A Star in a Bottle

An audacious plan to create a new energy source could save the planet from catastrophe. But time is running out.

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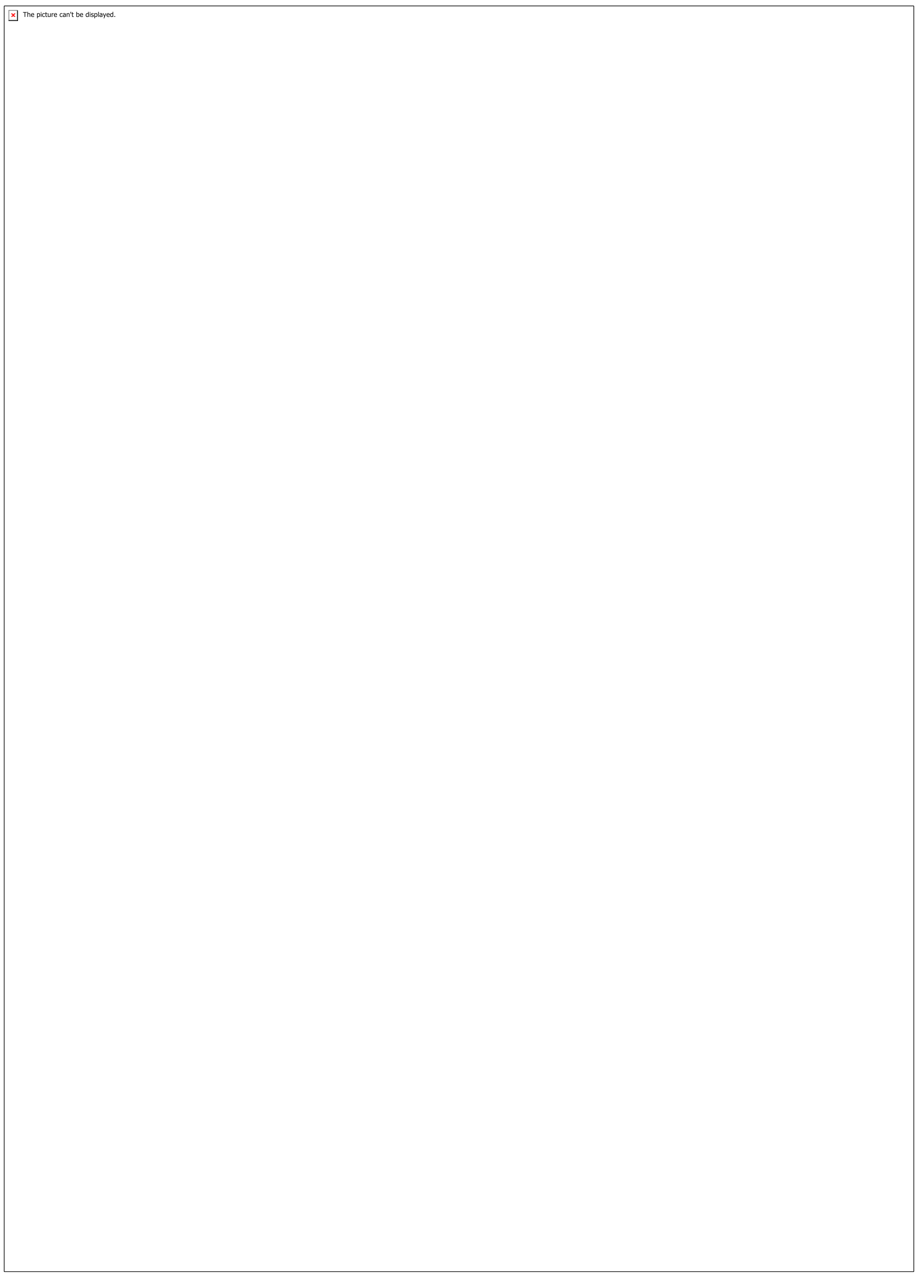

Commercial reactors modelled on *ITER* could generate power with no carbon, virtually no pollution, and scant radioactive waste. Illustration by Jacob Escobedo

Years from now—maybe in a decade, maybe sooner—if all goes according to plan, the most complex machine ever built will be switched on in an Alpine forest in the South of France. The machine, called the International Thermonuclear Experimental Reactor, or *ITER*, will stand a hundred feet tall, and it will weigh twenty-three thousand tons—more than twice the weight of the Eiffel Tower. At its core, densely packed high-precision equipment will encase a cavernous vacuum chamber, in which a super-hot cloud of heavy hydrogen will rotate faster than the speed of sound, twisting like a strand of DNA as it circulates. The cloud will be scorched by electric current (a surge so forceful that it will make lightning seem like a tiny arc of static electricity), and bombarded by concentrated waves of radiation. Beams of uncharged particles—the energy in them so great it could vaporize a car in seconds—will pour into the chamber, adding tremendous heat. In this way, the circulating hydrogen will become ionized, and achieve temperatures exceeding two hundred million degrees Celsius—more than ten times as hot as the sun at its blazing core.

No natural phenomenon on Earth will be hotter. Like the sun, the cloud will go nuclear. The zooming hydrogen atoms, in a state of extreme kinetic excitement, will slam into one another, fusing to form a new element—helium—and with each atomic coupling explosive energy will be released: intense heat, gamma rays, X rays, a torrential flux of fast-moving neutrons propelled in every direction. There isn't a physical substance that could contain such a thing. Metals, plastics, ceramics, concrete, even pure diamond—all would be obliterated on contact, and so the machine will hold the superheated cloud in a "magnetic bottle," using the largest system of superconducting magnets in the world. Just feet from the reactor's core, the magnets will be cooled to two hundred and sixty-nine degrees below zero, nearly the temperature of deep space. Caught in the grip of their titanic forces, the artificial earthbound sun will be suspended, under tremendous pressure, in the pristine nothingness of *ITER*'s vacuum interior.

For the machine's creators, this process—sparking and controlling a self-sustaining synthetic star—will be the culmination of decades of preparation, billions of dollars' worth of investment, and immeasurable ingenuity, misdirection, recalibration, infighting, heartache, and ridicule. Few engineering feats can compare, in scale, in technical complexity, in ambition or hubris. Even the *ITER* organization, a makeshift scientific United Nations, assembled eight years ago to construct the machine, is unprecedented. Thirty-five countries, representing more than half the world's population, are invested in the project, which is so complex to finance that it requires its own currency: the *ITER* Unit of Account.

No one knows *ITER*'s true cost, which may be incalculable, but estimates have been rising steadily, and a conservative figure rests at twenty billion dollars—a sum that makes *ITER* the most expensive scientific instrument on Earth. But if it is truly possible to bottle up a star, and to do so economically, the technology could solve the world's energy problems for the next thirty million years, and help save the planet from environmental catastrophe. Hydrogen, a primordial element, is the most abundant atom in the universe, a potential fuel that poses little risk of scarcity. Eventually, physicists hope, commercial reactors modelled on *ITER* will be built, too—generating terawatts of power with no carbon, virtually no pollution, and scant radioactive waste. The reactor would run on no more than seawater and lithium. It would never melt down. It would realize a yearning, as old as the story of Prometheus, to bring the light of the heavens to Earth, and bend it to humanity's will. *ITER*, in Latin, means "the way."

The main road to the *ITER* construction site from Aix-en-Provence, where I had booked a room, is the A51 highway. The drive is about half an hour, winding north past farmland and the sun-glittered Durance River. Just about every form of energy is in evidence nearby, from hydroelectric dams to floating solar panels. Seams of lignite, a soft brownish coal, run beneath the soil in Provence, but the deposits have become too expensive to mine. Several miles from Aix, a large coal plant, with a chimney that climbs hundreds of feet into the sky, is being converted to burn biomass—leaves, branches, and agricultural debris. *ITER* is being built a mile or two from the wooded campus of the Commissariat à l'Énergie Atomique et aux Énergies Alternatives, a state-funded research organization, created in 1945 to advance nuclear power, and now also renewable energy. Evergreen oak and Aleppo pine cover the foothills; beneath them, the French government maintains its largest strategic oil reserve.

ITER's headquarters, a five-floor edifice, was erected two years ago. An undulating wave of gray concrete slats shade its floor-to-ceiling windows. Its interior is simple: whitewashed walls, polished-concrete floors. The building's southern façade overlooks a work site, more than a hundred acres of construction on the opposite side of a berm. By the time the reactor is turned on—the formal target date for its first experiment is 2020—the site will be home to a small city. Nearly forty buildings will surround the machine, from cooling towers to a cryogenics plant, which will produce liquid helium to cool the superconducting magnets. A skywalk extends from the second floor of the headquarters to the berm, where a capacious *NASA*-style control room will one day be built. For now, the bridge ends in a pile of ochre dirt, and the only way to the vast expanse of construction is via a circuitous drive.

When I arrived, on a late-summer morning, the air was dry and warm—filled with the aroma of pine, lavender, and wild thyme. Five hundred people work for *ITER*'s central organization, but an unusual sense of quiet and vacancy permeated the place; this was August in France, and many workers had taken time off. The atmosphere seemed to be drawn from the imagination of J. G. Ballard: the modernist husk of a utopian project, half-finished, half-populated, isolated amid a primeval forest. A few people with clipboards stood beneath the sun to map out an expansion to the headquarters. To save money, an entire wing had been abandoned during the construction, and employees worked out of temporary annexes—their staircases and walls hollow, like stage sets—built several hundred yards away, with shuttle buses moving among the buildings. The busing has proved to be impractical, and so the wing will be constructed after all, though now at greater expense.

