

# 1. Coal will 'dominate global power sector for decades'

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**COAL will dominate the power sector globally for decades to come, according to a paper that miners say undermines campaigns by green activists to "demonise" coal.**

The paper - written by an International Energy Agency consultant and to be sent to Industry Minister Ian Macfarlane - says coal will remain the dominant power-sector fuel for at least the next quarter of a century despite efforts to diversify power sources and concerns about slower economic growth.

It says the development of carbon capture and storage technology will be essential to "reconcile the ongoing importance of coal-fired power with the global environmental objectives", with two projects coming on line soon in North America that could help secure the continuation of coal.

It also says that while coal use is declining in OECD

countries, there will be a strong growth in power output in China, then later in India and Association of Southeast Asian Nations countries, and coal will be the biggest driver of this.

Miners have seized on the paper to declare that coal will remain the backbone of affordable global energy for decades, and that attempts to undermine Australia's coal industry are "simply a reckless attack on Australian jobs and the economy".

Minerals Council of Australia chief executive Brendan Pearson said: "It will not stop the world using coal. Activist campaigns seeking to demonise Australian coal fail to acknowledge that it will be the principal global energy source for decades - transforming economies and helping eliminate poverty."

Green groups have been pushing the government to reject Clive Palmer's Galilee Basin mine and the Abbot Point coal terminal expansion in the Great Barrier Reef because of doubts about coal demand. Last month, the Greens seized on an Oxford University study finding that coal projects in Australia could become stranded because of sagging demand from China to insist there was a "global freefall" in coal demand.

The new paper was commissioned by the Energy Policy Institute of Australia, which wants to use it to shape the energy white paper being formulated by Mr Macfarlane.

The paper was produced by Ian Cronshaw, a consultant to the office of the chief economist in the International Energy Agency, who was last year responsible for the coal chapters of the IEA's World Energy Outlook publication.

The paper draws heavily on IEA research and closely reiterates previously published comments from the office of IEA chief economist Fatih Birol, including about the role of coal-fuelled electricity in lifting hundreds of millions of people out of poverty and allowing them to use refrigerators, do homework and run small businesses.

Mr Cronshaw was part of a team working in Mr Birol's unit that last year drafted a paper published by Mr Birol, which formed an extensive basis for the work he did for the Energy Policy Institute. The IEA's views are likely to carry weight with Mr Macfarlane as he has previously chaired IEA ministerial-level meetings, while the white paper team is also familiar with IEA work.

Mr Cronshaw's paper was based on the most recent figures from the IEA and other sources.

Anglo American Australian advisory board chairman Graham Bradley said the findings should be welcomed as coal "will remain one of our largest export earners for decades to come provided that government policies continue to support the industry".

"Much of the green polemic is not grounded in the

fundamental reality that the world needs the lowest-cost energy and at the end of the day the economics will prevail and investment will follow," Mr Bradley said.

## 2. Japan's Fukushima nuclear plant leaks radioactive water

<http://www.bbc.co.uk/news/world-asia-26254140>

**Around 100 tonnes of highly radioactive water have leaked from a storage tank at Japan's Fukushima nuclear plant, operator Tokyo Electric (Tepco) says.**

The toxic water may have overflowed after a valve was left open by mistake, Tepco said.

However the water was unlikely to have reached the ocean, the operator added.

The plant, which was damaged by an earthquake and tsunami in 2011, has faced multiple problems including leaks and power cuts since the disaster.

The latest leak is the most serious since August, when the plant leaked 300 tonnes of water, prompting Japan's nuclear agency to raise the incident's alert level.

### **'Contaminated earth'**

The water from Wednesday's leak was radioactive, with a reading of 230 million becquerels per litre of radioactive isotopes, Tepco spokesman Masayuki Ono told reporters.

A becquerel is a unit used to measure radioactivity. **WHO guidance** advises against drinking water with radioactivity levels higher than 10 becquerels per litre.

Tepco says the radioactive water overflowed from a storage tank

on Wednesday, but the leak was not discovered for several hours, the BBC's Rupert Wingfield-Hayes in Tokyo reports.

The operator says the leak occurred when contaminated water was accidentally pumped into a large storage tank that was already full, our correspondent adds.

"We apologise for worrying the public with such a leak," Mr Ono said. "Water is unlikely to have reached the ocean as there is no drainage in that tank area."

"We are now in the process of recovering the leaked water and the earth it has contaminated," he added.

On 11 March 2011, an earthquake and tsunami crippled the plant. Waves knocked out cooling systems for the reactors, leading to meltdowns at three of them.

Water is being pumped in to cool the reactors. However, this creates large amounts of contaminated water that must be stored securely.

The Fukushima nuclear power plant suffered a number of setbacks last year, including worker errors and a series of toxic water leaks that have led to concerns contaminated water is mixing with groundwater that is flowing into the sea.

