The ITER project, a collaboration of 35 countries to build the first industrial-scale fusion energy facility, is progressing in the south of France. ITER components are manufactured in factories around the world, then shipped to the ITER site for assembly and installation. Strong progress towards First Plasma in 2025 has been possible due in part to substantial achievements in research and development on fusion technologies to support ITER’s demanding engineering specifications. India is a core contributor.

Introduction

Fusion is the nuclear reaction that powers the Sun and stars. Fusion energy holds transformational potential as a source of safe, clean, and virtually unlimited power. Building on six decades of global research, the ITER project (originally known as the International Thermonuclear Experimental Reactor) is the critical remaining experimental step towards commercial fusion power plants. As such, ITER is the convergence point in the fusion roadmaps of each of its seven members: China, Europe, India, Japan, Korea, Russia, and the United States. The brainchild of U.S. President Ronald Reagan and Soviet Secretary Mikhail Gorbachev during their 1985 Geneva summit, the ITER project was soon joined by Europe and Japan. More than a decade of conceptual and engineering design followed, followed by political

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Box 1. Nine Steps to Fusion Power

1. A few grams of deuterium and tritium (hydrogen) gas are added to a donut-shaped tokamak chamber.
2. The hydrogen gas is heated until it becomes an ionized plasma.
3. Giant superconducting magnets confine and shape the plasma, keeping it from the metal walls.
4. When the plasma reaches 150 million °C—ten times hotter than the core of the Sun—fusion occurs.
5. In the fusion reaction, a tiny amount of mass is converted to a huge amount of energy ($E = mc^2$).
6. Ultra-high-energy neutrons from the fusion escape the magnetic field and hit the metal walls, conveying heat.
7. Some neutrons react with lithium in the walls to breed tritium fuel.
8. Water circulating in the walls absorbs heat to make steam that will drive turbines in industrial reactors.
9. ITER will be the first tokamak to achieve a ‘burning’, or self-heating plasma.

ITER’s unusual procurement arrangements reflect the desire of its members to gain expertise in fusion technologies at industrial scale (see Box 1). Approximately 80–90% of the funding provided by each member is ‘in-kind’, contributed in the form of components. These components are often first-of-a-kind, calling for extreme parameters of size, precision, and other technical specifications. Thus as each ITER member awards manufacturing contracts to its own companies, the innovation required creates value in the form of new industrial expertise, in fields ranging from materials science and advanced manufacturing to cryogenics, electromagnetics, robotics, vacuum systems, and power electronics.

More than one million components, fabricated in factories and laboratories around the world, must ship on schedule to the ITER worksite for assembly and installation into a first-of-a-kind machine. Managing this complexity requires extraordinary project management, systems engineering, and configuration control. A broad breakdown of tokamak procurement is shown in Figure 1.
As of mid-2019, the ITER Project has completed 65% of the work required for First Plasma, the initial machine operation scheduled for December 2025. Key buildings, such as the tokamak assembly building, the cryogenic plant, and the magnet power supply building, have been completed, and the associated systems are being installed. The tokamak building will be ready for equipment in 2020. The physical plant is moving towards completion, and systems are beginning to enter the commissioning phase. The current status of the worksite is shown in Figure 2. As will

**Figure 1.** Cutaway view of the ITER tokamak, with simplified breakdown to show which members are manufacturing which components.

**Figure 2.** ITER, July 2019. Key structures are: (1) ITER HQ; (2) Tokamak building; (3) Assembly Hall; (4) Cooling water building; (5) Cryostat workshop (owned by India); (6) Poloidal field magnet factory; (7) Cryogenics plant; (8) Magnet conversion buildings; (9) Electrical switchyard.
On 23 July 2019, ITER-India celebrated the completion of the cryostat base and lower cylinder, which together represent more than 60% of the cryostat. Shown: Group Leader Anil Bhardwaj points to the wall of the recently completed base, observed by ITER Director-General Bernard Bigot (blue hat, left) and Anil Kakodkar, former Chairman of the Indian Atomic Energy Commission and Secretary to the Government of India (yellow hat, center).

