ITER appears unstoppable despite recent setbacks

Repairs could take up to two years, but project officials believe they can perform them in parallel with the machine's assembly. Regulatory concerns are unresolved.

ITER, the international project to build a giant tokamak to achieve a burning fusion plasma, already faced years of delays and cost increases even before defective components were discovered last year. But project officials say they likely can't provide an estimate of the length of the delays or how much more ITER will cost until the end of 2024.

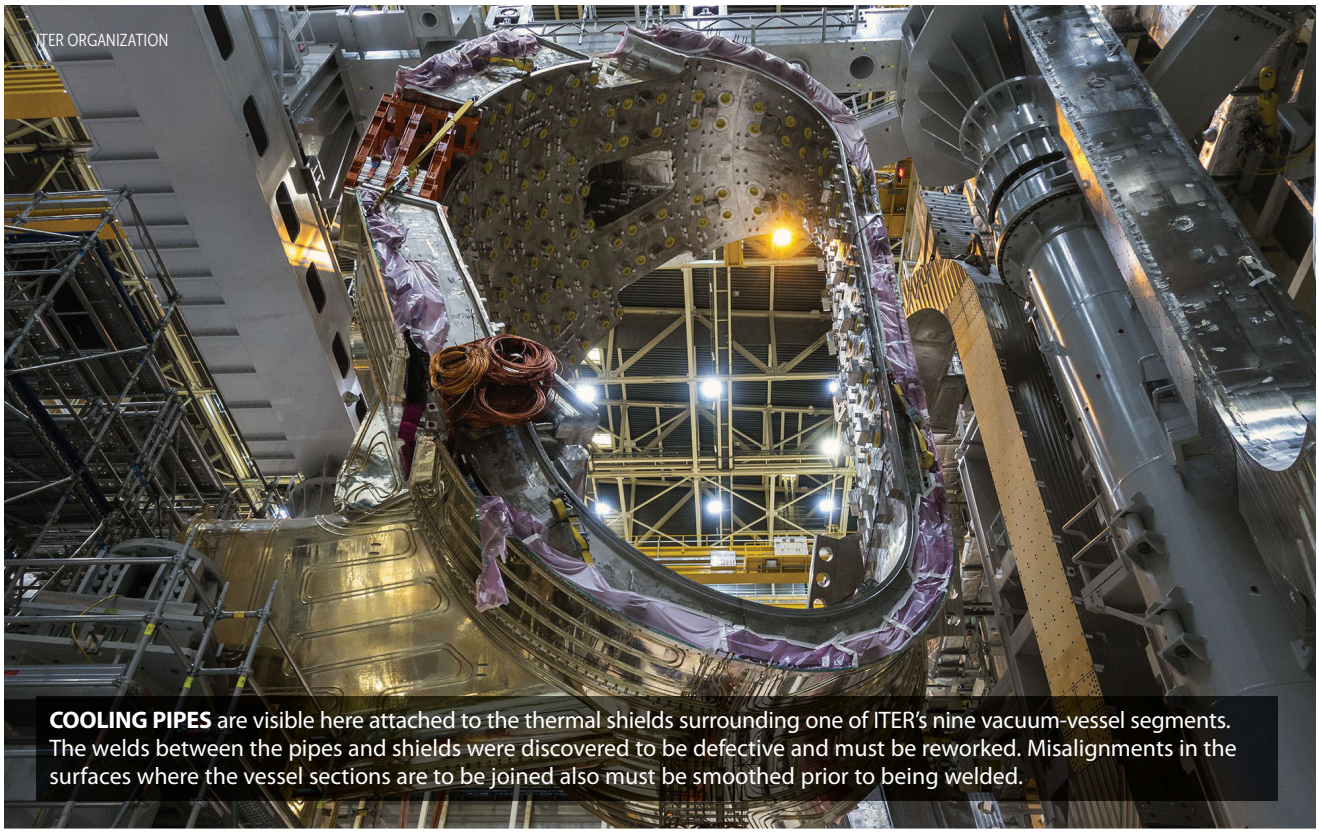
Some internal estimates have indicated ITER's completion could be delayed by as much as 35 months from 2025, the date for the machine's commissioning envisioned in the project's 2016 baseline, says ITER spokesperson Laban Coblentz. Shorter delay estimates also have been discussed internally, he says, but "none of the numbers are official or reliable." Project leaders first warned in 2020 that the 2025 start date is not achievable.