### **3. Alcator C-Mod experiment operates with restored funds**

Warren visits as fusion experiment resumes operations

**By Tushar Kamath**

NEWS EDITOR

February 25, 2014

<http://tech.mit.edu/V134/N7/cmod.html>

In a large, press-filled event at MIT's Plasma Science and Fusion Center (PSFC) Monday, scientists and legislators celebrated the restoration of funding to Alcator C-Mod. The ceremony began with the press of a giant red button, signifying the restart of nuclear fusion experiments at the facility.

Alcator C-Mod, MIT's magnetically confined nuclear fusion device

(a tokamak), was a winner in the most recent U.S. budget deal, receiving \$22.2 million to continue nuclear fusion tests. The experiment remained in inactive maintenance mode during 2013 due to funding cuts from the Department of Energy as part of the sequestration. The restoration of funding is not without uncertainty, however, as the funding will only last until the end of September.

Present at the ceremony were legislators, including Senator Elizabeth A. Warren and U.S. Representative for Massachusetts' fifth district Katherine M. Clark, as well as MIT administrators, including President L. Rafael Reif, Vice President for Research Maria T. Zuber, and Professor Miklos Porkolab, the Director of the PSFC. All were provided a tour of the facility and were allowed to converse with the faculty and graduate students who oversee the lab.

“It is great to be represented in Congress by people who understand the value and importance of basic science and the connection between basic science and innovation,” said President Reif, who applauded the efforts by Senator Warren and Rep. Clark to secure funding for the project as part of the nation’s most recent budget deal.

During interviews with the press contingent, both Warren and Clark expressed the necessity for continued basic research in the nuclear fusion field. “It’s not only the energy research we are doing here today but the investments in the students that are here and the science and the work they’re going on to do whether it’s in fusion or beyond”, commented Rep. Clark. Clark, a Massachusetts Democrat, won the special election in December 2013 to represent the 5th district of Massachusetts. Her victory came directly before the passing of the new budget deal.

Warren, also a Massachusetts Democrat and former Harvard Law Professor, started her term in the U.S. Senate in November, 2012. “What goes on here is something we all need to support. This is our future in science, but also our future in power,” stated Warren, affirming her continued support of C-Mod.

While both the legislators and the MIT administration conveyed similar attitudes toward the funding, the future remains uncertain for C-Mod. As it stands, the \$22.2 million will only last through the end of September, and no budget has been set for the Department

of Energy, the primary source of funds for C-Mod, by Congress for fiscal year 2015. The legislators, administrators, and scientists at the event agreed this will be a continuous problem.

“In the long term, we have to have assured long-range funding. It is not enough to fight year to year. Grad students need to be able to come here and work and know that they can start projects and that the lab will still be open a year from now, three years, and five years from now” claimed Warren. Professor Zuber agreed with Warren and mentioned a “plan to recommend C-Mod to continue for years to come,” seeing the recent budget deal as a vote of confidence from Washington to further plasma research in Cambridge.

The lack of continuous support most directly affected graduate students and their effort to finish up research at MIT. “It was a big worry because many of us were planning at that point to do our experiments,” said Theodore Golfinopoulos G, a graduate student in the Electrical Engineering and Computer Science department conducting research with C-Mod. He continued, “It really makes you think hard about your career decisions if the rug can get pulled out from under you like that. For now, nobody can predict what is going to happen in the future.”

Alcator C-Mod’s funding cuts are part of the larger context of the U.S.’s future energy policy. The cuts at the beginning of fiscal year 2013, allowed Congress to redirect funding to an international effort, the International Thermonuclear Experimental Reactor (ITER), a large tokamak project under construction in France. But, according to an article in *The New Yorker*, “members of Congress were invited to view the inert machine [ITER], and they returned to the Hill expressing outrage.” Only after the Department of Energy submitted a revised proposal did Feinstein agree to continue funding support.

Professors and graduate students linked C-Mod’s cash-strapped situation to the future of science in the U.S. “The U.S. should not play a backseat as other nations, particularly China, Japan, South Korea in the East and the European Union in the West, move forward [with plasma research]” commented Golfinopoulos, “The U.S. has to decide whether it wants to be a leader in this and other areas of science.”

“The cuts made me turn away so many qualified students... now we

need a long-term solution to best identify the policy for U.S. fusion going forward. The U.S. needs to figure out what role we play in the international community for fusion research,” commented Anne E. White, Assistant Professor in the Nuclear Science and Engineering (NSE) program.

When asked how they would convince D.C. lawmakers to continue C-Mod funding, both Professor White and Professor Dennis G. Whyte, also in the NSE department, emphasized the uniqueness of the Alcator C-Mod facility. Whyte argued that C-Mod “gains its strength being in a niche as a smaller academic lab. We are nimble and have a good solid group of students, which provide for innovative new research. This keeps us fresh.”

