With its big political hurdle behind it, the make-or-break project must run a gauntlet of technical challenges to see whether fusion can fulfill its promise of almost limitless energy

ITER’s $12 Billion Gamble

ABINGDON, U.K., AND GARCHING, GERMANY—Several times a year, hunters gather in the forests around Saint Paul lez Durance in southern France to shoot wild boar. Over the coming decade, however, a portion of their hunting ground will be cleared, and the town’s cafes will gradually fill up with newcomers from San Diego and Seoul, Moscow and Munich, Naka and New Delhi. Rising out of that forest clearing will be a 20,000-tonne experiment that just might point a way out of the world’s looming energy crisis.

In November, politicians representing more than half the world’s population will sign an agreement that fires the starting pistol for the International Thermonuclear Experimental Reactor (ITER). Although first mooted in 1985, ITER has so far existed only on paper. The governments of China, the European Union (E.U.), India, Japan, South Korea, Russia, and the United States are now ready to hand over a $6 billion check for ITER’s construction, followed by a similarly sized one for 20 years’ operation. Then it is up to an international team of scientists and engineers to show that the thing will work.

If it does, the rewards could be huge. With the global population due to climb from 6.5 billion to 8.1 billion by 2030 and the economies of China, India, and others hungry for power, many new generating plants will have to be built. The choices are stark: Burn more coal, with the inevitable impact on climate; build new nuclear fission plants and deal with the radioactive waste and risk of terrorism; or try alternative sources such as solar power, although this option remains expensive and lacks efficiency.

But there is an outside bet: fusion. If it can be built, a fusion power station would emit no greenhouse gases and produce little radioactive waste, it cannot explode in a runaway reaction, and its fuel is found in seawater in virtually limitless quantities. Such a plant, unlike alternative sources, would produce the steady, reliable baseload power that cities need. And the economics are astounding: A 1-gigawatt coal-fired plant burns about 10,000 tonne of coal per day, whereas a 1-gigawatt fusion plant would need roughly 1 kilogram of deuterium-tritium fuel.

We’re not even close yet, however. Indeed, skeptics joke that “Fusion is the power of the future and always will be.” The sun is a gigantic fusion reactor, but recreating the conditions here on Earth in which atomic nuclei collide with such force that they fuse together has proved fiendishly difficult. A few dozen examples of the currently favored reactor design—a doughnut-shaped vessel known as a tokamak—have been built since the 1950s, but only a handful have managed to get fusion in their plasma. In 1997, the Joint European Torus (JET) in Abingdon, U.K., the biggest existing tokamak, managed to produce 16 megawatts, but that was only 65% of the power used to keep the reaction running.

By studying those earlier reactors, plasma physicists have derived scaling laws that predict that a bigger tokamak (ITER is twice the size of JET in linear dimensions) would overcome many of the problems. But ITER is not a prototype power plant; it is an experiment designed to finally decide whether taming the sun’s energy to generate electricity is even viable. ITER aims to produce 500 megawatts of power, 10 times the amount needed to keep it running. But a moneymaking energy utility would need several times that amount, and it would have to keep on doing it steadily for years without a break.

ITER needs to show such performance is at least possible. But it faces many challenges: Scientists and engineers need to find a lining for its inner walls that can withstand the intense heat; they must tame the plasma instabilities that plague existing reactors; and they must find a way to run the reactor in a steady state rather than the short pulses of existing reactors. ITER must do all of this and, for the first time, maintain the plasma temperature with heat from the fusion reaction itself rather than an external source.

“There’s no doubt that it’s an experiment. But it’s absolutely necessary. We have to build something like ITER,” says Lorne Horton of the Max Planck Institute for Plasma Physics (IPP) in Garching, Germany. Researchers are reasonably confident that ITER can achieve the basic goals laid out in the project’s plans, but there is less certainty about what comes after that. “I’m pretty confident ITER will work as advertised, but you can’t be 100% sure,” says Christopher
**Hotter than the sun.** ITER’s interior must endure colossal heat loads and neutron bombardment.

Llewellyn-Smith, director of the U.K. Atomic Energy Authority’s Culham Laboratory in Abingdon, home of JET. IPP’s Hartmut Zohm agrees: “Certainly there’s an element of risk. I’m very confident, 90-something percent, that we can produce a plasma dominated by fusion. But I’m much more uncertain that it will make a viable fusion power reactor.” German physicist Norbert Holtkamp says that ITER’s goal of generating excess power is clear: “Either it can do it, or it can’t. If it fails, the tokamak is out.”

