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TRITIUM: CHANGING LEAD INTO GOLD

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EDITORIAL

Alchemists dreamed of changing lead into gold. At ITER, physicists and scientists will be changing lithium – a metal as common as lead – into tritium, an element that is more rare and precious than gold. How? Why? This 8th issue of *ITER Mag* will lift the curtain on "Test Breeding Modules," experimental components that, when integrated into the ITER vacuum vessel, will accomplish this transmutation (page 3).

That's for the physics. But ITER is also increasingly about industry. The first giant machine components were delivered (page 2) and specialized tooling is being installed for the fabrication of ITER's largest poloidal field coils. Too large to be transported by sea or road, these coils will be produced in an on-site winding facility (page 4).

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THE ITER CRYOSTAT: ON YOUR MARK, GET SET . . .

Unloaded, unwrapped, and carefully stored in the Cryostat Workshop, where welding and assembly activities will soon begin, the segments already give us an idea of the size of the ITER machine.

For the past year, the pace of highly exceptional (HEL) component deliveries has been accelerating. Some of the components, such as the electrical transformers received between January and May from the United States, have already been installed on site; others have been placed in storage. Albeit spectacular, the late-night arrival of these convoys is now a firmly established part of life on the worksite.

The convoy that passed the ITER gates at 2:30 a.m. on 10 December 2015, however, was welcomed with an extra dose of emotion. The three flatbed trucks carried the very first segments of the ITER cryostat – the giant "thermos" that will completely surround the tokamak, provide structural support, and ensure the thermal insulation of the superconducting magnets. (*See ITER Mag #6, February 2015*)

One week later, a second convoy arrived with three identical elements, weighing 50 tonnes each, followed by trucks carrying a number of 19-tonne elements – in all, 460 tonnes of polished steel that will form Tier 1 of the cryostat base.

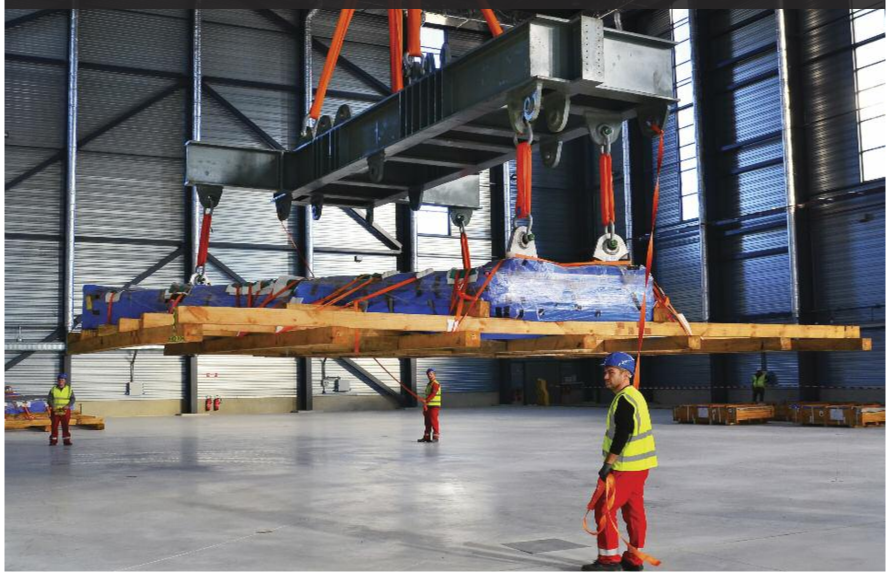
Unloaded, unwrapped, and carefully stored in the Cryostat Workshop where welding and assembly activities will soon begin, these segments representing less than one-eighth of the total mass of the cryostat (3,850 tonnes) already give us an idea of the size of the ITER device.

The arrival of these first machine components, which were procured by India and manufactured at Larsen & Toubro's Hazira plant, was achieved a few weeks in advance in relation to the ITER calendar. It was the first milestone achieved of the 29 validated in November 2015 by the ITER Council for the period 2016-2017.

"We can celebrate a great accomplishment, one that is the fruit of remarkably integrated work and coordinated effort," said ITER Director-General Bernard Bigot during a brief ceremony organized in the imposing Cryostat Workshop. "Collaboration is the cornerstone of the ITER Project and the first condition of our success."