The Alcator C-Mod tokamak is one of three in the United States, the others located at the Princeton Plasma Physics Laboratory affiliated with Princeton University, and General Atomics, a private industry endeavor. C-Mod is the only facility with such an involved academic program, as the lab is able to support up to 25 full-time graduate students.

Despite this unique position, only time will tell if the U.S. will back continued small-scale academic research in favor of larger projects. As a last plug for C-Mod to lawmakers and the public, Golfinopoulos stated, “Plasma is the ideal source of baseload energy. We can’t afford not to pursue this avenue. There aren’t that many other options, and we can’t stay with coal forever.”

## 4. **Myths and wishful thinking pollute global warming debate**

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<http://www.theaustralian.com.au/national-affairs/opinion/myths-and-wishful-thinking-pollute-global-warming-debate/story-e6frgd0x-1226834154278#>

**AT the World Economic Forum's annual meeting in Davos last month, leading participants called for a rapid shift to cleaner energy to tackle climate change.**

There is something unsettling about the global power elite jetting into an exclusive Swiss ski resort and telling the rest of the world to stop using fossil fuels.

The apocalyptic bombast is even more disturbing. According to Angel Gurría, secretary-general of the OECD, “our planet is warming dangerously” and we need to act now “to avoid catastrophe”; the United Nations climate chief, Christiana Figueres, maintains global warming means “the world economy is at risk.”

Former UN secretary-general Kofi Annan takes the prize for the most extreme rhetoric, claiming not curbing global warming is “a terrible gamble with the future of the planet and with life itself”.

Yet, the rhetoric is unconvincing. Yes, global warming is real and man-made. But creating panic and proposing unrealistic policies will not help in tackling the problem.

Both Annan and Gurría cited Typhoon Haiyan in the Philippines last November as evidence of increased climate-change-related damage.

Never mind that the latest report by the UN Intergovernmental Panel on Climate Change found “current datasets indicate no significant observed

trends in global tropical cyclone frequency over the past century” and reported “low confidence” that any changes in hurricanes in recent (or future) decades had anything to do with global warming.

Annan and Gurria also neglected to note that global Accumulated Cyclone Energy, an index for total hurricane activity, is hovering at the lowest values seen since the 1970s.

Indeed, the trend for strong hurricanes around the Philippines has declined since 1951.

Similarly, Gurria tells us that Hurricane Sandy, which slammed into New York City in 2012, is an example of inaction on climate change, costing the US “the equivalent of 0.5 per cent of its GDP” each year.

In fact, the US currently is experiencing the longest absence of intense landfall hurricanes since records began in 1900, while the adjusted damage cost for the US during this period, including Hurricane Sandy, has fallen slightly.

Figueres claims “that current annual losses worldwide due to extreme weather and disasters could be a staggering 12 per cent of annual global GDP”.

But the study she cites shows only a possible loss of 1 per cent to 12 per cent of gross domestic product in the future, and this is estimated not globally but within just eight carefully selected, climate-vulnerable regions or cities.

By contrast, according to the IPCC, “long-term trends in economic disaster losses adjusted for wealth and population increases have not been attributed to climate change”.

On the contrary, the bulk of peer-reviewed economic evidence indicates that, up to about 2050-2070, the net global economic impact of rising temperatures is likely to be positive.

Although global warming will create costs stemming from more heat-related deaths and water stress, they will be outweighed by the benefits from many fewer cold-related deaths and higher agricultural productivity from higher levels of carbon dioxide.

Global warming is a long-term problem. Most models indicate the cost towards the end of the century will be between 1 per cent and 5 per cent of world GDP. This is not a trivial loss; but nor does it put “the world economy at risk”. For comparison, the IPCC expects that by the end of the century, the average person in the developing world will be between 1400 per cent and 1800 per cent richer than today.

Such incorrect statements by leading officials reinforce wasteful policies based on wishful thinking. Figueres sees “momentum growing towards” climate policies as countries such as China “reduce coal use”. In the real world, China accounts for almost 60 per cent of the global increase in coal consumption from 2012 to 2014, according to the International Energy Agency. While Figueres lauds China for dramatically

increasing its solar-power capacity last year, the increase in China's reliance on coal power was 27 times greater.

Figueres's weak grasp on the facts has led her not only to conclude China is "doing it right" on climate change, but also to speculate that China has succeeded because its "political system avoids some of the legislative hurdles seen in countries including the US". In other words, the UN's top climate official seems to be suggesting an authoritarian political system is better for the planet.

The fact remains that global wind and solar power usage in 2012 cut, at most, 275 million tonnes of CO<sub>2</sub>, while soaking up \$US60 billion (\$66bn) in subsidies.

With the electricity worth possibly \$US10bn, the average cost of cutting a tonne of CO<sub>2</sub> is about \$US180. The biggest peer-reviewed estimate of the damage cost of CO<sub>2</sub> is about \$US5 per tonne. This means solar and wind power avoid about \$US0.03 of climate damage for every dollar spent.

