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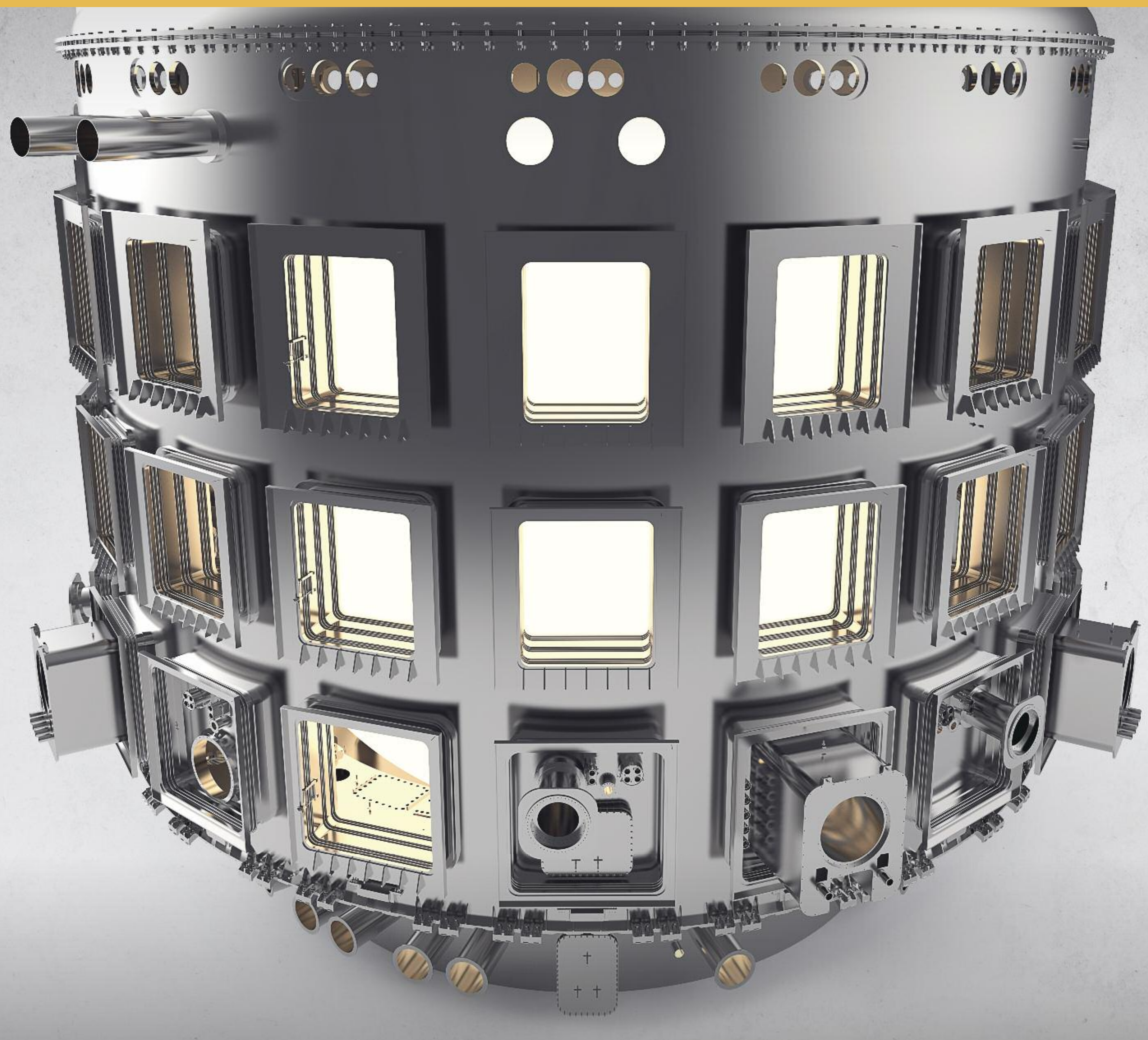


Keeping it cold

Editorial

This month, *ITER Mag* takes you into the Industeel-Le Creusot plant in central France, where high-performance "niche" steels are fabricated for ITER and shipped to points all over the globe to be incorporated into some of the machine's most technically challenging components. Nearly 4,000 tons of specialized steel will be required for the cryostat alone, which – as you'll learn in this issue – will act as a kind of giant thermos, surrounding the tokamak and maintaining the magnet system at a temperature close to absolute zero.

