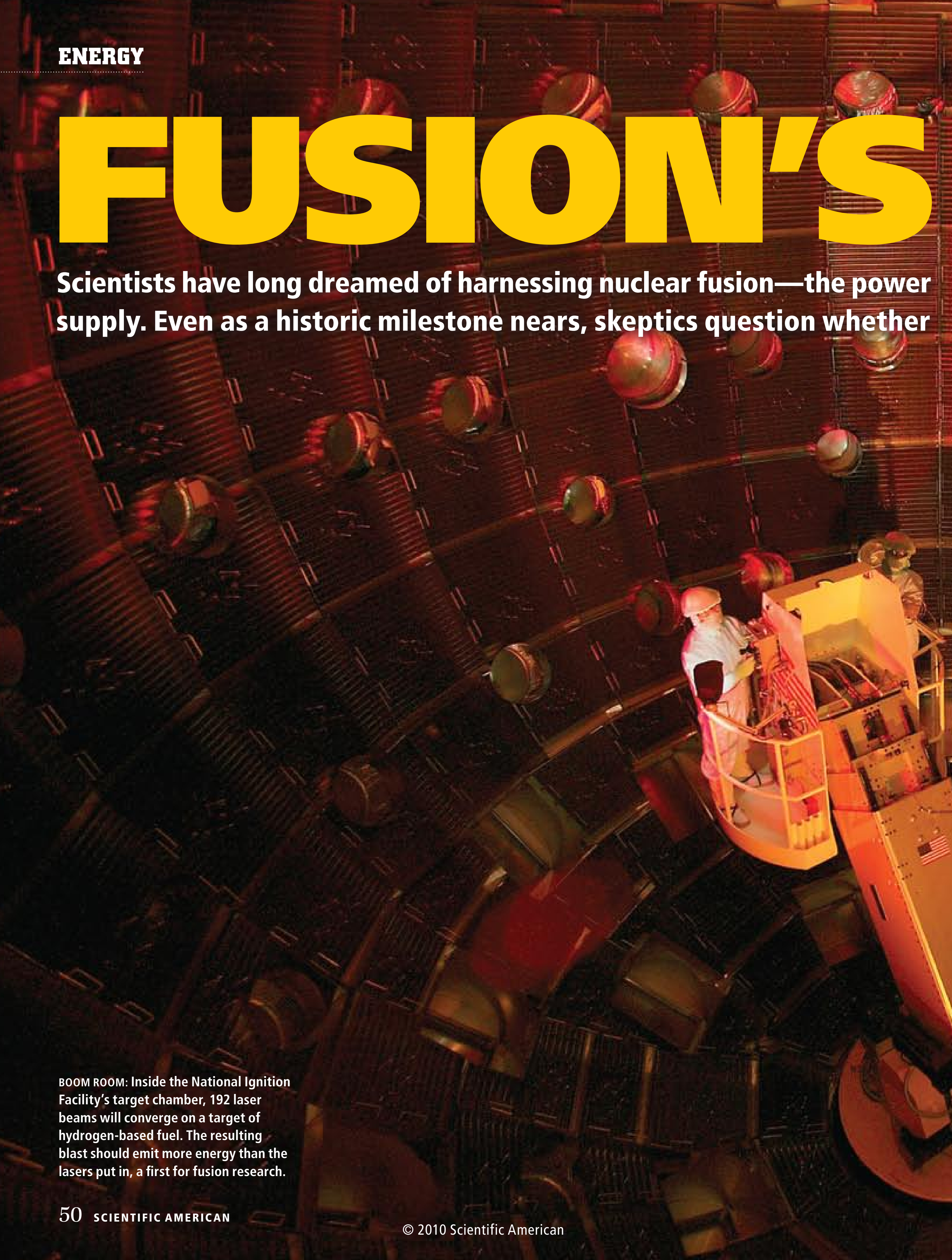
FUSION'S

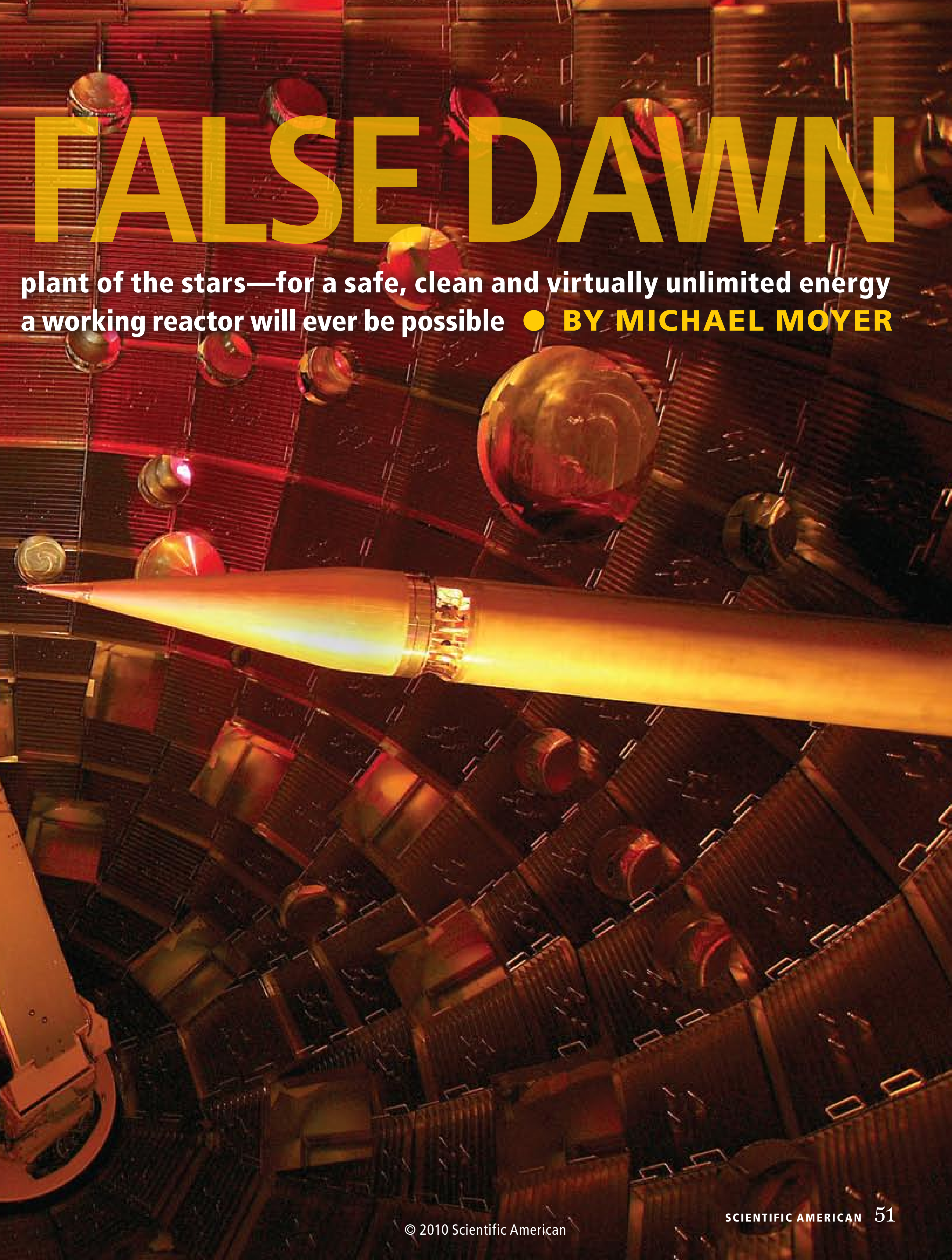
Scientists have long dreamed of harnessing nuclear fusion—the power supply. Even as a historic milestone nears, skeptics question whether



BOOM ROOM: Inside the National Ignition Facility's target chamber, 192 laser beams will converge on a target of hydrogen-based fuel. The resulting blast should emit more energy than the lasers put in, a first for fusion research.

FALSE DAWN

plant of the stars—for a safe, clean and virtually unlimited energy a working reactor will ever be possible ● **BY MICHAEL MOYER**



KEY CONCEPTS

- The fusion of hydrogen isotopes is expected to soon emit more energy than is required to make the particles fuse together—a critical milestone in the many-decade quest for fusion energy.
- If this excess energy could be harnessed, it could form the basis for a revolutionary power plant.
- Yet scientists are now uncovering serious engineering challenges that could forestall the construction of such a plant for years to come.

—The Editors

Ignition is close now. Within a year or two the 192 laser beams at the National Ignition Facility (NIF)—the world's largest and most powerful laser system, a 13-year, $4-billion enterprise—will focus their energy onto a pellet no bigger than a peppercorn. Energy from the laser beams will crush the pellet's core with such force that the hydrogen isotopes inside will fuse together and release energy, an H-bomb in miniature.

The trick has been tried before—and with success. But every time scientists have fused together these isotopes, they have had to pump far more energy into the lasers than the reaction spat out. This time the ledger will flip. The boom at the pellet's center will release more energy than the lasers squeezed in, a switch more important than mere accounting would suggest. In theory, this excess energy could be collected and made to run a power plant. Its fuel would be materials found in ordinary seawater; its emissions—both atmospheric and nuclear—would be zero. It would be like capturing a star to run the machines of the earth. It would feed humanity's endless thirst for energy, and it would do so forever.