In a bare lobby, I wandered over to a model of the reactor core: a cylinder, dense with mechanical parts, rendered in brightly colored bits of machined plastic. *ITER*'s design is based on an idea that Andrei Sakharov and another Russian physicist, Igor Tamm, sketched out in the nineteen-fifties. It is called a tokamak—old Soviet shorthand for a more precise and geometrical name, *toroidalnaya kamera s aksialnym magnitnym polem*, or "toroidal chamber with an axial magnetic field." Sakharov's rough sketch depicted a doughnut-shaped vacuum chamber, or torus, ringed with electromagnets, and that is how *ITER*'s core will look, too, once it is completed.

In myriad ways, the project is a fragment of the Cold War stranded in the present day. Sakharov had predicted that a reactor based on his sketch would produce energy in only ten or fifteen years. Subsequent physicists who built and ran experimental tokamaks were equally optimistic, always predicting success in a decade or two or three. Yet, while other scientific challenges have been overcome—launching Yuri Gagarin into orbit; delivering a rover to Mars; sequencing the human genome; discovering the Higgs boson in *CERN*'s Large Hadron Collider—controlled thermonuclear energy has remained elusive. The National Academy of Engineering regards the construction of a commercial thermonuclear reactor—the kind of device that would follow *ITER*—as one of the top engineering challenges of the twenty-first century. Some in the field believe that a working machine would be a monument to human achievement surpassing the pyramids of Giza.

ITER was first proposed in 1985, during a tense summit in Geneva between Ronald Reagan and Mikhail Gorbachev, who agreed to collaborate "in obtaining this source of energy, which is essentially inexhaustible, for the benefit for all mankind." Since then, the coöperation has expanded to include the European Union, China, Japan, South Korea, and India. In the *ITER* lexicon, each partner is a Domestic Agency. Unlike any previous scientific collaboration, no partner has full control, and there is no over-all central budget. Each country makes its primary contribution in the form of finished components, which the *ITER* organization will assemble in France. The arrangement could serve as a model for future collaborations—or as one to avoid. At the headquarters, there is a circular dais, where representatives from the Domestic Agencies come and sit, with flags and placards before them, like members of the U.N. Security Council. But there are limits to diplomacy in nuclear engineering. Big machines either work as they're supposed to or they don't. Compromise and politesse can be disastrous. Thousands of components—many of them huge machines in their own right—must be slotted beside one another, more or less perfectly, and there will be scant ability to correct imperfections after they are delivered. Ultimately, the project's success may rest on a simple question: Will everything fit together?

Stefano Chiocchio, *ITER*'s head of design integration—its chief puzzle master—works in one of the temporary annexes near the headquarters. His BlackBerry typically contains an impossible schedule of overlapping appointments, forcing him to conduct meeting triage as he rushes around like a zigzagging atomic particle. Rather than take the shuttle among the buildings, he drives his car to save minutes. When he speaks, he often gets halfway through a sentence, stops, and says, "O.K."—ending his thought right there. Sometimes a friend will stop him mid-stride, and say, "Stefano," and smooth out his rumpled collar.

Chiocchio's engineers are, in a sense, the project's Praetorian Guard, as one *ITER* official told me. So far, the vast machine exists only as 1.8 terabytes of digital information, accessible on a secure computing cloud, and backed up every night to a bank of hard drives in Barcelona. The hard drives are secured, but the main threat to the files is the work itself—with alterations to the design coming simultaneously from the *ITER* headquarters, from the Domestic Agencies, and from subcontractors around the world. Ideally, the changes are added only with the Praetorian Guard's approval. Still, incompatibilities proliferate, with many lying in wait like insurgents. Chiocchio's team must hunt down entire taxonomies of conflicts—"nonconformities" and "clashes" and "deviations." On most days, it seems that there aren't enough hours to do it.

I was supposed to meet Chiocchio on the fifth floor of the main building, but when I arrived there was no receptionist, no security to speak of, no one I could find to ask where he was. I heard my footsteps echo down the long, sunlit corridors as I looked for him. In one conference room, I interrupted a meeting, and a few seconds later a short, smiling man in his fifties came rushing out. It was Chiocchio. His hair, virtually gone on top, graying and wavy on the sides, framed a tired face with rounded features. Greeting me warmly, he ushered me back into the room, and urged me to sit.

Two dozen engineers were seated around tables arranged in a horseshoe, and the mood was sombre. A sense of crisis has come to surround *ITER* like the concentric nebulae of a dying sun. The project has been falling behind schedule almost since it began—in 1993, it was thought that the machine could be ready by 2010—and there will certainly be further delays. Morale is through the floor, and one can expect cynicism, disagreements, black humor. "There is anxiety here that it is all going to implode," one physicist told me. Many engineers and physicists at *ITER* believe that the delays are self-inflicted, having little to do with engineering or physics and everything to do with the way that *ITER* is organized and managed. Key members of the technical staff have left; others have taken "stress leave" to recuperate. Not long ago, the director-general, Osamu Motojima, a Japanese physicist, who has run the organization since 2010, ordered workmen to install at the headquarters' entrance a granite slab proclaiming *ITER*'s presence. People call it a tombstone.

Chiocchio's engineers had assembled to discuss their most urgent problem: delays in constructing the enormous building that will house the tokamak. The holdup had its own history. *ITER* had ended up in Provence following years of geopolitical argument over its location. The fight narrowed until just two countries remained, France and Japan, and finally a compromise was struck: the site would be in France, but *ITER*'s director-general would be Japanese. There are many reasons that building a project like *ITER* in France makes good sense; France is singularly reliant on nuclear power, and Europe has built some of the world's most well-regarded tokamaks. But the region is prone to earthquakes, and to winds so strong that they can cause a large building to sway several inches. So the machine, along with two structures housing critical equipment, will be built on a special foundation—a concrete slab, called the B2 slab—that will be supported by hundreds of anti-seismic plinths, in what *ITER* engineers call the Tokamak Seismic Isolation Pit. The slab must support three hundred and sixty thousand tons of equipment and infrastructure.

Early on, to maintain the schedule, construction was rushed forward, even though significant portions of the tokamak design were incomplete. It was like building the shell of a rocket before its engine is designed—or worse, because, as Chiocchio said, "one of the difficulties with this nuclear building is that after it is built, in many cases, you cannot drill a hole in it. Once a wall is finished, that's it. The building has a safety function, a confinement function, and one of the main requirements is that it has no cracks through which radioactivity can migrate and escape. We have to be sure that we have not missed anything—every pipe, every cable—because if we do miss something, and someone says, 'O.K., let's just bolt this to the wall'—well, no, we cannot do that." And yet *ITER*'s tremendous scale and machine density make it virtually impossible to know where everything will go. Six thousand miles of cable will run through the machine, delivering electrical power to two hundred and fifty thousand terminal points. One heating system will send a million watts of microwave radiation through a window made of a large synthetic diamond. The system will require perfectly straight tubular guides to transport the waves; no other component can impede them.

To solve the riddle of building-before-machine, the engineers have been designing special portals throughout the structure. "Basically, what we have to do now is make sure we have predefined places, with steel plates embedded in the walls, where we can support all the systems that we have inside," Chiocchio explained. "We have to put in a lot of these embedment plates, more than eighty thousand, but each one costs a lot of money, and the European Domestic Agency, which is responsible for the building, is complaining that we are putting in too many." Complaints become arguments, arguments become delays, and delays with the building now threaten the whole project. "If the building is not finished, we will have components sitting along the road. A day of delay now starts costing, I don't know, probably close to a million euros."

In the conference room, the engineers studied a PowerPoint presentation titled "TKM Complex—B1 level status week 34 and actions week 35." A member of the design-integration team, Jean-Jacques Cordier, was leading the discussion. As the meeting ended, he noted that there was not enough time to vet the components that occupy the third floor: plans had to be gathered, specifications brought up to date, problems reconciled. "It is not reasonable," he said. "It means that we would need to process thousands of data points in three weeks." Chiocchio asked if things would speed up after early floors were finished, but there were simply too many details to work through before delivering drawings to the contractor. "We have no more float," Cordier said. "If we delay now, we will have a real delay. The only way to avoid a schedule loss is to increase our resources to cope with it."

That afternoon, Chiocchio joined me for lunch. He seemed exhausted. *ITER*, by the time it is finished, will contain ten million individual parts, but he had only twenty-eight people working for him. He later showed me a room near his office where three men sit at workstations every day to hunt down conflicts. Before each man, there was the huge *ITER* puzzle in miniature, filling up two computer screens. Up close, the design looked as though someone had taken the industrial landscape that runs alongside the New Jersey Turnpike and compressed it into a cube the volume of a Holiday Inn. "We have to check everything, from clashes to interfaces—like here," one of the men said, pointing to a schematic where a support structure for the tokamak was not lining up with an embedment plate. To fix it, he would have to inform a team of designers two floors below. Usually, members of the Guard relay messages that others do not want to hear, he said, adding, "In fact, we are not well loved by everybody."

As Chiocchio saw it, many design conflicts arise because of the project's political underpinnings. Changes to one component often make others (built in other countries) more expensive, and the ensuing arguments are difficult to resolve. From the outset, each Domestic Agency vied to build the machine's state-of-the-art components, so that its industries could gain the know-how; as a result, the design and the manufacture of the most sophisticated parts have been split apart in ways that are politically expedient but are at odds with engineering prudence. A single manufacturer should build *ITER*'s vacuum chamber, a high-precision device that must operate with perfect symmetry. Instead, it will be constructed in nine segments, two in Korea and the rest in Europe. The design calls for certain features to be welded, but the Europeans decided to use bolts, which are cheaper. The Praetorian Guard, with little more than the power of persuasion, must insure that the device is whole.

