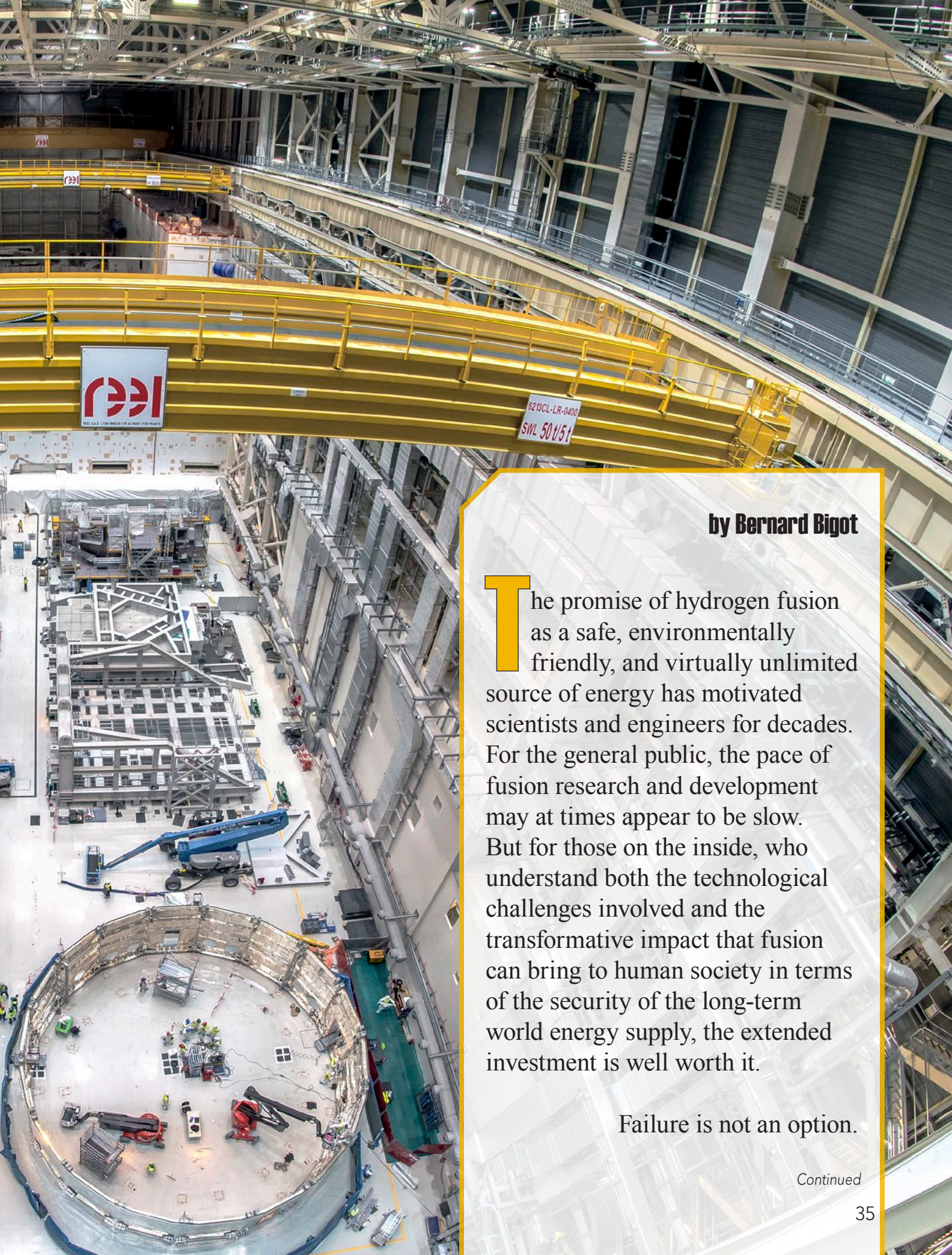


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# Understanding the **ITER Project** in the context of **GLOBAL PROGRESS ON FUSION**

ITER Project gangway assembly.



by **Bernard Bigot**

**T**he promise of hydrogen fusion as a safe, environmentally friendly, and virtually unlimited source of energy has motivated scientists and engineers for decades. For the general public, the pace of fusion research and development may at times appear to be slow. But for those on the inside, who understand both the technological challenges involved and the transformative impact that fusion can bring to human society in terms of the security of the long-term world energy supply, the extended investment is well worth it.