Coblentz insists that no official estimate can be provided until ITER management produces a revised baseline—and the ITER Council, ITER's governing body, approves it. "Every journalist—and every stakeholder—would prefer to have a precise answer about the new expected schedule," says Coblentz. "But the evaluation is complex, and the easy choice is to cite selective elements and extrapolate conclusions."

In April 2022, cracks were found in some of the 23 km of pipes that will conduct cooling water through the thermal shields sandwiched between ITER's vacuum chamber and the surrounding superconducting toroidal-field magnet coils. The defects were traced to inadequate surface preparation prior to welding the pipes to the shields. Most of the shields have been delivered to the ITER site at Cadarache, in southern France. The one vacuum chamber section that's been installed in the reactor so far was removed in July and is being taken apart to allow rework of the faulty components.

A second major defect, misalignments in the welding surfaces of the four vacuum-chamber segments manufactured in South Korea, was discovered in 2020. (See Physics Today, May 2022, page 20.) The surfaces must be smoothed out—voids filled in and high points ground off—before they can be welded together. The remaining five segments of the doughnut-shaped vacuum chamber are still being manufactured in the European Union (EU).

Repair work on the two defects began



COOLING PIPES are visible here attached to the thermal shields surrounding one of ITER's nine vacuum-vessel segments. The welds between the pipes and shields were discovered to be defective and must be reworked. Misalignments in the surfaces where the vessel sections are to be joined also must be smoothed prior to being welded.

in July and is expected to take two years to complete, says Coblentz. But he and Tim Luce, ITER's head of science and operation, say the work can be done in parallel with the machine's assembly and won't necessarily further delay the project schedule. "We don't need all nine sectors to begin to assemble the vacuum vessel. We need the first three," says Luce. The assembly sequence can proceed as the others continue to be repaired.

Many causes for delays

Much of the yet-to-be-quantified delay is attributable to the COVID-19 pandemic and related supply-chain issues. Technical challenges tied to first-of-a-kind components with multiyear fabrication timelines, such as the magnets and vacuum-vessel sectors, also played a role, says Coblentz.

