VOLUME 248 NOVEMBER 2025 NUMBER 5

# NATIONAL GEOGRAPHIC


Inside the 200-foot-tall assembly hall in Saint-Paul-lès-Durance, France, hangs a piece of ITER, the International Thermonuclear Experimental Reactor. The audacious goal shared by workers from 90 countries over the past four decades is to use groundbreaking fusion technology to solve the global energy crisis.


# INSIDE THE COLOSSAL QUEST FOR LIMITLESS ENERGY

**Around the world, the race is on to harness the near-infinite power of nuclear fusion. In a small town in the south of France, a scientific megaproject of extraordinary dimension is inching closer to solving our global energy needs forever—by building a star on Earth.**

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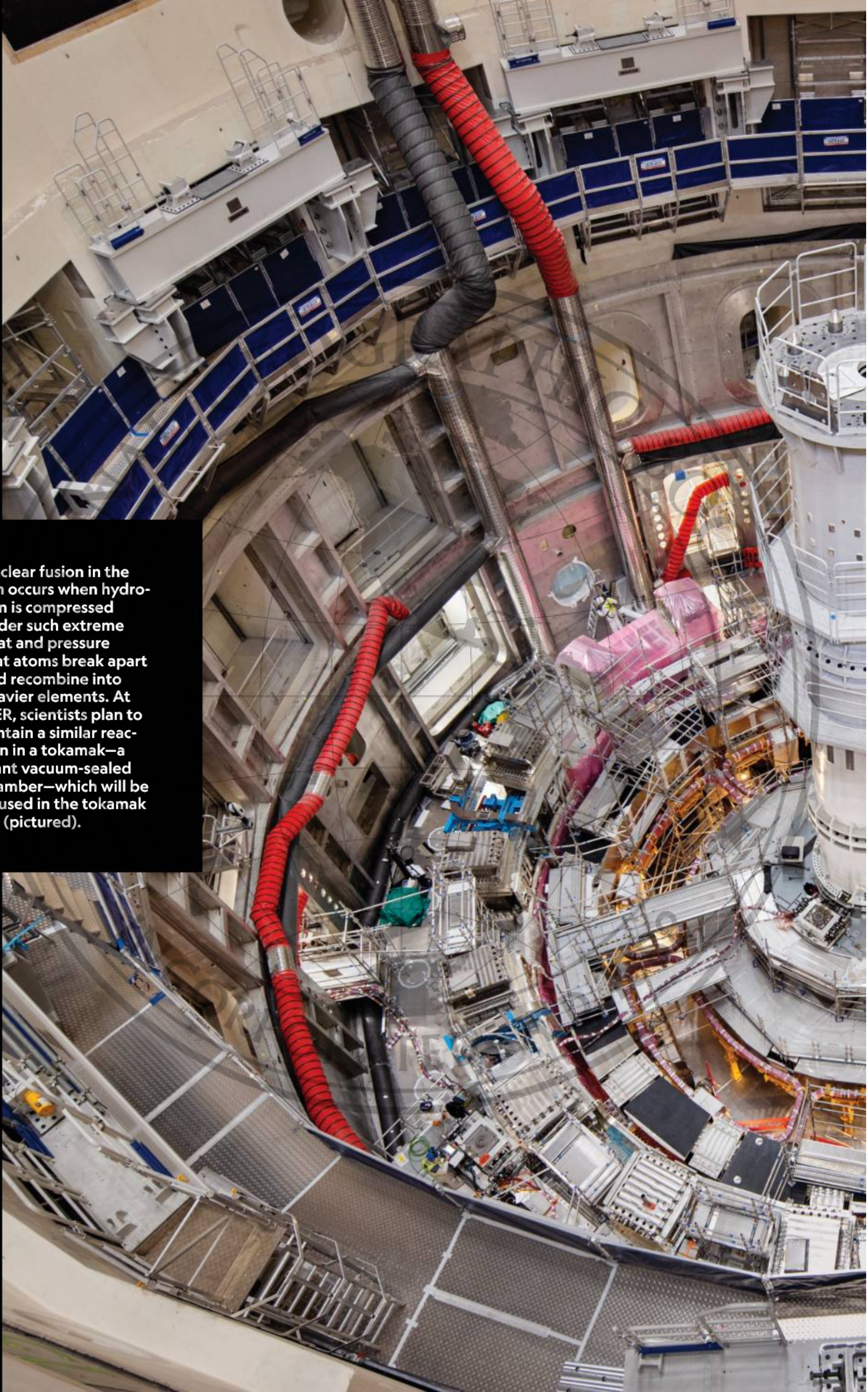
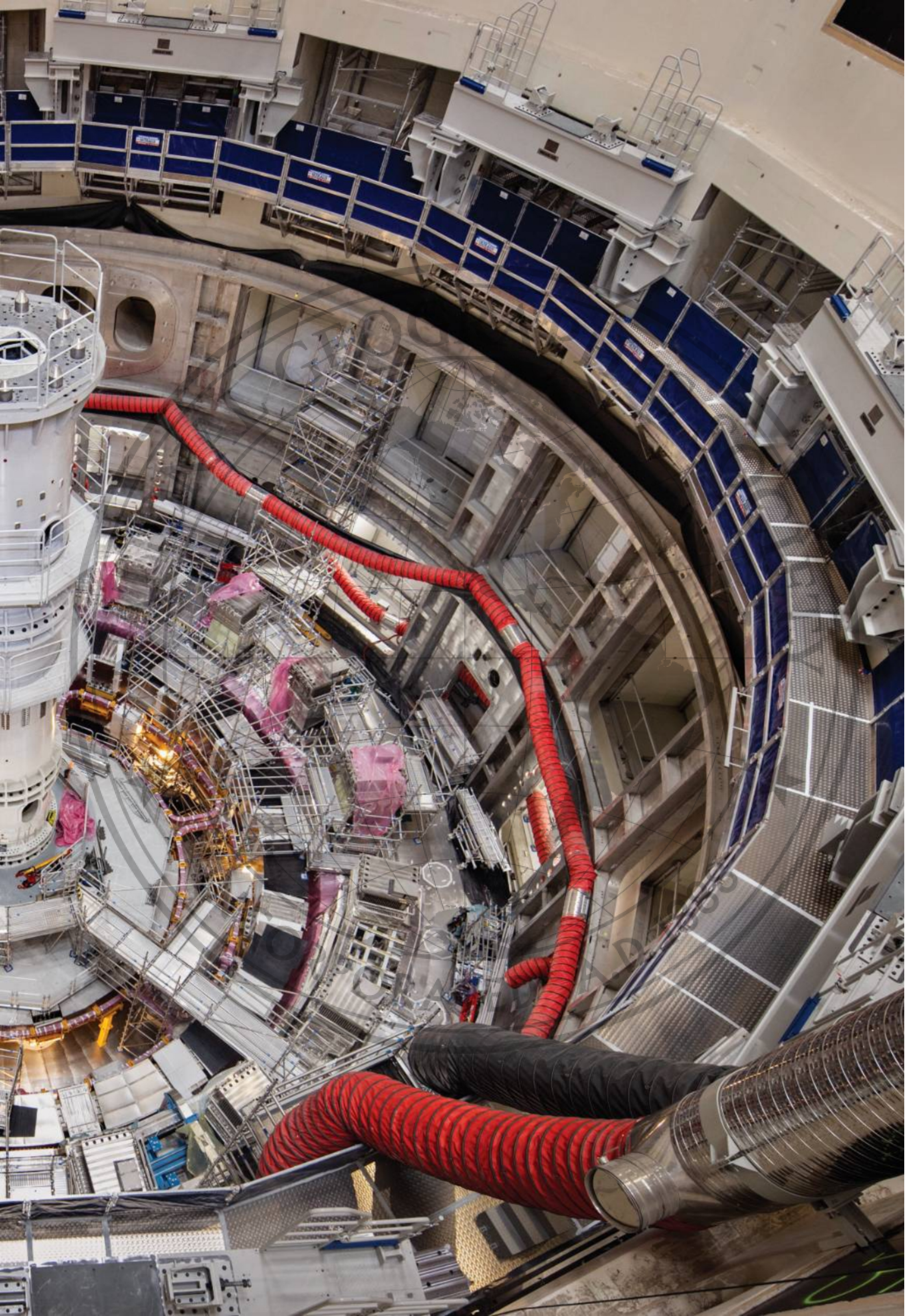


Nuclear fusion in the sun occurs when hydro-gen is compressed under such extreme heat and pressure that atoms break apart and recombine into heavier elements. At ITER, scientists plan to contain a similar reac-tion in a tokamak—a giant vacuum-sealed chamber—which will be housed in the tokamak pit (pictured).



