Ready to roll. Ground is prepared at the ITER site in France. Cement mixers are due next spring.

FUSION

# ITER Blueprints Near Completion, But Financial Hurdles Lie Ahead

**As staff put finishing touches to the fusion project's final design, member governments mull over the latest cost estimates and prepare to raid piggybanks**

**CADARACHE, FRANCE—**When diplomat Kaname Ikeda took the job of director-general of the ITER fusion reactor project in 2006, he quickly realized that he was building something literally from the ground up. "There was just a forest here when I started and six or seven people working," he says. Now a large, if temporary, office building houses more than 400 staff members and another one is taking shape next door. Meters away, beyond a fence and up a bank, stretches a vast flat expanse of gravel, 1 kilometer long and 500 meters wide, made by slicing off the top of a hill. Next spring, this area—which ITER staff members jokingly liken to a huge terrain for pétanque, the game of bowls played in towns and villages across France—will be a bustling construction site as the world's largest scientific experiment takes shape. But for now, quiet expectation reigns.

But this quiet is not a sign of inactivity. Inside headquarters, researchers are working feverishly toward one of the project's early milestones: completion of the Project Baseline, a complete description of the machine's scope, design, construction schedule, and cost. This set of documents, which runs to thousands of pages, will be presented for approval on 18 November to the ITER Council, representing the project's seven international partners: China, the European Union, India, Japan, South Korea, Russia, and the United States. The meeting will be a turning point for the project. "It's a bit like a starting pistol. It [the baseline] is a big framework on which to hang the work of the next 10 years," says David Campbell, deputy head of ITER's fusion science and technology department. From the point of view of the project's paymasters, one part of the baseline will be subject to special scrutiny: the cost.

ITER, or the International Thermonuclear Experimental Reactor, seeks to demonstrate that nuclear fusion—the power source of the sun and stars—can be tamed on Earth to generate electricity. In the 3 years since the partners formally agreed to work together on the project, its estimated cost has ballooned. Earlier underestimates, rising construction costs, and design and schedule changes aimed at reducing risks have landed the partners with bills substantially higher than they were expecting. Although all appear committed to the project, tough discussion is likely at this month's council meeting. "Everyone's concerned about cost containment," says Campbell. "There's a tension between cost and time to completion, but if you move too fast you can get technical difficulties. You have to strike the right balance."

Plasma physicists have been working on the design of ITER since the mid-1980s. When the agreement was signed to set the ball rolling in 2006, the estimated cost was roughly €5 billion to build the reactor and another €5 billion to operate it for 20 years. Those figures, however, were based on a 5-year-old design drawn up before the site was decided (Cadarache was chosen in 2005) and when only three partners (the European Union, Japan, and Russia) were on board. In addition, fusion science had moved on since 2001, and researchers were itching to make changes to ensure that the project was a success.

So even as the ink was drying on the ITER agreement, the seven partners called for a design review. "We asked the whole international community to say what their worries were" by filling out "issue cards," says Campbell. By early 2007, researchers had registered about 500 issues. ITER staff and external experts were assembled into eight panels that worked through all the issues. Some problems required only minor tweaks and some could be discounted, Campbell says. By the end of 2007, the panels had whittled the number down to 13 major issues that needed more effort. "We spent another 6 to 12 months working on them. Some significant changes in design were needed," Campbell says.

One of the most significant changes was a new system to help control the plasma, a maelstrom of ionized hydrogen gas heated to 150 million degrees so that nuclei will have enough energy to smash together and fuse. But instabilities in the plasma called edge-localized modes (ELMs) act like quakes at the plasma boundary. They can make it bulge out unpredictably, damaging the wall of the doughnut-shaped reactor, known as a tokamak, or the divertor, a structure around the bottom of the reactor that extracts helium, the spent fuel of fusion. "ELMs have a devastating effect. A reliable mitigation technique would have tremendous value,"


**First milestone.** Staff from ITER and French and European agencies celebrate the end of site preparation.

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says Norbert Holtkamp, ITER's second in command and construction leader.

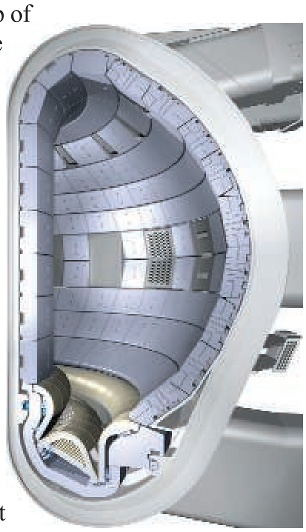
ITER already had one system for combating ELMs: firing small pellets of frozen deuterium into the plasma at regular intervals to provoke small quakes, which do less damage and seem to suppress the larger ones. But researchers working with the U.S. tokamak DIII-D in San Diego, California, discovered that they could suppress ELMs with an extra magnetic field. So the review team modified the design to include magnetic coils for quelling ELMs behind the blanket tiles that line the inside of the reactor vessel.