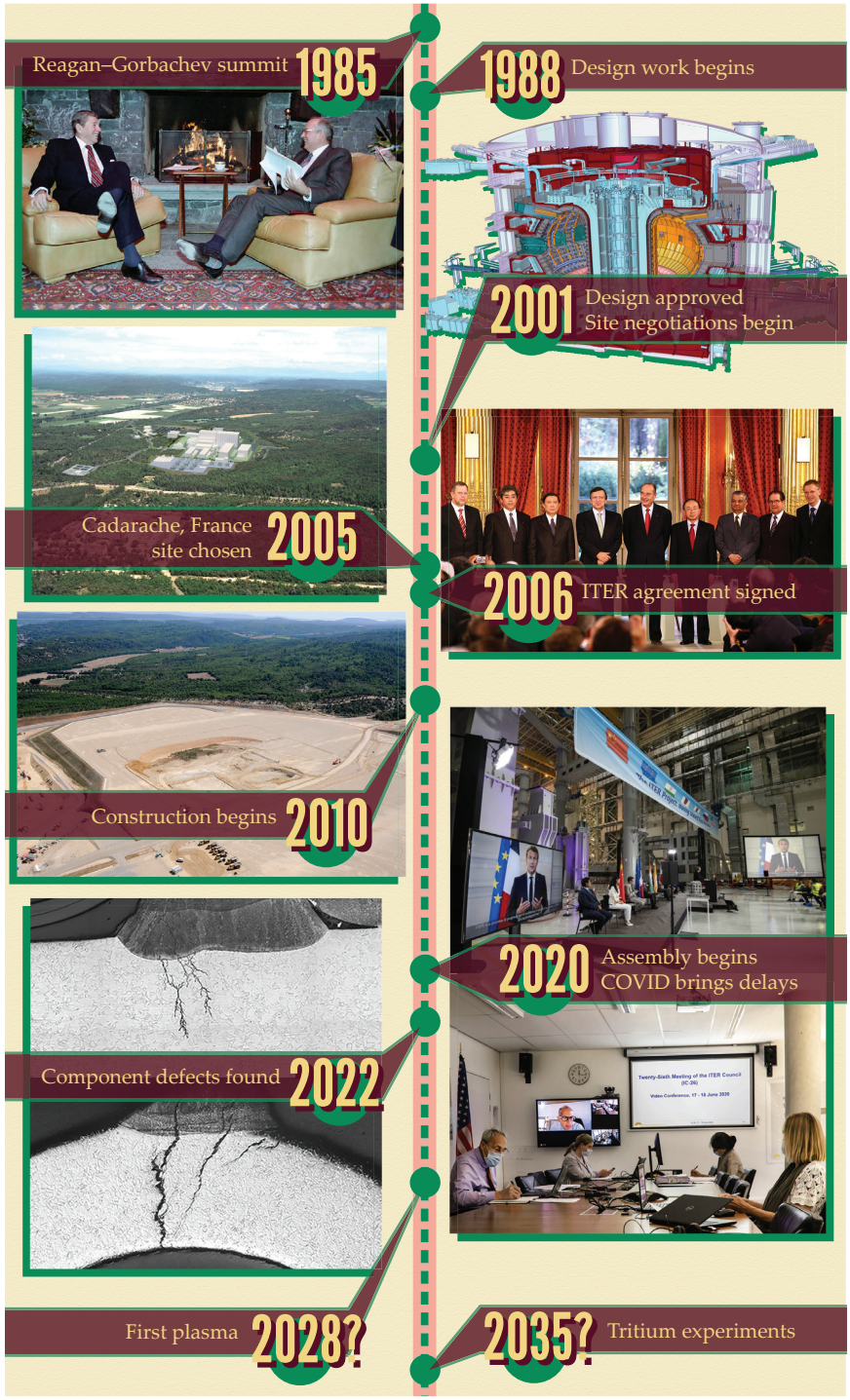
Another delay will come from testing components to offset future risks. For example, revised plans call for testing the toroidal field coils at 4 K in the completed cryogenics plant prior to their installation. Such testing wasn't specified in the original baseline.

A proposed schedule that was reviewed and rejected last year by the ITER Council would have been immediately outdated with the discovery of the manufacturing defects, says Luce.

ITER director general Pietro Barabaschi, who declined an interview request, acknowledged in news releases that the cost of the repairs "will not be insubstantial." Barabaschi took over following the death of Bernard Bigot last year.

ITER's schedule will also be affected by the French Nuclear Safety Authority (ASN), whose February 2022 order to halt assembly remains in effect. The agency has questioned the adequacy of ITER's radiological shielding, and it worries that adding on to the 3-m-thick concrete shielding that already surrounds the reactor pit would raise the mass of the reactor beyond the capacity of its support system. The ASN also expressed concern over the vacuum-vessel welds. ITER officials had hoped the ASN would lift its hold last fall, but an ASN spokesperson said in late June that ITER had yet to satisfactorily respond to the regulatory issues.

As part of the re-baselining exercise, ITER management is planning to compress the previous timetable for the onset of deuterium-only experiments. The goal would be to adhere as closely as possible to the previous 2035 target date for the onset of tritium experiments. The current baseline, says Luce, calls for a "first plasma" upon completion of construction, to ensure that the vacuum vessel, magnets, and other physical plant components function



ITER'S LIFE began during a 1985 summit of US president Ronald Reagan and Soviet leader Mikhail Gorbachev. Following years of design efforts and negotiations over the location, a site in France was selected and construction began in 2010. Completion, originally planned for 2025, will be delayed, officials acknowledge, but a new timetable won't be available until next year. (All images courtesy of ITER Organization.)