Manufacturing progress is equally impressive. In the next section, we will cover the Tokamak Systems in more detail, including the cryostat. The cryostat is a crucial component of the ITER vacuum vessel and the superconducting magnets. India’s fabrication of the cryostat is, in itself, a complex international operation. At nearly 30 meters height and 30 meters diameter, the cryostat will be installed in four segments: base, lower cylinder, upper cylinder, and top lid. But these segments are too large and heavy to be shipped in their entirety. As a result, Larson & Toubro is fabricating more than 50 individual cryostat pieces at their Hazira plant in Gujarat state, shipping the pieces to the ITER site in southern France, and then supervising welders from the German company MAN as final fabrication takes place under French nuclear regulation. (Figure 3.)

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**Figure 3.** On 23 July 2019, ITER-India celebrated the completion of the cryostat base and lower cylinder, which together represent more than 60% of the cryostat. Shown: Group Leader Anil Bhardwaj points to the wall of the recently completed base, observed by ITER Director-General Bernard Bigot (blue hat, left) and Anil Kakodkar, former Chairman of the Indian Atomic Energy Commission and Secretary to the Government of India (yellow hat, center).

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\(^2\)Cryostat (from cryo meaning cold and stat meaning stable) is a device used to maintain low cryogenic temperatures of samples or devices mounted within the cryostat.
Vacuum Vessel

Fabrication of the vacuum vessel sub-components is progressing under the responsibility of multiple ITER Members. Korea is fabricating four main sectors, equatorial ports, lower ports and gravity supports. The European Union is making five main sectors (see Figure 4). India is manufacturing the thousands of in-wall shielding tiles. Russia is contributing the upper ports. And the ITER Organization is directly procuring the in-service inspection tools, lower penetrations and port shielding, sealing flanges\(^3\) and instrumentation.

Coordination of this collective activity takes place under the responsibility of the Vacuum Vessel Project Team, to improve efficiency, accelerate decision-making, and increase quality. This close collaboration helps to ensure that all vacuum vessel components under manufacturing receive good quality assurance and control at various industry suppliers worldwide. Factory and site acceptance tests, which include pressure tests, leak tests, and dimensional control tests, validate that the technical specifications are respected. Coordination also entails ensuring that the vacuum vessel sector components interface properly with other systems such as in-vessel components, diagnostics, heating systems, fuelling, and the cooling water system.

Vacuum vessel component fabrication is more than 75% complete. The first completed sector is expected to arrive onsite from Korea in early 2020.

Magnets

The ITER magnet system is made up of 18 toroidal field (TF) coils, 6 central solenoid (CS) coils, and 6 poloidal field (PF) coils. These magnets are fabricated from superconductor alloys: niobium-tin is used for the TF and CS coils, and niobium-titanium for the PF coils. These alloys become superconducting when they are cooled (using liquid helium) to a temperature of 4 Kelvin. Superconducting magnets can carry higher current and produce stronger magnetic fields while using less current.

\[^3\text{Flange is a method of connecting pipes, valves, pumps and other equipment to form a piping system.}\]

ITER magnets are made with a ‘cable-in-conduit’ structure in which bundled superconducting strands—mixed with copper—are cabled together and encased in a structural steel housing.
**Figure 4.** Manufacturing of subsectors of the vacuum vessel taking place at the Walter Tosto factory in Italy.

**Figure 5.** In Japan, the first winding pack has been inserted into its structural case to form TF coil #12.

ITER magnets are made with a ‘cable-in-conduit’ structure in which bundled superconducting strands—mixed with copper—are cabled together and encased in a structural steel\(^4\) housing. The large-scale industrial production for ITER required a scale-up of global capacity from 15 metric tonnes/year to 100 metric tons/year. For the niobium-tin alone, 500 metric tonnes of strands (more than 100,000 kilometres) were produced by a total of nine suppliers. Central solenoid fabrication, led by the US, is about

\(^4\) Structural steel is a category of steel used for making construction materials in a variety of shapes.
60% complete. Toroidal field coils, produced jointly by Japan and Europe, are more than 50% complete (see Figure 5). Poloidal field coil manufacturing, taking place in Russia, China and Europe, is more than 30% complete. Additionally, the production of magnet ‘feeders’, which carry the electricity and cooling to the magnets, is progressing well; the first such feeder was installed at ITER in December 2018.

Heating and Current Drive Systems

To create the hydrogen plasma and heat it to the required operating temperature—150 million Kelvin—ITER will employ three systems: neutral beam heating, ion cyclotron resonance heating, and electron cyclotron heating. Together, these three systems are designed to inject 73 megawatts (MW) of heating power to the plasma, which could eventually be upgraded to as much as 110 MW.

