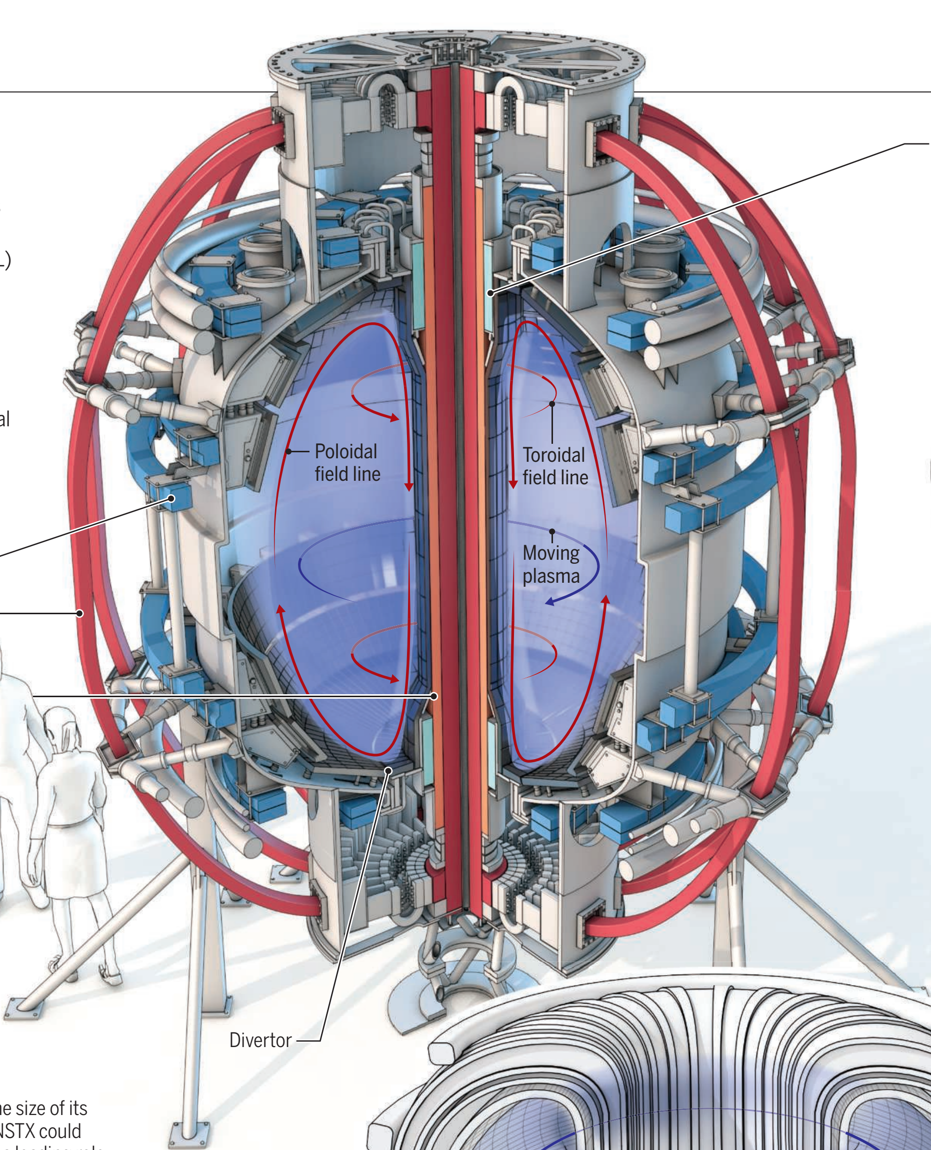
Perhaps most important, in 2018 Princeton University, which runs the lab for DOE, hired a new lab director. Steven Cowley, a strapping 60-year-old Englishman with a shock of silver hair and a knighthood, makes no bones about his role as an agent of change. "My job as a director is not to be an administrator," he says in his velvety baritone. "It's about scientific vision. What should we be doing? What are the interesting questions? How do we get to fusion?" He already has a plan to diversify the lab's work, grow its staff, and start to build things again.