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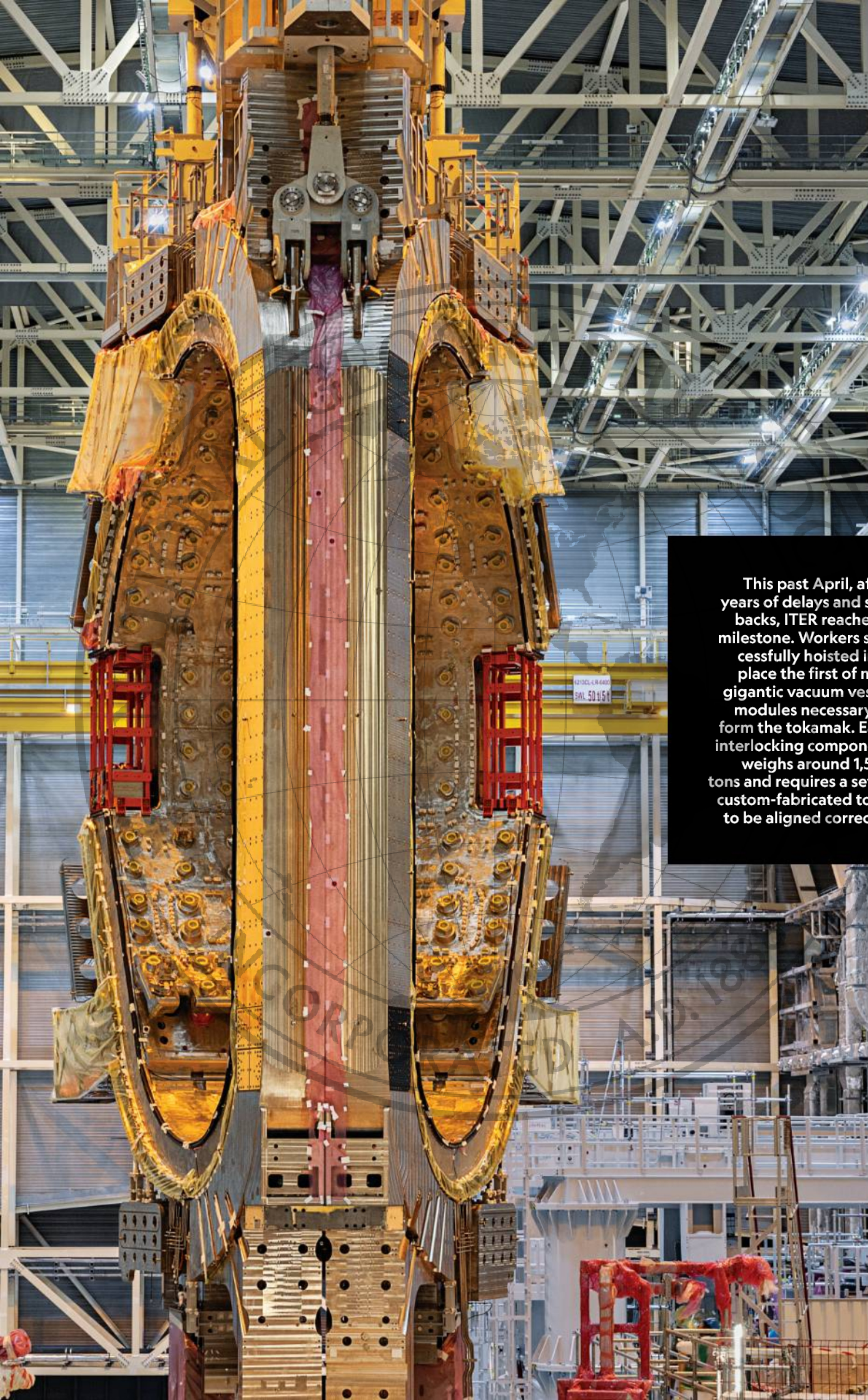
**REAL STARS, THE ONES IN SPACE, ARE SIMPLE BEASTS.**

Our sun formed some 4.6 billion years ago from a cloud consisting of essentially one ingredient: hydrogen, the most basic and abundant element in the universe. Gravity kneaded the cloud into a big, rotating ball and kept squeezing from there, density and warmth spiking, until its core reached about 27 million degrees Fahrenheit.

Hydrogen crumbles when collisions occur at this temperature and pressure, creating the soupy jumble of atomic parts known as plasma, the fourth state of matter after solid, liquid, and gas. Though rare on Earth outside of lightning bolts and neon signs, plasma accounts for over 99 percent of the solar system's mass, most of it stored, highly agitated, in the sun. Throughout the sun's soup, trillions of times



This past April, after years of delays and setbacks, ITER reached a milestone. Workers successfully hoisted into place the first of nine gigantic vacuum vessel modules necessary to form the tokamak. Each interlocking component weighs around 1,500 tons and requires a set of custom-fabricated tools to be aligned correctly.


every instant, four hydrogen atoms lock together in a series of steps to make helium. With a much higher fusion point, helium bobs placidly amid the solar havoc, a sturdy lifeboat, not even breaking a sweat at 27 million degrees—and there's enough hydrogen in the sun to keep forging helium for another five billion years.

One further process takes place in each of these nuclear fusion reactions. A helium atom is just a speck lighter than four hydrogen atoms, and the leftover bits of matter, unleashed and energetic, thrash through the plasma, shimmy gradually to the sun's surface, and stream into space. Those headed in the right direction deliver morsels of heat and light to Earth.

Here's how mighty our sun is: The total energy it produces each second would power the entire Earth, gluttonously, for hundreds of thousands of years. And the process by which a star does this seems tantalizingly easy. What if we could create a smaller sun here on Earth and tap into its power? Then, theoretically, we'd have a virtually unlimited source of clean and cheap energy, emitting no carbon dioxide, potentially halting global warming and environmental collapse. The world would literally be saved. It sounds improbable, but such an endeavor has long been under way at a vast construction site in the south of France, where both the hard science and the need for human collaboration

The nonprofit National Geographic Society, committed to illuminating and protecting the wonder of our world, funded the work of National Geographic Explorer and photographer Paolo Verzone featured in this story.

NGM MAPS

Construction manager Claire Laugier is one of over 2,000 people who work at ITER's 100-acre site nestled into the French countryside about 30 miles from the Mediterranean Sea. The workers span a wide range of specialties, from physicists to machinists, and some have spent decades devoted to the fusion initiative.

are unprecedented and unpredictable, and the dream of a better future can be witnessed coming to life.

THE ARTIFICIAL STAR is called ITER (pronounced "eater"), the Latin word for "the way" and an acronym for the International Thermonuclear Experimental Reactor. The 100-acre work area, pancake flat, is an hour's drive inland from the Mediterranean Sea, tucked amid pine forests and vineyards, with craggy hills on the horizon.

Each weekday, more than 2,000 people, physicists to welders, arrive at the site. Smaller crews toil at night. Thirty-three nations representing half the world's population are official ITER members, and workers from 90 countries have been involved in its creation—a web of cultures knitting a singular machine. In the middle of the jobsite,

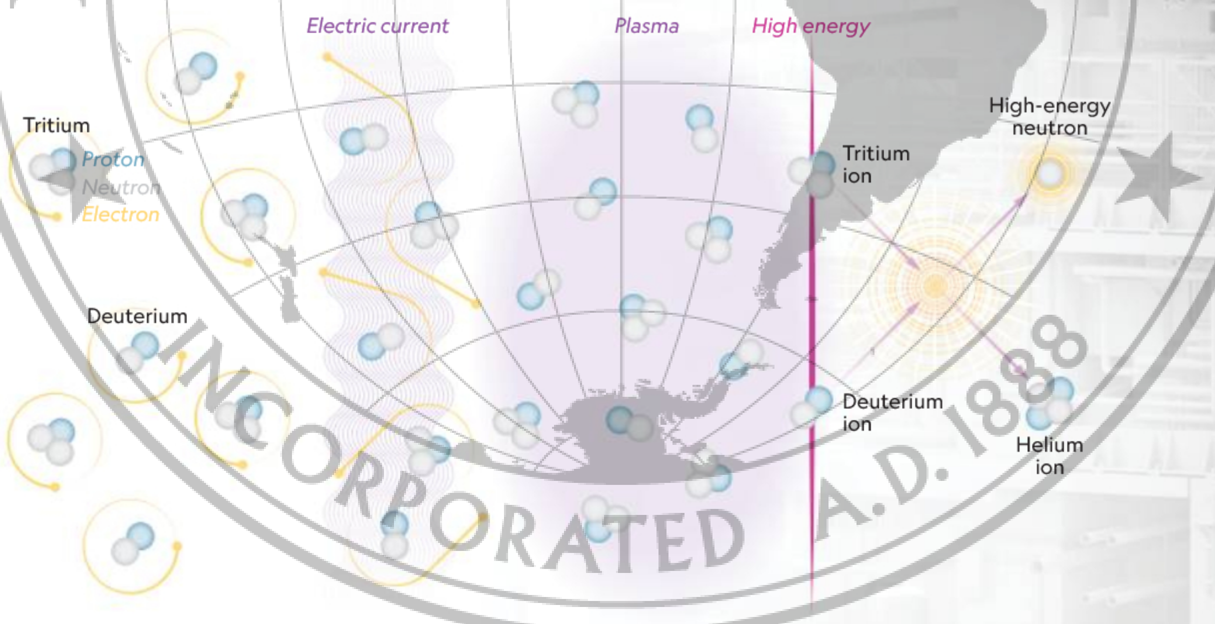
# HOW NUCLEAR FUSION WORKS

Nuclear fusion holds the promise of nearly limitless emission-free energy. The catch: figuring out how to create and then harness the power of a star here on Earth, which requires temperatures of at least 270 million degrees Fahrenheit. When fully operational, ITER could very well provide a template for producing the fuel of the future.

*Illustration by* TOMÁŠ MULLER

## THE BASICS OF FUSING ATOMS

To capture the energy released during fusion, a reactor must confine plasma, an ionized gas that occurs when atoms have been stripped of their electrons. Fusion facilities are designed to channel and control that reaction for as long as possible, beginning with a multistep process to generate self-sustaining power.




**Combine essential elements**
While different materials can be used as fuel, heavy hydrogen isotopes deuterium and tritium are the most common, and are introduced into a containment chamber as a gas.

**Create the plasma**
In ITER, an electric current separates electrons from the isotopes, resulting in a plasma of charged particles, which must be confined by a magnetic field.