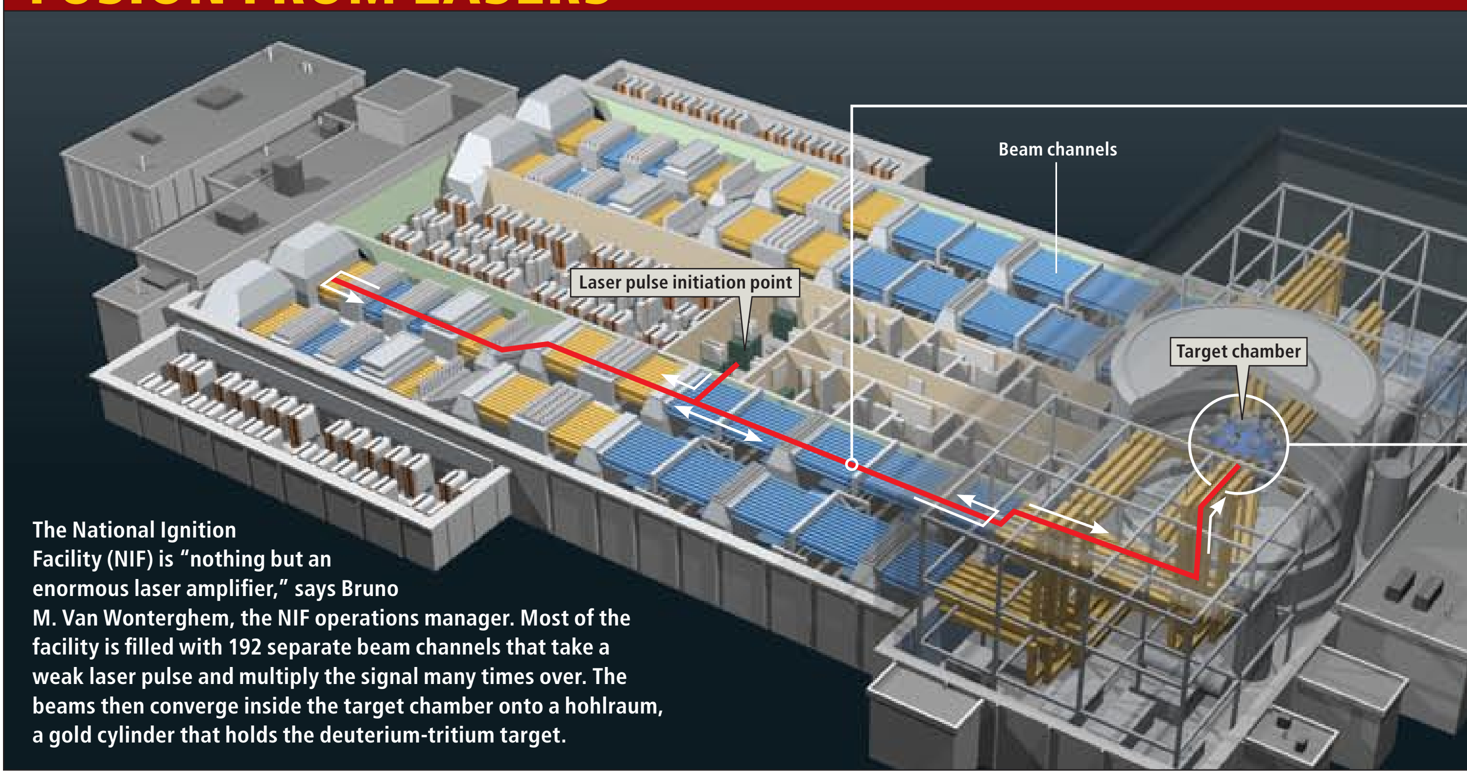
Construction has also begun at the world's other major fusion facility, a $14-billion project based outside the village of Cadarache in the south of France. ITER (pronounced "eater") will not rely on a vise of lasers; its superconducting magnets will hold hydrogen isotopes together and heat them to 150 million degrees Celsius—25,000 times hotter than the surface of the sun. This experiment is also expected to produce a net energy gain. Moreover, unlike the laser system's intermittent bursts of energy, magnets will be able to hold the plasma together for tens or perhaps hundreds of seconds, generating a continuous blaze of power.

The achievements will be a milestone in the quest, fervent since the dawn of the nuclear age, to tame the processes at work in the center of stars and manipulate them for our own ends. Yet the flash of ignition may be the easy part. There is a growing recognition among veteran fusion scientists that the challenges of constructing and operating a fusion-based power plant could be more severe than the physics challenge of generating the fireballs in the first place. Some physicists who are not directly involved with fusion research question whether the feat is possible even in theory. A working reactor would have to be made of materials that can withstand temperatures of millions of degrees for years on end. It would be constantly bombarded by high-energy nuclear particles—conditions that turn ordinary

COURTESY OF LAWRENCE LIVERMORE NATIONAL LABORATORY *(preceding pages)*

HOW IT WORKS

FUSION FROM LASERS



The National Ignition Facility (NIF) is "nothing but an enormous laser amplifier," says Bruno M. Van Wonterghem, the NIF operations manager. Most of the facility is filled with 192 separate beam channels that take a weak laser pulse and multiply the signal many times over. The beams then converge inside the target chamber onto a hohlraum, a gold cylinder that holds the deuterium-tritium target.

materials brittle and radioactive. It has to make its own nuclear fuel in a complex breeding process. And to be a useful energy-producing member of the electricity grid, it has to do these things pretty much constantly—with no outages, interruptions or mishaps—for decades on end.

"The idea has been that 'okay, these are hard problems, but they are solvable problems, and let's concentrate on the fusion core itself,' " says Richard D. Hazeltine, director of the Institute for Fusion Studies at the University of Texas at Austin. "That may have been a mistake."