Compare this with smarter technological solutions. In the short run, the US shale-energy revolution has replaced high-polluting coal with cheaper, cleaner natural gas.

This has cut about 300 million tonnes of US emissions - more than all the world's solar and wind power combined - and at the same time has profited

Americans by saving them \$US100bn in energy costs.

In the long run, current investment in green research and development will help drive the price of future renewable energy below that of fossil fuels, enabling a choice that is both environmentally and economically sound. In the meantime, even dramatic cuts in CO2 emissions will have very little impact on hurricanes 50 to 100 years from now.

Lifting billions of people out of poverty, however, would not only be intrinsically good; it would also make societies much more resilient in the face of extreme weather, whether caused by global warming or not.

Unfortunately, as we saw at Davos, the global climate debate is polluted with myths and wishful thinking. If we want to do more good at lower cost, we should start by cleaning it up.

*Bjorn Lomborg, an adjunct professor at the Copenhagen Business School, founded and directs the Copenhagen Consensus Centre. He is the author of The Skeptical Environmentalist and Cool It, and is the editor of How Much have Global Problems Cost the World.*

## **5. 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.

BY RAFFI KHATCHADOURIAN

[http://www.newyorker.com/reporting/2014/03/03/140303fa\\_fact\\_kh](http://www.newyorker.com/reporting/2014/03/03/140303fa_fact_kh)

[atchadourian?currentPage=all](#)

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 cooperation 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' worth of hydrogen. Six hundred 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 worked under Werner Heisenberg. 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 Perhasatron, 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 Chiochio 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.

Iter 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, Chiochio 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 it 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 fusioner, 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 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 began 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 through 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?” Chiochio 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 Feinsein 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. Twenty 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 fusioners 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<sub>2</sub> from coal deep into the earth, but, I mean, do you want to live over land with high-pressure CO<sub>2</sub> underneath it? And the energy and expense to capture and transport that CO<sub>2</sub> 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<sub>2</sub>, 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 fusioners 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.” ♦

## 6. **New Review Slams Fusion Project's Management**

25 February 2014 2:15 pm

Daniel Clery is a deputy news editor for *Science*.

<http://news.sciencemag.org/people-events/2014/02/new-review-slams-fusion-projects-management>

ITER, the international fusion reactor project in France, is reeling from an assessment that found serious problems with the project's leadership, management, and governance. The report is so damning, *Science* has learned, that after a 13 February special session that reviewed and accepted the report's conclusions and recommendations, the ITER Council—the project's governing body—restricted its readership to a small number of senior managers and council members. “We feared that if [the assessment] leaked to people who don't know about the ITER agreement, the project could be interpreted as a major failure, which is not what the management assessor intended,” says nuclear engineer Bob Iotti of the consulting firm CH2M HILL, who chairs that council.

Backed by China, the European Union, India, Japan, Russia, South Korea, and the United States, ITER aims to build a testbed for fusion energy. Under construction at Cadarache in southern France, it is often described as the most complex machine ever built. In its cavernous doughnut-shaped vacuum vessel, the reactor will heat heavy hydrogen to 150 million °C so that the nuclei will fuse to form helium, releasing energy.

Since the project began in earnest in 2006, the expected completion date has slipped from 2016 to 2018 to 2020, the estimated cost has tripled to at least €16 billion, and there's been a

major change of leadership. "ITER had to create a project, a design, a laboratory, and an institutional culture. That's very many things to create at once," says Steve Cowley, head of the Culham Centre for Fusion Energy in the United Kingdom.

The ITER agreement requires management assessments every 2 years. The previous two were critical, but nothing like the latest, conducted by Bill Madia, former director of the Pacific Northwest and Oak Ridge national laboratories. "It didn't mince words," Iotti says. "It could be read as an indictment of the current director general [Osamu Motojima], but one should also look at the obstacles in his path. Some are not under his control."

Because all the partners want to gain experience from building ITER for what could be a lucrative future industry, the ITER agreement carves up the construction of reactor components among partners, each of which has created a "domestic agency" to handle the contracts. The result is far from efficient: Superconducting cable for the reactor's magnets is manufactured in six different nations and the 5000-tonne vacuum vessel is being built partly in Korea and partly in Europe.

ITER management acts as ringmaster, overseeing the reactor design, enforcing technical standards, and resolving conflicts. "The ITER Organization and the seven domestic agencies should work as a single project team," says Jean Jacquinet, scientific adviser to the head of France's Atomic Energy Commission. "But that's not really the case. Communication is not ideal."

The relationship is often acrimonious and when conflicts arise, domestic agencies sometimes go behind the central management's back and put pressure on it via their delegates to the ITER Council. Iotti believes this antagonism is "one of the biggest problems." The assessment found that voting on the council is often swayed by political considerations and that it acts only on unanimous decisions, which has had a devastating effect on the project's cost and schedule. Iotti, who took over the council chair at the start of the year, accepts the criticism. "We need to simplify our activities. ... Then we can focus on the controversial issues," he says.