Failure is not an option.

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Given recent progress, enthusiasm about the future of fusion is greater than ever. Consider the news of just the past few weeks. The JT-60SA tokamak in Japan has reached the milestone of superconductivity in all of its magnets, with first plasma lying just ahead. South Korea's KSTAR has achieved a record-setting 100 million degrees for a 20-second pulse. China's HL-2M tokamak reached first plasma on December 4, and—looking farther ahead—China is well into plans for its CFETR (China Fusion Engineering Test Reactor).

The United Kingdom has launched the search for a site for its STEP reactor (Spherical Tokamak for Energy Production), with the ambitious goal of an operational prototype fusion power plant by 2040. The Fusion Energy Science Advisory Committee of the U.S. Department of Energy released its report for a long-range strategic plan for the U.S. fusion program on December 4, reflecting the collective vision of the American academic, industrial, and private sectors. And private sector investment is now funding more than a dozen fusion energy projects, including, notably, the Massachusetts Institute of Technology's SPARC tokamak, Tokamak Energy's venture in the United Kingdom, the magnetized target fusion project led by General Fusion in Vancou-

or largely self-heating plasma with pulses as long as 400 seconds and a Q factor of 10 (Q being the ratio between produced fusion power and injected heating power in the burning plasma), the physics phenomenon that scientists must be able to study as a prerequisite to optimizing the design of industrial fusion plants. Second, ITER has compiled a remarkable number of engineering breakthroughs, in fields ranging from electromagnetics to robotics, as a first-of-a-kind machine with multiple first-of-a-kind components that have demanded innovation by the best minds in many of the world's top engineering firms. Third, ITER is a groundbreaking collaboration of 35 countries engaged jointly in pursuit of a common goal for the betterment of humankind. Each of these aspects is important and worth considering.

The tokamaks of the past 50 years of research have successfully demonstrated most of the technologies required to make fusion a practical source of electricity generation. The use of superconducting magnets to create a strong magnetic field, the production of fusion energy using deuterium-tritium fuel, and the design of heating systems capable of raising plasma temperatures to over 100 million degrees are a few examples. But in order to achieve a burning plasma—the core element of ITER's mission—the ratio of thermal output power versus heating input power, the Q factor, must be well above breakeven. This Q ratio is governed by three factors: the density of the plasma, the strength of the magnetic field, and the volume of the vacuum vessel.

It is this formula that provided the basis for ITER's size and design specifications. ITER is designed to achieve  $Q \geq 10$ : 500 megawatts of fusion power output from 50 megawatts of plasma heating in a 400-second pulse, and in subsequent experiments, a steady-state Q of about 5. Based on the strength of the magnetic field achievable with ITER's superconductors, the goal of  $Q \geq 10$  determined not only the size of the ITER vacuum vessel, but also many of the other components: the 10,000 tonnes (metric tons) of niobium-tin and niobium-titanium superconducting magnets with a combined stored magnetic energy of 51 gigajoules, the cryogenics plant circulating nearly 25 tonnes of liquid helium at -269 degrees Celsius, and many other tokamak features and support systems with similarly extreme parameters. These design requirements have, by necessity, led

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Within this family of fusion enterprises, the ITER Project occupies a unique place. First, ITER is the only tokamak under construction at the required scale and design specifications to achieve a “burning,”

to breakthroughs in the fabrication of ITER's components and systems.

The year 2020 has been a time of exceptional integrated achievement in the face of uncommon challenges. The onset of the spread of COVID-19 coincided precisely, in the ITER schedule, with the planned completion and delivery of many first-of-a-kind components from ITER member countries, including some of those hardest hit by the pandemic:

■ On March 27, 12 days after France entered its coronavirus lockdown, ITER's European Domestic Agency, Fusion for Energy, successfully completed the turnover of the joined Tokamak Building and Assembly Hall. This milestone would enable the twin 750-tonne overhead cranes to traverse a distance of more than 100 meters, carrying and precisely positioning ITER's massive components into the tokamak pit.