### The waiting game

The ITER project is currently in a state of limbo. Researchers nailed down the design of the reactor in 2001 after a 13-year effort costing about $1 billion. Since then, governments have been in charge. The ITER partners at that time—the E.U., Japan, and Russia (the United States had pulled out in 1999)—began negotiating who would construct which parts of the reactor. By December 2003, China and South Korea had joined the team, the United States had rejoined, a division of labor had been agreed upon, and the list of sites had been whittled down from four to two: Rokkasho in northern Japan and Cadarache, near Saint Paul lez Durance. Politicians gathered in Washington, D.C., to close the deal but failed to decide between the two sites, and the inaugural of the agreement was put off (Science, 2 January 2004, p. 22).

Acrimonious negotiations continued for 18 months. Finally, in June 2005, a deal was struck: Japan agreed to support Cadarache, and in exchange, the E.U. will place some of its contracts with Japanese companies and will share the cost of extra research facilities in Japan (Science, 1 July 2005, p. 28).

Since then, negotiators have reworked the international agreement ahead of the signing next month. India has also joined, and key appointments have been made. Kaname Ikeda, a Japanese diplomat with experience of nuclear engineering, will be ITER’s director general; its principal deputy director general will be Holtkamp, who managed accelerator building on the Spallation Neutron Source at Oak Ridge National Laboratory in Tennessee. Six other deputies—one from each partner apart from Japan—were appointed in July.

By the end of this year, the ITER organization will employ no more than 200 people. But across the globe, as many as 4000 researchers are already working directly or indirectly on the project, and they’re itching to have some input. Fusion science has moved on in the 5 years since ITER’s design was completed, and many want to make changes in the light of recent results. This generates a creative tension between the wider fusion community, which would like an adaptable machine to test as many scenarios as possible, and the ITER staff, who want the machine built on time, on budget, and ready for the next step: a power plant prototype.

“The physics community still wants modifications, all the bells and whistles. We’ll always keep asking. It’s healthy,” says Horton. Valery Chuyanov, head of ITER’s work site in Garching and now the nominee deputy director general for fusion science and technology, counters that physicists “must understand the boundary conditions. We must respect the agreement and keep within the set cost. They can’t expect miracles.”

Holtkamp has heeded calls for a design review and will convene a meeting in December. But, as Chuyanov points out, not everything has to be set in stone now. Contracts for big-ticket items such as the building, the vacuum vessel, and the superconducting magnets must be signed almost immediately, but other systems are years away from procurement. “The design review is not a moment in time but a continuous process,” Chuyanov says.

Above all, researchers want the ITER design to be flexible. Since it was fired up in 1983, JET has had numerous transformations including the retrofitting of a divertor, a

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**How to Squeeze a Plasma**

After numerous attempts during the 1940s and 1950s to find an arrangement of magnets to confine a plasma—an ionized gas—Soviet physicists Igor Tamm and Andrei Sakharov came up with the tokamak. The name derives from the Russian words for “toroidal chamber in magnetic coils.”

The searingly hot plasma is kept in place by the combined effects of two magnetic fields. The first, known as the toroidal field, is generated by vertical magnetic coils ringing the vacuum vessel—in the case of the International Thermonuclear Experimental Reactor (ITER), 18 of them made from a niobium-tin superconductor. These create a field that loops horizontally through the tokamak’s “doughnut.”

The second, poloidal field forms vertical loops. It is generated by the plasma flowing around the torus in a current of 15 million amps. This current is itself created by electromagnetic induction: The plasma current acts as the secondary windings of a transformer, with superconducting coils in the middle of the torus acting as the primary windings. A rising current in the primary coils induces the plasma current to flow around the torus.

The combined magnetic field carves a slow spiral around the whole of the torus, and plasma particles zip around the ring in tight orbits around the spiraling magnetic field lines. The configuration keeps the particles clear of the walls and maintains a pressure in the plasma that is key to fusion.

The tokamak is not the only way to confine a plasma. Physicists are actively pursuing other schemes, such as stellarators and reverse-field pinch machines. But the tokamak is the most successful design so far and forms the basis of ITER and, most likely, the commercial power reactors that will come after it.

—D.C.
The problem is that if the plasma wobbles and strikes the surface, it would set loose tungsten ions. Because tungsten has a high atomic number, once it is stripped of all its electrons it has a huge positive charge, so even a few ions would severely dilute the plasma. As a compromise, some tokamaks have experimented with beryllium, the metal with the lowest atomic number (4, compared with tungsten’s 74). But beryllium has a low melting point, so it cannot be used in areas with a large heat load, it erodes easily, and neutrons can transmute it into hydrogen or helium.