Physicists are watching PPPL as a bellwether for the fortunes of the U.S. fusion program, whose share of the world's public fusion research has slipped to just one-sixth. And some observers who have been critical of the lab's previous leadership and culture think PPPL is finally on the right track. "Steve is the best person on the planet for the job," says William Madia, former director of two other DOE national labs, who urged Princeton to hire Cowley. "I'm optimistic." Yet the lab still faces obstacles on the path to redemption.

NSTX RESEMBLES an extraterrestrial spaceship. The two-story orb nestles in a cocoon of pipes and cables, the red coils of its main magnet arching up out of the chaos like flying buttresses. Within the orb—the reactor's partially disassembled vacuum chamber—copper plates and graphite tiles line the silvery walls. One could imagine that some reptilian alien slumbered away the eons here while traveling to the Solar System. During

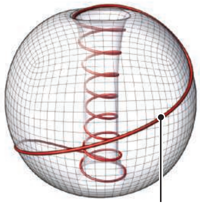
Sun in a bottle

When it restarts in 2021, the repaired National Spherical Torus Experiment (NSTX) at Princeton Plasma Physics Laboratory (PPPL) will use magnetic fields to trap and squeeze a hot ionized gas, or plasma, coaxing atomic nuclei to fuse and generate energy the same way as in the Sun. NSTX will test how efficiently a spherical shape can squeeze the plasma. It will also test using liquid lithium to protect NSTX's chamber wall and help shunt out heat.



Rev it up!
During a secondslong run, a current of 24,000 amps quickly reverses in the tubelike central solenoid coil to propel the plasma around the torus 40,000 times per second. That motion helps generate the poloidal field.

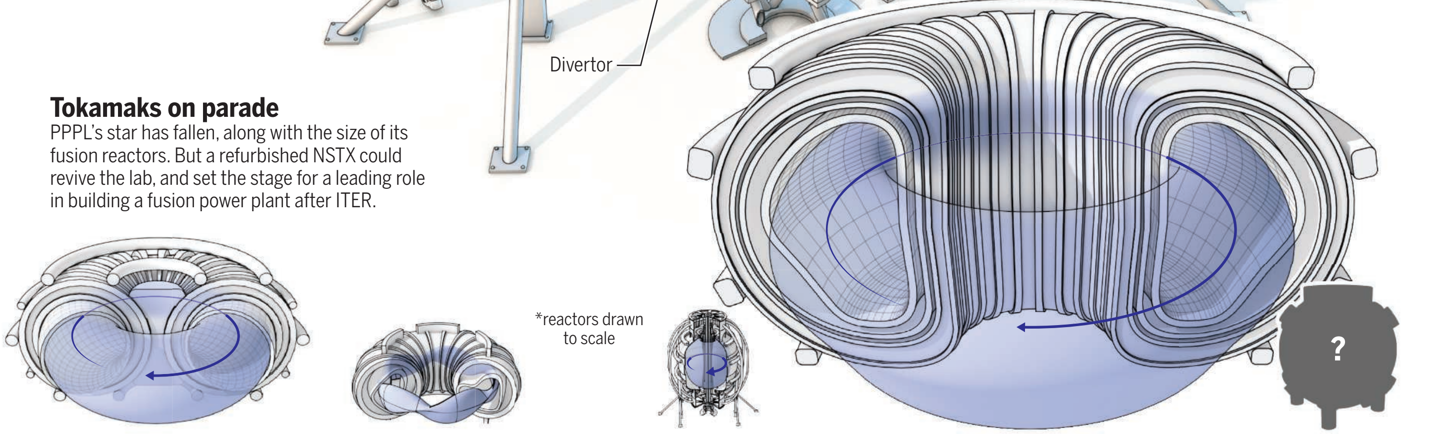
Achilles' heel
In 2016, soon after an upgrade, an upper coil failed. The machine was disassembled and has sat idle, forcing a reckoning over PPPL's future.



A crucial twist
To trap a plasma and keep it away from the walls of the vacuum chamber, the total magnetic field—the sum of the toroidal and poloidal fields—must twist like a candy cane. That winding is produced by the current in the plasma itself.