What's old is new in DOE's choice of fusion hopefuls

Among the eight fusion startup companies that will share $46 million in grants to help build commercial power plants are four that are pursuing approaches—stellarator, magnetic mirror, and Z pinch—that were once major programs in Department of Energy labs before being mostly abandoned in favor of tokamaks.

Awardees also include two companies that are pursuing differing approaches to inertial fusion. Two others are developing tokamaks.

DOE says the grants will assist the companies to develop their respective designs for commercial fusion pilot plants in 5–10 years. At least one recipient, the MIT spin-off Commonwealth Fusion Systems, has said it will begin constructing a pilot power plant within five years. It has raised more than $2 billion. The well-established Cambridge University spin-off Tokamak Energy has been working on its spherical tokamak design for more than a decade in the UK. Officially, its award went to a US subsidiary in West Virginia.

The 18-month grants are the first tranche of an anticipated $415 million in DOE support over five years. But awardees won't receive any of the money unless they produce acceptable "pre-conceptual designs and technology roadmaps" for their power plants within the next year and a half. According to DOE a preconceptual design is similar to a conceptual design but at lower levels of fidelity and with greater uncertainties. A technology road map details the required critical-path R&D, including any intermediate test facilities, required for a particular pilot plant conceptual design.

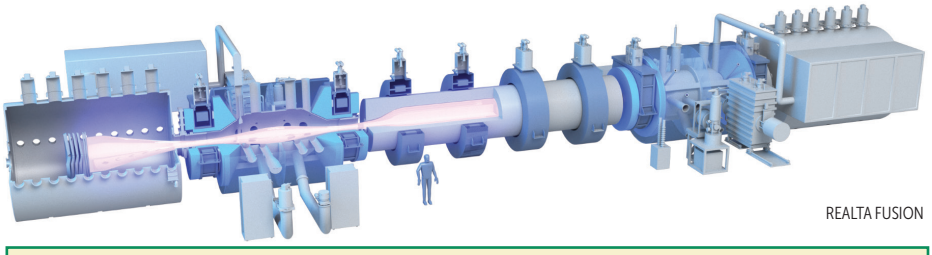
Thea Energy of New Jersey, and Type One Energy Group, based in Madison, Wisconsin, each are betting on stellarators, a magnetic-confinement concept that Lyman Spitzer pursued when he founded in the 1950s what would become the Princeton Plasma Physics Laboratory. Like the tokamak, a stellarator creates a doughnut-shaped plasma, but it does so with a twist that requires a complex configuration of magnets to maintain.

Another Madison-based firm, Realta Fusion, is counting on magnetic mirrors, which was a major DOE program in the 1970s and early 1980s. In those cylindrical-shaped devices, charged plasma particles trapped in a magnetic field hit a point along the field line where they reverse direction. Some will collide with others and fuse as they bounce back and forth.

Zap Energy, in Everett, Washington, hopes to create commercial fusion using Z pinch, a technology that Los Alamos National Laboratory explored with its Perhapsatron machine in the 1950s. In a Z pinch, a thin line of plasma is magnetically confined and compressed by an electrical current running through the plasma. One version of Z pinch is the massive Z machine at Sandia National Laboratories, which is primarily used in support of nuclear weapons. By comparison, Zap's reactor would fit on a tabletop.

In recent decades, DOE's Fusion Energy Sciences program has focused nearly exclusively on tokamaks. But it has continued to support small-scale nonmainstream concepts. The Advanced Research Projects Agency–Energy in particular has backed academic and privately funded research on non-tokamak approaches in recent years. In a news release, the agency boasted that the milestone awards validated its own technology choices.

Focused Energy, located in Austin, Texas, and Darmstadt,



REALTA FUSION

A RENDERING of Realta Fusion's conceptual tandem-mirror reactor, consisting of two end cells on either side of a longer central cell in which most of the fusion will occur.