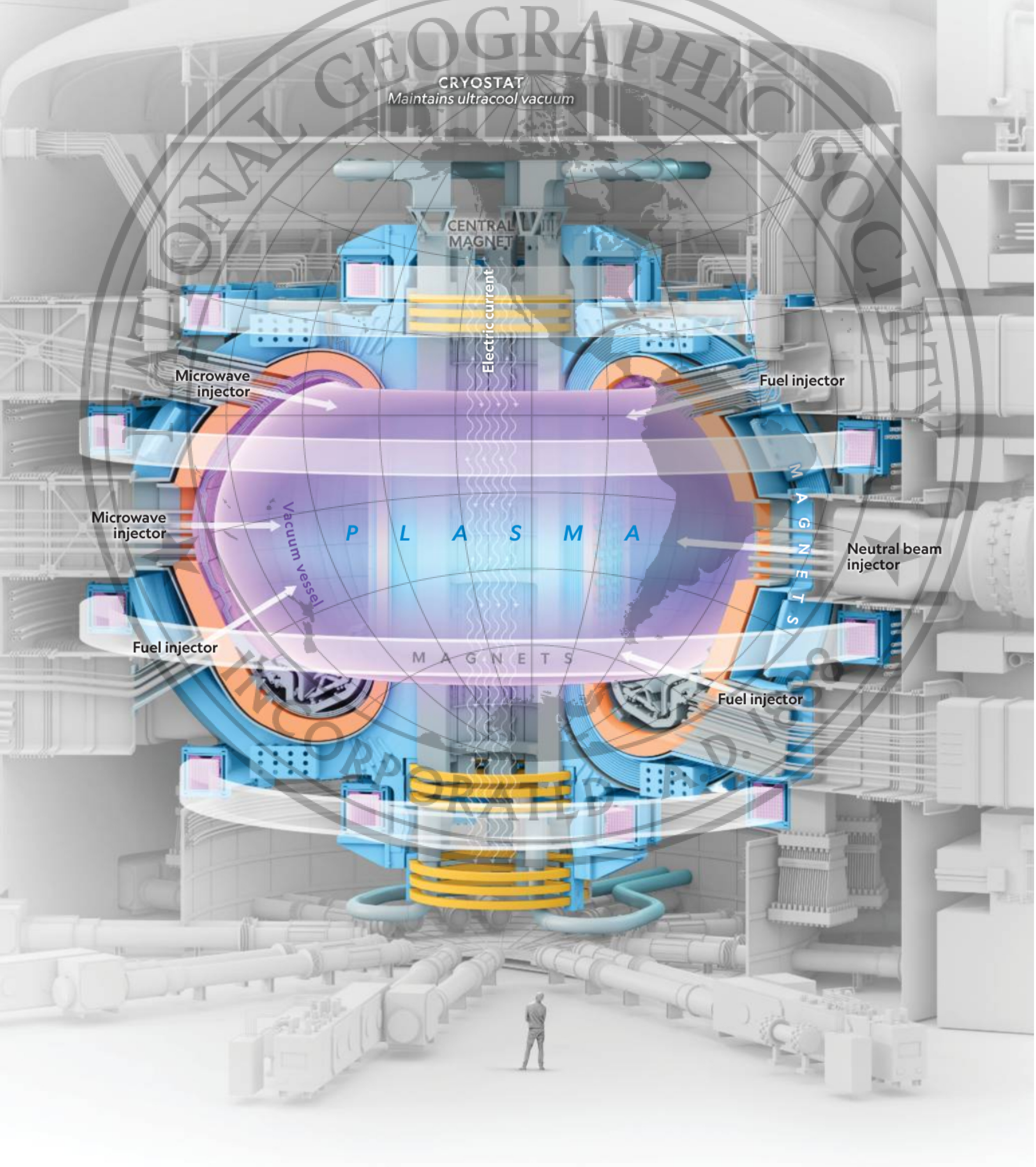
**Now, fuse atoms**
High-energy beams heat the plasma, causing pairs of deuterium and tritium nuclei to collide and fuse. This releases high-energy neutrons that heat materials, enabling energy capture.

GRAPHIC: JASON TREAT AND ALEXANDER STEGMAIER, NGM STAFF
SOURCE: ITER

## MAGNETIC CONFINEMENT

ITER will rely on a large doughnut-shaped machine called a tokamak (below) to induce fusion. A central electromagnet creates an electric current that changes the deuterium and tritium gas into an ionized plasma. Then the electromagnet, working together with 24 other magnets, shapes and holds the plasma in place as it is bombarded with high-energy beams that raise its temperature to 270 million degrees Fahrenheit.

**ITER**
*Saint-Paul-lès-Durance, France*
Fuel: deuterium-tritium



dominating the view, a windowless cement edifice rises like a volcano.

To enter this structure, you must visit the attached dressing room and swap your footwear for white clean-room shoes, then use the electric shoe scrubber to ensure that any dirt or contaminants are gone, and march in place on a sticky mat to eliminate gunk on the soles. The machine being built needs to be kept fastidiously pristine. A dropped pen cap or stray fingerprint could cause damage. You also have to wear a white lab coat, a hairnet, a hard hat, protective eyewear, and white gloves.

Once properly dressed, you pass through a plastic strip curtain and unzip a canvas flap, like a tent door, and zip it shut behind you. Then walk down a narrow corridor, fluorescently lit, the walls, floor, and ceiling all the same bright white as your shoes. The air is still and stifling.

At the end of the hallway, unzip and rezip another door, navigate a second white corridor, climb up a layer of scaffolding jungle-gym style, and duck through one more zippered portal. There's a claustrophobic sense of being lost in a labyrinth. Traverse yet another dizzying white hallway and open a further door and there you are, inside the great machine room.

It's an industrial ecosystem of ducts and pipes and metal slabs on some wild scale that skews your bearings. Only when you spot the white-clad workers, tethered to scaffolding amid the overwhelming gadgetry, ants on a hill, does the enormity emerge. The contraption fills a space the equivalent of a 20-story building. It will eventually contain 10 million parts—hundreds of thousands of them uniquely fabricated—and along with its housing weigh nearly 450,000 tons. ITER is likely the most complex machine humans have ever attempted to build.

A lot of the metal is burnished to a brilliant shine, many pieces plated in silver, an ideal material for deflecting heat from sensitive components. Pipes run here and there in parallel rows like raked sand in Zen gardens, wending through the works. The heart of the machine is in the form of a giant sphere, with a doughnut-shaped hollow where plasma may one day whirl. The device is called a tokamak. There are few sharp edges on a tokamak, and massive segments of ITER's machinery are sculpted with graceful, sandstone-like curves.

> **THE CONTRAPTION FILLS A SPACE THE EQUIVALENT OF A 20-STORY BUILDING. IT IS LIKELY THE MOST COMPLEX MACHINE HUMANS HAVE EVER ATTEMPTED TO BUILD.**

ITER is publicly funded, billions of dollars shouldered by dozens of governments, with no profit motive or military aim. "We are contributing to world peace," says Kijung Jung, head of the project's South Korean unit, expressing an admirable objective that is somewhat belied by decades of international disputes. The project is open source; if ITER operates as planned, any nation or private company can access its intellectual property, free of charge. This is not going to happen soon. The quest for a mechanical star has been unfolding for a century, and still has years to go.

But in a world that can feel quick-tempered and fractious, ITER appears to be a crazily ambitious long-term project rooted in optimism and a desire for unity. The endeavor has already extended across careers and lifetimes, with each step forward seemingly offset by unanticipated setbacks. "It will be a savior for future generations," promises Dutch physicist Akko Maas, a 25-year veteran of ITER, speaking from his office overlooking the teeming construction area. A few scientists have observed that ITER may be our era's version of the Egyptian pyramids or the Gothic cathedrals of Europe. Some visitors permitted to see the machine have been moved to tears, for it can seem a miracle that ITER exists at all.

OTHER OBSERVERS, including some of the most powerful voices in science, have not been swayed by ITER's charms. Three separate Nobel Prize winners in physics—Pierre-Gilles de Gennes of France, his countryman Georges Charpak, and Masatoshi Koshiba of Japan—independently declared that attempts to create a miniature sun to help power the Earth are a waste of money and effort, doomed to fizzle out, and possibly dangerous.

Despite such criticism, an ITER-like facility, if completed and hooked to the energy grid, would presumably be safer, cleaner, and more productive than any nuclear power plant now in use. All of the world's 400-plus nuclear reactors operating across some 30 nations rely on fission. Fusion and fission are similar-looking words based on the same concept of creating energy from excess matter in atomic reactions, but otherwise they're opposites. In a fusion plant, lightweight atoms—hydrogen has just one electron, one proton, and zero, one, or two neutrons—are forced together. With fission, heavier elements such as uranium or plutonium, each with a total of more than 300 electrons, protons, and neutrons, are split apart.

The great advantage of fission is that reactions are easy to start. One good jolt and particles drop from the big atoms like fruit from a tree. But fission is messy—some of the radioactive waste will be toxic to humans for tens of thousands of years. Fusion, too, produces hazardous radioactive by-products, but nothing remotely comparable. Also, fissile material like uranium may be depleted within a century, while the type of hydrogen best suited for fusion is almost endlessly abundant in seawater.

There's also fission's limited but unavoidable record of catastrophe: Three Mile Island, Pennsylvania, in 1979; Chernobyl, Ukraine (then part of the U.S.S.R.), in 1986; Fukushima, Japan, in 2011. Fission reactions, without careful control, can become explosive, prone to gallop off uncontrollably. With fusion, runaway reactions and meltdowns aren't possible. In a fusion plant, any accident or system failure, or even a small instability in the plasma, immediately causes the reaction to lose strength and extinguish itself.