Tokamaks on parade

PPPL's star has fallen, along with the size of its fusion reactors. But a refurbished NSTX could revive the lab, and set the stage for a leading role in building a fusion power plant after ITER.



Tokamak Fusion Test Reactor
PPPL's biggest machine ran from 1982 to 1997. In 1994, it set a U.S. record for power produced.

National Compact Stellarator Experiment
Canceled in 2008, NCSX would have generated a twisting field with asymmetric coils, enabling it to run continuously with a stationary plasma.

National Spherical Torus Experiment
Built in 1999, NSTX tests how a spherical shape boosts plasma pressures. Tests will resume in 2021.

International Thermonuclear Experimental Reactor
The $25 billion reactor, an international effort under construction in France, aims to produce more energy than it consumes. It should begin operations in 2025.

Compact Pilot Plant
To be built in the 2030s, the prototype power plant would leverage emerging technologies and be smaller and cheaper than ITER.

a run, something nearly as otherworldly fills the chamber: a wispy ionized gas, or plasma, heated to 100 million degrees Celsius—hotter than the core of the Sun. Injected microwaves and churning magnetic fields heat and squeeze the plasma and whirl it around the chamber 40,000 times per second.

The plasma is made of deuterium, a heavier isotope of hydrogen, and the goal is to bring it to temperatures and pressures at which colliding nuclei can fuse to form helium. The reactions release energy, carried away by free-flying neutrons. Replacing some of the deuterium with tritium, an even heavier isotope of hydrogen, could make the reactions self-sustaining. Such fusion promises abundant, carbon-free energy with little of the radioactive waste generated by fission-powered nuclear reactors. That prospect has fired PPPL for the past half-century. Yet, on a rainy Monday morning in October 2019, the lab is eerily quiet.

Nestled among pines in a technology park east of tony Princeton, PPPL grew out of the university's classified work on the hydrogen bomb and astrophysicist Lyman Spitzer's parallel effort to tame fusion as a power source. Founded in 1961, PPPL built a series of ever bigger devices that in 1982 culminated in TFTR, a reactor three times as wide

The plasma chamber of NSTX seen in 2014, before a short forced it to be disassembled.

as NSTX that set its power record while running on deuterium and tritium. "We made a tremendous splash in the newspapers," recalls Michael Zarnstorff, PPPL's chief scientist. "People would ask, 'When are you going to have electricity from fusion?'"

That prospect has eluded physicists. ITER aims to be the first tokamak to produce more energy than it consumes. But TFTR was also supposed to do that and it came up short. Controlling a plasma turned out to be harder than anticipated, the electromagnetic equivalent of grasping an eel. After DOE shut down TFTR, PPPL researchers developed two smaller, more radical machines with different advantages.

NSTX was the more conventional design. A traditional tokamak has the shape of a doughnut. But a spherical torus like NSTX resembles a cored apple. For the same magnetic field, the rounder shape should put more pressure on the plasma, says Richard Hawryluk, a physicist at PPPL. "Basically you want to optimize the bang for the buck," he says. From 1999 to 2009, NSTX confirmed that prediction, which could make reaching the elusive break-even power point easier.

All tokamaks, including spherical ones, suffer from a limitation, however. To trap a plasma, the magnetic field going around the torus must twist like the stripes on a candy cane. To generate that twist, the plasma itself has to race around the doughnut to produce a current. And the laws of electrodynamics state that to push the plasma around, physicists need another rapidly changing magnetic field, which is generated by a coil in the doughnut hole. A run lasts as long as it takes to reverse the current in the coil—just a couple of seconds. Moreover, in a spherical torus, several different magnet coils are crammed precariously into the narrow hole.

A machine called a stellarator avoids the first limitation by generating the twist not with a moving plasma, but with twisted magnetic coils. In principle it can run steadily and more efficiently (*Science*, 23 October 2015, p. 369). In 2001, PPPL started work on one called the National Compact Stellarator Experiment (NCSX). However, by 2008—a year after it was supposed to be finished—its cost had nearly tripled to $170 million. DOE canceled the project, leaving PPPL with one machine and a black eye.