Common frames of reference are often hard to find, and Chiocchio was constantly working to prevent *ITER* from becoming a scientific Tower of Babel. He pushes scientists to use the same terminology (even, occasionally, the same language), and to use the same metric standard of measurement. It is the job of a scold, but he has been with *ITER* for two decades, and, like many people who build tokamaks, he came to the project with a sense of mission. Thermonuclear energy—or nuclear fusion, as it is also called—differs from fission, the type of atomic reactions harnessed by existing reactors, and its promise is vastly greater. An engineer who has devoted his career to the goal of a working reactor once told me, "Fusion has an interesting pathology to it—the allure of it is so immense." In the *ITER* headquarters, one can sense this: a psychological force that attenuates, or confines, pessimism like a magnetic field. I picked up on it one afternoon when a dispirited physicist brightened as he made the case, half joking, that the spaceship in "Star Trek" was powered by fusion.

Chiocchio has been touched by it, too. He had started his career in fission, his interest emerging out of dire predictions about peak oil. "There was this story of limited growth, how the planet would be affected by its lack of resources, and I thought nuclear energy would help solve this," he told me. "But, after a few years, I was, let's say, *impacted* by Chernobyl, which stopped nuclear activities worldwide. In Italy, the project that I was working on came slowly to an end—O.K., it wasn't stopped, but it was clear that there was no more political support for building new nuclear plants." He eventually found contract work with a European tokamak called the Joint European Torus, or *JET*, and later made his way to *ITER*. "Fusion looked like it would have a chance—a clean alternative to fission," he said. "But there is a difference: fission is a reality. Fusion is on its way toward reality."

II—THE STAR BUILDERS

The basic physics of thermonuclear energy is seductively simple. Fission produces energy by atomic fracture, fusion by tiny acts of atomic union. Every atom contains at least one proton, and all protons are positively charged, which means that they repel one another, like identical ends of a magnet. As protons are forced closer together, their electromagnetic opposition grows stronger. If electromagnetism were the only force in nature, the universe might exist only as single-proton hydrogen atoms keeping solitary company. But as protons get very near—no farther than 0.000000000000001 metres—another fundamental force, called the strong force, takes over. It is about a hundred times more powerful than electromagnetism, and it binds together everything inside the atomic nucleus.

Getting protons close enough to cross this barrier and to allow the strong force to bind them requires tremendous energy. Every atom in the universe is moving, and the hotter something is the greater its kinetic agitation. Thermonuclear temperatures—in the sun's core, fifteen million degrees—are high enough to cause protons to slam together so forcefully that they are united by the strong force. Hydrogen nuclei slam together and form helium. Helium nuclei slam together and form beryllium. The atoms take on more protons, and become heavier. But, strangely, with each coupling a tiny amount of mass is lost, too. In 1905, Einstein demonstrated, with his most famous equation, $E=mc^2$, that the missing mass is released in the form of energy as the nucleus is bound together. The quantity of energy is awesome—in some cases, a thousand times what is needed to get atoms to bind in the first place. Without it, stars would not burn, and space would remain forever cold.

The sun is, essentially, a four-hundred-quintillion-megawatt thermonuclear power plant, fuelled by billions of years' worth of hydrogen. Five* million tons of it is converted into energy every second. "If you go back, really far, you see the first caveman crawl out of his cave and be surprised every time the sun came up—that was the first time mankind encountered a fusion reactor," Ned Sauthoff, a physicist at Oak Ridge National Laboratory, in Tennessee, who serves as *ITER*'s American project manager, told me. "It was ninety-three million miles away. But, of course, the caveman was impressed by the warmth and the light, and, being human, he said, 'How can I have one of those?' "

In this quest, humanity first dabbled with fire, a pale facsimile of the sun, and then with scientific fraud. In 1951, Argentina's President, Juan Perón, announced that, on the island of Huemul, his scientists had built the world's first thermonuclear reactor—something that neither the United States nor the Soviet Union, with their grand weapons programs, had sought to do. Crude fission reactors, yes: Enrico Fermi had created one in Chicago as early as 1942. But, at that time, fusion had only one real place in the American scientific imagination: the hydrogen bomb, still in secret development, not yet detonated.

The announcement was front-page news in the *Times*. Perón extolled the reactor, pronouncing it "transcendental." Instead of providing details, he introduced the project's chief designer, Ronald Richter, a scientist from Austrian-controlled Czechoslovakia who had conducted military-sponsored research in Germany during the Third Reich**. On Huemul, Richter had built a concrete bunker, nearly the shape of a cube, which housed a machine that he called a "thermotron." Few people had access to the device, and what little Richter described quickly raised doubts. Some physicists suspected that he was a swindler, or crazy—though an American intelligence assessment wondered if he was a "mad genius" who was "thinking in the year 1970." When public pressure grew for a demonstration, Richter began to act erratically. He made requests for gunpowder, to improve the efficacy of his machine. Eventually, military technicians went to visit Huemul, and returned announcing the "Richter discovery a colossal bluff."

The triumphant announcement, followed by scientific retreat and humiliation, set a pattern that would plague the field for decades. Still, Richter's thermotron did have an unexpected consequence: it prompted American physicists to consider what a genuine thermonuclear reactor might look like. The day the *Times* published the story, Lyman Spitzer, a thirty-six-year-old Princeton astrophysicist who had been recruited to work on the hydrogen bomb, rushed out to get a copy. Spitzer was among the thermotron's skeptics, but he was intrigued. With fusion reactions a million times more energetic than fire, two and a half pounds of the right hydrogen isotopes could produce as much energy as eighteen million pounds of coal.

Spitzer was on his way to Aspen for a ski trip, and as he went up the chairlifts, again and again, he turned the idea over in his head. As an astrophysicist, he was familiar with the punishing conditions that stars require to burn, and the lack of any physical material to contain them. At the super-high temperatures necessary for fusion, the hydrogen atoms would be unlike any of the common states of matter—solids, liquids, or gases—but would exist as ionized gas, or plasma, which would have unique electrical properties. Ninety-nine per cent of the visible universe is plasma. Spitzer knew that the ionized gas, with its free-floating charged particles, would respond to magnetic fields. Perhaps, he reasoned, a system of magnets could contain a thermonuclear cloud in a vacuum. The plasma would never have to touch a thing.

Spitzer was given time off from his bomb work to set up a secret thermonuclear-energy project in an old rabbit hutch at Princeton. He designed a tabletop device, which he called a stellarator, that looked like a pipe twisted into a figure eight. When the device was first turned on in the darkened hutch, an instantaneous purple glow appeared: the plasma, lasting a millisecond. Eventually, Spitzer was able to heat the ions to a million degrees. As he tinkered with his stellarator, government investment in thermonuclear energy began to increase, with budgets entering the millions, and competing scientists developed different magnetic bottles. There was the Perhapsatron, the "mirror" machine, the Fusor.

No matter the approach, the physicists reasoned that, as the plasma became denser, hotter, and longer-lasting, the conditions for fusion would eventually be met. But, because the point of the research was to build a commercial reactor, simply fusing atoms would not be enough. The plasma would have to produce at least as much energy as the physicists were pouring into it—an atomic breakeven—and then, beyond that, generate a net gain in energy. The ultimate goal, which the physicists called "ignition," is to excite the plasma to a state where it will heat itself like a star, requiring the barest effort to sustain and control.

The early machines performed terribly. They sucked up huge amounts of energy, only to run instantaneous plasmas. As the physicists quickly realized, they were working against physical conditions totally inhospitable to thermonuclear energy. In the sun's inner core, gravity is so crushing that light and heat from fusion can take more than a hundred thousand years to zigzag through the thick gas and reach Earth. With that kind of pressure impossible to replicate here, the scientists sought to compensate with extreme temperature. But the plasma had other ideas. Merely containing it long enough to heat was a challenge. One had only to look at the surface of the sun—a roiling sea of plasma instability—to see why. One scientist compared the effort to holding jelly in rubber bands.

In 1958, with progress largely stalled, the work was declassified and exchanged with academics, and even with the Soviets. The West learned of Sakharov's tokamak, conceived during a break in his bomb work. The tokamak had trouble with plasmas, too, but it was a remarkably elegant design. Spitzer had fashioned his vacuum chamber into a figure eight to correct for an unavoidable imbalance in magnetic fields. Sakharov had designed a chamber that was compact, symmetrical, shaped like a doughnut—the torus. To correct for the same magnetic imbalance, he decided to drive a powerful current through the plasma, to keep it from drifting. The process would not only stabilize the swirling ionized gas but also heat it. Soon, tokamaks were achieving new milestones: denser, hotter plasmas. No device was more promising. If a self-sustaining star could be formed inside Sakharov's chamber, the heat could drive turbines that would provide near-limitless energy.

By the time Chiocchio joined *ITER*, in 1993, the field of fusion had travelled an uneven road of setbacks and accomplishments. Scientists were building bigger and bigger tokamaks, having calculated that as the chamber's volume increased so would its capacity to maintain a plasma that was stable and energetic enough to heat itself. The bigger the machines got, the more expensive they became, and more was expected of them. In Washington, their shortcomings were harshly judged—especially as the oil crises of the nineteen-seventies waned, and oil seemed plentiful. In the eighties, two chemists announced that they had produced "cold fusion": thermonuclear reactions, at room temperatures, in what looked like an ordinary test tube. The claims were quickly exposed as a fraud, adding a patina of credulousness to genuine research that was already struggling with credibility. And yet, by 1993, physicists were making a clear approach toward breakeven. They were hopeful that if they could build a big enough machine the barrier could be breached—decades of frustrating effort would finally yield energy.