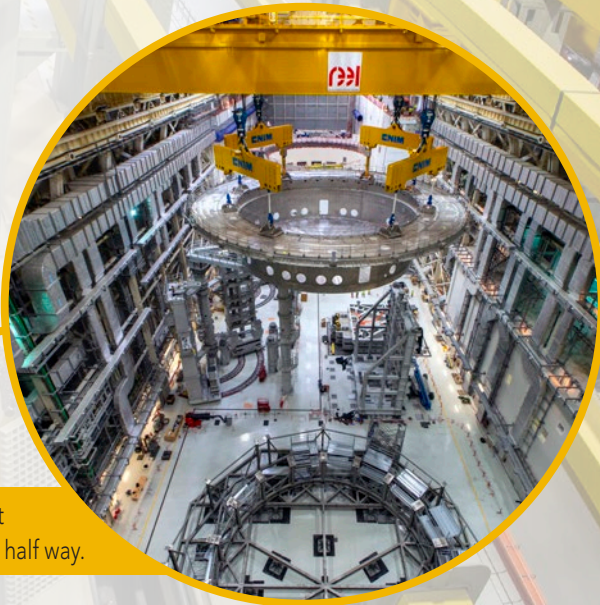
■ In April, ITER received the first of its D-shaped toroidal field (TF) magnets, TF12 and TF9, from Japan and Italy, respectively. In total, there will be 18 such TF magnets, each approximately  $9 \times 17$  meters in size and weighing more than 360 tonnes. Two more TF magnets arrived in July and September.

■ In May, ITER engineers raised the 1,250-tonne cryostat base to a height of nearly 60 meters, transported it across the crane hall, and placed it onto a circle of 18 spherical bearings on the steel-reinforced concrete "crown" of the tokamak pit. At 30 meters in diameter, the cryostat base was positioned with a precision of under 3 millimeters at all metrology points.

■ On June 23, the first ring-shaped poloidal field (PF) magnet, manufactured in China under a European procurement arrangement, arrived at the ITER site. At 10 meters in diameter and weighing more than 400 tonnes, PF6 required the local French authorities to chip away parts of the cliffs adjoining the road to enable its passage, part of a 104-kilometer journey from the Marseille harbor to the ITER site using a 342-wheeled remote-controlled transport vehicle. PF1, at 9 meters in diameter, is also nearing completion in Saint Petersburg, Russia. PF5 and PF2, at 17 meters in diameter, are in their final stages at the ITER site, and fabrication has started on the 24-meter-diameter PF3 and PF4.

■ Also in June, India completed the fabrication of all elements of the cryostat, a total of 54 massive but precisely forged pieces of steel, which were shipped to the ITER site to be assembled by German welders under Indian supervision in accordance with French nuclear regulations.

Toroidal field magnets TF12 and TF9.



Cryostat base lift half way.



PF6 arrival on site.



Machine-welding 6A.

■ On July 22, the first of ITER's vacuum vessel (VV) sections, VV S6, arrived from Korea. More than five years in manufacturing, the double-walled structure, with its maze of internal cooling water manifolds, diagnostic fittings, and external interfaces, and fitted with Russian-made port plugs, represents a marvel of engineering. Eight additional vacuum vessel sections, three in Korea and five in Europe, are under manufacturing and are 60 to 95 percent complete.