Nature's Promise

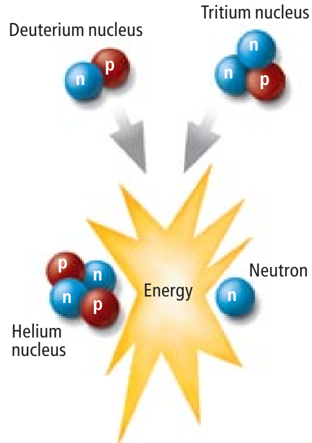
Fusion—or rather, the lack thereof—has been confounding scientists since at least the 1860s. Charles Darwin's new theory of evolution by natural selection required billions of years of incremental change to explain the incredible diversity of life on earth. Yet the era's best estimate of the sun's age—provided by the eminent British physicist William Thompson (better remembered as Lord Kelvin)—concluded that the sun could not be more than a few tens of millions of years old. As Charles Seife recounts in his excellent book *Sun in a Bottle* (Viking, 2008), Darwin considered Thompson's critique one of the gravest blows to the theory of evolution. He lamely countered that scientists should hold off on judgment, so incomplete was our understanding of the laws of the cosmos.

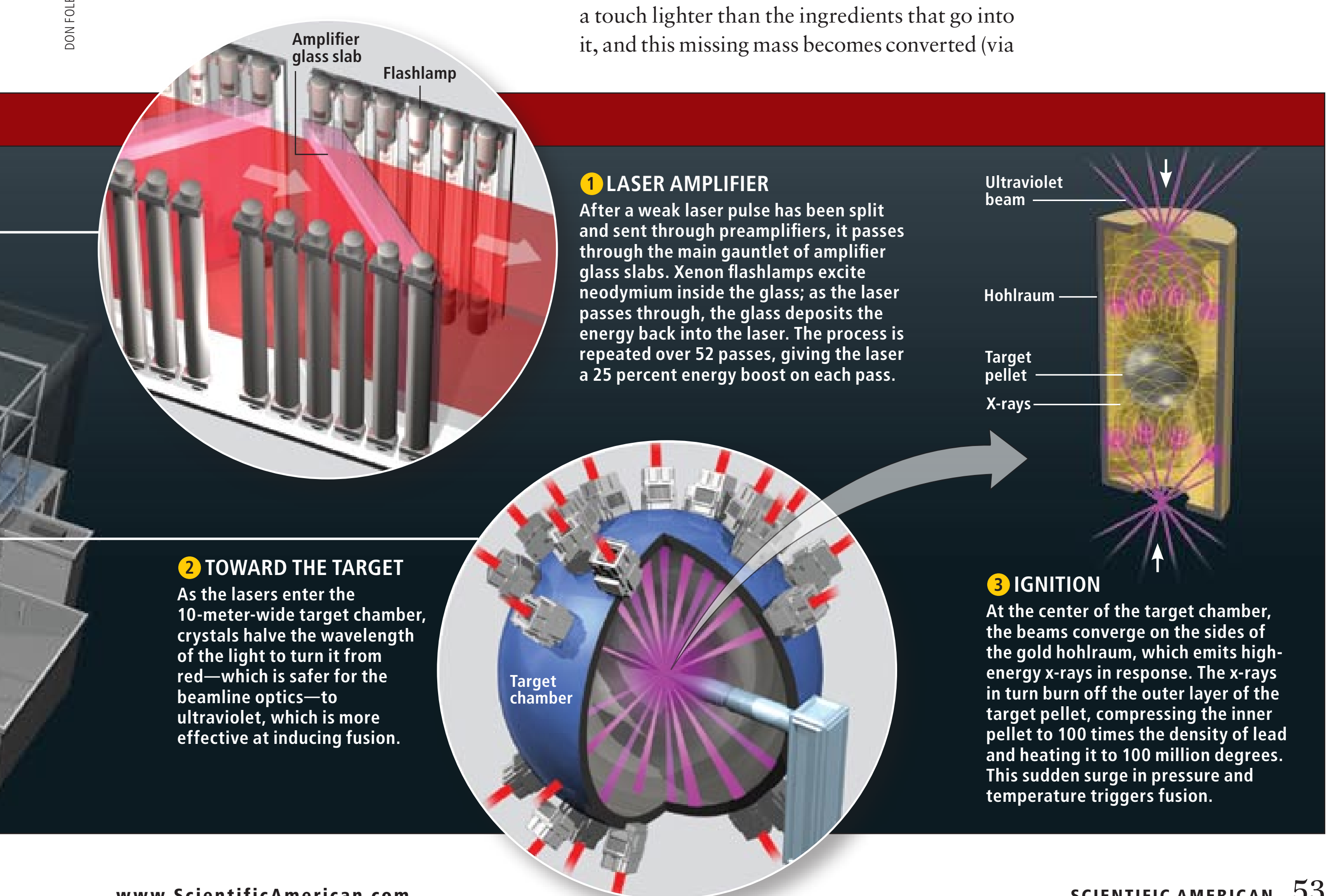
Darwin was right. It would be another seven decades before scientists would develop the tools necessary to understand what made the sun shine. By the 1930s scientists knew that all matter is made of atoms and that these atoms have a nucleus of positively charged protons and neutral neutrons. (Hydrogen is the sole exception—its nucleus has only a proton.) Albert Einstein had demonstrated via $E = mc^2$ that mass can become energy. And spectrographic studies showed that the sun is not made of molten rock, as Thompson assumed—it is composed mostly of hydrogen, along with some helium.