ITER’s designers have opted for a compromise: The first wall will be 80% beryllium with 5% to 7% carbon and about 12% tungsten, both concentrated in the divertor region (see diagram, p. 241). But researchers know that beryllium is just not tough enough for a generating plant and is highly toxic. “I’m convinced that at a late stage we need to convert ITER to full tungsten coverage to learn if this scenario is compatible with a power reactor,” says Bolt, head of materials research at IPP.

But Kimihiro Ioki, who heads the vacuum vessel and blanket division in the existing ITER organization, warns that changing the 700 square meters of the first wall would be a mean feat. The 421 panels of the main wall (excluding the divertor) together weigh more than 1 ton, and technicians would have to extract them one by one through a small port using a many-jointed mechanical arm. Ioki estimates it would take at least a year.

To run a power reactor with an all-tungsten first wall, operators would have to be sure that the plasma will behave and not touch the sides. Today, it’s far from clear that researchers will be able to guarantee that. “A tokamak is the worst lab experiment you can do. It’s an extremely hostile environment, and there are too many variables. It’s a very difficult process to understand,” says plasma physicist Steven Lisgo of the Culham lab. Phenomena at work in a tokamak range in size from micrometers to meters across, operate over time periods ranging from microseconds to years, and interact in complex nonlinear ways. It’s the antithesis of a nice, clean controlled experiment, and theorists still struggle to understand everything that is going on.

Feeling the heat

In the beginning, during the 1950s, researchers thought it was going to be easy. Theorists made a calculation, based on standard random diffusion of particles, about the transport of energy and particles from the burning center of the plasma to the edge and concluded that a fusion reactor would only...
the most fusion power out of their tokamak, they must squeeze the balloon full of plasma as much as possible, but more pressure breeds more instabilities, which ultimately doom the fusion.

Researchers are fighting instabilities in a number of ways. One is to tweak the distribution of the plasma current flowing around the tokamak ring. Looking at a cross section of the ring, if the heating beams are used to give the current a boost in one spot here and another spot there, this can calm instabilities and allow the plasma to reach a higher pressure. “You can make very small changes in the internal current distribution, and instabilities can go away,” says Zohm.

Another method is to change the shape of the plasma. In early tokamaks, the plasma was usually circular in cross section, but more modern machines have D-shaped plasmas or almost triangular ones. That helps because the magnetic surfaces that you cross as you move outward from the center of the plasma keep changing direction slightly, an effect known as “magnetic shear.” “Shear suppresses [turbulent] eddies, and so transport is less efficient. It keeps energy in,” says Richard Buttery of the Culham lab.

Researchers also found another way to keep plasma pressure confined when they were trying to solve a different problem: how to siphon off waste particles and heat from the edge of the plasma. When a deuterium nucleus fuses with a tritium nucleus, they produce a fast-moving helium nucleus, or alpha particle, and a speedy neutron. The neutrons are unaffected by the tokamak’s magnetic fields, so they zip straight out and bury themselves in the surrounding “blanket” material, where their energy can raise steam to drive an electricity-generating turbine.

The charged alpha particles are held inside the tokamak and heat up the plasma. But once they’ve imparted their energy, these alphas become waste and must be removed from the plasma before they quell the fusion. In the late 1980s, researchers decided to try reshaping the magnetic field toward the bottom of the plasma vessel so that some of the outer magnetic surfaces, instead of bending round and up again, actually diverge at the bottom and pass through the vessel wall. The result is that any particles that stray out near the edge of the plasma eventually get swept down to the bottom and dumped into the divertor, a heat-resistant target where particles are cooled and then pumped out of the vessel.

JET was first fitted with a divertor in 1991. The devices are...
now considered indispensable because they
not only remove waste but also help confine
the plasma. Although researchers don’t yet
understand why, these open, diverging mag-
netic surfaces create a “transport barrier”
inside the bulk of the plasma, near the edge.
The pressure increases very steeply across
this barrier so that the core of the plasma can
be maintained at a significantly higher
pressure—a configuration that plasma physicists
call H-mode.

H-mode has been so successful that it is
now part of ITER’s baseline scenario, but it
does have a downside: Running the plasma in
H-mode can lead to the mother of all instabil-
ities, known as edge-localized modes (ELMs). These happen because the transport
barrier doesn’t let out excess energy gradu-
ally but bottles it up until it’s finally released
all at once. “ELMs are not fully understood.
They are bursts of power, like earthquakes,”
says Jerome Pamela, head of the JET project.
ELMs can damage the first wall or send a
blast of energy down to the divertor. Few
believe that they will be able to banish ELMs
altogether, but if they can be made small and
regular, they are manageable. “The name of
the game is to let the energy out smoothly,”
says Buttery.