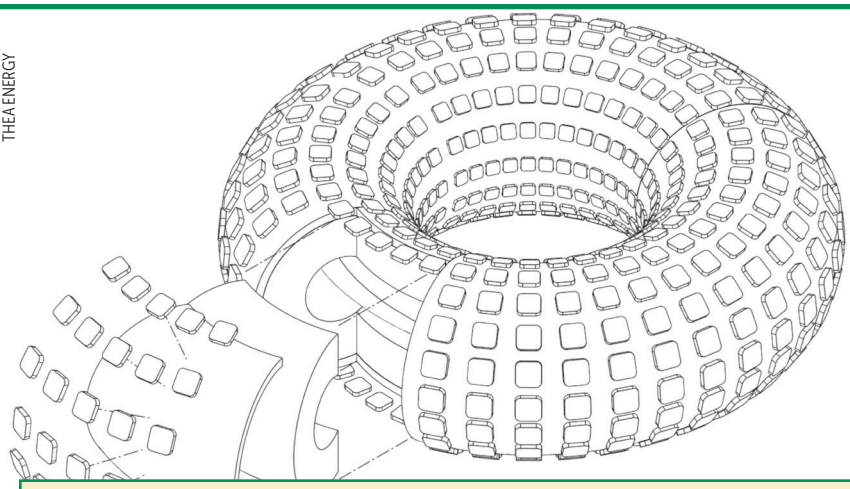
properly. A two-year pause was then planned to permit the installation of remaining vacuum-vessel components and additional heating systems. Only then would experiments with deuterium begin.

Project officials have decided to jettison the plan to coat the vacuum chamber's walls with beryllium. While workforce exposure to the toxic metal contributed to the decision to replace it with tungsten, Luce says the major reason for the design change is to increase ITER's relevance to future commercial fusion power plants. Tungsten is expected to better withstand the constant bombardment by high-energy fusion neutrons.

Costs are a mystery

As the host ITER partner, the EU contributes 45% of ITER's cost. The other ITER partners—China, India, Japan, Russia, South Korea, and the US—each contribute 9%. Because the seven partners each have different labor, materials, and other expenses associated with their contributions, which are mainly in the form of fabricated reactor components, the project's exact cost in dollars or euros may never be known. Indeed, ITER has its own currency, called ITER Units of Account.

At the request of the House Science, Space, and Technology Committee, however, Bigot in 2017 estimated ITER's cost would total $25 billion through 2035, when tritium experiments were then supposed to begin. But the EU that same year estimated its share of the project alone would total €18.1 billion ($19.6 billion) through 2035. By extrapolation, the total ITER cost during that period would be €41 billion if the entire project were to be undertaken in the EU.



THEA ENERGY

THEA ENERGY'S stellarator design consists of arrays of small magnet coils, seen here as the outer layer of squares. Other stellarators have used thicker and more complex three-dimensional coils. The coils will be held in place by a support structure, which surrounds a thicker layer, called the blanket, encompassing the plasma.

Germany, was another award recipient, as was Xcimer Energy, in Redwood City, California. They are pursuing different laser pathways to inertial fusion (see Physics Today, March 2023, page 25).

The awards provide an imprimatur of sorts from DOE. "The amount is less important than being part of the program," says Benj Conway, CEO of Zap Energy, which stands to get $5 million. "Being selected as part of the program reflects our progress, the credibility of our approach, what we've managed to achieve, and the plan going forward." Zap, which has raised over $200 million, has commissioned an experimental device that Conway says he expects to achieve breakeven—when fusion energy produced equals the input energy—within a year.

Assuming they meet their milestones, awardees will be eligible for follow-on grants for up to five years. The $415 million Congress has authorized for the program is subject to annual appropriations. The program's success will depend on receiving the full out-year funding, says Conway. "That's where it will make the real difference to us."

Realta chief technology officer Cary Forest and Thea Energy CEO Brian Berzin say the advent of high-temperature, high-field superconducting magnets has been an important element in their respective development paths. Commonwealth Fusion Systems is supplying the high-temperature superconductor magnets for Realta's next-generation mirror device.