In 1938 physicist Hans Bethe realized that at the center of the sun, the pressure must be so great that individual hydrogen nuclei would be squeezed together with such force that they could overcome the repulsion that ordinarily keeps ions of like charge apart. Bethe laid out the four-step chain by which hydrogen ions fuse together. The final products of the reaction are a touch lighter than the ingredients that go into it, and this missing mass becomes converted (via

THE D-T REACTION

When the hydrogen isotopes deuterium and tritium are forced close together (via high temperatures and pressures), they overcome their mutual electromagnetic repulsion and fuse. The reaction forms helium, a neutron and a surfeit of energy.





DON FOLEY (*facility*); JESSICA HUPPI (*d-t reaction*)

$E = mc^2$) into the energy that powers the sun.

This complex chain reaction requires pressures that exist only in the center of stars. A comparatively easy way to induce fusion is to start with two isotopes of hydrogen—deuterium, which has a proton and a neutron in its nucleus, and tritium, which has one proton and two neutrons. Bring deuterium and tritium close enough together, and they will join to form helium (two protons, two neutrons), a neutron, and a burst of energy. The reaction requires relatively little in the way of temperature and pressure, yet it still generates the monumental energies that characterize fusion reactions.

If scientists could catalyze fusion in a controlled environment, the world's energy problems would disappear. The fuels are abundant: deuterium is found in seawater, and tritium can be generated inside a reactor. And unlike in ordinary fission-based nuclear reactors, fusion does not create long-lived radioactive by-products—nuclear waste, as it is more commonly known. In theory, a gallon of deuterium-infused water could produce as much energy as a supertanker full of oil, with a puff of helium as its only exhaust. "You have no geopolitics, clean energy and a limitless supply of fuel," says Edward I. Moses, director of the National Ignition Facility. "It is too good to be true."

And indeed it was. The first designs for fusion reactors came in the early 1950s, when Lyman Spitzer, a professor at Princeton University, estimated that his "Stellarator" (from the Latin for "star") would produce 150 million watts of power, enough to power 150,000 homes. His design relied on the fact that at the high temperatures required for fusion, all electrons would be torn from their parent atoms. This forms a soup of charged particles called a plasma that can be controlled with magnetic fields. Spitzer's Stellarator was essentially a magnetic bottle that would hold the plasma in place even as it was heated to temperatures of millions of degrees.

Yet Spitzer and others who would follow him did not have a thorough understanding of how plasmas behaved. What they were soon to learn—much to their disappointment—is that plasmas do not behave very well at all.

Imagine holding a large, squishy balloon. Now squeeze it down to as small as it will go. No matter how evenly you apply pressure, the balloon will always squirt out through a space between your fingers. The same problem applies to plasmas. Anytime scientists tried to clench them down into a tight enough ball to induce fusion, the plasma would find a way to squirt out the sides. It is a paradox germane to all types of fusion reactors—the hotter you make the plasma and the tighter you squeeze it, the more it fights your efforts to contain it.

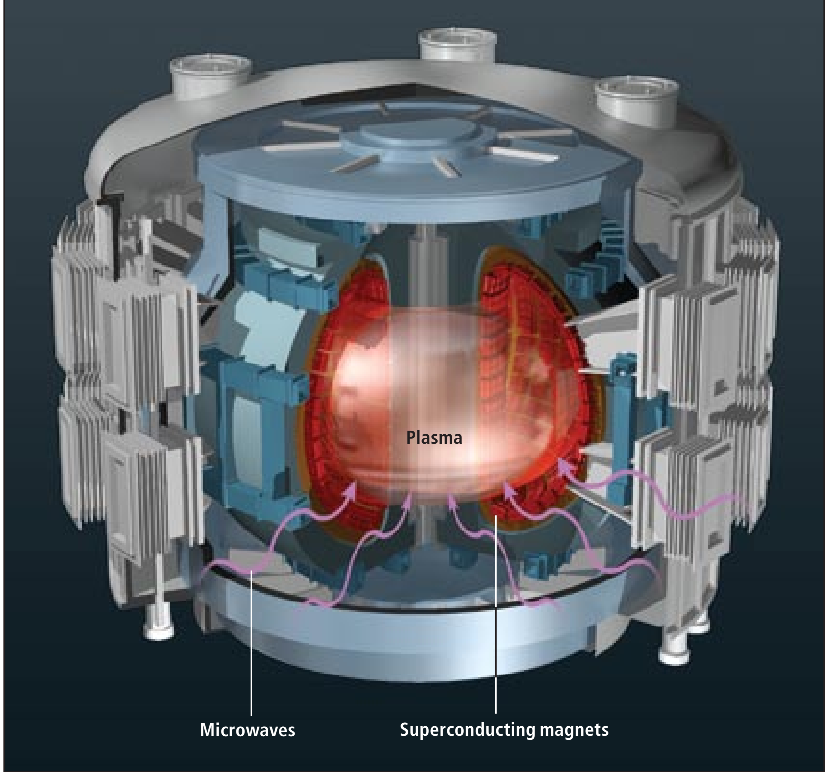
In the six decades since, scientists have struggled to tame plasmas using ever larger magnetic bottles. Every time physicists unveiled an improved machine that was designed to correct the problems that turned up on the last go-around, the higher energies uncovered new varieties of problems. "No matter what you do with them," says Charles Baker, former director of fusion programs at Argonne and Oak Ridge national laboratories and current chair of the U.S. ITER technical advisory committee, "plasmas are always a little unstable."