Then came the failure of NSTX after its upgrade, which aimed to double the strength of its magnetic field. An investigation revealed numerous problems in addition to the shorted coil, Hawryluk says. "We felt strongly that we really needed to understand what was going on," he says, "and not just fix one thing and then come back and say, 'Well, now something else is wrong.'" Additionally, DOE put PPPL's $199 million repair plan through the same yearslong approval process it requires for a whole new project.

That was an overreaction, says Martin Greenwald, a physicist at the Massachusetts Institute of Technology. "Instead [of fixing the problem] it's like, 'Oh, we're going have a million reviews,'" he says. But Madia says the lab brought the scrutiny on itself by failing to catch the problem and reacting slowly to it. "The problem was really leadership at the lab," he says.

If NSTX's failure strained the lab's relations with DOE, it nearly broke those with the university, Meade says. The lab's director at the time, Stewart Prager, was forced out and a few months later Princeton President Christopher Eisgruber took the staff to task in an all-hands meeting, Meade says. "He gave about a 20-minute talk admonishing the laboratory, telling them how deeply dis-

PHOTO: ELLE STARKMAN/PRINCETON PLASMA PHYSICS LABORATORY appointed and embarrassed he was about this incident," he says. Eisgruber says he simply told researchers the situation was urgent. "It's our obligation to deliver on the contracts we form with DOE," he says. "There has to be a commitment to excellence."

IN SOME WAYS, Cowley seems an odd choice to guide the beleaguered lab—a Brit who doesn't drive leading an American lab in car-clogged New Jersey. (He takes the bus to work.) For a person in the hot seat, Cowley also exudes a curious ebullience. "I'm a very lucky person because my serotonin level is pretty much always right," he says. "So I pretty much like anywhere I am."

Cowley is no stranger to PPPL. He earned his doctorate here in 1985, before going on to positions at the University of California, Los Angeles, and University College London. He also has ample leadership experience. From 2009 to 2016, he served as CEO of the UK Atomic Energy Authority and director of the Culham Centre for Fusion Energy. There he oversaw work on a competitor to NSTX, the Mega Ampere Spherical Tokamak, which was upgraded last year.

At PPPL, job No. 1 is to get NSTX running again. To do that, Cowley brought in John Galayda, an accelerator physicist who led construction of the world's first hard x-ray laser, the Linac Coherent Light Source at SLAC National Accelerator Laboratory, which in 2009 worked on the first attempt. PPPL researchers have begun to fabricate new parts and aim to have NSTX running in summer 2021. For Jessica Guttenfelder, a mechanical engineer who started at PPPL weeks before the machine conked out, it feels like a rebirth. "Everything you're exposed to is so unique," says Guttenfelder, who is in charge of a device that shoots hydrogen atoms into NSTX's plasma to help it spin.

The 20-year-old reactor still has work to do, Hawryluk says. With its stronger magnetic field, NSTX will test whether a spherical tokamak's favorable scaling of pressure with magnetic field persists at temperatures where fusion can occur. Physicists will also have to figure out how to handle unprecedented loads on the divertors, an exhaust system for the reactor's heat. They will explore whether lining the reactor with molten lithium helps stabilize the plasma and tame the exhaust.

At the same time, Cowley aims to transform PPPL into a multipurpose lab with much stronger ties to the university and industry. PPPL's nonfusion work has typically focused on the plasmas in stars and interstellar space. Cowley plans to expand into the use of cold plasmas to process materials, in particular to make ever-more-advanced microchips. "The U.S. dominates the industry that makes the machines that make the chips," he says. "If we're not careful we'll lose that to China."

Cowley plans to double the lab's staff, with the cold plasma work accounting for 30% to 50% of the total. Craig Arnold, director of the Princeton Institute for the Science and Technology of Materials, envisions close ties to PPPL. "You have these two entities that are literally next door to each other and part of the same overall organization. It's silly for us not to be working together," he says. The university and the lab are negotiating to construct a $100 million building at PPPL for the cold plasma and material science work.