The assessment also found that ITER's day-to-day management team is inflexible and top-heavy, in part because the nationalities of senior management and the staff as a whole must reflect the division of funding. "Inefficiencies were built in with the full consent of the parties," lotti says. The number of managers should be reduced, the report says, identifying one whole level that, if removed entirely, would improve efficiency and decision-making.

lotti says that in response to the assessment, Motojima and ITER's senior management have proposed organizational changes that the council has "temporarily endorsed" because it "is not convinced that it is the ultimate answer." The council has asked for more information and justification for the changes. "ITER is still a young organization and it takes a very long time for different cultures to work as a single team," Jacquinot says.

Perhaps most controversially, a source tells *Science*, the assessment calls for the council to "accelerate the transition to a new director general." Brought in as part of a 2010 management reboot, Motojima ends his 5-year term in June 2015. Motojima, who declined comment, insists on consensus in decision-making and has surrounded himself with a coterie of staff, all Japanese, who meet with him daily outside the normal management structure, according to people who have worked closely with ITER officials.

ITER's schedule continues to slip, which will push up costs. ITER has said its reactor will power up for the first time before the end of 2020, but that date is widely discounted. "We don't have a realistic, believable, very high quality schedule," lotti says. The council is now planning to announce an updated schedule at its meeting in June 2015. "We need to be sure," lotti says. "Once we have a schedule, then we can talk about cost." ITER leaders fear that further delays, combined with the damning assessment, could cause backers to pull their funding; the United States has threatened doing so more than once.

Despite the problems, lotti is optimistic. "The project is making progress; things are being built," he says. This summer, the first items of hardware will start arriving on site. "When stuff comes together, you will see a completely different attitude ... [but] there

are still going to be difficult times ahead.”

## 7. Uniformity: the secret of better fusion ignition (Vol. 45 No. 1)

**M. Temporal, B. Canaud, W.J. Garbett, F. Philippe and R. Ramis**, “Polar Direct Drive Illumination Uniformity Provided by the Orion Facility”, *Eur. Phys. J. D*, **67**, 205 (2013) [[Abstract](#)]

One of the ways to achieve thermonuclear fusion is through a controlled reaction between deuterium and tritium. The authors have made theoretical calculations indicating how best to improve the ignition stage of fusion reaction. This approach involves increasing the uniformity of irradiation using high-power laser beams on the external shell of a spherical capsule containing a mix of deuterium and tritium.

Reaching uniformity of irradiation matters for reaching the ignition conditions of thermonuclear fusion. In this study, the authors analyse the possibility of using the UK-based Orion facility’s high-power laser beams to study uniformity. Specifically, the authors use numerical simulations to analyse the uniformity of the illumination of a spherical target both in the case of circular or elliptical laser intensity profiles. They demonstrate that this approach reduces considerably the non-uniformity of the capsule irradiation—by 50% and 35%, for elliptical and circular intensity profiles respectively.

## 8. US taking a hard look at its involvement in ITER

David Kramer

February 2014

<http://scitation.aip.org/content/aip/magazine/physicstoday/article/67/2/10.1063/PT.3.2271>

Regulatory uncertainties and an incomplete design are cited in a new review of the US contribution to the seven-party project.

Payment is required to read the article!

## 9. McNider and Christy: Why Kerry Is Flat Wrong on

# Climate Change

It was the scientific skeptics who bucked the 'consensus' and said the Earth was round.

By RICHARD MCNIDER And JOHN CHRISTY

Updated Feb. 19, 2014 7:31 p.m. ET

<http://online.wsj.com/news/articles/SB10001424052702303945704579391611041331266>

In a Feb. 16 speech in Indonesia, Secretary of State John [Kerry](#) assailed climate-change skeptics as members of the "Flat Earth Society" for doubting the reality of catastrophic climate change. He said, "We should not allow a tiny minority of shoddy scientists" and "extreme ideologues to compete with scientific facts."

But who are the Flat Earthers, and who is ignoring the scientific facts? In ancient times, the notion of a flat Earth was the scientific consensus, and it was only a minority who dared question this belief. We are among today's scientists who are skeptical about the so-called consensus on climate change. Does that make us modern-day Flat Earthers, as Mr. Kerry suggests, or are we among those who defy the prevailing wisdom to declare that the world is round?

Most of us who are skeptical about the dangers of climate change actually embrace many of the facts that people like Bill Nye, the ubiquitous TV "science guy," say we ignore. The two fundamental facts are that carbon-dioxide levels in the atmosphere have increased due to the burning of fossil fuels, and carbon dioxide in the atmosphere is a greenhouse gas, trapping heat before it can escape into space.

What is not a known fact is by how much the Earth's atmosphere will warm in response to this added carbon dioxide. The warming numbers most commonly advanced are created by climate computer models built almost entirely by scientists who believe in catastrophic global warming. The rate of warming forecast by these models depends on many

assumptions and engineering to replicate a complex world in tractable terms, such as how water vapor and clouds will react to the direct heat added by carbon dioxide or the rate of heat uptake, or absorption, by the oceans.