The energy crisis of the 1970s also saw the birth of a parallel research program toward fusion, one that would attempt to avoid some of the problems related to magnetically confined plasmas. These techniques used a bevy of lasers to compress and heat a pellet made of deuterium

INSIDE LOOK

FUSION FROM MAGNETS

The ITER project in southern France will attempt to create fusion by heating a plasma of deuterium and tritium. The plasma is held in place by powerful superconducting magnets, and beams of microwaves are used to heat the plasma to 150 million degrees Celsius. The process is not intermittent like the laser-based NIF is, so fusion could be sustained for tens or even hundreds of seconds.



DON FOLEY

The lasers will crush the target with a pulse that outshines the nation's entire electricity consumption.

and tritium. The research—carried out at Lawrence Livermore National Laboratory, home of the U.S. fusion weapons programs—started with a simple two-beam test bed. Advances in laser power led to Shiva (named for the Hindu god of creation and destruction) in 1977, then Nova in 1984. Each program defeated Livermore's own world records for production of the most powerful laser blast on the planet, but as in the magnetic programs, they still could not reach breakeven—the point where fusion produced as much energy as the lasers put in. For that, Livermore would need a laser 70 times more potent than any that had come before. In 1997 construction began on the National Ignition Facility.

Little Blasts

From the outside, the National Ignition Facility doesn't look like much. It is windowless, about the size of an airplane hanger, and painted in a muted beige that would not be out of place in a suburban office park. But like most big-science projects—the Large Hadron Collider comes immediately to mind—it is the deep-buried guts of the project that inspire awe. Inside, dozens of meter-wide tubes stretch far across the facility. The tubes lead to the target chamber, a three-story-high sphere studded with portholes for the lasers to pass through. At the center of this chamber, the deuterium-tritium target is held in place by what looks like a giant pencil tip. The lasers will focus to within millimeters of the center point, crushing the target with a pulse that—at least for small fraction of a second—outshines the nation's entire electricity consumption.

Although the NIF is designed to reach breakeven, its primary mission relates to national security. In 1996 President Bill Clinton signed the comprehensive test ban treaty and outlawed all U.S. nuclear weapons testing. To ensure that the weapons in the stockpile will continue to operate as intended—that is, individual warheads will detonate if the president orders a strike and never otherwise—the nation's nuclear weapons laboratories at Los Alamos and Livermore instituted the stockpile stewardship program, a system of maintenance and testing designed to ensure the reliability of the estimated 5,200 warheads currently in the stockpile.

Most nuclear weapons maintenance is simply routine inspection and replacement of parts. Another key component is computer modeling of nuclear explosions. Such computer models are exquisitely sensitive to the initial conditions; the NIF is designed to provide data from miniature deuterium-tritium blasts to feed into the models. (The facility will also be used for pure-science experiments—one of the first involves a study of the shock waves of a supernova.)

Yet when the facility finally came online last May, its potential for power generation garnered most of the ink. A column by Thomas Friedman in the *New York Times* that ran under the title "The Next Really Cool Thing" provides a typical example. In it, he wrote "each crushed pellet gives off a burst of energy that can then be harnessed to heat up liquid salt and produce massive amounts of steam to drive a turbine and create electricity for your home—just like coal does today."

In theory, yes. But the NIF was never intended to be a machine that could generate usable energy. Under the current operating plan, the NIF will begin experiments with deuterium-tritium fusion later this year and then, if all goes well, hit breakeven a year or so after that. Mind you, this is not "power plant breakeven," as Moses explains. This is just getting more energy out of the pellet than the laser system puts in (the net energy that goes into creating the 4.2-million-joule laser and the losses that occur en route to the target are written off of this ledger). Even still, it should reach the milestone more than 15 years before ITER.

Reactor Roadblocks

No matter how you make fusion happen—whether you use megajoule lasers or the crunch of magnetic fields—energy payout will come in the currency of neutrons. Because these particles are neutral, they are not affected by electric or magnetic fields. Moreover, they pass straight through most solid materials as well.

The only way to make a neutron stop is to have it directly strike an atomic nucleus. Such collisions are often ruinous. The neutrons coming out of a deuterium-tritium fusion reaction are so energetic that they can knock out of position an atom in what would ordinarily be a strong metal—steel, for instance. Over time these whacks weaken a reactor, turning structural components brittle.

Other times the neutrons will turn benign material radioactive. When a neutron hits an atomic nucleus, the nucleus can absorb the neutron and become unstable. A steady stream of neutrons—even if they come from a "clean" reaction such as fusion—would make any ordinary container dangerously radioactive, Baker

THE SHORT HISTORY OF FUSION

1950: Soviet scientist Andrei Sakharov designs a magnetic bottle, called a tokamak, that can hold a plasma. Sakharov's nuclear weapons work pulls him away from the project.