Also, fusion produces four times as much energy as fission with the same quantity of fuel. And fusion is about four million times more energetic, and vastly cleaner, than chemical reactions that burn oil or coal. Renewable energy sources including solar, wind, and geothermal are, like nuclear power, largely carbon free, but none of them appear capable of scaling up to meet global demand.

Fusion fills the bill of energy savior, except that it's difficult to begin the reaction and harder to maintain it. Atoms naturally repel one another, and enormous forces are required to slam them together and fuse them. Even then, plasma is skittish and fragile, constantly seeking to dissipate. The largest detonation of all time, the big bang, could maintain fusion for only three minutes before it faded away. For the next hundred million years, fusion didn't exist in the universe, until gravity muscled enough hydrogen together for the first stars to ignite. Virtually every lab experiment involving fusion has consumed more energy than it has produced, contrary to the goal of a power plant.

Fusion energy currently sits at the maddening intersection of conceptual simplicity and technological perplexity. Some fusion experts have concluded, across several decades now, that controlling fusion is beyond the limits of human capability.

Daniel Jassby, who worked at the Princeton Plasma Physics Lab for 25 years, wrote after his retirement that a fusion plant would be too convoluted, requiring endless maintenance, and "cause more problems than it would solve." The late Lawrence Lidsky, an associate director of MIT's fusion center and founding editor of the *Journal of Fusion Energy,* declared after a long career that fusion power is a fantasy, noting that it's widely regarded as "the hardest scientific and technical problem ever tackled." Walter Marshall, former chairman of the United Kingdom Atomic Energy Authority, reportedly said that "fusion is an idea with infinite possibility and zero chance of success."

There's no shortage of scientists who support ITER—Stephen Hawking once said that fusion was the single idea with the greatest potential to advance humanity—but the project's detractors mostly articulate the same idea: ITER's complexity can seem absurd.

The more you know about the machine, the less it may appear to make sense. "This is high risk, high reward," says Kathryn McCarthy, director of the United States' ITER bureau. The idea is undeniably a long shot, possibly a wild-goose chase, that might in fact exceed human capacity. But for many who've dedicated their working lives to ITER, it's precisely this uncertainty and absurdity that make the effort alluring. How can we know our limits unless we try our hardest to exceed them?

A CHIEF ABSURDITY is the heat. Of the three fusion requirements, plasma confinement, pressure, and heat, humans are most limited by pressure. A million Earths could fit inside the sun, and this size difference is insurmountable—the center of the sun is 13 times denser than lead. There's no known way we can create a squeeze like that on our planet.

To make up for this, a lot of heat is needed. The main source of ITER's heat comes from

**Pipe fitter Zeljko Slunjski inspects a thermal shield, one of several key components in the tokamak's modules that have needed repair or reinstallation in recent years. Along the way, ITER has faced criticism as costs increased and major construction errors occurred. Some Nobel Prize-winning physicists have deemed its objective impossible to achieve.**



a pair of giant laserlike particle guns called neutral beam injectors. Each gun is the size of two city buses parked end to end; their barrels point into the tokamak. They will fire one-million-volt particle beams continuously for an hour. To power the guns and other components, ITER has built a 10-acre electrical switchyard capable of drawing as much energy from the French national grid as a city of one million people, though the machine, once operational, should prove that this debt can be repaid at least tenfold.

When the guns open fire, hydrogen gas in the tokamak will swirl through the doughnut, increasing in velocity as the temperature rises—one million degrees Fahrenheit, two million, 10 million. The atoms will move faster than the speed of sound, then swifter still, as the heat exceeds the 27 million degrees at the center of the sun, then passes 50 million, 100 million, 200 million. The force of accelerating particles in the tokamak will

Construction worker Zhang Yue stands near pallets containing large building materials that will be lifted by overhead cranes into the tokamak pit. Many of these pieces end up being combined to form even larger devices. The scale of the contraption is so huge that people are often dwarfed by their tools and scaffolding.


Spider 43T

equal that of two space shuttles launching at once. Only at 270 million degrees, 10 times the temperature of the sun's core, will hydrogen atoms in ITER collide and shed electrons, then fuse together as helium.

How do you contain something so hot? No known material could do it. A tokamak made of pure diamonds would vaporize instantly. But here the nature of plasma is helpful—the stew of atomic parts includes a large number of positively charged protons and negatively charged electrons. Since these particles are affected by magnetic forces, the jar confining ITER's plasma will be formed of electromagnetic fields.

Like many ideas being implemented at ITER, the development of the electromagnetic system draws on the most promising discoveries from years of research at laboratories worldwide that have nothing to do with nuclear fusion. The magnets at ITER, also absurd, start with the central solenoid, which will fill the hole of the doughnut. It's like a grain silo six stories high, and will become the backbone of the world's most powerful magnetic system, generating forces that could lift an aircraft carrier out of the water. Circling the machine like Hula-Hoops will be six immense poloidal magnets, and hanging vertically will be 18 D-shaped toroidal magnets, each over 50 feet tall, enclosing the plasma's loop. Together the magnets will weigh more than 11,000 tons, and they must be machined with extraordinary precision, the margin for error less than the thickness of a sheet of paper. "To create this," says one ITER worker, "you have to be a little crazy."

These are all superconducting magnets, which means that they can carry strong electrical currents without resistance, allowing the intense fields required to corral ITER's plasma. For superconductivity to work, these magnets must be kept extremely cold. ITER has also built a cryoplant big enough to house a soccer field—"the most complicated refrigerator in the world," as an ITER cryogenic engineer put it—that will circulate liquid helium through the magnets.

ITER's magnets need to be cooled to negative 450 degrees Fahrenheit. This is just a few ticks above absolute zero, the point at which atomic energy has reached its minimum, nearly motionless state. Perhaps the ultimate absurdity of ITER is that it will contain one of the hottest known places in the universe and one of the coldest, little more than a body's length apart. "We are playing with Mother Nature's forces," says Alberto Loarte, director of ITER's science division, jotting down a page of mathematical calculations showing just how great these forces are. "I can't predict the difficulties we will face. We may learn that we understand nothing."

**'WE ARE PLAYING WITH MOTHER NATURE'S FORCES,' SAYS ALBERTO LOARTE, DIRECTOR OF ITER'S SCIENCE DIVISION. 'I CAN'T PREDICT THE DIFFICULTIES WE WILL FACE.'**

HERE'S HOW IT'S SUPPOSED to work: The doughnut-shaped area in the tokamak will be pumped clear, forming a vacuum—any stray molecules can pollute the plasma. The magnets will be supercooled and activated, then hydrogen gas will be injected into the vacuum chamber at about half a gram per second. This gas will be heavier than common hydrogen. ITER's recipe calls for a combination of deuterium, which adds one neutron to the normally neutronless atom, and tritium, which adds two.

Without these isotopes, the tokamak would have to be heated hundreds of millions of degrees higher, yet this efficiency also brings complications. Deuterium, though rare, can be plucked out of seawater; our oceans contain a many-million-year global supply. But tritium doesn't naturally occur, and is slightly radioactive, so ITER will also be testing first-of-a-kind components that, it's hoped, will permit the machine to safely breed its own tritium.

Once the neutral beam injectors have zapped the gas to the necessary 270 million degrees, the resulting plasma will glow faintly red, like an aurora—the northern and southern lights are also plasmas—and, says an ITER physicist, emit a sound like the screech of an alley cat. Newly fused helium atoms will drop out of the plasma, a sort of ash, and collect in a huge dish known as the divertor at the bottom of the tokamak.

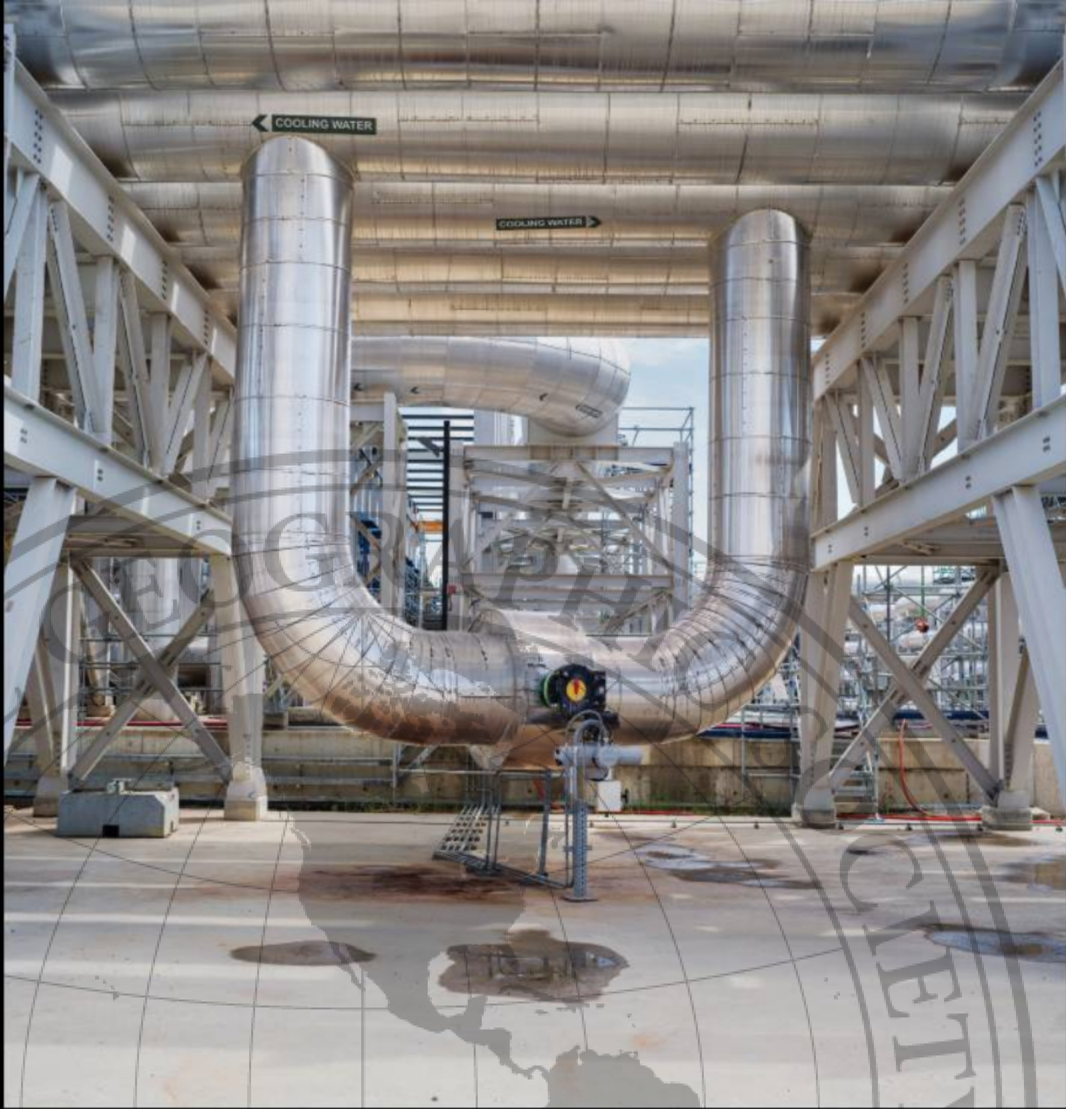
Heavy hydrogen will continually be added, keeping the plasma fed. Another benefit of using deuterium and tritium is that about half of the fusion reaction's by-products are neutrons. Neutrons, well named, are neutral, unaffected by magnetism. Loose neutrons will fly through the plasma in all directions and crash against the walls of the tokamak, striking what's called the blanket.