> **"What's the facility after NSTX? My mission is to define that and get it to happen."**
> **Steven Cowley**, Princeton Plasma Physics Laboratory

In the longer term, Cowley says he wants to get PPPL back to building big machines. "What's the facility after NSTX?" he asks. "My mission is to define that and get it to happen." In particular, he would like to revisit the idea of building a stellarator. But instead of fashioning bizarrely shaped coils for the machine, Cowley envisions using conventional ones and adding high-strength permanent magnets on electronically adjustable mounts to shape the field. "It's just an idea and maybe it'll go nowhere," says Cowley, who sketches out the idea with colleagues in a paper in press at *Physical Review Letters*.

Other U.S. fusion physicists welcome his ambitions, noting that aside from parts for ITER, DOE hasn't built a major fusion machine since NSTX. "At some point we need to be building," says Erik Trask, a physicist at the fusion startup TAE Technologies. "I would love to see many midscale machines get built." Eisgruber says he is "greatly enthusiastic" about the plans for the lab. "Steve Cowley has a vision that I fully support."

THE PLAN ALSO SEEMS to dovetail with the vision outlined in the December 2018 NASEM report, which urged the United States to build a prototype power plant in the 2030s as a successor to ITER. Taking advantage of innovations such as powerful magnet coils made from high temperature superconductors, that Compact Pilot Plant (CPP) would be smaller and cheaper than ITER, a $25 billion behemoth. Such miniaturization will be vital in the U.S. energy market, Cowley predicts, as no utility will buy a plant that expensive.

The call to build the CPP might help fill PPPL's sails. PPPL wouldn't build the machine on its campus, researchers say, because it would produce too much radioactive material for a densely populated place like Princeton. But the lab would undoubtedly play a leading role in designing and building the machine. "We're enthusiastic about the report," Zarnstorff says. The first step for the CPP would be to make it into DOE's next long-range plan for fusion, which researchers and the agency aim to hash out by year's end.

But that rosy scenario faces several uncertainties. For example, even if DOE embraces the CPP, it would likely build a power plant only as part of a public-private partnership, Zarnstorff says. So the fate of the project may depend on whether companies such as TAE Technologies and Commonwealth Fusion Systems can help bear the costs and risks of the project.

The push toward a working fusion power plant also highlights a tension within DOE. Since 1998, the department's fusion energy science program has resided in its basic research wing, the Office of Science. Many U.S. fusion researchers say the basic research tag handcuffs them. "There's a lot of cutting edge research in fusion technology that we can't support that because it's not science," Greenwald says. Zarnstorff says that to pursue the CPP, DOE ultimately may have to move fusion into applied research.

Cowley says such talk is premature. "I don't think we can get to commercial fusion power without solving some really quite profound scientific problems," he says. For instance, he says, researchers still need to figure out how to deal with exhaust heat.

And then there's the question of money. The NASEM report calls for a $200-million-per-year increase in U.S. fusion research, and Congress boosted DOE's budget for fusion energy sciences from $564 million in fiscal year 2019 to $671 million this year. But all of that increase will go to ITER, and it remains to be seen whether Congress will continue to ramp up the fusion budget.

For now, Cowley is focused on rejuvenating a fallen lab and boosting its morale. Over a group lunch in a conference room, Laura Xin Zhang, a fourth-year graduate student at Princeton, says she chose fusion because she was seeking a mission in her work. "We're the generation of climate change, so everyone wants to do something with climate change," says Zhang, a native of Dalian, China. Fusion could offer an answer. "Someone has to work on this, or it will never happen," Zhang says.

"It will happen in your lifetime," Cowley interjects.

"You think?" Zhang says.

"Mine, it's touch and go," Cowley says with a smile. "I need to keep fit." ■

Rekindling the flame

Adrian Cho

Science **367** (6478), 618-621.
DOI: 10.1126/science.367.6478.618

Science (print ISSN 0036-8075; online ISSN 1095-9203) is published by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005. The title *Science* is a registered trademark of AAAS.