We might forgive these modelers if their forecasts had not been so consistently and spectacularly wrong. From the beginning of climate modeling in the 1980s, these forecasts have, on average, always overstated the degree to which the Earth is warming compared with what we see in the real climate.

For instance, in 1994 we published an article in the journal *Nature* showing that the actual global temperature trend was "one-quarter of the magnitude of climate model results." As the nearby graph shows, the disparity between the predicted temperature increases and real-world evidence has only grown in the past 20 years.

When the failure of its predictions become clear, the modeling industry always comes back with new models that soften their previous warming forecasts, claiming, for instance, that an unexpected increase in the human use of aerosols had skewed the results. After these changes, the models tended to agree better with the actual numbers that came in—but the forecasts for future temperatures have continued to be too warm.

The modelers insist that they are unlucky because natural temperature variability is masking the real warming. They might be right, but when a batter goes 0 for 10, he's better off questioning his swing than blaming the umpire.

The models mostly miss warming in the deep atmosphere—from the Earth's surface to 75,000 feet—which is supposed to be one of the real signals of warming caused by carbon dioxide. Here, the consensus ignores the reality of temperature observations of the deep atmosphere collected by satellites and balloons, which have continually shown less than half of the warming shown in the average model forecasts.

The climate-change-consensus community points to such indirect evidence of warming as glaciers melting, coral being bleached, more droughts and stronger storms. Yet observations show that the warming of the deep atmosphere (the fundamental sign of carbon-dioxide-caused climate change, which is supposedly behind these natural phenomena) is not occurring at an alarming rate: Instruments aboard NASA and National Oceanic and Atmospheric Association satellites put the Mid-Tropospheric warming rate since late 1978 at about 0.7 degrees Celsius, or 1.3 degrees Fahrenheit, per 100 years. For the same period, the models on average give 2.1 degrees Celsius, or 3.8 degrees Fahrenheit, per 100 years (see graph).

The models also fail to get details of the past climate right. For example, most of the observed warming over land in the past century occurred at night. The same models used to predict future warming models showed day and night warming over the last century at nearly the same rates.

Past models also missed the dramatic recent warming found in observations in the Arctic. With this information as hindsight, the latest, adjusted set of climate models did manage to show more warming in the Arctic. But the tweaking resulted in too-warm predictions—disproved by real-world evidence—for the rest of the planet compared with earlier models.

Shouldn't modelers be more humble and open to saying that perhaps the Arctic warming is due to something we don't understand?

While none of these inconsistencies refutes the fundamental concern about greenhouse-gas-enhanced climate change, it is disturbing that "consensus science" will not acknowledge that such discrepancies are major problems. From the Intergovernmental Panel on Climate Change's beginning, that largely self-selected panel of scientists has embraced the notion that consensus on climate change is the necessary path to taking action and reducing man-made carbon

emissions around the world. The consensus community uses this to push the view that "the science is settled" and hold up skeptics to ridicule, as [John Kerry](#) did on Sunday.

We are reminded of the dangers of consensus science in the past. For example, in the 18th century, more British sailors died of scurvy than died in battle. In this disease, brought on by a lack of vitamin C, the body loses its ability to manufacture collagen, and gums and other tissues bleed and disintegrate. These deaths were especially tragic because many sea captains and some ships' doctors knew, based on observations early in the century, that fresh vegetables and citrus cured scurvy.

Nonetheless, the British Admiralty's onshore Sick and Health Board of scientists and physicians (somewhat akin to the current Intergovernmental Panel on Climate Change) dismissed this evidence for more than 50 years because it did not fit their consensus theory that putrefaction (or internal decay) caused scurvy, which they felt could be cured by fresh air, exercise and laxatives.

"Consensus" science that ignores reality can have tragic consequences if cures are ignored or promising research is abandoned. The climate-change consensus is not endangering lives, but the way it imperils economic growth and warps government policy making has made the future considerably bleaker. The recent Obama administration announcement that it would not provide aid for fossil-fuel energy in developing countries, thereby consigning millions of people to energy poverty, is all too reminiscent of the Sick and Health Board denying fresh fruit to dying British sailors.

We should not have a climate-science research program that searches only for ways to confirm prevailing theories, and we should not honor government leaders, such as Secretary Kerry, who attack others for their inconvenient, fact-based views.