In a few months Tier 2 of the base will arrive, followed by the segments that will make up the lower cylinder of the 30-metre-wide ITER cryostat. The 1,250-tonne base section will be the single heaviest load of ITER Tokamak assembly.

Six of the components that reached ITER in December weighed 50 tonnes each. Assembled with six auxiliary segments and welded, they will form Tier 1 of the cryostat base, the heaviest single "piece" of the ITER machine (1,250 tonnes).



Conceived in Geneva

On a cold November morning in Geneva, 30 years ago, two men met for the first time. Ronald Reagan and Mikhail Gorbachev, at the head of the world's two superpowers, had much to talk about.

November 1985: the two most powerful men in the world give the necessary political impetus to creating "the widest practicable" international cooperation in the domain of fusion.

At that moment in history, tension between the Soviet Union and the United States was high and there was a real risk that the Cold War would escalate – something that both men, despite their differences, were determined to avoid.

For the two days of the Geneva Summit (19-20 November 1985), the heads of state discussed reductions in nuclear stockpiles, the threat of a Third World War, and their common desire for lasting peace. "A nuclear war cannot be won and must never be fought," declared the joint statement at the end of the Summit.

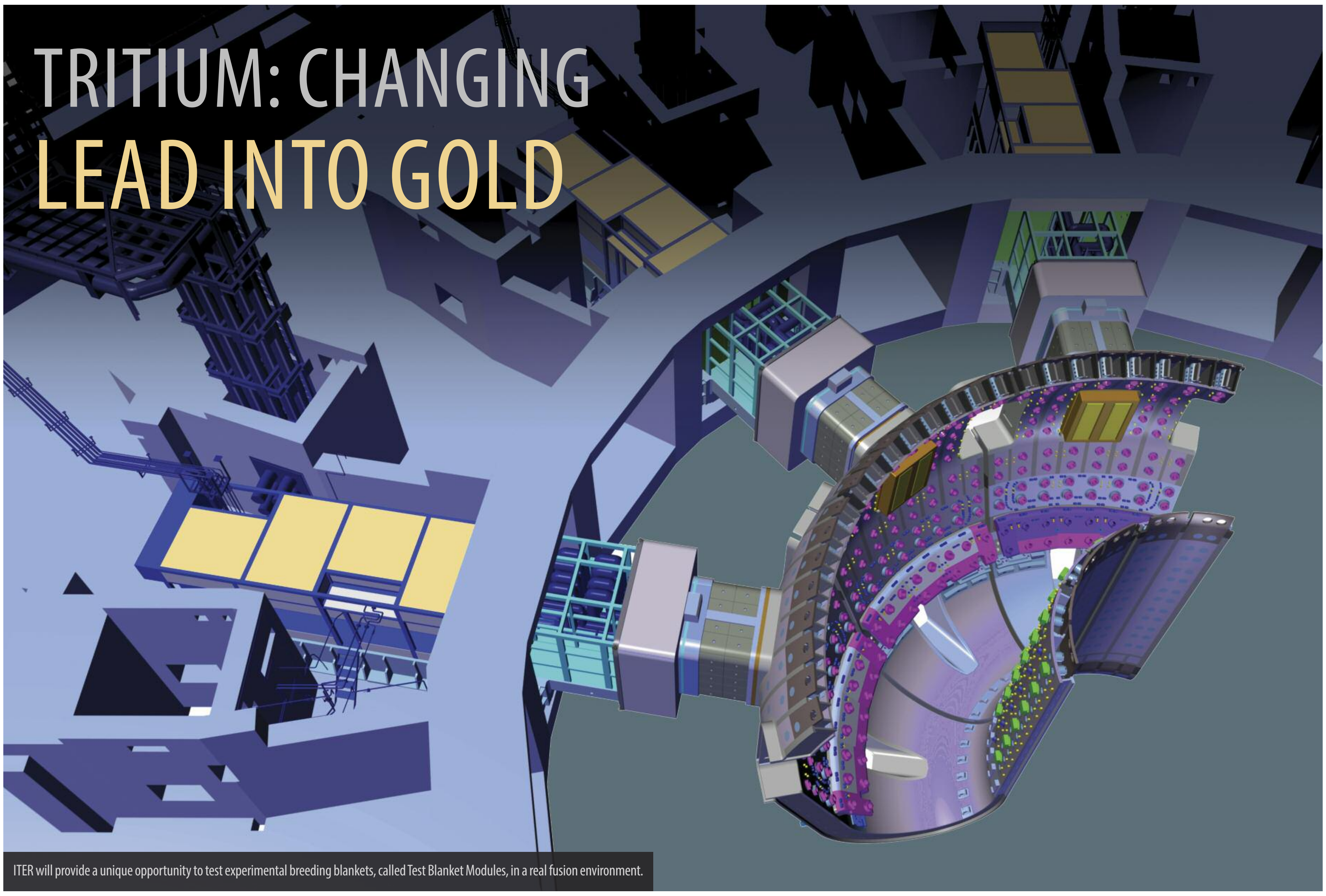
The statement also advocated "the widest practicable development of international cooperation" in nuclear fusion in order to obtain a "source of energy, which is essentially inexhaustible, for the benefit of all mankind."

