iter magazine

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#4 JULY – AUGUST 2014

The world's largest Erector Set

Editorial

On 4 August 2010, a lone digger began the excavation of what would soon become the Tokamak Complex Seismic Pit.

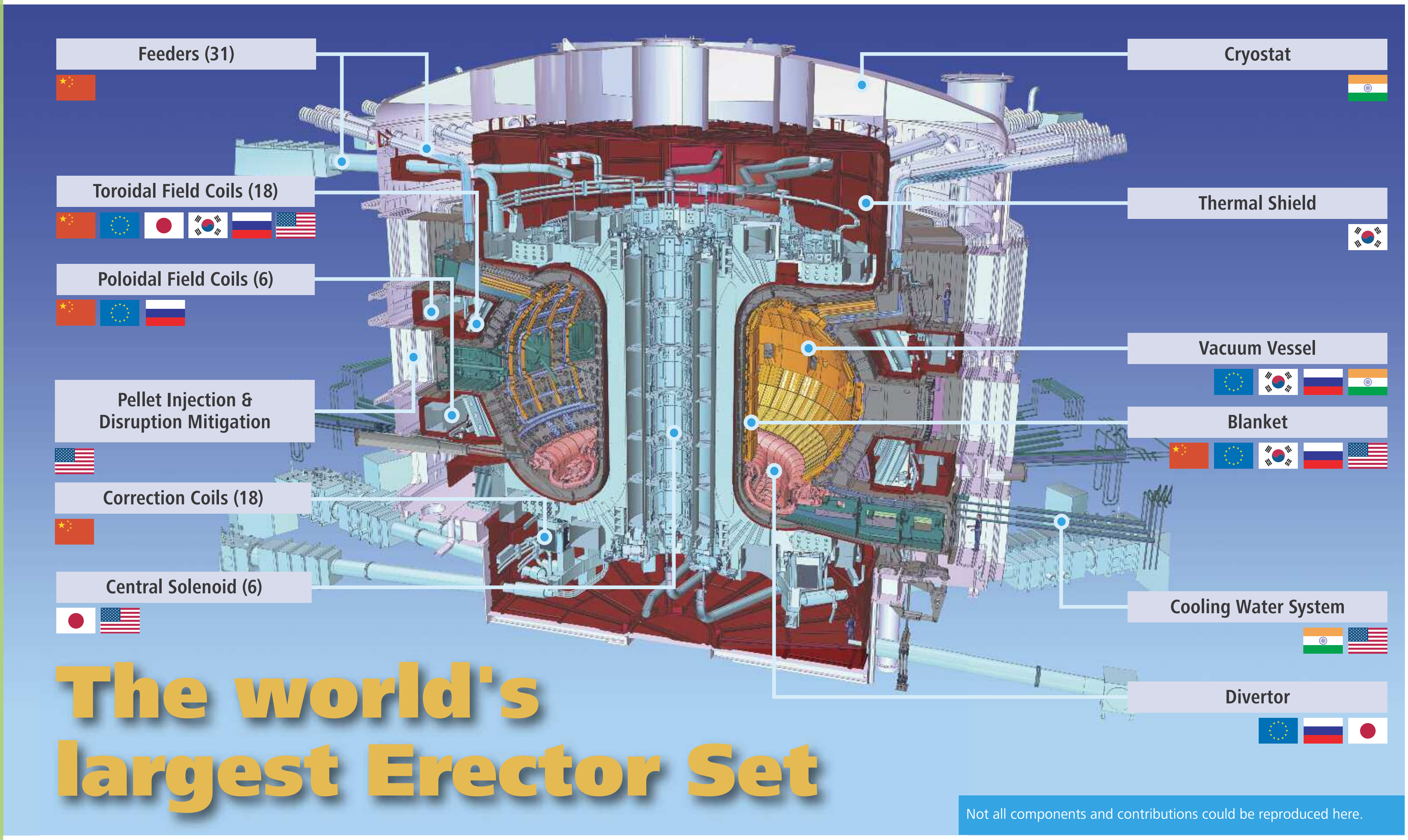
Four years later, workers have just completed the reinforced concrete basemat that is designed to support the most complex machine that human ingenuity has ever conceived.

In Europe, Asia and America, factories are working around the clock to produce the millions of parts necessary to assemble the ITER Tokamak and plant systems. This worldwide procurement program is incredibly complex and absolutely unique.