*Messrs. McNider and Christy are professors of atmospheric science at the University of Alabama in Huntsville and fellows*

*of the American Meteorological Society. Mr. Christy was a member of the Intergovernmental Panel on Climate Change that shared the 2007 Nobel Peace Prize with former Vice President Al Gore. Mr. Christy was a member of the Intergovernmental Panel on Climate Change that shared the 2007 Nobel Peace Prize with Vice President Al Gore.*

## **10. International research into controlled nuclear fusion (ITER project), gets more computer resources with expansion of the Helios supercomputer**

Paris, March 12, 2014 -

[http://www.wcm.bull.com/internet/pr/new\\_rend.jsp?DocId=858051&lang=en](http://www.wcm.bull.com/internet/pr/new_rend.jsp?DocId=858051&lang=en)

Designed and operated by Bull, the Helios supercomputer installed in Rokkasho, Japan, is boosted by an additional 380 Intel® Xeon Phi™ coprocessors to increase its power to almost 2 Petaflops<sup>1</sup>. Intel® Xeon Phi™ coprocessors - which foreshadow technologies that will ultimately lead to Exa-scale computing - will advance research into nuclear fusion aimed at developing a sustainable source of energy with a low-carbon footprint.

The French Alternative Energies and Atomic Energy Commission (the CEA) - working on behalf of F4E<sup>2</sup> to implement and run the Data Center for nuclear fusion at Rokkasho in Japan - is expanding the power of the Helios supercomputer by equipping it with additional bullx™ nodes featuring Intel® Xeon Phi™ coprocessors.

Helios, which is designed and operated by Bull, supports research work aimed at controlling nuclear fusion, so as to refine a sustainable energy source that produces no carbon dioxide emissions or other greenhouse gasses. The system provides modeling and simulation capacity which is open to all European and Japanese researchers under the 'Broader Approach', a research program that complements the international cooperative ITER program.

The new Intel® Xeon Phi™ coprocessors that will be incorporated into Helios will enable researchers to take advantage of exceptional computing performance. Their massively parallel architecture delivering leading performance per watt, foreshadows technologies that will ultimately lead to Exa-scale computing<sup>3</sup>.

*"We are delighted to be helping the CEA and the community working on*

*Nuclear Fusion to develop the knowhow and computing resources that will allow them to significantly expand the potential for research associated with the ITER program," said Pascal Barbolosi, Vice-President, Extreme Computing at Bull.*

*"Computer simulation plays an essential role in the development of research into Nuclear Fusion - both in terms of understanding the extremely complex physical phenomena involved and in scoping future tokamaks. The Nuclear Fusion community already has very advanced parallel simulation software. Adapting these for processors with an extremely high levels of parallelization is essential to guarantee their ability to fully utilize future generations of supercomputers, and the integration of Intel® Xeon Phi coprocessors into Helios is an important move in this direction," explained Gabriele Fioni, Director of Materials Sciences at the CEA.*

The architecture of the Helios supercomputer initially featured 4,410 bullx B510 compute nodes, with 8,820 Intel® Xeon® E5 processors producing a power of 1.5 Petaflops. The 180 new bullx B515 compute nodes will each include two Intel® Xeon Phi™ coprocessors delivering an additional 400 Teraflops, taking the total power of the Helios system to almost 2 Petaflops.

*"Intel is convinced that Exascale computing will represent a major technological advance for the scientific community working on Nuclear Fusion projects. The Intel Xeon Phi range of coprocessors has been designed with this in mind, and we are very pleased that the Helios supercomputer will be benefiting from this," explained Stéphane Negre, CEO of Intel France and Regional Manager of Intel Western Europe.*

The Center of Expertise for Parallel Programming - created by Bull in close cooperation with Intel and based at Bull's offices in Grenoble, France - is closely involved in this project, providing training, porting and optimization of computing codes dedicated to this vital area of energy research.

<sup>1</sup> *2 million billion operations a second. If everyone in the world completed one operation a second, it would take them a day and a half to achieve what Helios can do in a single second.* <sup>2</sup> *F4E, Fusion For Energy, is the 'domestic' agency coordinating Europe's contribution to the construction of ITER and the Broader Approach.* <http://www.fusionforenergy.europa.eu> <sup>3</sup> *1 billion billion operations a second, or 500 times the power of Helios. The first Exa-scale supercomputers are set to appear from around 2020.*

## **About the CEA**

The French Alternative Energies and Atomic Energy Commission (CEA) is a public technological research organization working in four main areas: low-carbon energies, information technologies and health technologies, very large-scale research facilities (TGIRs), and global defense and security.

Building on excellence in fundamental research and on recognized expertise, the CEA takes part in organizing cooperation projects with a wide range of academic and industrial partners. With its 16,000 researchers and employees, it is a major player in European research and is also expanding its international presence.

For more information, visit [www.cea.fr](http://www.cea.fr)

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## About Bull

Bull is the trusted partner for enterprise data. The Group, which is firmly established in the Cloud and in Big Data, integrates and manages high-performance systems and end-to-end security solutions. Bull's offerings enable its customers to process all the data at their disposal, creating new types of demand. Bull converts data into value for organisations in a completely secure manner.

Bull currently employs around 9,200 people across more than 50 countries, with over 700 staff totally focused on R&D. In 2013, Bull recorded revenues of €1.3 billion.