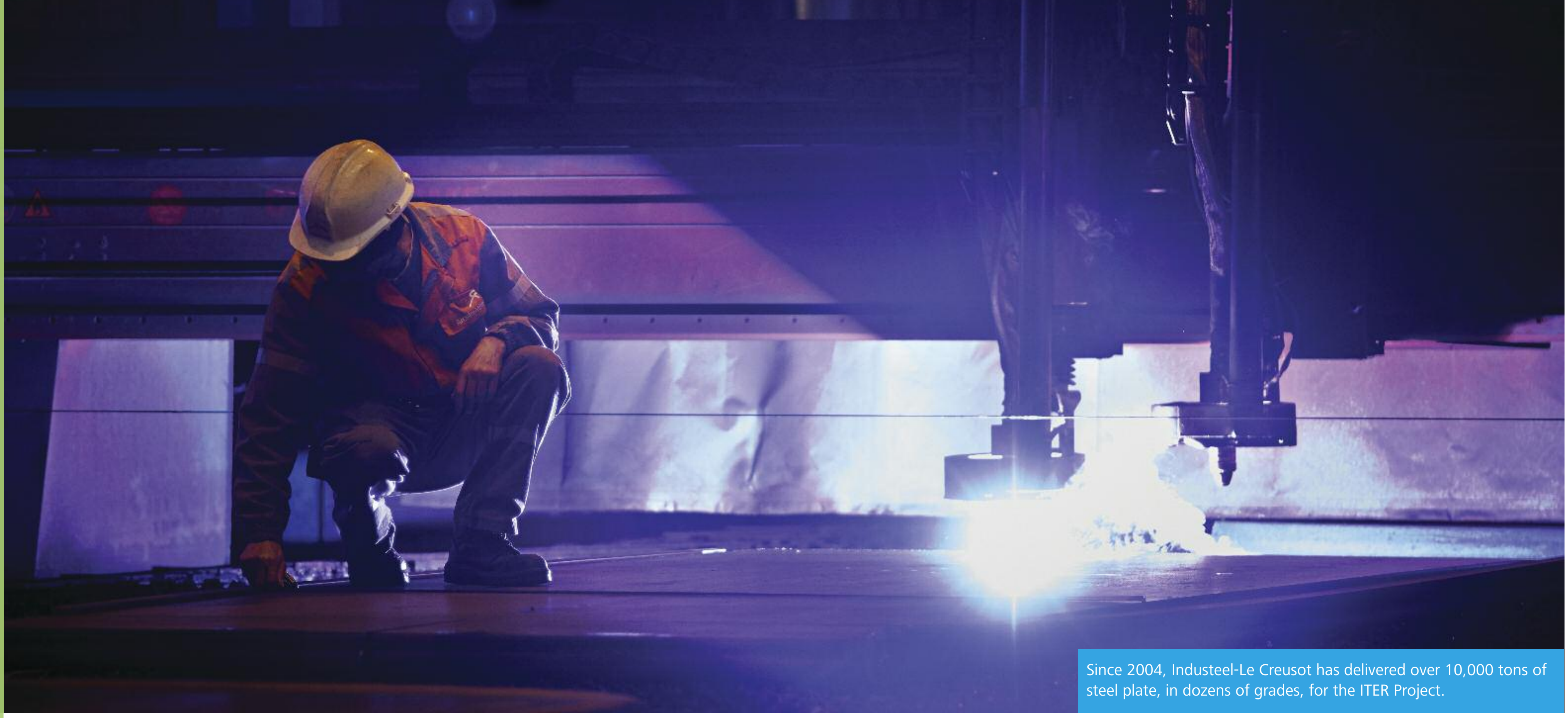
This sixth issue also invites you to the movies. For over 30 years, fusion has made an appearance in science fiction films, where the power of fusion is used to run electrical plants, launch rockets, or even fuel time machines.

***ITER Mag* team**
editormag@iter.org

iter

china eu india japan korea russia usa

In the forges of ITER



Since 2004, Industeel-Le Creusot has delivered over 10,000 tons of steel plate, in dozens of grades, for the ITER Project.

Men of the Iron Age, long before the term was coined, accidently discovered that by adding a bit of carbon to molten iron, a harder and more durable metal was created – steel.

Three thousand years have gone by and steel is still at the centre of our civilization. World production passed 1.5 billion tons in 2013 – a factor of fifty increase over the early 1900s.

But today's steel is a far cry from the one produced in Iron Age kilns. Although the basic recipe hasn't changed (iron and a small amount of carbon), manufacturers are capable of producing wide palette of grades – steel manufacturing today often resembles the elaboration of a sophisticated perfume, where fragrances are combined to realize the desired effect. Steelmakers in France, in fact, have borrowed the word "*nuance*" from the perfume industry to characterize the variety of grades they produce.