In those early years, *ITER* had—for the only time in its history—a single visionary at its helm: a French physicist named Paul-Henri Rebut. Balding, with intense eyes darting behind large glasses, Rebut had designed *JET*, a widely praised machine with a vacuum chamber big enough to walk through. Some colleagues referred to him as a genius; he could attend to engineering obstacles with extreme focus, and was able to visualize simple solutions for intricate problems. At *JET*, Rebut wandered the halls of the design office at night—he thought more clearly while pacing—and sometimes he went from workstation to workstation, penning corrections or x-ing out whole ideas. "He could be brutal," Chiocchio recalled. "But he was very, very clever."

Once Rebut had agreed to take charge of *ITER*, he moved with characteristic boldness. For years, in various workshops, a conceptual design had been sketched out for a dual-purpose machine that was partly an experiment to prove fusion's feasibility and partly a prototype for a commercial reactor. Rebut tossed out the design and replaced it with his own: a gargantuan device, in effect a full prototype. In his mind, fusion was already feasible—and, as he had once explained, "There is a general tendency not to be harsh enough in this field and to go too slowly, not to make the necessary step large enough." He envisioned a vacuum vessel seventy-two feet in diameter. Its plasma would produce a gigawatt, or a billion watts, possibly more, and run for a thousand seconds. He saw no point in the massive global effort without chasing the ultimate goal: ignition.

At that time, *ITER* had no formal organization. "All of us were basically assigned to this international team from our own countries," Chiocchio recalled. Three offices were opened: one in Garching, Germany, where components inside the vacuum chamber were being worked on; another in Naka, Japan, which concentrated mostly on magnets; and a design center in San Diego, where Rebut was based. Chiocchio worked in Germany, but he sometimes flew to see Rebut. "I remember he had a chair with wheels, and was rolling among the workstations of the designers," he recalled. "Rebut himself was the integrator. We were sending them faxes every evening, and they were sending us responses by fax every morning. We were joking, this is design by 'strategic fax.' But the approach was not entirely entropic. It had an advantage. Instead of working eight hours a day, we were working sixteen."

The design was extremely elastic: features shifted continually in relation to other features that were also shifting. "The team was not so big, so we knew each other well," Chiocchio said. Working at the conceptual level—without worrying over fine details—they could grasp what colleagues in other divisions were doing. The plasma was constantly exerting new and unforeseen forces, which the *ITER* engineers struggled to measure and to incorporate into their designs. "The mentality of fission is that there is a systematic process—you define your loads, your criteria, and then you produce a design," Chiocchio told me. "At the beginning, at *ITER*, sometimes I would ask my boss, 'Can you tell me what the main requirements are for this component?' And he would say, 'What are you talking about? Try to find a solution.' It was a bit more of a, let's say, *creative* engineering environment."

Rebut himself did not bother documenting the requirements. This was information that he kept easily in his head. An American representative urged him to work in a more standardized way, but he refused. The design was growing in scale and cost, and Rebut's intuitive style and unwillingness to engage in basic diplomacy began to work against him. In 1994, the United States succeeded in having him removed. As it was not Rebut's way to leave subtly, he went to Congress, and argued that the *ITER* organization had insufficient legal authority, insufficient independent funding, and, perhaps worst of all, a leadership of incompetent bureaucrats. By focussing on consensus, he argued, the parties made decisions based on the lowest common denominator. The representatives assigned to the *ITER* Council were "more concerned with the work awarded to each home team than by the success of the engineering design activity." If things did not change, Rebut predicted, the machine would never succeed.

I*TER* was only an idea, a pile of schematics worked out in three countries by intercontinental fax, and yet the collaboration was already fraying. In the United States, the 1994 Republican revolution ushered into Congress lawmakers hostile to internationalism—especially in the case of a scientific project that offered no immediate utility. No one could doubt the vision in Rebut's design, but the price—ten billion dollars—was conspicuous for a field that had generated not one electron of net power. Even within the fusion community, there was growing skepticism. Fearing that the American contribution to *ITER* would soak up funding for domestic research, some scientists quietly lobbied against it. In 1996, two physicists from the University of Texas at Austin, William Dorland and Michael Kotschenreuther, joined with researchers at Princeton to run a computer model based on the *ITER* design; it suggested that the reactor had no chance of meeting its goals. The story made the *Times*. The people who were with the project embraced the news, Chiocchio told me: "The team reacted in the right way. It was not 'No, no, no'—it was really trying to understand, based on their analysis, how we should correct anything." But within political circles the *Times* story could not have been encouraging.

The *ITER* team reached out to James Sensenbrenner, the chair of the House Committee on Science, which oversaw the fusion-research budget. "Sensenbrenner visited Naka, to see the prototypes that we had built for the vacuum vessel and the magnets," Chiocchio said. "The people who organized the visit told me, ‘Ah, we really managed to convince him that we are using the taxpayers’ money well.’ ” Sensenbrenner returned to Washington and set out to insure that *ITER* would never be built. Congress cut funding for the project, and in 1999 the United States withdrew; the San Diego office was shut down, flights were cancelled, and American physicists were instructed not to participate. Chiocchio told me, “We thought it was the end of *ITER*.”

The timing was painfully ironic: the justification for the project was only growing stronger. For decades, physicists had been working with a heavy hydrogen isotope called deuterium, which is abundant in seawater. Calculations had long indicated that a half-and-half mixture of deuterium and tritium—an even heavier hydrogen isotope—would produce the ideal conditions, but tritium is rare and radioactive; it would irradiate expensive machines that were not fully designed for it. In the nineties, two tokamaks experimented with it sparingly. One, at Princeton, achieved temperatures as high as five hundred million degrees, and in three years of experiments made huge advances. In Europe, scientists at *JET*, using only ten-per-cent tritium, produced more than a megawatt of fusion power. The trial fell short of breakeven, but the scientists estimated that, with the ideal tritium mixture, their plasma would have produced more energy than was put into it—for the first time, in theory, a net gain. Several years later, they set out to confirm their estimate, and succeeded in producing a sixteen-megawatt plasma, a record, though they still narrowly missed breakeven. As Chiocchio put it, “There was really this impression that we were very close to the target.”

The history of physics is littered with unrealized grand experiments: old blueprints buried in file drawers, half-built machinery packed in crates, excavated earth filled with pooling rainwater—the detritus of Big Science. As the frontier of human knowledge pushes forward, so, too, does the cost and the complexity of further exploration. Telescopes grow larger. Space is probed at greater depths. Atomic particles are smashed more forcefully. Many scientific questions now demand resources that no individual can marshal—no single university, no single company, and, increasingly, no single government. “But big science has the special problem that it can’t easily be scaled down,” the physicist Steven Weinberg recently observed in *The New York Review of Books*. “It does no good to build an accelerator tunnel that only goes halfway around the circle.” And so such projects are often born out of vexed politics, then hampered by limited funding, and by a willingness to abandon them at any time. To some extent, the experiments that succeed are aided by a willful dose of unrealism—budgets imagined too lean, timetables too short, human behavior too nearly ideal. Crisis emerges when reality finally asserts itself.

In facing such a crisis, *ITER* was not alone. Many large machines have been commissioned, and then, as costs soared, cancelled midway. Last summer, at the Princeton Plasma Physics Laboratory—a federally funded institution that grew out of Lyman Spitzer’s rabbit hutch—I was shown the partially assembled segments of a device called the National Compact Stellarator Experiment. Each piece was an exquisite metallic artifact, made primarily of stainless steel, curving and twisting in ways that could not have been designed before the advent of supercomputers. The assembly requirements were so precise that building the thing in the way that the laboratory promised was impossible. The project—tens of millions of dollars over budget, and years behind schedule—was killed five years ago, though it was hard to tell, as the scientists spoke dreamily about seeing it assembled one day. In a way, the machine suffered a less painful fate than the Mirror Fusion Test Facility, at Lawrence Livermore National Laboratory, which was fully built before it was defunded, in 1986—without being used even once.

In the nineties, there was every reason to think that *ITER* had reached its end, too, with America's role in it so significant, and the mood in Washington so austere. But, as Weinberg told me, "It is hard to turn off international collaborations"—large-scale bureaucratic inertia can be its own saving grace. By the time the United States withdrew, another French physicist, Robert Aymar, was in charge, and he decided to reduce the astronomical cost by making a smaller machine. The redesign had to be conducted on a tight budget, with a small staff; begun in 1998, it was not completed until 2001. The new machine would be built for the ideal tritium mixture, but it would no longer strive to attain ignition. Instead, it would produce ten times the energy fired into the plasma, at half a gigawatt. Aymar put its value at five billion dollars, and the number—precisely (and conveniently) half of *ITER*'s earlier cost—was soon cited as its price. But the estimate was intended only as a guide to divide work among the parties, and did not consider real-world manufacturing expenses, or the unusual way the work would ultimately be split up. The design was still far from complete, and just about everyone knew that the figure was a gross underestimate. "Of course, bureaucrats wanted to get *ITER* approved, and politicians were happy to turn a blind eye," an official told me. "If they would have said, 'Oh, instead of five billion this will be fifteen billion,' then probably nobody would have wanted to build it."

Urged by a consensus of American academics, the United States rejoined; an agreement formally binding the parties together was finally signed, and offices for the American Domestic Agency were opened at Oak Ridge. But the willful unrealism remained. The first two leaders of *ITER* had no background in plasma physics. The director-general, Kaname Ikeda, was a Japanese civil servant and a nuclear engineer. His chief deputy, Norbert Holtkamp, came from the world of high-energy particle accelerators. Holtkamp did what he could to shield the fledgling organization. "He once said, 'If you spend as much money as you can, after the first billion no one is going to stop us,' and so he spent and spent and spent," one former *ITER* engineer told me. "The design wasn't finished! But he just wanted to go already: move, move, move." (Holtkamp denies making the comment.) Science and politics fused. When European engineers who had invested decades of research on tokamak inner walls proposed building *ITER*'s, a Chinese official stood and, deeply upset, argued vehemently that it was the height of arrogance to presume that China could not manufacture a wall. And so it was decided: China would make part of the wall.