Two neutral beam injectors will deliver a total of 33 MW of heating power. Research and development is being carried out at the Neutral Beam Test Facility in Padua, Italy, with support from Europe, Japan and India. Here, test beds for the ion source (known

Figure 6. In India, manufacturing and testing are in progress for the beam source and beam line components of ITER’s diagnostic neutral beam. Shown: the ‘angled’ plasma grid segments, part of this first-of-a-kind manufacturing.

Another Indian contribution in this area will be to the ion cyclotron resonance heating system (ICRH). The ICRH system will contribute 20 MW of plasma heating power.
Figure 7. ITER engineers test the 3.4-metre long, 8-tonne, first-of-a-kind cryopump that will be used to create the ultra-high vacuum in the vacuum vessel of the ITER tokamak.

as ‘SPIDER’) and the full-scale injector (known as ‘MITICA’) will enable proof-of-concept testing for ITER components. SPIDER, which is the world’s largest negative ion source, was inaugurated in June 2018; and in May 2019 first celebrated the acceleration of a beam of ions. India is also contributing a 100kV diagnostic neutral beam (see Figure 6), which will be installed to probe the helium ash content in the plasma core region.

Another Indian contribution in this area will be to the ion cyclotron resonance heating system (ICRH). The ICRH system will contribute 20 MW of plasma heating power. India has completed testing the prototype radio-frequency heating sources for this system, and finalizing the detailed design and series production will be the next steps. Testing has also been completed on the prototype high-voltage power supply.

The electron cyclotron heating (ECH) system will contribute 20 MW of plasma heating power. It will also be used to initiate each plasma discharge (if needed) and to provide local stability control. Following multiple decades of R&D, gyrotron series production began in 2017, in Russia, Japan, and Europe. ECH power will be transmitted to the plasma through windows that are sealed by synthetic diamond disks. Following the successful testing of prototypes, industrial production of these disks is beginning.
2. Plant Systems

Vacuum Systems

The overall ITER vacuum system comprise several large volume systems. These include the cryostat (∼8500 m³), the vacuum vessel (∼1330 m³), and the neutral beam injectors (∼180 m³ each). In addition, there are several lower-volume systems, such as the service vacuum system, diagnostics, and heating systems. Most of these systems are essential for First Plasma operations and will form part of the fuel cycle, and hence play a key role in the confinement and processing of tritium.

Given the challenging parameters of these ITER systems, it has been necessary to develop new processes and new technologies. The cryogenic viscous flow compressor (CVC) is one example. Six CVCs form the heart of the roughing system. The CVC cryogenically condenses hydrogen isotope mixtures and functions in combination with a roots mechanical pumping set that compresses helium ash originating from the fusion process. A second example is the development of a highly efficient tokamak dust filtering system that uses sintered stainless steel cloth that functions effectively in atmospheric and vacuum conditions. A range of doubly sealed standardized vacuum flanges has been designed to enable contamination control and remote handling compatibility. And new technologies are being explored for vacuum leak localization, including the development of a ‘robotic worm’ capable of localizing leaks in small diameter cryogenic pipes.

To support ITER’s vacuum system, new first-of-a-kind cryogenic pumps are required (see Figure 7). The final design and manufacturing process for the torus, cryostat, and neutral beam cryopumps include many novel design features and innovative processes, most of which have been successfully validated.

Cryogenics

ITER will require the largest single-platform cryogenics plant ever constructed, circulating more than 25 tonnes of liquid he-
Figure 8. Manufacturing of the ITER cryolines began in 2017 at the Cryo Scientific Division of INOX-CVA, an Indian company with more than 50 years of experience in cryogenics. The dedicated workshop is located in the outskirts of Vadodara in western Gujarat state.

India is providing the complex system of cryoline piping and distribution boxes that connect the various clients to the cryoplant. Much of this equipment has been delivered to the ITER worksite and is being installed. The cryogenics building is complete, and more than 75% of the cryogenic equipment in the building (refrigerators, 80 K plants, storage tanks, recovery and purification systems, quench tanks, etc.) has been installed. Operational acceptance tests are expected in 2020.