According to the specific needs of each customer, the chemical composition of the steel can be adjusted: steel for an automobile, for example, is different from the one used in the metal structure of a building; steel for a high-speed train rail has very little in common with the one chosen for a water cistern.

And some customers, some activities, require an even greater level of sophistication…

At the Industeel-Le Creusot plant in central France (a business unit of the global giant Arcelor-Mittal), some 450 different grades are available. At the top of the line are the steels that will be used in ITER components. From the first mockups and prototypes produced in 2004 for the ITER vacuum vessel, to orders on the books today from companies with ITER contracts in Korea, India, Russia and Europe, the steelworks in Le Creusot has booked some 10,000 tons of steel plate in a dozen different grades and ranging in thickness from 5 to 150 millimetres.

These specialized steels must meet ITER's demanding functional, safety and technological requirements. Some will be exposed to ultra-hot plasma and high vacuum, others to the extreme cold of the cryogenic fluid. Some must be completely permeable to magnetic fields; others, on the contrary, must act to influence them...

It's all a matter of chemistry: a good dose of chromium prevents oxidation; a small percentage of nitrogen improves mechanical properties; a zest of titanium, niobium or molybdenum increases resistance to corrosion; and boron can be added for better neutron absorption – an essential quality for certain ITER components.

And if chemistry is important, manufacturing processes also play an important role in the final product. "The Korean company SFA Engineering Corp, responsible for manufacturing the thermal shield system for ITER, will add a thin layer of silver to the plates that we supply," explains Jean-Christophe Gagnepain, the sales manager at Industeel-Le Creusot. "The quality of this layer depends on the quality of the plate's surface, and ultimately on our production expertise."

Industeel-Le Creusot has already shipped 5,000 tons of stainless steel plates to India, 3,500 tons each to Japan and Korea, and 300 tons to Russia, where they'll become a part of the ITER vacuum vessel, cryostat, thermal shield or magnet system.

In a rural area of central France, a steelworks founded in the early years of the 19th century is helping to meet the challenges of one of the most complex machines of the 21st.

The lightest of the "heavy" loads

The voyage got off to a start in mid-November in the industrial port of Ulsan, Korea – more than 9,000 kilometres from the ITER site. Two months later, in January 2015, the "freight" was delivered to ITER.

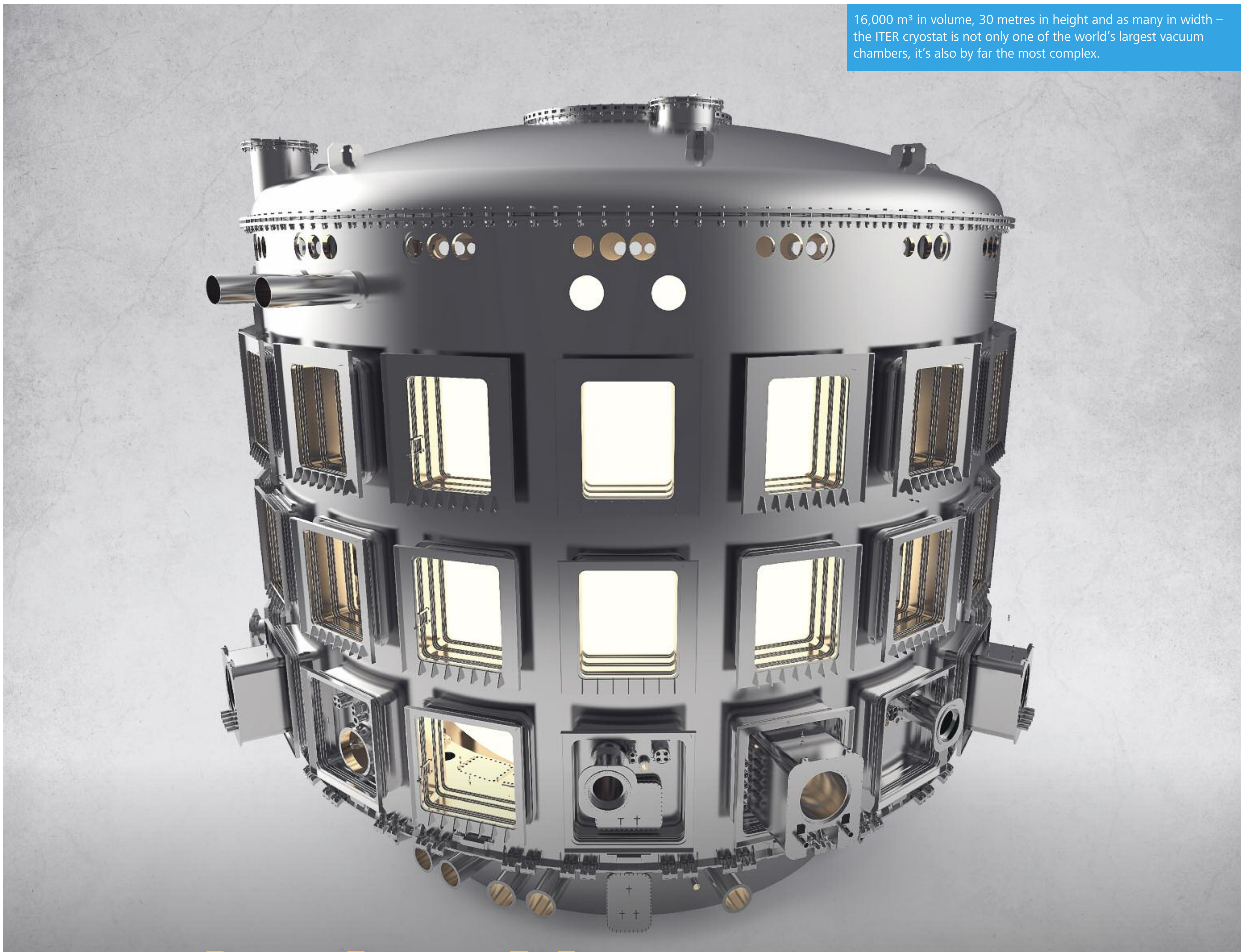
The last two legs of the trip were the most delicate: unloading from the container vessel and storage during the holidays; followed by trailer transport – first by road, then by barge across the inland sea Etang de Berre, and finally along the 104-kilometre ITER Itinerary to the ITER site.