Soon enough, reality again asserted itself: the schedule slipped, and costs rose. In 2010, Ikeda and Holtkamp were out, and Osamu Motojima was in. As a plasma physicist, as a fusioneer, Motojima understood what was at stake: if *ITER* fails, the quest for thermonuclear energy might be set back indefinitely. After taking the helm, he declared, "The dream is alive!" One afternoon, David Campbell, *ITER*'s chief physicist, told me, "I can go across the hall and look at the construction site, and sometimes I have to tell myself, 'We're building *ITER* out there!' It took a long time to get this far. Even though there are frustrations with the system, even though the members are not happy because the cost has gone up and the schedule is longer than they want, everyone is committed to it."

III—INTO THE MACHINE

When I walked up to the Commissariat à l'Énergie Atomique, Chiocchio was standing at the front gate, shielding his eyes from the sun. He seemed taken aback by my presence, and then he smiled warmly and told me that there wasn't much time. It was 8 *A.M.*, and we were trying to make an 8 *A.M.* meeting in a "virtual reality room" that *ITER* was renting from the C.E.A., in order to study the tokamak design in three dimensions. We still had to get credentialled, and then drive through the sprawling grounds.

A few minutes later, we parked at the back entrance of a concrete building, and I followed him through a steel door and into a massive hall. "This is the building for Tore Supra—the first European superconducting tokamak," he said. We walked past the machine, a twenty-five-year-old behemoth designed by Aymar. Tokamaks, as they are currently designed, work in pulses, and in 2003 Tore Supra set a record for the longest plasma pulse: six minutes. A few years later, a Japanese tokamak ran for five hours. These long pulses did not attempt to generate energy; rather, they attempted to show that a tokamak could one day produce a plasma that engineers call "steady state." *ITER* is being designed to run its highest-performing plasmas for up to five hundred seconds; but a real reactor would need to work continuously—something that no one has figured out how to do.

We rushed through a dim lobby and then into a small room, where about fifteen engineers had convened. A blurry rendition of the *ITER* tokamak was projected on a large screen, and polarized goggles were being handed out so that the 3-D effect would be perceptible. I put on the goggles and looked at the cylindrical reactor core, its dense crush of parts, rendered in bright colors, seeming to float in a vast gray horizonless space. The projection had the tactility of an object. Chiocchio walked over to the window, and stood next to another engineer. "You better take your seat or you will lose it," he said. He pointed to an empty chair and laughed. "This is how it works: competition, O.K.—" There was no point in his sitting anyway. He could stay for only a few minutes before the next meeting.

A senior member of the Praetorian Guard was running the review: Jens Reich, a lanky German mechanical engineer with the intensity of an overworked Ph.D. candidate. Reich grew up near the Baltic Sea, and started his career in R. & D. for washing machines and other household appliances. When money for the research dried up, he applied for a job at the Max Planck Institute for Plasma Physics, which was hiring people to build a billion-dollar stellarator called Wendelstein 7-X. Right away, he sensed that he belonged to an important but easily misunderstood mission. "I have friends working on solar power," he told me. "What we are doing is not so obvious."

The purpose of Reich's review was primarily to evaluate changes that various Domestic Agencies were proposing for the magnets, beginning with one called the central solenoid, the most important American contribution to *ITER*. In grade school, children often make solenoids by wrapping wire around a nail and then attaching the wire to a battery: the current magnetizes the coil. *ITER*'s solenoid will work in the same way, but it will weigh a thousand tons, and stand as a forty-foot column in the center of the vacuum chamber. Its coil will be more than twenty miles long, and it will be made with niobium-3-tin, an exotic material rarely used in large industrial projects. The metal was selected because it can generate extreme magnetic fields: two hundred and sixty thousand times greater than Earth's. Key to the original Soviet tokamak design, the solenoid will send huge pulses of electricity through the plasma, to heat and stabilize it. David Everitt, the engineer at Oak Ridge in charge of the magnet's construction, told me to think of it as a giant sparkplug. "It will be a technological wonder," he said. "It has to do so many things. The current is not constant. It has a very high magnetic field—not the highest ever, but very high—and where the current in one module is opposite the one in the adjacent module there is a very large separating force."

When *ITER* engineers talk of a very large separating force, what they mean is a cataclysmic rupture. The solenoid will be built in six modules, stacked one atop another like poker chips. The benefit of this design is that the various modules can run opposing magnetic fields, giving physicists the ability to mold the plasma in different ways. The drawback is that those fields also create tremendous opposing forces, which are inclined to blow the stack apart if they are not severely counterbalanced. The magnet's designers have calculated that the forces can reach sixty meganewtons, or twice the thrust that a *NASA* Space Shuttle requires for liftoff. The stack can compress just as powerfully. When structural engineers learned of the design, their reaction was: Holy mackerel! You want to do *what*?

Depending on whom you talk to, the history of the central solenoid epitomizes either *ITER*'s flaws or its ability to overcome them. From the start, the magnet's technical requirements indicated that it would be extremely difficult to build. To prevent the solenoid from launching through the roof, a thousand and eighty screws must be fixed to the top and the bottom, to keep the stack in viselike compression. Moreover, niobium-3-tin is difficult to work with. It does not attain its superconducting properties until it is baked: cables made with strands of it must be coiled into a module, then heated for days in a custom-made furnace flooded with argon gas. The strands, each one less than a millimetre thick, are interwoven with copper. In the furnace, the metals bind into a fragile matrix that later cannot be flexed.

"The challenge for the central solenoid is that it has to ramp up every time you do a plasma shot, which is thousands of times during the lifetime of the machine—so you have to create a superconducting cable that can pulse tens of thousands of times without degrading, and that is very hard with niobium-3-tin," an engineer who worked on the magnet told me. "It is a brittle material. How is it not going to become dust? With each pulse, you are literally breaking it, micro-fracturing it. So what is the solution? Don't pulse so many times, or pulse with less energy. But you cannot do either. If you pulse with less energy, then you don't get the heating that you need, and if you pulse fewer times then the life of the machine is shorter. So you are pushing up against the limit of what the material can do."

The project's internecine politics made matters only worse. People at *ITER* use the term "conductor zoo" to refer to the menagerie of materials going into the magnets. The niobium-3-tin strand is produced by a dizzying array of subcontractors in six countries, in ways so disparate that their samples even look different. As Chiocchio explained, “You have suppliers from all over the world, and it is really a nightmare.” Japan, which had worked on the prototype for the solenoid, wanted a hand in developing its cables, so it campaigned to supply its own materials to the zoo. In 2010, two Japanese companies sent samples to a test facility in Switzerland. The results were spectacularly poor. The solenoid is designed to run sixty thousand pulses in *ITER*’s lifetime, but the Japanese cable was degrading after six thousand. Engineers began to worry: “Is this going to be a fatal flaw for *ITER*?”

Officials at Oak Ridge, concerned that the schedule was at risk, contacted an *ITER* supplier in New Jersey, Oxford Superconducting Technology, which was producing niobium-3-tin strand for other large magnets in the machine. They requested a sample that could work for the solenoid, and in 2012, after it performed well in tests, they urged the Japanese to purchase the material from Oxford. “In the structure of *ITER*, it was very hard to convince the Japanese that was something they wanted to do: spend a lot of money in the U.S. on conductors,” a former Oak Ridge official told me. The Japanese refused, and the threat of delay grew. The engineers—attempting to maintain the spirit of collaboration—tried twisting the Japanese cable more tightly, in the hope that it would perform better. New samples were sent to Switzerland, and, after more than two years of discussion and trials, the Japanese product finally worked. “There was a whole lot of relief around the world,” the former official said. Some engineers were proud of the teamwork, but the problem need not have existed, and the issue remains sensitive. When *Science* published a news item about the success, Motojima wrote to say that it was unfair to imply that the Japanese manufacturers had ever failed. “This is not correct,” he insisted.

The effects of the delay are still evident on the ground. Officials at Oak Ridge had subcontracted the construction of the solenoid to General Atomics, a family-owned company in San Diego, with a portfolio that ranges from nuclear batteries to algae-based animal feed. After winning the contract, in 2011, General Atomics constructed a sixty-thousand-square-foot workspace, in a large building overlooking the dry arroyos of Sycamore Canyon. (The building belongs to a corporate affiliate that makes Predator drones, though that part is “secure.”) Before I flew to France, the solenoid project’s chief engineer gave me a tour of the vast, mostly empty space. He talked about the problem of how to move the extremely heavy modules among workstations. In addition to a thirty-five-ton crane, he had purchased a large pallet that glides on a cushion of compressed air. A company called Airfloat makes them for various industries; an airplane fuselage or a locomotive built on an Airfloat pallet can slide like a shopping cart.

“That magnet is so heavy that we had to spend time super-duper reinforcing the floor,” a spokesperson for the company said. Nearly a million dollars’ worth of concrete had been poured, mostly to a depth of eighteen inches—capable of bearing two hundred tons, the combined weight of a module and the equipment needed to work on it. As the concrete set, it was precisely levelled: a tilt of more than an eighth of an inch spanning ten feet was unacceptable. Too great an incline would disturb the air beneath the pallet, allowing millions of dollars’ worth of superconducting cable to drift out of control. The floor looked like a shelf of polished glass; as we crossed it, I asked the chief engineer if he was ever tempted to put on skates and race across.