For more

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## 11. Danish measuring equipment to measure 200 million degrees plasma

Physics and chemistry  
Energy

<http://www.dtu.dk/english/Research/Research-at-DTU/Research-news/Nyhed?id=f566bee0-cdeb-47b8-8d64-1f391456dfee>

DTU researchers have concluded the biggest Danish contract to date with ITER, the world's first major experimental fusion power plant.

Danish equipment will measure fusion plasma at temperatures of up to

200 million degrees in the ITER experiment, which is the world's largest fusion experiment. ITER is presently under construction in the south of France. Here work is underway to generate energy by fusing atomic nuclei. DTU has just been awarded the task of designing the measuring equipment. This is the biggest Danish order to date from Fusion for Energy (F4E), the agency responsible for European deliveries to ITER.

The contract will run for the next four years and takes the form of a framework agreement between F4E and a consortium comprising DTU and the Portuguese **Instituto Superior Technico** (IST) in Lisbon. The measuring equipment, the so-called CTS system (Collective Thomson Scattering), will monitor the fast ion particles in fusion plasma at ITER, which is scheduled for completion in 2020. The system has been developed in the **Plasma Physics and Fusion Energy Section** at DTU Physics, which is at the international forefront of development and operation of CTS systems. **Challenging technique** “For the first time ever, ITER will make it possible for us to study the behaviour of a fully operational fusion plasma. The CTS diagnostic is crucial for understanding the dynamics of ions in the plasma,” says Søren Bang Korsholm, Senior Scientist at DTU Physics and head of the project.

The measuring system will provide information about how fast ions from the fusion process behave, and how the balance between deuterium and tritium in the plasma affects the fusion efficiency. The system will contain a microwave source—a so-called gyrotron—which sends an electromagnetic wave beam with a power of 1 MW and a frequency of 60 GHz into the plasma. The electromagnetic waves interact with the electron density perturbations and are scattered in different directions with a given frequency shift. A number of mirrors and horns outside the plasma capture part of the scattered electromagnetic waves, and the received spectrum of the signal makes it possible to establish the movement and distribution of the ions in the plasma—especially the fast ions from fusion processes.

## 12. **Beijing seeks billions for more nuclear plants**

YVONNE LEE

THE WALL STREET JOURNAL

MARCH 07, 2014 12:00AM

<http://www.theaustralian.com.au/business/wall-street-journal/beijing-seeks-billions-for-more-nuclear-plants/story-fnay3ubk-1226847416583#>

**WHILE** debate continues in Tokyo over

**whether to restart reactors that were shut following the Fukushima Daiichi meltdown three years ago, Beijing is approving more nuclear plants, and the country's top nuclear companies, both state-owned, are gearing up for initial public offerings they hope will raise billions of dollars to help fund reactor construction.**

China General Nuclear Power, the country's biggest nuclear energy company by installed capacity, wants to raise about \$US2 billion (\$2.21bn) from a Hong Kong IPO this year, sources said.

It has hired China International Capital and Deutsche Bank to handle the listing, and proceeds will be used to expand its power projects, they said.

Beijing-based China National Nuclear is preparing for a Shanghai IPO and has hired Citic Securities and UBS, according to the China Securities Regulatory Commission's website.

Although the nuclear power operator hasn't given a fund-raising target, in 2012 it said proceeds would be allocated to five projects needing a total investment of 173.5bn yuan (\$31bn).

“The two nuclear firms may need to raise more capital from the market after listing, given their big capex and expansion plans,” said Castor Pang, Core Pacific-Yamaichi's head of research in Hong Kong.

“Even though the Fukushima disaster has reignited fears over nuclear safety, nuclear power will still play a core role in China’s energy strategy as it is cheaper and cleaner than coal-fired power generation.”

China, the world’s largest energy consumer, is pushing to expand its nuclear sector to trim reliance on coal, now used to generate about 70 per cent of its power, and to reduce the pollution choking large parts of the country.

It resumed building nuclear power plants in late 2012, has 20 nuclear reactors in operation and 28 under construction, nearly half the total being built world-wide, according to the World Nuclear Association, an industry body.

Nuclear power’s share of power generation in China is expected to rise to 5.1 per cent by 2020, from 1.8 per cent in 2010, brokerage CLSA says.

Securing enough uranium to feed its reactors is a challenge. China spent \$US1.5bn buying overseas uranium mines in the past two years, according to Dealogic. In January, China National Nuclear agreed to buy a 25 per cent stake in the Langer Heinrich mine in Namibia from Australian uranium producer Paladin Energy for \$US190m.

“We expect demand for uranium to rise over the next four to five years as new reactors from countries including China will start operating,” said an official from a unit of China National

Nuclear. “The current market price of uranium products is still at a low level. We will continue to look for opportunities and invest in overseas uranium resources.”

The price of uranium is now around \$US36 a pound, having fallen 46 per cent since the Fukushima disaster.