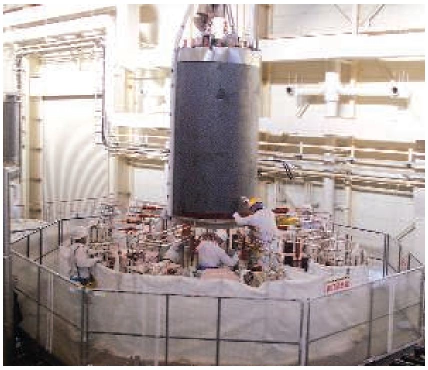
The blanket also came under scrutiny in the design review. It absorbs the heat and fast-moving neutrons flying out of the plasma once fusion is taking place, protecting components, and people, outside. It is made up of 440 tiles, most of them 4.6-tonne slabs of copper and steel measuring 1 meter by 1.5 meters. The plasma-facing side of the tiles is key. It must be tough enough to withstand the touch of plasma at 150 million degrees but also made of a material that won't pollute the plasma if it does get burned off. This "first wall" will be made of beryllium, but other materials may be tested later. The first wall of the divertor, which faces a higher heat load, will be carbon composite and tungsten. "We needed to review the heat loads and make corrections to the design," says Gary Johnson, head of ITER's tokamak department.

Another key change to come out of the design review was a requirement to test all of ITER's magnets at cryogenic temperatures. ITER uses 48 huge magnet coils to control the plasma. Each of the 18 toroidal field magnets, which loop through the center of the tokamak, weighs more than 360 tonnes, as much as a fully laden Boeing 747. The magnets are made of superconducting cable that works at about 4 kelvin. Thorough testing "can reduce the risk of installing a flawed device," says Johnson, so new facilities will be built on site and elsewhere in Europe to test each magnet at low temperature.

These and other changes resulting from the design review "have a major impact scientifically," says Holtkamp, but they increase the project's cost by less than 15%. As work progressed, however, it emerged that the 2001 design had seriously underestimated the cost. And as staff continued refining the design and drawing up the project baseline, it soon became obvious that the planned construction and schedule was "too risky," Holtkamp says. "Certain things needed to be added or adjusted to ensure the scientific goals were achieved." But such changes would bring higher costs, delays, or both.

The issue came to a head at the council meeting in June 2008 when the partners told ITER staff members that they had to get a better handle on costs and not let the start date slip. "We received clear guidance," Holtkamp says. "Make a schedule to reach first plasma by 2018, quantify the risk, and report back." At the same time, the council formed two independent panels to assess the work of the ITER organization: one looking at how costs are estimated and managed, the other at systems engineering and management.





**Heart of the matter.** A cross section through the ITER tokamak (*left*) showing the vacuum vessel, blanket tiles, and the divertor at the bottom. A coil of prototype superconducting cable (*above*) is tested by engineers in Japan.

One reason for the uncertainty in ITER's cost is the way in which the reactor is constructed and paid for. The ITER organization does not have a large sum of money to buy all the parts. Instead, partner countries carve up the design and then each pays its own industries to make their share of the components and ship them to Cadarache. Hence ITER staff members control only 10% of the machine's cost; the rest comes as these in-kind contributions. As a result, ITER's true cost is very hard to pin down. The 2001 design had put a value on each component so they could be shared out fairly and then calculated an overall cost from those values. But "different countries [cost things] in different ways," Campbell says, and the 2001 estimates have proved inaccurate. Because of the different systems in different parts of the world, "a simple addition of the cost in each country is an unfair representation of the cost of ITER," Holtkamp says.

Another factor pushing up the cost is the ITER collaboration's principle that all partners get an equal share in the knowledge of how to build the reactor. "Each member wants to learn how to make everything," says Ikeda. So large items, such as the magnets and the vacuum vessel, are not built in one place but are divided between the partners. That approach seemed reasonable for three partners in 2001, but with seven partners economies of scale are lost. ITER staff members have negotiated some cost-saving rationalizations with relevant agencies in the seven partner countries, although Holtkamp emphasizes that the council has yet to approve them.

Over the past year, as staff members continued to analyze the construction schedule, "it became clear we had to change something in the sequence of assembly. We had to take an approach that reduces risk for the project," says Holtkamp. To reduce pressure on the schedule, ITER planners proposed firing up a stripped-down version of the reactor in 2018 without many components needed for later power-producing plasmas. "If something is wrong, it will be easier to repair," says Holtkamp. "Once we know this is okay, we can install the rest." Some 15% to 20% of components would be installed later, and the scheduled start date of 2026 for power production is little changed.

In June, the council approved the new schedule, contingent on its approving the full baseline this month. The issue of cost still hangs heavy in the air. E.U. documents suggest it may need to fork out twice what was originally forecast. (The European Union, as host, must pay a 45% share of ITER's construction costs; the others pay 9% each.) A few months ago, "the E.U. had asked for a number of remedial measures for cost containment and improved management to be put in place. This is work in progress," says E.U. research spokesperson Catherine Ray. "We need a realistic timetable, we need to be sure that we are basing our decisions on credible cost estimates, and we need to be sure that responsible organizations will be able to deliver on it."

"The fact that it will cost more is more or less accepted. Parties are carefully addressing how to handle the increase, such as through cost optimization," says Ikeda, though he concedes that "some partners may be struggling." "The partners want to understand the risk," says Holtkamp. "All countries want to find a comfort level. Has [all our work] provided comfort? I hope so. We'll find out soon."

**–DANIEL CLERY**

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