Cooling Water

The ITER cooling water system is composed of four main systems: the tokamak cooling water system (TCWS), the component cooling water system (CCWS), the chilled water system (CHWS), and the heat rejection system (HRS). The TCWS removes the 500 MW heating output from the fusion reaction through the vacuum vessel primary heat transfer system. The TCWS also em-
ploys supporting systems such as the draining and refilling system, the drying system, and the chemical and volume control system. From the TCWS, heat is transferred to the CCWS, which is an intermediate closed loop that, in turn, transfers heat to the HRS for final disposal to the atmosphere. CCWS also provides cooling for some other nuclear clients, such as tritium plant components. The non-nuclear clients (e.g., power supply, busbars, cryoplant, chillers) are cooled by separate loops of the CCWS, tailored to each client. Two chilled water systems provide cooling for important components and other clients via direct air heat transfer.

The United States is responsible for procurement of the TCWS. India is responsible for the design and procurement of the CCWS, CHWS, and HRS. The ITER Organization is also involved in both efforts.

Procurement of all cooling water systems is well underway. Certain TCWS tanks, for example, have already been fabricated, delivered, and installed because they are ‘captive’ components due to building construction constraints. For the HRS, CCWS, and CHWS, roughly 90% of the piping and 80% of other equipment has been completed. Thousands of pipe spools, supports, and valves have been delivered, as well as cooling tower components, electrical components, heat exchangers, instruments, chillers, and chemical systems. India has completed factory acceptance tests on 13 vertical turbine pumps for the HRS and 34 horizontal pumps for the CCWS and CHWS circuits.

**Steady State Electrical Distribution and Magnet Power Supplies**

ITER’s electrical distribution system consists of the steady state electrical network (SSEN) and the pulsed power electrical network (PPEN). For the SSEN, ITER’s 400 kV switchyard and the four main step-down transformers have been installed and commissioned, and the system became operational in January 2019.

The PPEN will supply power to ITER’s superconducting magnets and heating and current drive systems. Progress is very far along, with most of the equipment having already been delivered,

Procurement of all cooling water systems is well underway. Certain TCWS tanks, for example, have already been fabricated, delivered, and installed because they are ‘captive’ components due to building construction constraints.
Figure 9. Work is proceeding efficiently on the magnet power conversion buildings and associated support equipment. Of a total of 32 transformers, 30 have been delivered to ITER from China and Korea so far. Shown: Chinese transformers are installed in their dedicated bays outside of one of the magnet power conversion buildings.

Figure 10. The ITER ‘staged approach’, which outlines the phases of operations and additional assembly from First Plasma 2025 through fusion power operation 2035.

and onsite installation well underway. The magnet power conversion buildings have been characterized as an excellent illustration of ITER’s international collaboration (see Figure 9). Europe has completed the twin buildings and handed them over to the ITER Organization for equipment installation. The piping has come from India; China and Korea have provided the transformers; Russia has manufactured the massive ‘busbar’ network and special cabling. ITER Director-General Bernard Bigot has said this activity, like many others at ITER, is a symbol of “the ONE-ITER spirit that unites us all.”

3. Conclusion

In summary, ITER is progressing efficiently along its planned schedule. The operational timeline envisions assembly and clo-
sure of the torus in the tokamak building by the end of 2022. Completion of the systems needed for the First Plasma, as indicated by the closure of the cryostat, will occur by the end of 2024. This will initiate a period of ‘Integrated Commissioning’, culminating in achievement of the First Plasma in ITER by the end of 2025.

The purpose of the First Plasma phase is to demonstrate that all of the fundamental components of the tokamak (vacuum vessel, magnets, and critical plant systems) are fully functional before proceeding with the installation of in-vessel shielding and plasma-facing components. Following the installation of these components (see Figure 10), ITER will proceed in a ‘staged approach’. Two pre-fusion power operating phases are envisioned to fully test all of the heating systems, diagnostics, and all supporting systems prior to the fusion power operation, now planned for 2035.

As an energy project capable of re-shaping the future of humanity, driven forward and built by the sustained collaboration of 35 countries, ITER is unparalleled in history. The potential benefits of fusion energy are extraordinary, including the implications for international peace that could be realized with the advantages of safe, clean, baseload energy and virtually unlimited fuel, available to all countries on Earth.

But in addition, the very process of reaching that goal is proving to have outstanding near-term benefits: the expansion of industrial expertise in the companies of each ITER member, through innovation and the creation of new, breakthrough technologies. The commitment of each ITER member to the ITER mission continues to be the project’s greatest strength.

Suggested Reading


[2] For more information, see www.iter.org