For years, influential members of the fusion community on both sides of great East-West divide had been calling for such a political initiative. "We knew that only a large international collaboration would permit us to build the 'Big Machine' that would demonstrate the scientific and technical feasibility of fusion energy," remembers Evgeny Velikhov, scientific advisor to Gorbachev and future president of the ITER Council (from 2010 to 2012).

The project was ambitious and likely to be expensive. In Geneva, the world's most powerful men had just given the needed political impetus.

An "international collaboration" had been set into motion. Two years later the initiative would have a name: ITER, for International Thermonuclear Experimental Reactor or, even more simply, "The Way" in Latin.

TRITIUM: CHANGING LEAD INTO GOLD



ITER will provide a unique opportunity to test experimental breeding blankets, called Test Blanket Modules, in a real fusion environment.

In order to produce energy from the fusion of light atoms, nature offers a dozen of possible combinations. Only one is accessible in the current state of technology: the fusion of hydrogen isotopes(1) deuterium and tritium.

But here's the challenge. While deuterium can be easily extracted from seawater, which contains 33 milligrams per cubic metre, tritium is much harder to source.

In nature, tritium is found only in trace amounts. The effect of cosmic rays on the outermost layers of the Earth's atmosphere produces anywhere from a couple of grams to a couple of kilograms every year (the estimates vary). A few dozen kilograms are also dissolved in oceans as a result of atmospheric nuclear testing carried out between 1945 and 1980.

Small quantities of tritium are also produced by CANDU-type nuclear reactors – on the order of 100 grams per year for a 600 MW reactor, or approximately 20 kilograms per year globally. This stock, unused today, will be enough to fuel ITER for the fifteen years of its deuterium-tritium campaign.

In the longer term, however, it will be necessary to develop solutions for the large-scale production of tritium. It is estimated that every fusion reactor will require on the order of 100 to 200 kilograms per year.

Nature, as if anticipating the problem, offers a solution that combines elegance and efficiency – the fusion reaction itself can produce the tritium that in turn will fuel the reaction. What's more, the process takes place within the vacuum vessel in a continuous, closed cycle.

When a deuterium nucleus fuses with a tritium nucleus inside of the fusion plasma, protons and neutrons are recombined into one helium atom and one neutron. The electric charge of the helium atom causes it to remain trapped within the magnetic cage that confines the plasma. The neutron, on the other hand, escapes at high speed and strikes the vacuum vessel walls, heating water that circulates under pressure and initiating a process that – in future reactors – will create electricity.

The neutron can serve another purpose, however. When it strikes an atom of lithium-6(2) it disrupts its building blocks (3 protons and 4 neutrons) and reorganizes them into one atom of helium (2 protons, 2 neutrons) and one atom of tritium (1 proton, 2 neutrons) while at the same time liberating energy.

From the point of view of the physics, then, the problem is solved – tritium can be produced within the tokamak if lithium is included in the walls of the vessel. It is now a matter of developing the technological solutions that will allow scientists and engineers to translate physics principles into a productive cycle of "tritium auto sufficiency" in tomorrow's fusion reactors.