He grinned, and said, “We’ve had all kinds of crazy ideas, about having a criterium in here—a bunch of us have bikes—or a roller-hockey tournament.”

A hundred feet away, two young people were working in what seemed like an Arctic encampment atop the shelf. They were wearing white Tyvek bodysuits, and were dipping the superconducting cable into epoxy, trying to figure out another problem: coils of the material seemed to be shrinking after they were vacuum-sealed. We walked over to a massive slinky: empty cable jacketing from Japan that had arrived in a plywood box stamped “Fragile.” The slinky contained half a mile of metal. This is how all the cable will come. The engineer shook his head at the scale.

General Atomics had wanted to make several changes to the solenoid’s design, and, with the *ITER* team convened in the C.E.A.’s virtual-reality room, Jens Reich begin to review them. Above the virtual tokamak, there was a command: “Navigate—fly.” The session’s pilot—a technician holding a joystick—stepped forward, and navigated the team through the cyberscape. We swooped toward *ITER*’s base, then into the vacuum chamber. The computer could not handle the entire *ITER* schematic in 3-D, so on Reich’s command the renderings for most of the machine were subtracted, leaving only the solenoid.

Working though a checklist from General Atomics, Reich guided the pilot to various locations. Some features—pipes and cables—were shielded in casings, so the pilot used a tool to cut through the shielding, as if it were an object. Reich asked the pilot to bisect the solenoid, and the team studied its cross-section. To manufacture the magnet, General Atomics wanted to alter its geometry, and when the pilot measured the modules it was clear that they had slightly widened. Reich made a note: if the available gaps in the design were too small, the consequences would be severe. A bit later, he noticed two pipes that went nowhere. “How about those?” he said. “What is that?” No one knew. “There is an intermediate piece missing,” he said, and noted it. On the whole, though, Reich was pleased. The design was nearly final, and he was already considering the magnet’s complex installation.

In May, the Japanese are scheduled to begin delivering the conductor to General Atomics, which is scheduled to complete all six modules by 2018. The company will ship the finished pieces to the Port of Galveston, with each module—fourteen feet in diameter—delivered on trucks propelled by as many as thirty axles, to support their weight. The journey will likely be made after midnight, because the trucks will need to occupy two highway lanes. In Galveston, the modules will be loaded onto a ship that will travel to Fos-sur-Mer, near Marseilles. From there, they will be hauled along a specially fortified road to the tokamak’s assembly hall, and stacked and compressed and wired and tested. The height of the hall is dictated by the height of the solenoid. Once the stack is built, it will be attached at its top to a crownlike jig. Suspended from the ceiling, a sliding crane—with four hooks hanging off steel cables—will lift the jig, and with it the solenoid, hanging vertically. Every variable will be precisely accounted for: the amount the cables will stretch while bearing the immense weight; the crane’s momentum as it moves; the degree to which the magnet will sway; even the weather—the wind hitting the building, and how the force of it might affect the crane’s journey. Slowly, the solenoid—all one thousand tons of it—will be carried to the tokamak and lowered into the center of the vacuum chamber. If it is just millimetres too wide, it will not fit in the tight cylindrical space designed for it. There is no room for error.

IV—THE RED BUTTON

What will happen when *ITER* is turned on? This much is certain: a synthetic star, as it takes shape inside an earthbound device, is a cryptic marvel. The only way to observe it is from the remove of a control room: the magnetic fields are invisible, the plasma makes no sound. But visit a working tokamak—in South Korea or Switzerland or India—and ask what would happen if you stood beside the machine, while it is on, and threw a kitchen magnet into the air. Answer: The magnet would zoom toward the core and blast a hole in the machine. What if the plasma suddenly dissipates? Answer: Gargantuan forces are likely to surge, perhaps even lifting the device, as runaway electron beams tear wildly into the machine. In the control room, it might appear that not much is happening, but you will be surrounded by a science of extremity.

What will happen when *ITER* is turned on? The answer, as with all experiments, is something of a mystery, since no one has yet produced a plasma that is hot and dense and durable enough to heat itself. Will such a thing be more difficult to contain, or will it possess an unforeseen equilibrium?

While *ITER* is running, the machine's central brain, a computer system called *CODAC*, will monitor a hundred and twenty thousand streams of information—among them the plasma's temperature, fluctuations in electromagnetic activity, and the forces that the reactions exert on the machine. Until then, physicists around the world are working with supercomputers to help predict how the atomic particles will behave. Since the first Soviet tokamaks, the plasma's volatile magnetic storms and turbulence are far better understood—one physicist described them to me as swirls within swirls within swirls—but they remain a perplexing scientific frontier. Physicists have developed an entire nomenclature for the instabilities: sawteeth, drift, tearing, sausage, interchange, counter-streaming, helical kink, bump-in-tail. They can seem, at times, like the scientists in Stanislaw Lem's "Solaris," peering into the "plasmatic eddies" of a sentient ocean, whose behavior is beyond understanding.

In the nineteen-eighties, tokamak performance had hit a ceiling because turbulence at the edge of plasmas was impossible to control: electromagnetic eddies carried energy outward from the superhot core in diffuse and unpredictable ways, abrading the tiles on the tokamak walls, sucking impurities into the plasma and cooling it. These instabilities seemed insurmountable until researchers in Germany stumbled upon a discovery: under the right heating conditions, the plasma contained itself by forming a steep, clean pedestal at its perimeter, with its inner temperature and density ballooning. At first, the effect was doubted. There was no theory to explain it, and plasmas had rarely offered gifts, only obstacles. But the pedestal was real, and it was christened H-Mode. It is now ubiquitous in tokamaks, though physicists still have only a general idea how it works, and maintaining it is hard: when the pressure behind the pedestal is too great, the plasma erupts into flares that must be quelled.

It is unclear whether *ITER* will have enough power to achieve H-Mode. The relevant heating systems on the largest existing tokamak are the size of five shipping containers; *ITER*'s will be three times larger, and will have to work in an unproved way, just as pliers the size of a skyscraper cannot be opened by hand. Even if the systems work, there might not be enough of them. Current extrapolations offer only a hazy guide to what *ITER* will require for the pedestal, with the range of uncertainty—what physicists call the error bar—remaining frustratingly large. Joe Snipes, a physicist at *ITER*'s headquarters, told me, "We tried and tried and tried—and when I say 'we' I mean the entire fusion community, experts from around the world working on different machines—we tried to reduce the error bar, but we really couldn't do it; the H-Mode depends on so many different factors that we don't understand." Some engineers wonder if the relevant heating systems—hardware, costing a billion dollars, first developed for Reagan's Star Wars Defense Initiative—have outlived their usefulness in tokamaks. Others believe that everything must be tried, because *ITER* ultimately remains an experiment: mapping the way is its purpose.

Snipes's job will be to run the plasma. Not long ago, in the headquarters, he gave a lecture for engineers titled "Operational Limits on *ITER*." Most of what he had to say involved the uncertainties of plasma behavior, but he reminded his colleagues that some limits might be imposed simply by the way *ITER* is built. While the Praetorian Guard was worrying over the gaps among components, trying to insure that there will be enough space to assemble the machine, the physicists were worrying over them, too. Neutrons are expected to pour out of *ITER*'s plasma like a tsunami. Because these particles have no charge, they will escape the grip of *ITER*'s magnets, advancing through any space that they can find, pushing into, or even through, obstructions—solid matter will not always stop them.

Early on, physicists understood that, as more gaps were introduced into the design, more neutrons would penetrate the machine, heating whatever absorbed them. To study the plasma's effects on the structure, they purchased a million C.P.U. hours on MareNostrum, a supercomputer in Barcelona that is housed in a pristine glass box in the dimly lit nave of a nineteenth-century chapel. *ITER*'s magnets will be encased in a cryostat and continuously cooled with liquid helium. If they get warmer than negative two hundred and sixty-seven degrees, they will "go normal," and lose the quality that makes them superconducting. At that point, the enormous electrical current running through them will look for an alternate outlet, like a dammed river. If all eighteen toroidal-field magnets were to experience this phenomenon at once, forty-one billion joules of energy would seek a new place to go. One scientist compared the outcome to two 747 airplanes simultaneously crashing into the machine.

Complex calculations are required to predict how many neutrons will hit the magnets, but gaps are being introduced faster than the analysis can be done. "The physicist responsible for this is constantly upgrading his models," Snipes told me. "Every little gap causes him tremendous headaches. Now, it probably won't be a problem—we will lower the plasma performance before we get to that dangerous state—but it will limit how high we can go." In other words, even if *ITER* is able to produce record thermonuclear reactions, the machine may not be able to cope with them—an immensely frustrating prospect. Since the days of Dorland and Kotschenreuther, there have been far more encouraging computer models; one predicts that *ITER* could theoretically reach ignition. But, if the gaps proceed apace, even the project's fundamental goals may be compromised.

"This is what happens when you are driven by a schedule that is not realistic, or when you are asked to build a machine with too few people, or too little money—so something has to give," a scientist affiliated with the project said. "Whenever the director-general celebrates a milestone, he doesn't acknowledge the shortcuts that have been taken to get to that milestone." *ITER* is continually being reshaped to meet the demands of lower cost. The tokamak once had two exhaust components, called diverters. Now it has one. "And that is risky," the scientist added. "That's like building only one Space Shuttle, and expecting it to run for thirty years. If something happens to that one diverter, it could take five years to make another, so that might be the end of the project." The compromises are a source of constant arguments, many of which go unresolved or are resolved cynically, people say, because Motojima fosters a culture antithetical to open science, because technical needs give right of way to diplomatic sensitivities, because *ITER*'s organizational structure is being modelled on that of a Japanese corporation—heavy on administration and intensely concerned with projecting an image of progress. "This project is supposed to be about hope, but fear runs rampant within it," the scientist said. "Efforts are made on many levels to hide the problems, in part because people believe the situation can't be remedied, and in part because some of the decision-makers will be dead by the time the big red button is pushed."