ITER's blanket, not soft, is formed from hunks of tungsten, steel, aluminum, and bronze, designed to absorb this hailstorm of neutrons, hundreds of trillions per second, and transfer the heat of the particles' kinetic energy from inside the tokamak to outside. In an actual fusion power plant, this heat could be used to boil water, creating steam, which can spin turbines and generate electricity.

The strange truth of ITER, however, is that it will never produce power. The machine is strictly an experiment to prove that all the steps are achievable. Steam turbines, old technology well understood, will presumably be installed in later generations of fusion plants that will be built all over the world. This step could easily be more than 50 years away. "The time scale is not compatible with our immediacy culture," says former ITER chief scientist Tim Luce—but, he implies, fusion energy may still arrive in time to save us all. Though ITER won't have energy-producing equipment, it will be outfitted with a wide array of diagnostic tools to judge the effectiveness of every test run. And while future plants may have to run almost continuously, the stated goal of ITER is to maintain a burning, energy-rich plasma for 400 seconds, or a bit less than seven minutes.

MORE THAN A HUNDRED years of effort and money have already been devoted to achieving these minutes. Painted across the lobby of the five-story ITER headquarters building, home to administrative offices and scientific think tanks, is a timeline of fusion milestones. It begins in 1919, when French physicist Jean Perrin hypothesized that stars produce energy through fusion. This was definitively proved in the 1930s, and soon after the power of fusion was grasped, scientists set about trying to kill people with it.

The bombs dropped on Hiroshima and Nagasaki in August 1945 used only fission. After World War II, the global arms race escalated, and the U.S. initiated a project to weaponize fusion. On November 1, 1952, the first hydrogen bomb, Ivy Mike—a two-stage explosive using fission and fusion—completely




*Top:* To regulate temperatures during fusion, cooled water will be recirculated through a set of pipes five feet in diameter located around ITER's facility.

*Bottom:* The water will then be pumped into one of 10 cooling cells with open pipes and air blasting over a chilling basin to restart the process.


*Top:* **Sunlight glints off reflective cladding affixed to the exterior of ITER's temperature-controlled reactor building.**

*Bottom:* **The facility's cooling cells are key to the creation of nuclear fusion, as hydrogen must be superheated to at least 270 million degrees Fahrenheit.**

eliminated one of the Marshall Islands in the Pacific, a blast equal to 700 Hiroshimas. This was just the start, as scientists swiftly realized that fission-fusion hybrid bombs could be boosted exponentially. The threat of destroying the planet with a single weapon was real.

Global powers attempted to change that trajectory. In 1953, U.S. president Dwight Eisenhower delivered what is known as the Atoms for Peace address at the United Nations in New York City, in which he called on "the entire body of the world's scientists and engineers" to abandon the military use of atomic reactions and instead adapt their studies "to the arts of peace."

Most scientists focused on fission, but a handful of researchers, regarded by some mainstream academics at the time as mavericks or dreamers or con artists, realized that fusion was the ultimate, world-changing prize, and set about trying to utilize it. The first generation of fusion machines, incorporating mirrors or lasers or electric currents, all ended in miserable failure. Some simply didn't work or were exposed as frauds, while others formed plasma that lasted a fraction of a second before collapsing.

Plasma, physicists learned, was a fiendish substance. Containing it has been compared to wrapping jelly in rubber bands. Volatilities in plasma—events that snuff the reaction—were given descriptive names: kink instability, sausage instability, bump-in-tail. The list totals more than 50. By the time of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, held in Geneva, Switzerland, in 1958, world leaders generally agreed that all nations' nuclear energy research should be declassified and shared. The Soviet Union, concurring, disclosed a breakthrough that was later given the name tokamak, a shortening of the Russian phrase "toroidal chamber with magnetic coil."

The tokamak was an elegant design that could achieve hotter plasmas and longer confinement times than anything before. No fusion device had ever been more promising, and scientists calculated that bigger tokamaks would provide the volume needed to maintain plasma in a stable and energetic state. By the late 1970s, three separate giant tokamaks were in development: in Princeton, New Jersey; Oxfordshire, England; and Naka, Japan. Hundreds of millions of dollars were spent on each one, and optimism surged. But years passed in which none of these new machines came close to proving that fusion was economically feasible. Fusion, observers like to say, is 20 years away—and always will be.

> IF IT ALTERS THE COURSE OF CIVILIZATION, THE REACTOR WILL BE SEEN AS A BARGAIN. BUT IT WILL BE, BY FAR, THE MOST EXPENSIVE SCIENTIFIC INSTRUMENT ON EARTH.

At a juncture when fusion could've easily been abandoned, it was unexpectedly revived. In 1985, Soviet leader Mikhail Gorbachev and U.S. president Ronald Reagan held a summit in Geneva, their first ever meeting. The agreement they reached included a declaration that the two nations, and any other countries willing to join them, would work together to build a fusion reactor "for the benefit of all mankind." And thus from the endgame of the Cold War was born ITER.

BICKERING AND INFIGHTING commenced immediately. ITER is inhuman in scope—hot, cold, immense, subatomic—yet can also seem like the most human thing ever, bloated by geopolitics, red tape, and hubris. Two dozen European countries and Japan promptly joined the alliance, and with no nation holding majority control, haggling began over ITER's technical design and cost. The squabbling dragged on for years, through the breakup of the Soviet Union in 1991—Russia remained with ITER—and bureaucratically onward into 1998, when the U.S., having spent $345 million on what some officials felt was basically nothing, quit the project.

The remaining members soldiered on and finished the design specs—ITER's machine will have five times the volume of the next largest tokamak—around the time that the U.S. government, urged by American academics, rejoined the program in 2003. That same year, China and South Korea also signed up, followed soon after by India. ITER had become the United Nations of science, a home for "the best and brightest from all over the world," as one ITER executive rosily described it. In reality, though, a disparate medley of cultures with rudderless governance meant that the project was behind schedule and over budget as a matter of course.

The battle over where to build the machine consumed more years of politicking, ultimately coming down to France or Japan. A compromise was reached, and it was decided that there would be a Japanese director general and a French worksite. Ground was broken in January 2007, a mere 21 years after the Gorbachev and Reagan accord in Geneva.

Seven more years of preparatory work ensued—clearing and leveling the site, then creating an elaborate foundation fitted with shock absorbers to protect the machine from potential earthquakes. Just over a decade ago, in 2014, construction finally began on the monumental tokamak housing, the centerpiece of the 39 buildings and technical areas sprawled across ITER's campus. Specialists in dozens of fields, plasma physics to electromagnetics to cement pouring, were recruited and hired. The ITER site has its own bus system, plying the paved perimeter roads, while dirt lanes in the middle are a cacophony of forklifts, dump trucks, and backhoes, with teams of hard-hatted workers marching around on foot. In late 2018, the first of the machine's 10 million pieces was put into place.

These pieces are being manufactured by member nations across the globe, then shipped to the worksite in France. The chief contribution of the U.S. is the central solenoid, the megamagnet, which is being built by General Atomics, a family-owned business in San Diego. Russia is contributing additional magnets and superconducting materials. Europe is creating some of the main tokamak hardware, and South Korea the rest. India is supplying cooling system apparatuses; Japan is fashioning heating structures. About 5,000 companies worldwide have been involved in the effort.

Some parts made abroad are the size of a basketball court and weigh more than a passenger jet. Many are heavily wrapped and encased in a protective frame before being loaded onto a cargo ship. From Asian countries, the trip to France takes more than a month. The package is then balanced on a barge and floated up a canal and across a lake. The last 65 miles are on roads, which were reinforced and widened, permitting a 352-wheeled transport platform to creep at three miles an hour all night for three or four nights to arrive at ITER.