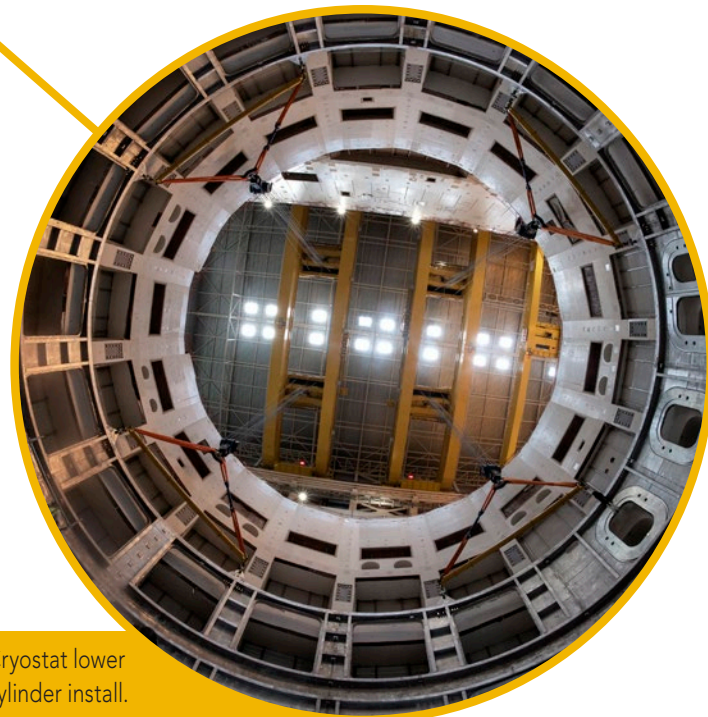
■ At the end of August, the cryostat lower cylinder was installed atop the cryostat base. At 30 meters in diameter and 10 meters high, it is ITER's largest component, roughly the size of Stonehenge. A team of human and robotic welders is now in the process of joining the lower cylinder to the base, an operation using more than 1 tonne of welding material along a 90-meter track at 8 centimeters per minute.

This recitation represents only a fraction of the progress at ITER, featuring the largest components, to give a feeling for the dimensions and complexity of the installation and assembly phase that will occupy the project for the coming three years. Supplementing this work on the tokamak complex, the balance of plant systems have made similar headway, including the electrical switchyard, the reactive power compensation system, the magnet conversion buildings and structures, the cryogenics facility, and the multiple cooling water systems that will ultimately remove the heat from the fusion reaction. And underlying the whole are the logistical arrangements for scheduling, transport, and temporary storage, plus the correspondingly complex aspects of risk management, interface matching, procurement and contract oversight, and safety and quality controls.

Each of these aspects of ITER design engineering, manufacturing, construction, and installation was foreseen to



ITER's vacuum vessel section VV S6.



Cryostat lower cylinder install.

Seven partners, together representing 35 nations, have joined under the ITER flag to take fusion to an industrial era. Credit: ITER



make 2020 and 2021 a challenging period. The onset of COVID-19 raised the stakes still higher. It would have been easy enough to shut down operations, but the intricacy of global partners, and the interdependency of the ITER assembly schedule, would have made a coherent restart nearly impossible.

With this in mind, ITER was perhaps fortunate to be able to learn from some of the member countries where the coronavirus hit earliest, and thereby to anticipate the onset and formulate a continuity plan. Critical path operations, many involving the first-of-a-kind components mentioned above, were given priority. A massive shift to teleworking for support staff, combined with a strong emphasis on individual responsibility in respecting hygienic measures to combat the spread of the virus, enabled the continuation of worksite activities. The resulting success was nearly miraculous. Despite heavy outbreaks in France, Spain, Italy, and other surrounding and member countries, the ITER project made it through the end of August without a single positive COVID-19 case on-site. Some cases have been seen since then, but without any transmissions that necessitated a broad work stoppage.

This integrated success in a time of global crisis leads to consideration of the last of ITER's unique features: international collaboration. It is not unprecedented for multiple world powers—even countries with differing ideologies—to join forces in pursuit of a common policy goal. But ITER goes well beyond any such effort in human

history: 35 countries, representing more than 50 percent of the world's population and 80 percent of the world's gross domestic product, are engaged in constructing a single machine. More than 1 million components are being sourced globally, roughly 9 percent each by China, India, Japan, Russia, South Korea, and the United States, and 45 percent by Europe as the host member. And this massive jigsaw puzzle must fit together with the precision of a Swiss watch, because a fusion tokamak, no matter how large, must create a magnetic field so tightly woven that it will prevent the escape of charged subatomic particles.