Procured by the United States, manufactured by Hyundai in Korea, transported by DAHER (ITER's global logistics provider), the electrical transformer was the first of many Highly Exceptional Loads that will be delivered to the project in the years to come. It was also the lightest of the "heavy" loads – 87 tons, whereas the most impressive ITER components will reach 600 tons (plus another 200 tons for the transport vehicle).

For all components that will travel along the ITER Itinerary (see "A successful journey" in *ITER Mag* #1), the transport will be organized by DAHER and Agence Iter France in collaboration with French authorities, and financed by the European Domestic Agency for ITER.

Before the ITER Tokamak and plant systems are in place, over 250 Highly Exceptional Loads will have travelled along the ITER Itinerary.

Procured by the United States, manufactured by Hyundai in Korea, transported by DAHER (ITER's global logistics provider), the first Highly Exceptional Load – an electrical transformer – arrived on site on 17 January 2015.



16,000 m³ in volume, 30 metres in height and as many in width – the ITER cryostat is not only one of the world's largest vacuum chambers, it's also by far the most complex.

Keeping it cold

For keeping your coffee warm, there's nothing like a thermos – an ingenious and simple device invented at the end of the 19th century. In between the two walls of a thermos, a vacuum provides the thermal insulation that keeps your hot drink hot.

And what works for the high end of the thermometer also works for the low – a chilled liquid, insulated from the external environment by the thermos' vacuum, will also conserve its temperature for several hours.

In the ITER Tokamak, the conservation of cold is essential for ensuring the superconductivity of the magnet system, which is cooled to -269 °C through the circulation of liquid helium (see *ITER Mag* #5). If this extraordinarily low temperature – colder than the environment of Pluto – isn't maintained, the ITER magnets would lose their superconducting properties and plasma operation would be brought to a halt.

To succeed, the magnet system must be isolated, as perfectly as possible, from the surrounding environment. How? By placing the machine and its magnets within an enormous thermos – a cylindrical vessel called the cryostat that measures 30 metres in height and as many in width.

Between the liquid helium circulating inside of the magnets and the tokamak environment, the difference in temperature is approximately 300 °C. This large temperature gradient is reduced by installing an intermediate thermal barrier – called a thermal shield – at a distance of about ten centimetres from the magnets. The ITER thermal shield will be actively cooled to -193 °C. A vacuum about one million times less dense than the air we breathe insulates the thermal shield from the cryostat, preventing thermal exchange between the two environments.

With a total volume of 16,000 m³, the ITER cryostat is not only one of the world's largest vacuum chambers[1], it's also by far the most complex.

Unlike a thermos, whose surface is never breached, the ITER cryostat will have some 280 penetrations – certain as large as four metres – which will provide access for piping, electricity, heating systems, diagnostics and remote handling systems. Each one of these openings will have to be as leak-tight as possible to preserve the cryostat's vacuum environment.