How much will all of this cost? It's hard to know exactly, as there is no official global accounting. The ITER agreement signed in 2006 claimed that the entire project, including the value of items made by members, would cost around six billion dollars, start to finish. That price has ballooned to $65 billion, more than 10 times the original estimate, according to the U.S. Department of Energy. If it alters the course of civilization, fusion supporters say, it'll be seen as a bargain—even the new figure represents less than three days of current global expenditures on energy—but ITER will be, by far, the most expensive scientific instrument on Earth.

Many of ITER's delays and cost overruns have been self-inflicted—an internal assessment of ITER's management practices detailed pricey design changes and administrative gridlock—but some have been beyond the project's control: storms at sea, pirates in the Suez Canal. The 2011 earthquake and tsunami in Japan interrupted parts production there for a year. The COVID pandemic slowed the world for two more. Yet through everything ITER churned inexorably on.

Then came an extraordinary accomplishment. ITER may be the world's largest jigsaw puzzle, but the most essential construction, the tokamak and attached components, has been reduced to nine massive pieces, called vacuum vessel modules. These will fit together like segments of an orange. Each weighs about 1,500 tons. To move one, ITER had to invent several new lifting machines. Workers rehearsed the sequence of events that needed to happen. And on May 12, 2022, the first module, made of parts supplied by almost every ITER member, was tucked perfectly into its spot.

The milestone, decades in the making, was a celebrated ITER triumph. Now that one module was in place, the other eight would surely follow. After all the hurdles, the machine was going to get built, and switched on. There was light at the end of the tunnel.

And then the project nearly self-destructed.

ITER IS ENTIRELY DEPENDENT on funding from federal governments, which can be fickle sources of money. Politicians like to hear about success and momentum, even when the reality is, according to the internal ITER report, that management is blundering and the engineering challenges are more formidable than anticipated. Some cheerleading by the project's leadership is expected—in 2015, the U.S. was reportedly considering a second ITER exit, and in

In 2006, ITER's cost was estimated at six billion dollars; that has since risen to an estimated $65 billion. The increase has partially stemmed from delays, inefficiencies, and mistakes. Here, thermal shielding expert Kevin Bhadaniya stands next to a panel of a vacuum vessel sector; recently, a portion of the panel needed to be replaced.



order to stay, needed to be convinced that progress was coming. But what happened at ITER is that showmanship seemed to have eclipsed honesty, and in a project of exacting, revolutionary science, this was bound to bring disaster.

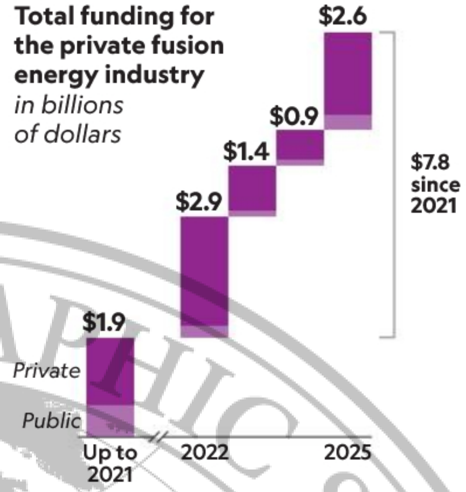
The placement of the vacuum vessel module in 2022 generated glowing news reports from major trade publications. The job, however, was apparently done in a corner-cutting rush. Inspections revealed tiny cracks and pinhole leaks. The tokamak was compromised. The module couldn't be repaired where it was, wedged tight, and the installation couldn't be reversed without partially tearing the machine apart. Workers didn't know what to do, and construction of the tokamak ground to a halt.

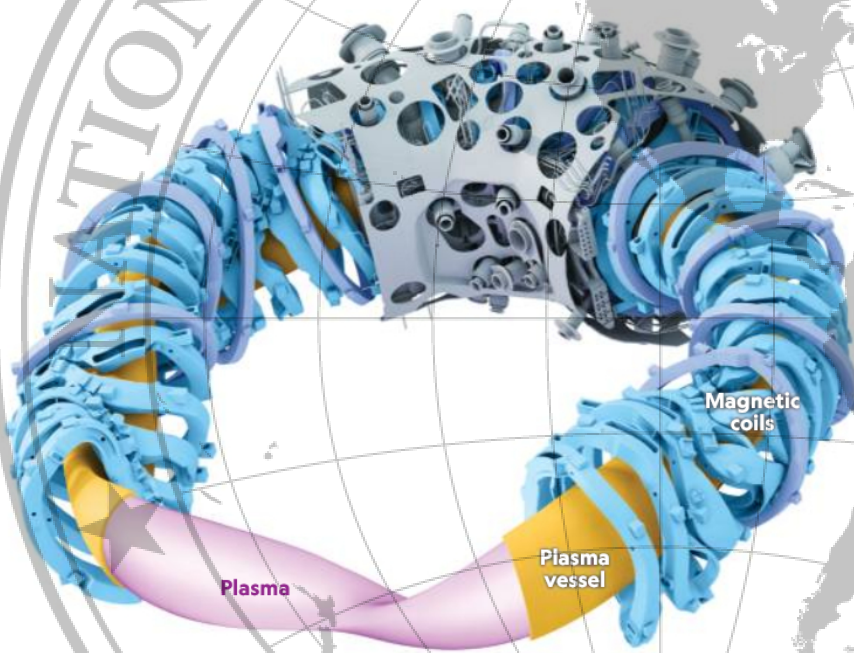
At the very moment ITER needed decisive leadership, there was none. Two days after the module was hung, the director general of ITER, Bernard Bigot, died of an illness at

# THE RACE FOR FUSION

ITER is by far the largest nuclear fusion endeavor, but it is by no means the only one. Government facilities like those at the Max Planck Institute and the Lawrence Livermore National Laboratory, as well as private companies like Zap Energy and TAE Technologies, are testing different methods to achieve fusion. Over the past four years, funding for the private industry has nearly quadrupled.

*Illustrations by* TOMÁŠ MULLER




## STELLARATOR

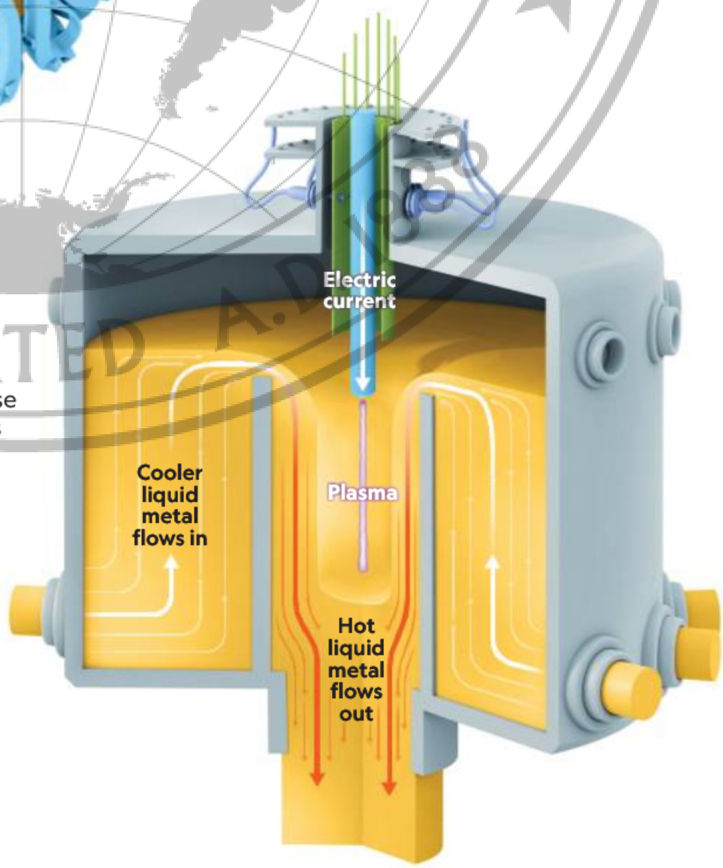
Invented in 1951, stellarators use a magnetic confinement method similar to that of ITER's tokamak. Their torqued design, as seen with the Wendelstein 7-X (left), requires absolute precision but potentially yields more stable plasma.

**Max Planck Institute for Plasma Physics**
*Greifswald, Germany*

## Z PINCH

Inspired by lightning strikes, the Z-pinch process uses electric currents to generate magnetic fields that rapidly compress and confine plasma, producing fusion reactions that release energy. Zap Energy hopes its device's compact, modular design will make it relatively simple to commercialize.