By summertime, the working atmosphere within the largest scientific collaboration in history was growing increasingly anxious. "*ITER* has always been a bit of a hectic place to work, eh?" Chiocchio had told me, but the frustrations were clearly mounting. In the previous year, *ITER* had met barely half its goals. The latest target date for turning on the machine—2020—was again slipping. Officials were now quietly talking about 2023 or 2024. What if the schedule continued to slide? Engineers operate in a world of strictly measured loads and heat fluxes, but political forces are impervious to precise measurement. Still, the ultimate repercussions were obvious: there would come a point, eventually, when frustrated politicians decided that *ITER* was simply not worth the increasing expense of delay.

In June, the *ITER* Council gathered in Tokyo, and it was evident that the organization was grappling with its own inner turbulence. At one point, the council member from Korea picked up his papers and stormed out. Ned Sauthoff, the U.S. project manager, bluntly made it known that he thought the project's nuclear-safety culture was lacking. America's involvement was growing more tenuous. The Department of Energy had cut funding for a tokamak at M.I.T. to help pay for *ITER*, and the decision had familiar implications; members of Congress were invited to view the inert machine, and they returned to the Hill expressing outrage. ("*ITER* is going to eat our whole domestic program.") Official estimates of the U.S. contribution had doubled, to a billion dollars, and then rose again, to $2.4 billion, merely to get to "first plasma"—essentially, just turning on the machine. Before summer's end, Dianne Feinstein, the chairwoman of the Senate subcommittee that handles appropriations for energy development, announced that she would discontinue all funding for *ITER* until the Department of Energy provided a detailed assessment of the total American financial commitment. The request was both logical and impossible to answer accurately; even people at *ITER* did not know. The department was reluctant to provide a number, and Sauthoff told me, "We are in unknown territory."

Motojima, meanwhile, was struggling to make the organization simpler and more centralized, but his efforts were trapped in a Catch-22: the Domestic Agencies wouldn't turn over more control to *ITER*'s headquarters without greater trust in its effectiveness, but the organization could never be more effective without greater central authority. Something clearly had to change. When I met Motojima, he had just returned from Siberia—to visit an *ITER* contributor in Novosibirsk—and he seemed tired. He had his own theory about the sinking morale: it was partly caused by the incessant work, but it also had a psychological component, in that people could not witness the physical manifestations of their work. Most *ITER* employees cannot see the construction site from their windows, or components built off-site. In time, large pieces would arrive. Progress would be measurable. Attitudes would shift. From his office, on the fifth floor, construction on the vast tokamak work site was always visible.

Still, Motojima was weathering fierce criticism. It had been decided in Tokyo that, once and for all, the schedule had to be made realistic. A council member told me, "Outsiders look in and say, 'This is rotten.' They say, 'Oh, the project of fusion itself is misguided,' that this is an impossible dream. No, no, no! The leadership at *ITER* is what is rotten. We have to converge on a solution, a possible way out of this mess. If we don't, then we will have trouble—I think a total shakeup of the whole project, the leadership, maybe something else. I mean, any partner country can leave, but that is not very useful, because the project is executable. All the member states are not getting together as one team, with one goal. We have to rectify this."

The shakeup was unavoidable. In October, a confidential management assessment determined that the project was "in a malaise and could drift out of control." It made eleven stark recommendations, among them that Motojima be replaced as quickly as possible. The *ITER* Council convened an emergency session. The stakes were particularly high for the American delegation, which still needed to placate Congress. The Department of Energy had offered Feinstein a new estimate of the U.S. contribution—ranging from four billion dollars to $6.5 billion—and she had agreed to fund *ITER* (and the M.I.T. machine), but not without conditions. About twelve per cent of the money would be withheld until the eleven recommendations were meaningfully followed. In essence, she was saying that *ITER* had to turn itself around, or the U.S. role might again be in jeopardy.

As people involved in *ITER* began to wonder who would succeed Motojima—one suggested Condoleezza Rice—he hastened to make changes. He summarily fired his head of magnets, an outspoken but respected veteran of twenty-six years, and merged the Praetorian Guard's work with that of other divisions. "I am no longer the head of design integration," Chiocchio told me, but, no matter how many times he tried to explain his new place in the bureaucracy, it was hard for me to grasp. He had gained a few responsibilities, and lost others. "Basically," he told me, "I keep doing exactly the same work."

V—THE APOLLO GAMBIT

When Chiocchio joined *ITER*, concerns about energy were largely economic. Climate change has made them a matter of survival. It is virtually an article of faith among some fusioneers that creating miniature stars on Earth is a non-optional part of humanity's future—a view that mirrors arguments put forth by a growing number of environmentalists who once decried nuclear power. The belief rests on a simple premise: burning fossil fuels is a paramount ecological ill, but no existing form of renewable energy can replace it. David MacKay, a physicist at Cambridge

University, once posed the question of what would need to happen for the United Kingdom to entirely stop using fossil fuels. He arrived at this instructive hypothetical: even if the country cut energy consumption by half, it would still require a wind farm the size of Wales, along with fifty new nuclear-fission plants, and photovoltaic cells with twice the surface area of Greater London—but situated in a far-off desert, with the electricity somehow delivered to British consumers.

On a warm afternoon, Chiocchio stopped by the office of Guenter Janeschitz—"*ITER*'s Schwarzenegger," an engineer had told me. Tall, blond, and Austrian, Janeschitz was a senior adviser in the director-general's office, but his role was broader and vaguer than that—as Chiocchio put it, "If you look at the organization, it's not clear where he is." Often, during a crisis, Janeschitz is there. Chiocchio had known him since the nineteen-nineties. "Once, I went to my wife, and I said, 'My life in fusion will be very brief, because I am always arguing with Guenter,' " he recalled. "But then one day he came to me, and he said, 'I like you. You do not say yes to me, and I need people like you.' This made me respect him: he has very strong opinions, but he also really listens to people."

Sitting at his computer, Janeschitz made his case for fusion: "In the next several decades, we have to replace oil, and in the next century we have to replace natural gas—and these two, taken together, represent sixty per cent of the total energy use of every country today. This is a huge amount of energy. To replace it would require many nuclear power stations, or coal-powered stations. Now, coal will be available for a long time, so coal is an option. China is building a coal-powered station almost every week—and that is just coal. But China also has an oil-usage growth of nine or ten per cent per year. This is an exponential curve. This is not sustainable. So we will see, at one point, an increase in the price of oil. When you have a barrel going for two hundred dollars or three hundred dollars, it will be felt throughout the world economies."

Janeschitz pointed to a pie chart of Germany's energy consumption. "You see the renewables are at twelve per cent," he said. "But most of this comes from biomass. Wind and solar make up only two per cent, and they are already built up quite a lot. So maybe we can go up to fifteen per cent, maybe even twenty. But that is it. And the fluctuation in energy for many renewables means that you need a lot of storage. If you have too much, where do you put it? And if you have too little—in Germany, with all this wind energy, they still have gas-powered stations that switch on if the wind is not blowing. Then you have to transfer the energy to where it is needed. In Germany, the wind blows in the North Sea, but much of the industry is in the south. So they have to build electric lines through the country. They are building them now, and the cost is a lot." I later looked it up: the cost is more than three billion euros.

"Fusion should come in at the price of wind," Janeschitz continued. "Some of our colleagues dream of fusion coming in at today's competitive energy prices, but that means that they have to produce science-fiction physics on science-fiction machines. If you are realistic, fusion will not be cheap. But, considering that oil prices will be higher than they are today, then it will be O.K. Coal might be cheap, but because of climate change it will be a big problem. Some people propose sequestering the CO_2 from coal deep into the earth, but, I mean, do you want to live over land with high-pressure CO_2 underneath it? And the energy and expense to capture and transport that CO_2 to a suitable site, and then to press it down—my God, you would have pipelines across the country. And, in two or three centuries, you wouldn't have enough sites to do it. It is like renewables: the problem is scale. Oh, I can harness the wind. I can harness solar. Yes, but now talk about numbers, which most politicians forget. Talk about gigawatts. Talk about terawatts—then things become interesting. This is thousands of nuclear power stations. This is millions of windmills—of course, while the wind is blowing. And, if it doesn't blow, what do you do?"

Critiques of nuclear fission often focus on the waste, but scientists like Janeschitz worry about the supply, too. It is estimated that, with the current reactor technology, the world's supply of uranium will be consumed in about a century. What then? There are designs for more efficient fission reactors, and for "breeder" reactors, which spawn their own fuel, but they will require billions of dollars in investment, and their widespread use might abet the proliferation of fissile material. Will the public accept this? Janeschitz seemed to think no. Robert Iotti, the chairman of the *ITER* Council and an executive in the nuclear-power industry for decades, concurred: "I think *ITER* is an absolute necessity for the world—otherwise I wouldn't put up with the frustrations."

Janeschitz envisions a future in which thousands of commercial thermonuclear reactors will one day operate, with plasmas burning within: points of astral light across the globe. "In my opinion, you need very big fusion power to make it viable—two- or three-gigawatt power stations," he told me. He believes that political will and imagination are the crucial factors in determining when this vision becomes reality. This belief, expressed in this way, is common among his peers, who often use "political will" as a synonym for money. South Korea has a lot of political will. At the moment, China is building a fusion-research facility, in Huainan, that resembles a small metropolis, with an Epcot-like orb at its center, and it is even designing a reactor prototype. As one *ITER* official joked, "We make a modification to *ITER* on a Friday, and by Monday they have added it to the design of their machine."