Perhaps the most heartwarming event of this challenging year came on July 28, when—in the middle of the global health crisis—leaders from around the world came together in a virtual ceremony to celebrate the start of the machine assembly phase at ITER. Due to the constraints on travel and socializing, the crowd gathered in the ITER Assembly Hall was small, but thanks to live broadcasting and video feed, the audience was global.

The occasion was historic. Seven heads of state and ministers from every ITER member offered statements reaffirming their support for the project. Their words gave a special resonance to the moment. Writing from Beijing, Chinese President Xi Jinping reaffirmed that “science is not bound by national borders. . . . International cooperation on science and technology is critical to humanity's response to global challenges.”

The description of ITER by Indian Prime Minister

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Narendra Modi was even more personal. “This shared endeavor for a common good is a perfect symbol of the age-old Indian belief that the entire world is one family,” he said. And this from South Korean President Moon Jae-in, speaking eloquently to the assembled gathering: “Dazzling stars in the night sky shine with fusion energy. Once we pool all the wisdom that the world has to offer, we will be able to have an artificial sun that lights our path towards the future.” As U.S. Secretary of Energy Dan Brouillette characterized it, “The ITER effort has helped to renew enthusiasm and optimism about the commercial promise of fusion energy.”

Perhaps it is no wonder that French President Emmanuel Macron, who hosted the ceremony, referred to ITER as “the promise of peace” and declared that ITER is “an act of confidence” in the future. “ITER belongs to the spirit of discovery, of ambition,” he said. “At its core is the conviction that science can truly make tomorrow better than today.”

Finally, in consideration of the American Nuclear Society audience, I will offer a few perspectives on the significant value that participation in the ITER project brings to U.S. fusion research, as well as to nuclear science and engineering.

The U.S. National Academies of Sciences, together with the Fusion Energy Sciences program within the Department of Energy, and with the support of the fusion community, has identified the creation, control, and understanding of burning plasmas as an essential element in fusion energy development. For the United States, ITER serves the burning plasma mission, as articulated above, and by sharing the costs and risks of building and operating ITER with six partners, the United States is able to leverage its resources.

As an ITER partner, the United States receives access to all ITER intellectual property and has the right to propose and conduct experiments at the facility. The know-how and expertise derived from ITER will inform future fusion devices and accelerate the U.S. path to fusion energy. So far, even before the start of operations, more than 5,000 papers about ITER’s design, technology, and supporting research are available through the DOE’s Office of Scientific and Technical Information ([osti.gov](https://www.osti.gov)).

U.S. technical contributions to ITER will also shatter the current performance limits of microwave and radiofrequency heating, plasma diagnostics, plasma fueling, and



tritium processing. The United States will soon send the first of seven modules of the ITER central solenoid, the world's largest and most powerful stacked superconducting magnet, to be positioned at the heart of the ITER tokamak. Within each of the U.S. contributions to ITER, including more than 600 contracts in 46 states and the District of Columbia, lies the opportunity for additional innovation, as well as exposure to international markets.

The development of a fusion workforce, with highly trained engineers and scientists, is aided by the anchor ITER provides for internships, postdoctoral research positions, early career training, and prime career research opportunities. The students and staff who contribute to ITER will be prepared to make contributions to other fusion endeavors, including prototype power plants. In every respect, U.S. participation in ITER is a sound investment in both the present and the future.

This year marks one hundred years since scientists first understood that fusion energy was the power source for the sun and stars, the source of all light and heat on earth, the sustenance of life itself. As we move into the assembly phase of the ITER machine, we feel the need for both

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urgency and patience. Above all, we feel the weight of history. When we succeed, when fusion power becomes the source of energy sustaining human progress, it will be worth every bit of the time and effort that have brought us to this point.

In the words of Secretary Brouillette, speaking at the ITER celebration in July, "Let's go to work. Let's change the world!" ☒

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Aerial view of the ITER Project.