In this fourth edition of ITER Mag we'll explain why, without the complexity, ITER couldn't exist.

ITER Mag team
editormag@iter.org

iter
china eu india japan korea russia usa



The world's largest Erector Set

Compared to the ITER Tokamak, a space shuttle, an aircraft carrier and a nuclear submarine are all relatively simple objects: their technologies are well tested and their fabrication is practically industrialized.

However ITER is completely unique, and a large number of its constituent parts will be first-of-a-kind. Although other large tokamaks have been built around the world, not one of them resembles the tokamak that will be assembled in Saint Paul-lez-Durance, France in terms of scale and complexity.

Adding to the complexity of ITER is a unique procurement program that divides the fabrication of the machine's components and systems among the seven ITER Members (China, the 28 members of the European Union plus Switzerland, India, Japan, Korea, Russia and the United States).

If the ITER Project was "only" about building and operating the largest tokamak in the world, things would be simpler. But ITER is more than that. From the beginning, the project was designed with the idea that the Members, through their participation, would each advance their own scientific, technological and industrial base in fusion and in this way prepare for the next-step machine – a demonstration fusion reactor (see "ITER ... and then what?" in *ITER Mag #3*).

As a result, the ITER Members are involved broadly in procuring components and systems (referred to as "in-kind" procurement). A few examples? The fabrication of the ITER vacuum vessel sectors has been divided between Europe (7 sectors) and Korea (2 sectors); the central solenoid is a collaboration between the United States and Japan; divertor manufacturing and testing is divided between Europe, Russia and Japan; India and the United States are sharing responsibility for ITER's cooling water systems; the blanket system will be produced by China, Europe, Korea, Russia and the United States; and finally, six ITER Members (all except India) are involved in the production of ITER magnets.

Finalized in early 2006, the distribution of in-kind fabrication tasks was based both on the interests and the technical and industrial capacities of each of the Members. China, India, Japan, Korea, Russia and the United States have each agreed to cover 9.1% of ITER construction (nine-tenths of this contribution will be supplied in kind to ITER, and only one-tenth in cash). Europe, host to the ITER Project, participates at the level of 45%, including a share of ITER components and systems as well as nearly all the buildings of the scientific facility. For its greater investment, Europe also reaps the lion's share of economic benefits (EUR 4 billion in contracts have been awarded for ITER on European territory since 2007).

To manage all of these in-kind contributions, the ITER Organization – which coordinates the project – has already signed nearly 100 Procurements Arrangements with the ITER Domestic Agencies (one Domestic Agency has been established in each ITER Member). These agencies, in turn, contract out to industry for the fabrication of the component according to the very specific conditions laid out in the Procurement Arrangement documents. Since the beginning of the process, more than 1,800 contracts for design or fabrication have been awarded by the ITER Domestic Agencies.

In factories on three continents, the components and systems of the ITER plant are now taking shape. Putting it all together will be like working on the largest Erector Set in the world, with at least one million components and more than 10 million individual parts.

Managing such a unique international procurement system may often seem unwieldy and complex, but without it ITER simply would not exist.

To conceive of the largest tokamak in the world ... to garner the support of international partners around a common project ... it was absolutely essential to go beyond the traditional client-supplier relationship. A whole new form of partnership had to be invented: one that preserved the interests of both the Members and the project as a whole.

That's the challenge of ITER, but also its appeal: a project founded on the idea of large-scale scientific collaboration for the good of all.

How much does ITER cost?

Whether you're manufacturing a T-shirt or an ITER blanket module, fabrication costs vary widely from one country to the next.

In a similar manner, the evolution of Member currencies as well as labour and material costs over the ten years of ITER construction can fluctuate dramatically.

The ITER Unit of Account (IUA) is an in-house currency that was created as part of the ITER Agreement to provide a stable base over time and to equitably allocate the value of in-kind procurement to each Member. It's in IUA, or more exactly, thousands of IUA (kUIA), that the ITER Organization assigns value to each one of the Procurement Arrangements signed with the Domestic Agencies.

Does that help us to know how much it will cost to build ITER? The European Union has estimated its global contribution to the costs of ITER construction at EUR 6.6 billion. The value of other Member contributions depends on the cost of industrial fabrication at home (which can be higher or lower) and the percentage contribution to ITER construction.