In the United States, political will has long been governed by a form of Washingtonian special relativity: depending on whether you are inside or outside the fusion community, the view differs dramatically. Typically, outsiders cannot comprehend how the massive expenditures never manage to yield energy. Typically, insiders cannot comprehend how little is being invested in a project that presents such immense technical obstacles and also such potential. A graph commonly passed around among the insiders—an enduring scrap of twentieth-century budgetary ephemera—depicts the 1976 federal plan to build a working thermonuclear reactor. The graph tracks various scenarios for attaining fusion energy. The "maximum" effort, the most expensive up front, with initial spending as high as nine billion dollars a year, was projected to yield a reactor by 1990. The "moderate" effort, with spending never exceeding four billion dollars in a year, would take fifteen more years. The fusion community might be easy to criticize for its many unmet milestones, but for decades the United States has never come close to even the moderate effort. In 1977, when the American fusion budget was at its peak, government investment in the research, adjusted for inflation, was seven hundred million dollars; by 1991, this had fallen by more than half. It is now half a billion, not appreciably more than the Korean budget. A Department of Energy official who was involved in the decision to shut down M.I.T.'s machine told me that American researchers should prepare to work on foreign technology.

After one of our talks, Janeschitz shared a rough sketch that he had worked on for an "ultra-fast track" to a commercial fusion reactor—an Apollo program-like commitment. "The Apollo program was a similar challenge," he said. "But it had unlimited money, and a central team that controlled the money." The United States spent more than a hundred billion (in today's dollars) on *NASA* missions in the fourteen years after Sputnik launched—almost eight billion per year. In Janeschitz's back-of-the-envelope calculations, the ultra-fast track, over a similar time frame, would cost thirty billion. The need is, without question, more pressing than it was for Apollo. By mid-century, the atmosphere will likely contain five hundred parts per million of CO_2, and by 2100 its effect on the oceans alone will be devastating: a near-total ecological collapse.

But even if *ITER* meets its objectives— even if it surpasses them, and achieves ignition—the work ahead is humbling. Assuming that the physics of tokamaks is perfected, and fusioneers can hold a synthetic star indefinitely in a magnetic bottle, someone will still have to solve the tricky problem of how to protect all the machinery that surrounds that bottle. The plasma in a commercial reactor will be a cloud of atom-size H-bombs detonating unceasingly. The tritium fuel is radioactive, but it will not be a source of radioactive waste—it will be transformed into helium. The machine itself will become the waste. Under constant neutron bombardment, nearly all of the tokamak's crucial parts will become "activated." Their radioactivity will be low, and will last only about a hundred years—a time frame that scientists tend to believe is manageable—but the structural impact of the neutrons will be awesome.

Janeschitz's ultra-fast track includes huge spending on research and development in materials science. Some would go toward developing metals resistant to activation, and some toward more immediate structural problems. Neutrons that drive into the wall of the steel vacuum chamber will cause gaseous bubbles to cavitate within it, diminishing the integrity of the chamber. In a commercial reactor, the neutrons, like a billiard break, would rearrange the entire molecular structure of key components. "Imagine a substance where every atom is displaced every two weeks," a scientist involved in the research told me. "The material completely remakes itself!"

A few years ago, in an academic paper, three materials scientists wondered if fusion's demands represented the single greatest challenge of their discipline. The lead author, Brian Wirth, who is affiliated with Oak Ridge, told me that his colleagues had documented a strange phenomenon on tokamak tiles made out of tungsten, an extremely dense metal. Tiles facing the plasma were degrading, even when the conditions were not especially severe: exposure to low-temperature plasmas was causing what scientists call "fuzz" to emerge on them. "The best way to describe it is the steel wool that you use to clean your pots, except that the steel wool is nanometre dimensions," he told me. "The tungsten has lost all its strength, and you can literally wipe off layers of this fuzz with your thumb. There is not a unified model for understanding why it forms, and whether we can control it."

I asked Wirth if the materials inside a commercial thermonuclear reactor had to be more resilient than the shielding for the International Space Station. "The simple answer is: if you told me that physicists could create a steady-state plasma device, I do not have the materials today to build that," he said. "There are certainly harsh radiation conditions in space, but the particle flux—the rate of particles hitting the Space Station—is about twelve to fifteen orders of magnitude less than the rate that they are going to hit the first wall in a prototype reactor."

There is, at the moment, very little political will to resolve this problem. But Wirth believes that "a billion-dollar-class machine"—a device that would be as complex as some of the world's largest particle accelerators—is needed to bombard different substances with neutrons in order to develop commercially relevant materials for fusion.

The magnitude of these challenges, combined with many others, has caused some early proponents of tokamaks to question whether the design itself is intrinsically flawed. In the seventies, Robert Hirsch directed the federal government's fusion program, and helped garner funding for some of the largest tokamaks ever built. But he has come to believe that there is no way a public utility will want to manage a device so complex and precarious, even if it can produce energy. For too long, he says, fusion has been in the hands of academics and government researchers who have neglected the practicality of their devices, focussing only on the physics within them.

Janeschitz told me, "When Benz invented the car, I am sure many people were saying, 'I will just take my horse—it is a lot simpler.' The truth is, most of the large tokamaks have been working for decades, and none have been retired for technical problems." Moreover, the design of a commercial reactor would inevitably be a lot simpler than *ITER*, because it would not need to retain the flexibility of an experiment. With an Apollo-like commitment, Janeschitz told me, fusion's remaining problems could be worked out within a lifetime. But the funding would need to come in significant amounts, and mostly at once, not dribbled over decades. As he sketched out his vision, he alluded to an aphorism by an early Soviet tokamak pioneer, a quote that practically echoes among the halls of *ITER*'s headquarters: "Fusion will be ready when society needs it."

Before I left France, I joined Janeschitz and Chiocchio, along with several other members of the Praetorian Guard, for a tour of the *ITER* construction site. It was noontime, and the sun was bright and warm. The group might have been burdened by complex physics and by even more complex politics, but this was still a beautiful afternoon in Provence. We headed down a dirt road through the trees, passing cables and transformers that would direct power from the French national grid into *ITER*. A dozen yellow earthmoving vehicles—dump trucks, backhoes, dozers—were lined up in a neat row. In the distance, cranes spanned upward, their L-shaped silhouettes still against the open sky. For a project that was desperate to make up time, the site was oddly quiescent.

"They are on lunch break," Janeschitz said dryly.

We passed an empty building as long as five Olympic pools. *ITER*'s poloidal field magnets, too large to move any great distance, will be made there. We passed a mockup station for the vast concrete slab that will eventually support the reactor. Construction on the slab had stalled, because of another conflict: to save money, the European Domestic Agency had insisted that it be half as thick as the design had specified—a change that the French regulator decided was unsafe. To resolve the impasse, *ITER*'s engineers designed a new structure to distribute the machine's weight more widely. Chiocchio then had to find space for it. "It took six months," he said. "The machine was already designed—every component was already designed. You couldn’t change anything.” Janeschitz shook his head, and said, “Of course, then you find there are complaints, because of cost and late changes.”

To get to the tokamak construction pit, we descended a metallic staircase until our feet hit earth, fifty-five feet below. The pit was so wide that it took some mental adjustment to appreciate its depth. We were in a canyon. The dirt at the bottom—sunbaked and cracked—had been rolled flat, and piles of equipment were stored across the expanse. Towering over the space where the B2 slab was being built were smooth retaining walls buttressing the pit. You could see the concrete plinths—four hundred and ninety-three of them—each a small monolith, topped with anti-seismic bearings. In an earthquake, the bearings will allow the slab to sway from side to side.

Even considering all the project’s difficulties, it was hard not to feel the majesty of what was being attempted. At the center of the base mat, miles of rebar were bent into an elegant spiderweb spanning nearly two hundred feet. One day, all of those lines would be buried in concrete, and the tokamak would stand at the center, where the webbing was densest. After pausing at the edge, taking in the expanse, everyone suddenly set out across a row of wooden planks toward the inner radius of the spiderweb, where the tokamak core will be supported: ground zero. It’s hard to know why we were all going out there; the center offered no better view of the huge slab than standing off to the side. There was, perhaps, the human impulse to be right there, where something notable will happen. Fusion, the most plentiful energy source in the universe, has never produced energy on Earth. Nature had shielded the planet from the punishing conditions it requires with a great buffer: millions of miles of empty space. What the physicists and the engineers in the South of France were attempting to do was to traverse that boundary. Thirty-five countries were trying somehow to cross it together. On some level, the arrangement would necessarily be a messy one.

That evening, at a café near the work site, I had a drink with an *ITER* physicist, who was despondent, fearing that the machine would never work. Why he was staying with the project he couldn’t say. But a few weeks later, after thinking about it, he told me that his mood had lifted. He had come to see his role in both small and sublime terms—akin to a stonemason toiling for years on the York Minster cathedral (begun 1220, finished 1472) without witnessing the work being completed. “I now expect to devote my full professional career before seeing a decent plasma in *ITER*,” he said. “This does not bug me. There have been many scientists before me, working for this same goal, who will not see this. Martin Luther King had a dream fifty years ago. He did not live long enough to see that dream realized. But, thanks to him, we have made wonderful strides in helping his dream be fulfilled. The scientists working on *ITER* have a dream that could be as powerful as Martin Luther King’s—not for human equality but for energy independence. We won’t see this dream realized. But each day I go to work I have a hidden smile knowing that I am helping us get one day closer to our *ITER* dream.” ♦

*A previous version of this article misstated how many tons of hydrogen are converted into energy every second.

**Richter did not work under Werner Heisbenberg, as previously stated.

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