Such is the value of H-mode that even at
this late stage ITER’s designers are consider-
ing design changes to cope with ELMs. One
scheme investigated at JET involves injecting
impurities such as nitrogen into the transport
barrier to make it a bit more leaky, but this
also degrades H-mode, so it is not popular.
Another tactic, tested at IPP with its Asdex
Upgrade tokamak, is to regularly fire pellets
of frozen deuterium into the barrier. This
sparks an ELM every time, keeping them
steady and small. This system “will be
installed” on ITER, says Chuyanov, “but is it
enough? We don’t know.”

A late entrant into the race is a system
developed in the United States using the
DIII-D tokamak at General Atomics in San
Diego, California. Extra magnetic coils
added to the tokamak create a sort of chaotic
static in the transport barrier, making it
leaky enough to avoid large ELMs. “It’s much
simpler than pellets, more reliable,”
says Pamela. The problem is where to put the
coils. Ideally, they would be inside the reac-
tor vessel, close to the plasma, but that sort
of reconfiguration would be one step too far
for ITER’s designers. “We’re working very
actively to find a solution for ITER, but it’s
impossible to put the coils inside,” says
Chuyanov. Researchers at JET are consider-
ing fitting them outside their vessel to see
whether that might work for ITER.

Even if one of these techniques does tame
ELMs, no one knows what will happen when
ITER’s self-heating regime kicks in. The fast-
moving alpha particles created by fusion will
have much more energy than the bulk of the
particles in the plasma, and these could open
up a whole hornets’ nest. “This is the first
time a plasma has been heated by alphas. It
could create new instabilities. Experts don’t
think it will, but we cannot logically exclude
that possibility,” says Llewellyn-Smith.
“That’s why we need ITER,” adds Zohm.
“We can’t simulate internal heating. It’s the
part we know least about.”

Seeking steady state
Although there may be surprises along the
way and whole new scenarios may have to be
developed, few doubt that ITER will
reach its goal of generating large amounts of
excess power. But power is not much use
commercially in bursts a few minutes long
followed by a long wait while the reactor is
reconfigured. Tokamaks are by their nature
pulsed devices. Some of the magnetic field
that confines the plasma is provided by
plasma particles flowing around the toka-
mak—a current of some 15 million amps.
This current is induced by a rising current
in coils in the central hole of the tokamak
ring, the coils and plasma acting like the
primary and secondary windings of a trans-
former. But the current in the coils can’t
keep rising forever, so the length of any
fusion run is limited. The French tokamak
at Cadarache, Tore Supra, holds the record
with 6-minute pulses.

But pulsed operation would put intoler-
able stresses on a power plant that must keep
working for decades, so researchers are
looking for other ways to drive the plasma
current. Firing the heating beams in a partic-
ular direction will push plasma around the
ring, but this will never provide all the nec-
essary current. In the 1980s, theorists pre-
dicted another way: If the pressure gradient
in the plasma is high enough, particles,
which move through the plasma by spiraling
around magnetic field lines, will interfere
with each other in such a way as to produce
a net current around the ring. This “boot-
strap” current was demonstrated in the
1990s, and the Asdex Upgrade, for example,
has produced as much as 30% to 40% of its
current from the bootstrap effect.

Getting more bootstrap is hard because of
the usual problem: It needs higher pressure
gradients in the plasma, which mean
more instabilities. Nevertheless, once
ITER has demonstrated its baseline sce-
nario to be easy. “It will be a real pain to get
to this,” says Zohm.

Ready when you are
With a total price tag of about $12 billion,
ITER is the most expensive experiment in
the world apart from the international space
station. Some plasma physicists are skepti-
cal that fusion will ever be a power source on
Earth and argue that we shouldn’t be wasting
our money on ITER. After 50 years of
research, even fusion’s flag-wavers concede
that it may still be another half-century until
we have a workable fusion power plant, but
ITER researchers are undaunted. “By the
middle of the century, we’ll know how to
do it. Then it’s up to the world community
to decide if they want it,” says Zohm. Soviet
fusion pioneer Lev Artsimovich, speaking
more than 3 decades ago, had the same mes-
sage. Asked when fusion power would be
available, he answered, “Fusion will be
ready when society needs it.” That time may
be fast approaching.

–DANIEL CLERY