Based on the European evaluation, we can estimate the cost of ITER construction for the seven Members at approximately EUR 13 billion (if all manufacturing was done in Europe). This cost will be shared over ten years by the 35 countries that make up the ITER Members (who, together, represent 80% of the planet's gross domestic product).

As one element of comparison, Qatar is investing EUR 150 billion in infrastructure for the 2022 World Cup.

The concrete employed at ITER plays a double role: it guarantees structural integrity as well as nuclear safety.

A concrete for every purpose

Gravel, sand, cement, water and sometimes an additive ... at first glance, concrete seems like a simple material. But not at ITER, where construction follows strict norms and regulations, and every step is verified not once ... but many times.

Two 1.5-metre-thick concrete basemats are already in place in the Tokamak Seismic Pit. For the lower basemat, which supports the 493 anti-seismic columns, a rather "standard" concrete was chosen that has a resistance to compression of approximately 3,000 tons per square metre.

For the upper-level basemat – the "floor" that will support the machine and the Tokamak Complex buildings – superior resistance is called for (4,000 tons per square metre) as well as particular qualities related to nuclear confinement, as the basemat must act as the ultimate confinement barrier after the vacuum vessel walls and the 3.5-metre thick bioshield.

Strongest of all is the concrete for the crown-shaped pedestal of the 23,000-ton ITER Tokamak, which is required to have a degree of resistance two to three times that of the Tokamak Complex floor. (This particular formula is still undergoing qualification activities.)

And finally, in the immediate proximity of the Tokamak (the bioshield, for example), contractors will employ "heavy concrete," where the typical granular materials are replaced by iron ore. For this concrete, the mass of one cubic metre increases from 2.4 to 3.6 tons.

Whether ordinary or exceptional, the concrete used in ITER construction is the object of control and verification at each stage of its elaboration and implementation. All concrete formulas are tested by the contractor in charge of concrete pouring, both in the laboratory and in real-scale mockups.

Consistency and spreadability are also important parameters in order to ensure the homogenous distribution of the concrete throughout tight matrixes of steel reinforcement. These parameters are tested as the concrete leaves the on-site batching plant and before it gets loaded into the mixer trucks.

For each realization on the worksite, samples are taken and stored in order to study the evolution of the concrete over the short and long term (2 to 90 days). "We rely on systematic verification and testing," say Damien Sorbier and Romain Paix, both engineers with the Engage consortium, which is in charge of detailed design and work supervision for the European Domestic Agency. "But everything is well prepared ahead of time so that we don't have any surprises..."

On pouring days, operators must also keep a close eye on ambient temperature. The concrete can't leave the batching plant if the thermometer displays a temperature of 10°C or lower; pouring is also cancelled if temperatures exceed 30°C. Mid-winter or mid-summer, the concrete is sometimes warmed or cooled to remain within acceptable parameters.

No effort is too great to ensure the quality of the concrete and its implementation because for ITER, this will determine the integrity and the safety of the entire installation.

José Manuel Barroso, the President of the European Commission, is convinced that the future of Europe is in science and innovation. On 11 July 2014, he visited ITER to reaffirm Europe's commitment to ITER.

Europe's Barroso: "Proud to have believed in ITER"

The European Commission president visits the ITER worksite at a crucial moment in construction progress.

In the official photo of the ITER Agreement – signed at the Elysée Palace in Paris on 21 November 2006 – he occupies the place of honour at French President Jacques Chirac's right.

José Manuel Barroso, whose second term as European Commission president ends in October, recollected that day during a recent visit to ITER on 11 July 2014. "Eight years ago, along with President Chirac, I worked hard for ITER to be located here. The European Commission is proud to have believed in this project."

Part of a tour of strategic projects in Europe aimed at fighting climate change and facilitating worldwide "energy transition," President Barroso's visit took place as concrete pouring was getting underway on the part of the Tokamak Complex basemat that will support the ITER machine – an important moment for ITER construction.

Accompanied by French Secretary of State for Higher Education and Research, Geneviève Fioraso, President Barroso strongly reaffirmed Europe's commitment to ITER, because, as he stressed, "the future of Europe is in science and innovation. As the gateway to industrial and commercial fusion, ITER presents a unique opportunity for our industry."

In a humorous aside to ITER Director-General Osamu Motojima, he concluded his visit by saying: "I'm responsible for coordinating the action of 28 countries – you, 35. I know it's not easy every day!"