1951: Lyman Spitzer of Princeton University introduces the Stellarator, another magnet-based fusion reactor.

1952: The U.S. detonates Ivy Mike, the world's first hydrogen bomb.

1969: Western scientists travel to Moscow to investigate Sakharov's tokamak design. They find that it produces a much hotter, denser plasma than their stellarators. Tokamaks begin to dominate magnetic fusion research.

1977: The Shiva laser attempts to induce fusion with laser blasts.

2010: The National Ignition Facility should begin deuterium-tritium fusion experiments later this year.

2018 (est.): Construction on ITER is scheduled to be complete. The first deuterium-tritium fusion tests are planned for 2026.

says. “If someone wants to sell you any kind of nuclear system and says there is no radioactivity, hang onto your wallet.”

A fusion-based power plant must also convert energy from the neutrons into heat that drives a turbine. Future reactor designs make the conversion in a region surrounding the fusion core called the blanket. Although the chance is small that a given neutron will hit any single atomic nucleus in a blanket, a blanket thick enough and made from the right material—a few meters’ worth of steel, perhaps—will capture nearly all the neutrons passing through. These collisions heat the blanket, and a liquid coolant such as molten salt draws that heat out of the reactor. The hot salt is then used to boil water, and as in any other generator, this steam spins a turbine to generate electricity.

Except it is not so simple. The blanket has another job, one just as critical to the ultimate success of the reactor as extracting energy. The blanket has to make the fuel that will eventually go back into the reactor.

Although deuterium is cheap and abundant, tritium is exceptionally rare and must be harvested from nuclear reactions. An ordinary nuclear power plant can make between two to three kilograms of it in a year, at an estimated cost of between \$80 million and \$120 million a kilogram. Unfortunately, a magnetic fusion plant will consume about a kilogram of tritium a week. “The fusion needs are way, way beyond what fission can supply,” says Mohamed Abdou, director of the Fusion Science and Technology Center at the University of California, Los Angeles.

For a fusion plant to generate its own tritium, it has to borrow some of the neutrons that would otherwise be used for energy. Inside the blanket channels of lithium, a soft, highly reactive metal, would capture energetic neutrons to make helium and tritium. The tritium would escape out through the channels, get captured by the reactor and be reinjected into the plasma.

When you get to the fine print, though, the accounting becomes precarious. Every fusion reaction devours exactly one tritium ion and produces exactly one neutron. So every neutron coming out of the reactor must make at least one tritium ion, or else the reactor will soon run a tritium deficit—consuming more than it creates. Avoiding this obstacle is possible only if scientists manage to induce a complicated cascade of reactions. First, a neutron hits a lithium 7 isotope, which, although it consumes energy, produces both a tritium ion and a neutron. Then this second neutron goes on to hit a lithium 6 isotope and produce a second tritium ion.

Moreover, all this tritium has to be collected and reintroduced to the plasma with near 100 percent efficiency. “In this chain reaction you cannot lose a single neutron, otherwise the reaction stops,” says Michael Dittmar, a particle physicist at the Swiss Federal Institute for Technology in Zurich. “The first thing one should do [before building a reactor] is to show that the tritium production can function. It is pretty obvious that this is completely out of the question.”

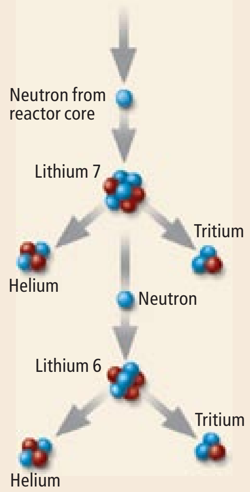
“This is a very fancy gadget, this fusion blanket,” Hazeltine says. “It is accepting a lot of heat and taking care of that heat without overheating itself. It is accepting neutrons, and it is made out of very sophisticated materials so it doesn’t have a short lifetime in the face of those neutrons. And it is taking those neutrons and using them to turn lithium into tritium.”

ITER, unfortunately, will not test blanket designs. That is why many scientists—especially those in the U.S., which is not playing a large role in the design, construction or operation of ITER—argue that a separate facility is needed to design and build a blanket. “You must show that you can do this in a practical system,” Abdou says, “and we have never built or tested a blanket. Never.” If such a test facility received funding tomorrow, Abdou estimates that it would take between 30 and 75 years to understand the issues sufficiently well to begin construction on an operational power plant. “I believe it’s doable,” he says, “but it’s a lot of work.”

The Big Lie

Let’s say it happens. The year is 2050. Both the NIF and ITER were unqualified successes, hitting their targets for energy gain on time and under budget. Mother Nature held no surprises as physicists ramped up the energy in each system; the ever unruly plasmas behaved as expected. A separate materials facility demonstrated how to build a blanket that could generate tritium and convert neutrons to electricity, as well as stand up to the subatomic stresses of daily use in a fusion plant. And let’s assume that the estimated cost for a working fusion plant is only \$10 billion. Will it be a useful option?