Luciano Giancarli has been interested in the question for nearly 30 years. At ITER, he heads the section that is in charge of the implementation of the Test Blanket Module (TBM) program – experimental blanket modules containing lithium that will be mounted inside the ITER vacuum vessel to test tritium breeding concepts. "The first challenge is the ratio between the neutrons generated by the fusion reaction and the tritium atoms actually produced," he explains. "For the system to work, the ratio must be higher than 1 meaning that – between the neutron and its lithium target – we'll need a 'neutron multiplier' like lead or beryllium.(3)"

The ITER Members have developed a number of concepts that will be tested in reactor-scale conditions in ITER. Although the TBM modules are all based on the same principle (the reaction between the neutron and lithium-6), each one is unique in its architecture, its structural materials, its cooling system, the form of its lithium (solid or liquid), and the manner in which the tritium will be extracted.

Inside of the ITER Tokamak, six spaces have been reserved for the breeding modules. Europe is planning two TBM systems; China, India, Japan and Korea are in charge of the four others. (As for the United States and Russia, they are participating in the program by supplying data that is important to the realization of the systems.)

Although the results of the tritium breeding experiments will be open to all Members, each provider will keep manufacturing details a secret due to the high commercial stakes linked to tritium production.

Whereas "ordinary" hydrogen (H) contains one proton, its isotope ^{3}H (tritium) contains one proton and two neutrons. Tritium is a radioactive element with a half-life of 12.3 years and low-energy beta decay.

Its radioactivity is so low that it can be stopped by skin or a simple piece of paper. Tritium only presents a health hazard if it is ingested or inhaled after combining with other elements (tritiated water, for example).

Tritium management at ITER will be the object of strict regulation and procedures.

"We estimate that, in ITER operating conditions, the maximum productive capacity of each of the test modules will be on the order of 20 milligrams per day. In a commercial tokamak, this production will be on par with the power of the machine – on the order of 150 grams per day and per gigawatt," says Luciano.

The conceptual design phase for each of the TBM systems has now ended. Just like the other elements of the ITER machine, these tritium-breeding concepts will be dissected, analyzed and reviewed by a special committee before formal approval. Fabrication activities are planned to start in 2020.

To reach ITER goals and those, in a larger sense, for the future of fusion, the six TBM modules will play a fundamental role. By demonstrating their capacity to transform an element that is as common as lead on Earth (lithium) into the more rare and precious tritium, they will open the way to the industrial and commercial exploitation of fusion energy.

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1 *Most elements of the periodic table exist in different forms called isotopes. The isotopes for a same element differ in the composition of their atomic nucleus. In a chemical reaction they act identically; in a nuclear reaction, isotopes can act in very different ways.*

2 *Lithium-6 is a stable lithium isotope present in natural lithium at the level of 7.5%.*

3 *When a neutron strikes an atom of lead or beryllium, its atomic structure is disrupted. After absorbing the neutron, the disrupted atom ejects two neutrons – which increases the number of neutrons available to generate, in a second step, tritium from the lithium-6 contained in the modules.*

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IN THE LAIR OF THE RING MAGNETS

Reels, de-spoolers, a winding table, impregnation moulds … little by little the 12,000 m² Poloidal Field Coils Winding Facility is being equipped with specialized tooling.

ITER's ring-like poloidal field coils are among the largest and heaviest components of the ITER machine. Ranging from 8 to 24 metres in diameter, and from 193 to 396 tonnes, six coils will encircle the ITER vacuum chamber like so many parallels of latitude to influence the shape of the plasma and contribute to its stability by "pinching" it away from the walls.

If the top and bottom coils (see image at right) are small enough to be produced off site and transported to ITER, the size of the four others precludes any transport by public waterway or road. For these massive machine components the European Domestic Agency has built the on-site Poloidal Field Coils Winding Facility, a 257-metre-long building with 12,000 metres of surface area and a circular spreader beam overhead for handling the components during the assembly process.

On the southern end of the building, contractors are currently installing specialized tooling – reels, de-spoolers, a winding table, impregnation moulds. When taken together, they reflect the monumental scale of the undertaking and the complexity of the procedures.