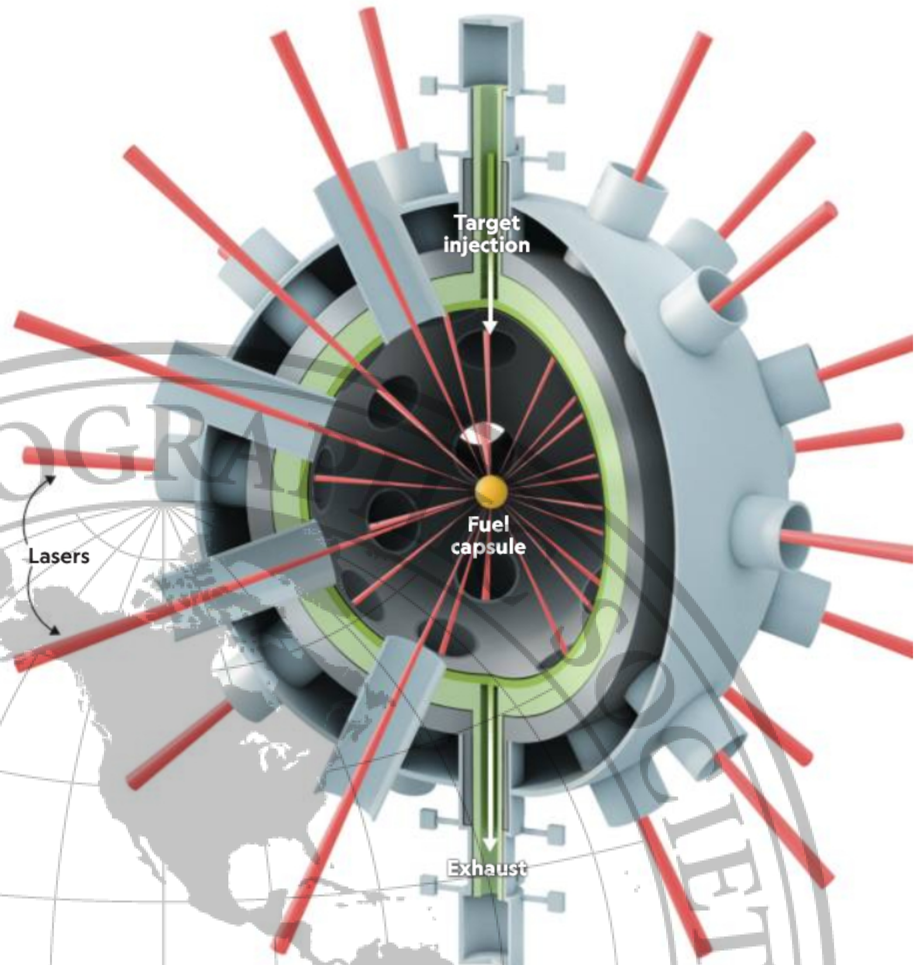
**Zap Energy**
*Seattle, Washington*

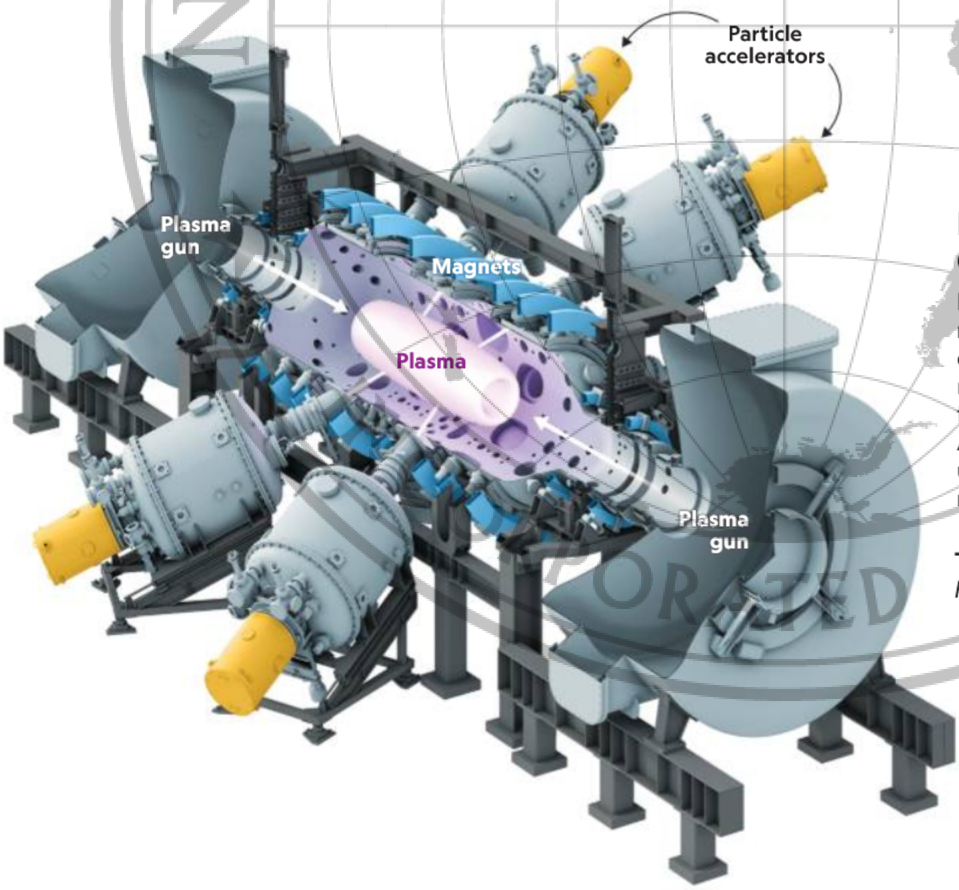


## INERTIAL CONFINEMENT

Inside a spherical chamber, high-energy lasers compress a tiny fuel capsule filled with deuterium and tritium, creating a fusion reaction. The publicly funded National Ignition Facility was the first fusion experiment to generate surplus energy, and is the basis for future inertial confinement designs.