David Kramer

The US Department of Energy in 2018 estimated ITER's cost would be $65 billion if all the work were to be done in the US. That didn't include operating expenses during the 2025–35 period of commissioning and initial experiments. DOE's estimates routinely include a large contingency; ITER's do not. (See "ITER disputes DOE's cost estimate of fusion project," Physics Today online, 16 April 2018.)

The latest ITER setbacks were shrugged off during a 13 June hearing by the House science committee devoted to fusion. Kathryn McCarthy, director of the US ITER Project office at Oak Ridge National Laboratory, mentioned the need for repairs in her testimony, but none of the lawmakers who were present pursued the topic. McCarthy noted that the problematic components were not made in the US.

Former representative Jerry McNerney (D-CA) caused a stir last year when, after a visit to ITER, he told his fellow science committee members he was informed that the defective components could be "project-ending." Luce, who met with McNerney, says that was a misunderstanding: a project official told

McNerney that it would have been extremely difficult to fix the shields had the defects not been uncovered until the reactor had been assembled.

No one has called, at least publicly, for ITER to be abandoned. Luce says he's seen no signs of any of the partners defecting. "In fact there have been positive signs," he says, one of which is that the US and India have recently paid their contribution arrears.

At the June semiannual meeting of the ITER Council in Cadarache, member nations "reaffirmed their strong belief in the value of the ITER mission, and resolved to work together to find timely solutions to facilitate ITER's success," according to a communiqué.

Even Robert Hirsch, the former head of DOE's fusion program and a longtime critic of tokamaks, says ITER should continue. "There's no question that there will be some benefit," he says. But because of their complexity, Hirsch predicts that tokamaks will never become a commercially viable energy source. "ITER never should have happened. Having said that, it is happening, and it seems to me that, practically speaking, people can't walk away from it."

Coblentz says that ITER has helped inspire the emergence of private-sector fusion companies. "We are demonstrating that these massive, precise components needed for fusion energy can be built at industrial scale, and we are developing the required new technologies as we go."

David Kramer

Tidal turbine development ebbs and flows

The renewable energy technology can benefit remote coastal communities that want to reduce carbon emissions.

ROWS OF TURBINES in the currents generated by the rise and fall of the tides offer a predictable way of producing electricity. Here, an array of 100 kW turbines sits on the Bluemull Sound seafloor off Scotland's Shetland Islands.

In Canada's Haida Gwaii archipelago, roughly 120 km off the northern coast of British Columbia, the north electrical grid uses more than 7 million liters of diesel to provide power to about 2500 people each year (the south grid uses roughly 3 million liters for roughly 2000 people). For long-term resident Laird Bateham, the predictability of the tides pointed to an obvious alternative. He founded Yourbrook Energy Systems in 2010 to develop a turbine for harvesting power from the local tidal currents. He and his team developed a prototype and are beginning front-end engineering of a project intended to deliver 500 kW of clean and reliable power to the isolated coastal community. That would provide for 20% of the population's average annual use. His colleague Clyde Greenough says, "We want to leave the world a better place by doing our part to slow climate change."

The twice-daily rise and fall of the tides drives powerful, predictable currents when seawater flows toward and away from Earth's coastlines. A turbine placed in the current's path can harness that power. The moving water pushes the turbines' blades, causing them to spin and drive a rotor that powers an electrical generator.

Tidal power has been harvested since the Middle Ages, when people retained incoming tidewater in storage ponds and used the outgoing flow to turn waterwheels for milling grain. In modern times, the world's largest tidal power plants are located in France and South Korea, with 240 MW and 254 MW electricity generation capacity, respectively. There, dam-like structures called barrages span ocean inlets or bays to capture incoming tidal water and generate electricity as the basin fills and empties. The installations can control flows using sluice gates, but because barrages are large scale (making them expensive to construct), they can disrupt the local ecosystem by altering lagoon salinity and animal movements.

In the past decade, motivated by advances in turbine technology and an increased urgency to find energy alternatives to fossil fuels, researchers have worked to generate electrical power by placing small numbers of turbines in strong tidal currents.

Projects like Yourbrook Energy are on