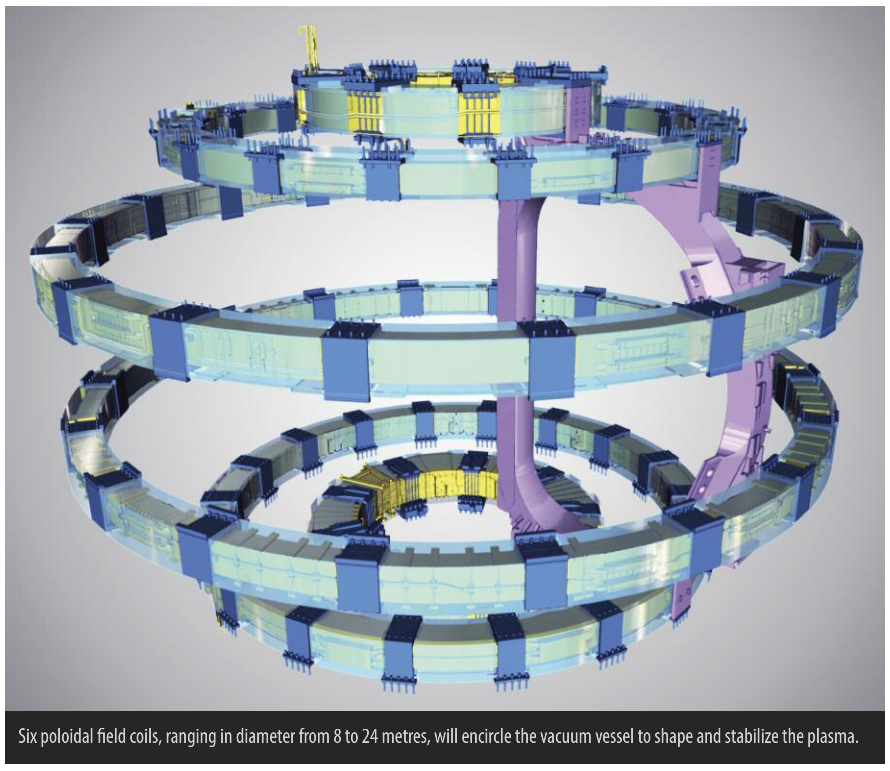
The multistage fabrication process begins with cable-in-conduit conductor (CICC) that will be delivered on large spools from manufacturing facilities in Europe, China and Russia. In this type of conductor, hundreds of superconducting strands are grouped, twisted and bundled together to form a cable that is inserted into a thick stainless steel jacket. Liquid helium circulates at -269 °C in the centre of the conductor to cool the magnets to superconducting temperatures. One metre of poloidal field conductor will weigh more than 25 kilograms; 65 kilometres of material will be necessary to wind the six coils (47 kilometres for the four coils to be produced on site) …

As they come off the spools, the lengths of poloidal field conductor will be straightened, cleaned, insulated with glass-fibre tape, and finally wound into spirals called double pancakes. Weighing 16 to 35 tonnes, these double pancakes are transferred to another station for vacuum pressure impregnation (VPI) with epoxy resin in order to harden into rigid assemblies.

In a third area, six to nine double pancakes will be stacked and joined to form the final coils. A second VPI procedure is performed to harden the stacked assembly and additional components such as clamps, protection covers, and pipes are added. The coils will undergo approximately three months of electric and cryogenic testing before transport to the Assembly Hall – the last stop before integration into the Tokamak arena.

To qualify the different stages of manufacturing, operators will soon begin winding a "dummy" coil to the dimensions of poloidal field coil #5 (17 metres). Manufacturing will then begin for poloidal field coils #5 and #2, which can be wound on the same equipment, before the tooling is changed for the winding of poloidal field coils #3 and #4 (24 metres). For each coil, approximately 18 months will be necessary to complete all of the manufacturing steps.

As Tokamak assembly advances, the poloidal field magnets will be positioned one by one in the Tokamak Pit beginning with #6 (produced by China under contract with Europe), followed by poloidal field coils 5, 4, 3 and 2 (fabricated by Europe), and finally coil #1, manufactured and delivered by Russia.



Six poloidal field coils, ranging in diameter from 8 to 24 metres, will encircle the vacuum vessel to shape and stabilize the plasma.