**National Ignition Facility**
*Lawrence Livermore National Laboratory, Livermore, California*



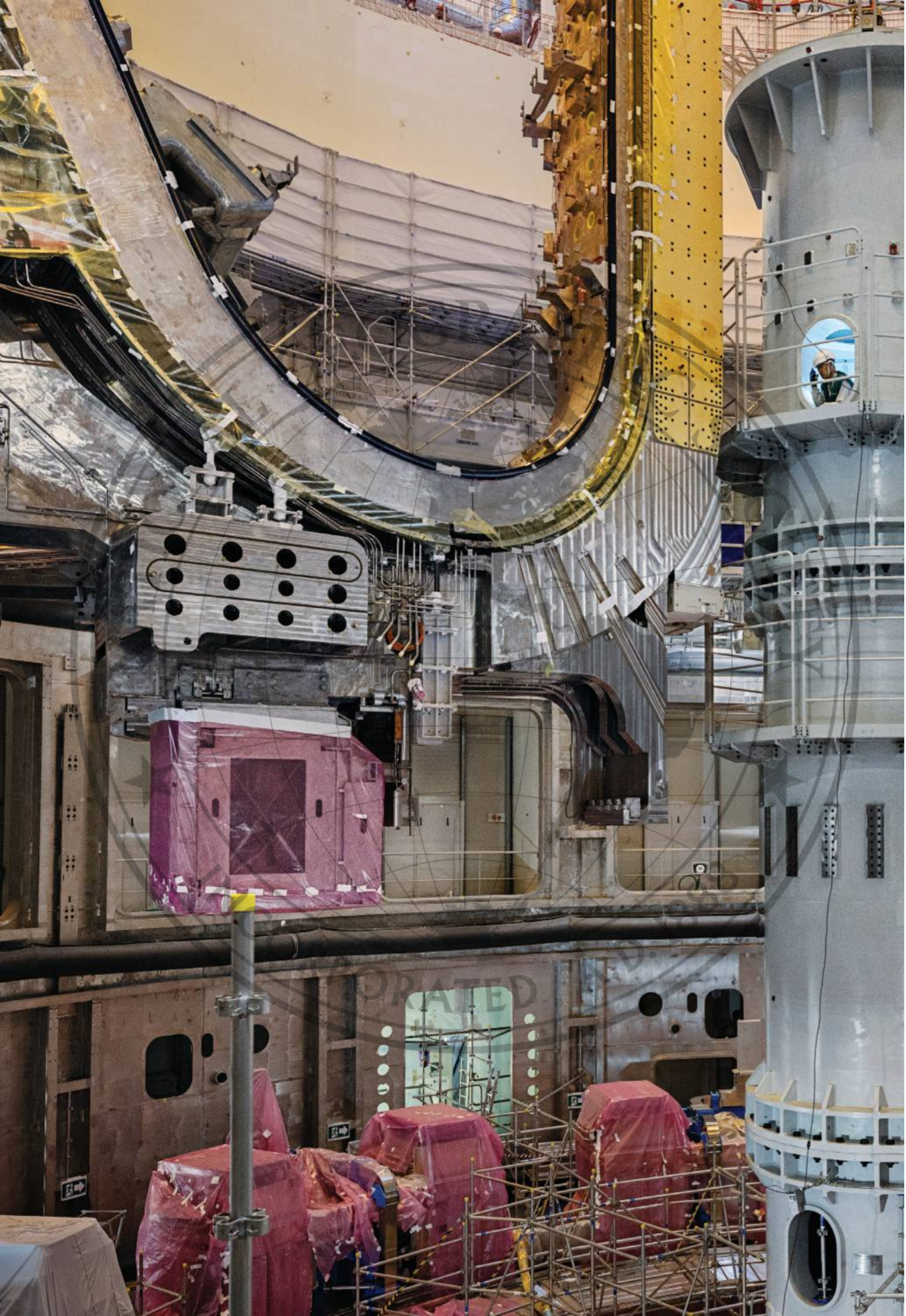

## FIELD-REVERSED CONFIGURATION

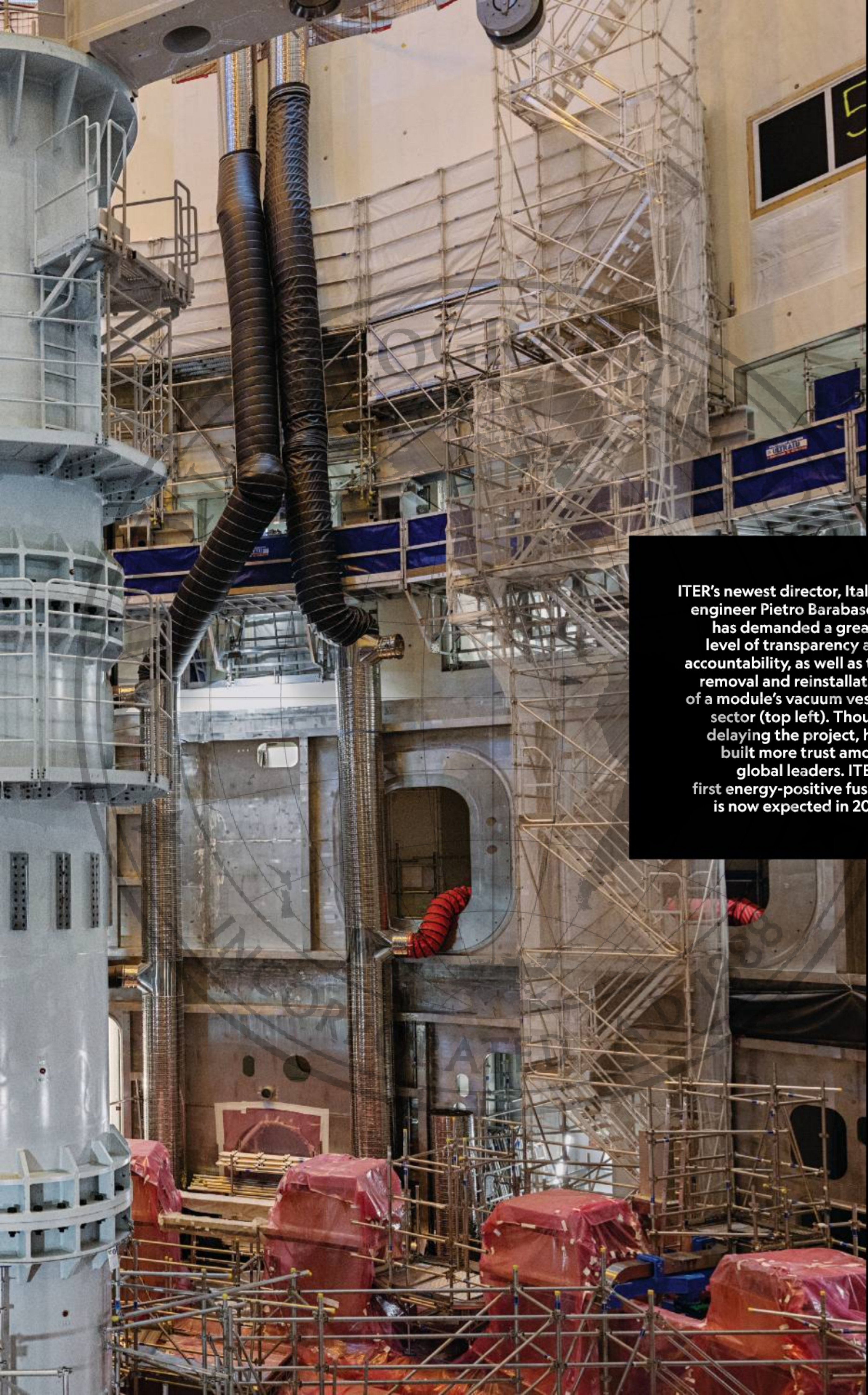
Neutral beams heat plasma in a smoke-ring-like formation and drive electric currents that generate internal magnetic fields, largely replacing the need for external magnetic confinement. Alternative fuels like hydrogen-boron used by TAE will produce no neutrons or radioactive waste—only helium.

**TAE Technologies**
*Foothill Ranch, California*

ILLUSTRATIONS BASED ON CURRENT EXPERIMENTS

GRAPHIC: JASON TREAT AND ALEXANDER STEGMAIER, NGM STAFF
SOURCES: FUSION INDUSTRY ASSOCIATION; MAX PLANCK INSTITUTE FOR PLASMA PHYSICS; LAWRENCE LIVERMORE NATIONAL LABORATORY; ZAP ENERGY; TAE TECHNOLOGIES





ITER's newest director, Italian engineer Pietro Barabaschi, has demanded a greater level of transparency and accountability, as well as the removal and reinstallation of a module's vacuum vessel sector (top left). Though delaying the project, he's built more trust among global leaders. ITER's first energy-positive fusion is now expected in 2039.

age 72. Bigot, a French physicist, was ITER's third chief, following two Japanese directors, Kaname Ikeda and Osamu Motojima. All three executives seemed to succumb, at least somewhat, to the organizational malaise known as "big project syndrome." A warehouse at ITER is filled with parts that nobody knows who ordered or why. The head of communications before Bigot's tenure, Michel Claessens, later admitted that ITER's public statements often contained "lies, propaganda, and misinformation," creating an atmosphere that resulted in the reckless installation of the vacuum vessel module.

An Italian electrical engineer named Pietro Barabaschi, who has a long history in fusion, was appointed by the project's governing body, the ITER Council, to take over. Approachable, energetic, informal—he often comes to work in jeans and running shoes, and everyone calls him Pietro—he seems comfortable amid chaos. He's 59 years old, lanky and tall, and speaks fluent Italian, English, and German, as well as workable French. Taming fusion, says Pietro, is like humans learning to harness fire for the second time in history. Being burned by mistakes is inevitable, and he publicly pledged that ITER would be transparent about them, and even published an article in the science journal *Nature Reviews Physics* titled "The Importance of Documenting Failure." Pietro's first major decision as director was that the vacuum vessel module would be removed, at enormous expense and multiple years of holdup. Either the project would be done right, he implied, or it wouldn't be done at all.

The sentiment among ITER workers seemed to be that Pietro clearly made the right choice, and might have just killed the project. "I thought that was it, the end of ITER," says communications officer Sabina Griffith, who has worked at the site for almost two decades. Lola Zedet, an ITER construction coordinator, said that

**BUILDING A GIANT FUSION MACHINE IS 'BOTH A SPRINT AND A MARATHON,' SAYS ITER'S NEW DIRECTOR PIETRO BARABASCHI, 'WITH SURPRISES AROUND EVERY CORNER.'**

the news of the module's removal was both understandable and shocking. After the insane scramble to get the vacuum vessel module in place, the world had been turned upside down. "Shifts of people were looking at each other and doing nothing," says Zedet. "It was almost surreal." But after some time and mental recalibration, she says, the crews returned to work, and the unbuilding of ITER began.

**MANY FUSION EXPERTS** believe that success is more probable from a nimble private company motivated by profit than from an overstuffed public project like ITER. There are currently more than a hundred private fusion initiatives worldwide battling for a potentially epic grand prize of an energy fortune.

ITER's avuncular stance is that there isn't competition at all—the true dream is fusion energy for the globe, and the more places attempting it, the better the chance it will happen. Private firms are welcome to visit the site, to study what's worked and what hasn't, and to tap into a fount of hard-earned wisdom. ITER, striving to distribute knowledge rather than produce commercial energy, is like the public library of fusion. Also, ITER shares the results of its extensive diagnostics and testing on parts and materials, allowing others to save time and money, and push on. It appears unlikely that any private firm will make the public effort obsolete.

From the outside, it seemed like ITER was going backward right through to the end of 2024, each day further from completion, the machine dismantled, the vacuum vessel module pulled out and then itself disassembled, then tests to determine the course of repairs. But on the vast campus, the culture had shifted toward progress. In Pietro's view, so many elements of the project were pioneering, entering the realm of the unknown, that ITER was like a scientific Lewis and Clark. They'd gotten lost for a while in the wilderness, but had reorganized and streamlined the management structure, and soon would be navigating smoothly again. For every problem that may be encountered, Pietro believes, there exists a reasonable solution. Government funding during this reset did not dry up.

In April 2025, just shy of three years since the vacuum vessel module had first been installed, it was put in again and the project was back to zero. Two months later, the second segment was mounted. The remaining seven are all in various stages of completion. The jobsite is buzzing, welding sparks flying from the construction zones, cranes swinging through the sky, physicists scribbling on whiteboards.

Pietro, putting in 12-hour days, bounces from meeting to meeting, often taking a total of six minutes for lunch, enough to wolf down a sandwich or salad. "It's both a sprint and a marathon," he says of ITER, "with surprises around every corner." But no matter how crammed his schedule, Pietro tries to observe two traditions. A couple of times a week, he puts on a hard hat and protective gear and goes alone to observe the tokamak construction, climbing up the scaffolding to get to his favorite spot, at the very top, with a bird's-eye view of the machine, all of the ambition and folly and genius of it. He just takes it in for a while, the sound of hammering echoing continuously, a metallic smell in the air. Then gets back to work.

The other tradition is his first meeting of the morning, usually at six o'clock, in the distinctly unfancy office of the head of construction, Sergio Orlandi, a longtime colleague of Pietro's and a fellow Italian. Orlandi is 69 years old and has worked on nuclear projects for 45 years. As the sun rises over the southern French hills outside Orlandi's window, they have coffee and discuss the plans for the day. Pietro calls this his moment of calm, but before he's halfway through his coffee, you can see his energy building, his left foot tapping, clicking his retractable pen, faster and faster, until the visit is done and he's out the door.

Orlandi says that he often doesn't interact with Pietro again for the rest of the day, but 30 minutes is all it takes for them to stay synchronized. The project has stuck to the schedule, without fail, for more than a year, which is an all-time ITER record, and Orlandi expects this progress to continue for the foreseeable future. He seems to feel that ITER has achieved unstoppable momentum. Perhaps this boost will be enough to follow the plans right up to the day of ITER's first energy-positive fusion, slated for 2039, a historic moment that could shape the planet's destiny, so long as nothing goes wrong. ▯