But the leak-tightness of joints and bellows is not the only challenge. In certain temperature conditions materials tend to "outgas" – that is, to liberate a small quantity of their constituent molecules. The quality of the vacuum is affected little by little by this outgassing and powerful cryopumps[2] are needed for the regular evacuation of these molecules.

Beyond its insulating role, the ITER cryostat also has a structural function to fulfil in ITER. "The cryostat is joined mechanically to the ITER machine and in this way is part of a structural assembly," says Igor Sekachev, the engineer responsible for the ITER cryostat. "The concrete and steel pedestal that has been designed to support it was sized for a total mass of 23,000 tons – the 3,850 tons of the cryostat itself as well as the 18,900 tons of the vacuum vessel, magnet system and thermal shield."

Larsen & Toubro, the Indian company that manufactured the rocket, antenna and radar of the Mars Orbiter Mission *Mangalyaan*, began the fabrication of the ITER cryostat in early 2014. The first segments of this enormous cylinder, made from steel from the forges of Industeel-Le Creusot (*see page 2*), will be shipped from the factory in September 2015.

From 54 segments, the four principal sections of the cryostat will be welded and assembled in an on-site facility that was inaugurated in 2014.

The assembly of the ITER Tokamak will begin and end with the cryostat: the base section of the cryostat will be the first large component installed in the Tokamak Pit and the top lid of the cryostat (600 tons) will be the last large component, set into place after the installation of the vacuum vessel, magnets, thermal shielding and central solenoid.

(1)-Only the NASA's Space Power Facility, built to re-create the high-vacuum environment in space for the testing of satellites and hardware, can boast a larger vacuum chamber (22,500m³). One of the most spectacular scenes of *The Avengers* was filmed there in 2011.

(2)-Cryopumps are used alongside regular pumps at ITER to create a high vacuum in large-volume environments (vacuum vessel, cryostat) by "trapping" gaseous molecules in their intense cold.

The spaceship that carries passengers on a quest for inhabitable planets in the 2014 blockbuster *Interstellar* is fuelled by compact tokamaks that also provide the vessel's electricity.

Fusion and fiction

In 1985 – the very year that a collaborative international project in fusion was proposed by General Secretary Mikhail Gorbatchev to President Ronald Reagan – fusion made a discreet but noteworthy appearance in a film that would be seen by millions around the world: *Back to the Future*.

In one of the last scenes of the movie, the sports car that had travelled through time thanks to a "flux capacitor" powered by plutonium is equipped with a brand-new apparatus: a coffee-grinder-shaped fusion generator called "Mr Fusion."

The successful harnessing of fusion power shows up in other blockbuster productions: cold fusion is at the centre of the intrigue in the spy thriller *The Saint* (1997); we encounter it in *Spider Man II* (2004) when another "Doc" (Octavius) wields its supposed devastating power. Superheroes seem to have a privileged relationship with fusion: take, for example, Iron Man (in a 2008 film of the same name) whose exoskeleton integrates a miniature fusion reactor; or Batman in *Dark Knight Rises* (2012), who prevents the villain from transforming an experimental fusion reactor into a thermonuclear bomb.

The action in *Oblivion* (2013) fast forwards us to the year 2077, where off-shore fusion power stations furnish energy to the colonies established on the largest of Saturn's moons, Titan. For the first time in movies, fusion is treated as the energy source it is, whose main vocation is to produce electricity.

A main vocation, perhaps, but not an exclusive one: for many years, scientists have been studying the possibility of using fusion for space propulsion. NASA, for example, is developing a conceptual vehicle that it calls *Discovery II* (in reference to the film *2001: A Space Odyssey*) based on a small, spherical tokamak that could produce enough energy to propel a spaceship to Jupiter in one hundred days. In its conceptual design, the energy produced by fusion reactions would heat and expel a propellant at high speed, providing the thrust to move the spaceship forward at 500 km/sec.

In last year's megahit *Interstellar*, the main characters travel aboard a fusion-powered spaceship, *Endurance*, on their quest for habitable planets outside of our solar system. In each of the vessel's modules a compact tokamak is responsible for propulsion and for providing electricity throughout the vessel.

The creation of a colony on Titan or the search for a habitable planet may belong to a far-off (and hypothetical) future, but in science fiction movies, the depiction of fusion energy is getting closer to the reality of tomorrow.

In this scene from the 1985 movie *Back to the Future*, fusion makes its film debut.

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

china eu india japan korea russia usa