Even for those who have spent their lives pursuing the dream of fusion energy, the question is a difficult one to answer. The problem is that fusion-based power plants—like ordinary fission plants—would be used to generate baseload



THE T TRICK

Fusion reactors must generate their own tritium fuel via a complex chain of reactions. A neutron first hits a lithium 7 ion implanted in a region surrounding the reactor called the blanket. This reaction creates helium, tritium and a neutron. This second neutron then goes on to hit a lithium 6 ion, which is also implanted in the blanket. This produces another helium ion and a tritium ion.

CHALLENGES

Before fusion can be a viable energy source, scientists must overcome a number of problems.

Heat: Materials that face the reactions must withstand extremely high temperatures for years on end.

Structure: The high-energy neutrons coming from fusion reactions turn ordinary materials brittle.

Fuel: A fusion reactor will have to “breed” its own tritium in a complex series of reactions [*see box above*].

Reliability: Laser reactors produce only intermittent blasts; magnet-based systems must maintain a plasma for weeks, not seconds.

JESSICA HUPPI

power. That is, to recoup their high initial costs, they would need to always be on. "Whenever you have any system that is capital-intensive, you want to run it around the clock because you are not paying for the fuel," Baker says.

Unfortunately, it is extremely difficult to keep a plasma going for any appreciable length of time. So far reactors have been able to maintain a fusing plasma for less than a second. The goal of ITER is to maintain a burning plasma for tens of seconds. Going from that duration to around-the-clock operation is yet another huge leap. "Fusion will need to hit 90 percent availability," says Baker, a figure that includes the downtime required for regular maintenance. "This is by far the greatest uncertainty in projecting the economic reliability of fusion systems."

NIF director Moses thinks he has the answer. He has introduced a proposed design for a hybrid fusion-fission reactor—one that uses the neutrons from laser-driven fusion reactions to drive fission reactions in a blanket of ordinary nuclear waste. He calls his system LIFE—for laser inertial fusion engine—and says he can have one connected to the grid in 20 years.

The system relies on the fact that only 5 percent of the uranium that goes into power plants gets used before it is pulled out and put into long-term storage. LIFE would bombard this spent fuel with neutrons, thus accelerating its decay into lighter and less radioactive elements, all the while producing heat that could be used for electricity. "Our studies show that we would be competitive with all the energy sources that are available today," Moses says. "Or even cheaper than them."

Of course, LIFE is not without its pitfalls. "You want to look at the big lie in each program," says Edward C. Morse, a professor of nuclear engineering at the University of California, Berkeley. "The big lie in [laser-based] fusion is that we can make these target capsules for a nickel a piece." The target capsules, the peppercorn-size balls of deuterium-tritium fuel, have to be exquisitely machined and precisely round to ensure that they compress evenly from all sides. Any bump on the pellet and the target won't blow, which makes current iterations of the pellets prohibitively expensive. Although Livermore, which plans to make its pellets on site, does not release anticipated costs, the Laboratory for Laser Energetics at the University of Rochester also makes similar deuterium-tritium balls. "The reality now is that the annual budget to make targets that are used at Rochester is several million dollars, and they make about six capsules a year," Morse says. "So you might say those are $1 million a piece."

And unlike in the current iteration of the NIF, which is capable of blasting one pellet every few hours, targets will cycle through the chamber with the speed of a Gatling gun. "This is a 600-rpm machine," Moses says. "It's like a million-horsepower car engine—except no carbon." A LIFE plant working around the clock will consume almost 90,000 targets a day.

Of course, it is impossible to predict what the worldwide energy situation will be 20 years out. Perhaps the need for fusion energy will be greater than ever. Or it could be that a breakthrough in solar, wind or some other as yet unforeseen alternative energy makes fusion appear expensive and unwieldy by comparison. "It is possible that people will say, 'Yeah, it works, that's great, but we don't need it anymore, because we've got a list of other things,' " Hazeltine says.

It used to be that fusion was held apart from these considerations. It was fundamentally different from dirty fossil fuels or dangerous uranium. It was beautiful and pure—a permanent fix, an end to our thirst for energy. It was as close to the perfection of the cosmos as humans were ever likely to get.

Now those visions are receding. Fusion is just one more option and one that will take decades of work to bear fruit. Ignition may be close, but the age of unlimited energy is not. ■

HOT GLOW: **A look at the plasma inside the Korea Superconducting Tokamak Advanced Research (KSTAR) project, which began operations in 2008.**

COURTESY OF NATIONAL FUSION RESEARCH INSTITUTE

MORE TO EXPLORE

Sun in a Bottle: The Strange History of Fusion and the Science of Wishful Thinking. Charles Seife. Viking, 2008.

Fusion as an Energy Source: Challenges and Opportunities. W. J. Nutall. Report of the Institute of Physics, September 2008. **www.iop.org/activity/policy/Publications/file_31695.pdf**

Safe and Sustainable Energy with LIFE. Arnie Heller in *Science and Technology Review.* Publication of Lawrence Livermore National Laboratory, April/May 2009. **http://str.llnl.gov/AprMay09/moses.html**

Research Needs for Magnetic Fusion Energy Sciences. Final workshop report, June 2009. **www.burningplasma.org/renew.html**