The European tokamak JET, enhanced with an ITER-like wall and divertor, is getting ready to renew experiments with a 50-50 mix of deuterium and tritium.

T-time for JET

In operational tokamaks around the world, plasmas are heated every day to temperatures that reach tens of thousands, or even millions, of degrees Celsius.

Run with hydrogen, deuterium or helium these experiments may not generate fusion energy, but they allow scientists to better understand the behaviour of plasma – the "fourth state of matter" – at very high temperatures. Such knowledge contributes to the design of ITER.

In order to generate large amounts of power in a tokamak, as ITER plans to do, the reactor must be fuelled with a combination of hydrogen isotopes known to produce the most efficient fusion reaction – a 50-50 mix of deuterium (D) and tritium (T). The use of the radioactive element tritium, however, generates significant operational constraints: D-T fusion is only possible in a nuclear facility subject to very draconian safety and security measures, and all maintenance activity must be carried out by robotics.

Only one tokamak in the world is capable today of D-T fusion: the Joint European Torus (JET), that has been in operation in the UK since 1983.

Until ITER enters operation, the JET tokamak holds three world records: it's the largest tokamak in the world; it is the first to have realized D-T fusion during its 1991 campaign; and it holds the record for fusion energy production (16 MW produced in 1997). The American tokamak TFTR (Tokamak Fusion Test Reactor) is the second machine to have produced significant fusion energy (10.7 MW) in 1994, before the machine was dismantled three years later.

Outside of a short experimental campaign in 2003, when small amounts of tritium were added to deuterium plasmas, it has been 17 years since the last D-T fusion experiments were carried out at JET – 17 years since a small, artificial star was briefly created on Earth.

This landmark science is about to be achieved again. JET, which has been updated with ITER-like materials including an inner wall of beryllium and tungsten, is about to return to the "real thing." The experimental campaign planned for 2017-2018 will prepare the way for the beginning of D-T operation in ITER, scheduled some ten years later, in 2027. *(During its first six years of operation, the ITER Tokamak will progressively scale up from hydrogen, then helium, then deuterium plasmas.)*

Preparations are underway now at JET. Before D-T plasma shots can begin again, the team at JET must fine-tune the machine, train a new generation of operators, and reactivate the knowledge and experience accumulated during the D-T experimental campaigns of the 1990s.

In three short years, JET will kick-off a new set of full-power fusion experiments using tritium fuel in a campaign that will act as an important "dress rehearsal" in preparation for ITER's operation with tritium.

The best combinations

Fusion reactions, obtained through the pairing of different isotopes of light elements, liberate on average four to five million times more energy than the most powerful chemical reactions such as the burning of coal, oil or gas. In the present state of fusion technology, the most efficient pairing is the reaction between two "heavy" isotopes of hydrogen – deuterium (D) and tritium (T).

D-T fusion, which is the reaction chosen for ITER and the first-generation fusion reactors, presents a certain number of challenges: tritium is radioactive and the impact of the high-energy neutrons produced by the fusion reaction will activate the internal components of the machine.

Other combinations of elements are conceivable with non-radioactive elements that produce no (or practically no) neutrons: it's the case of the helium isotope helium-3, for example, which can fuse with other helium-3 nuclei or with deuterium. Technically impossible to achieve today due to the extreme temperatures necessary for its realization, helium-3 fusion also presents another major disadvantage – the nearest deposits are captured within Moon rock.

The most "ideal" reaction – which may be the source of power for the fusion reactors in the centuries to come – is proton-boron fusion. Completely aneutronic, this fusion reaction is the Holy Grail of researchers. Among its technical challenges: temperatures on the order of 6.5 billion degrees Celsius and a method of confinement that has not yet been invented ...

Cover image: The Chinese institute ASIPP is preparing to launch the fabrication of ITER's 18 correction coils (part of the magnet system) after having successfully fabricated a full-scale mockup.

ITER Organization Headquarters
Route de Vinon-sur-Verdon
CS 90 046
13067 St. Paul-lez-Durance Cedex
France

Publications Director
Michel Claessens
michel.claessens@iter.org

Editor
Robert Arnoux
robert.arnoux@iter.org

Contributors
Krista Dulon

www.iter.org

iter
china eu india japan korea russia usa