Only fusion can meet the energy challenge mankind is facing

Imitating the processes at work within the core of the stars opens the way to a new, safe and sustainable energy source for the generation of electricity on a massive scale: this is what the international project ITER is about.

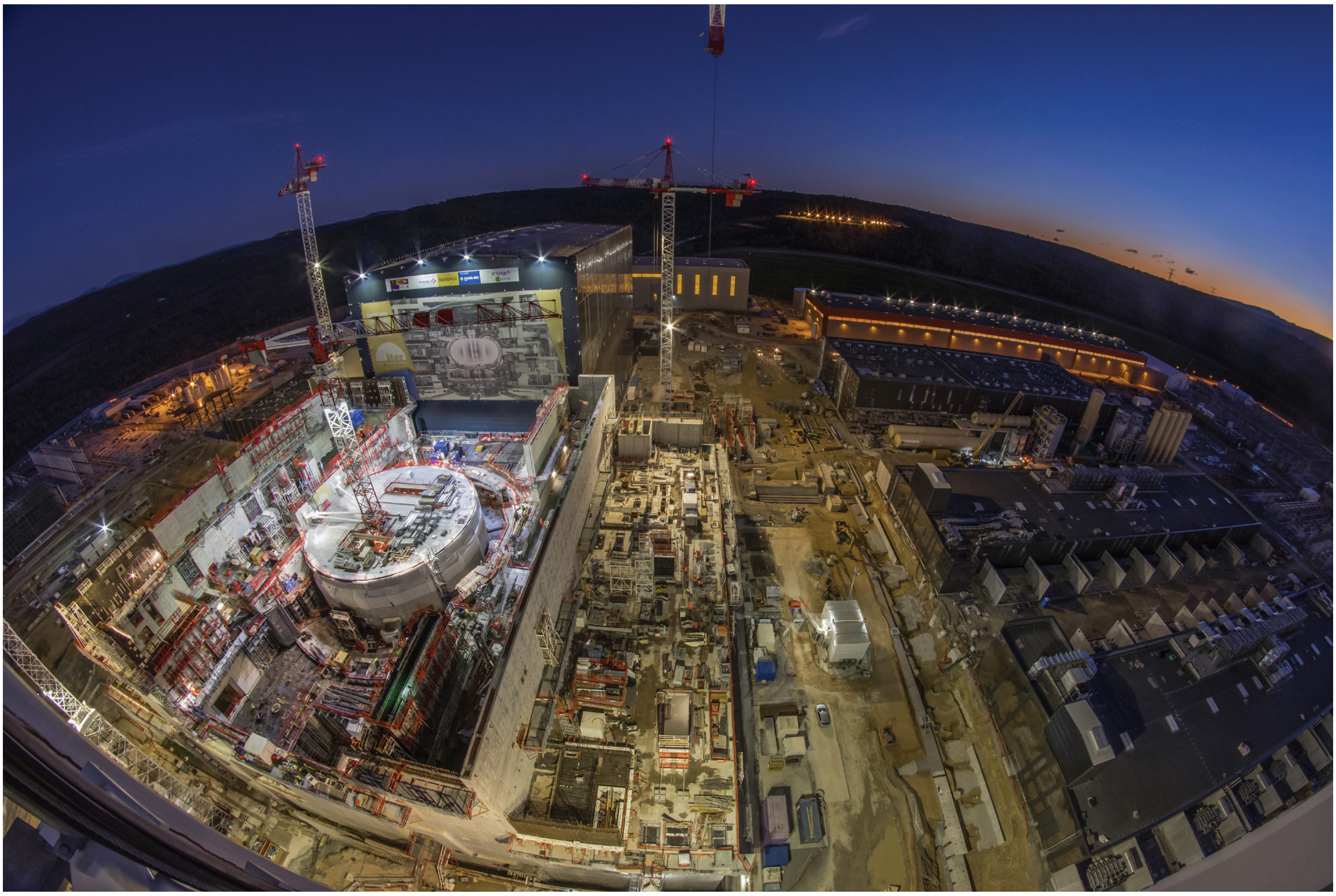
Whatever the projections or scenarios, and despite all the energy-saving measures we might implement, one thing is certain: we will need to produce more and more clean energy during this century to meet the needs of the planet's ever-growing population. By the end of this century, as the number of humans passes the ten billion mark, world energy demand will have increased by a factor of three. The share of electricity in global energy consumption, which is approximately 20 percent today, will have grown up to 50 percent. Meeting this huge increase in demand is one of the most daunting challenges mankind has ever had to face.

Our options are limited. The burning of fossil fuels, which drove the industrial revolution of the 19th century and ensured the economic, technological and social development of our civilisation up to this day, is now recognized as threatening to the planet's environment and climate balance. Renewable energies, although attractive on many counts and necessary to invest in, have inherent limitations – notably as they are diffuse and intermittent.

Fission…

What are we left with? Nuclear energy, or more accurately nuclear *fission* energy.
Today, nuclear fission accounts for approximately 10 percent of electricity production in the world – France is a major exception with 58 reactors producing more than 75 percent of the country's electricity.

As France's High Commissioner for Atomic Energy (2003-2009), and as Chairman and CEO of the French Alternative Energies and Atomic Energy Commission (2009-2015), I have devoted a good part of my professional life to nuclear fission. I know its merits, its limitations and its challenges.



The heart of the ITER installation: to the left, the Tokamak Complex with the circular structure of the "bioshield", a 3-meter-thick steel-and-concrete cylinder that will enclose the ITER Tokamak; to the right, the installation's industrial facilities (power conversion buildings, cryoplant, winding facility, etc.) (December 2018). © ITER Organization.

The 23,000-tonne ITER Tokamak will rest on a massive circular "crown" at the bottom of the bioshield. The openings in the cylindrical structure are for the different systems that need to reach into the machine: power feeders, vacuum pumping, heating, cryogenics, cooling water, diagnostics, etc. © ITER Organization.

The major attraction of nuclear fission is to provide a baseload source of massive power production without generating CO_2 or other greenhouse gases. However, the mineral resource it is based upon (uranium) is limited, with at best a horizon of two to three hundred years based on current thermal neutron technology. As for the challenges, they are many and I will only mention the two most important: continued improvement in safety, and long-term management of nuclear waste. And by "long-term" I mean several hundreds of thousands of years for the most active fission products.

My conviction is that nuclear fission energy is a valuable transitory solution for a limited number of countries; in no way can it be a long-term solution.

Operating the entire fission cycle, from uranium enrichment to fuel recycling and waste storage, not only requires scientific and technological expertise and a considerable industrial infrastructure; it also demands strong state institutions, independent control and long-term political stability.

Few countries possess these assets or can offer these guarantees today. And even fewer can pretend to sustain them for the dozens of millennia that long-life/high-activity nuclear waste management requires.

Fortunately, fission is not the only way to tap into the energy of the atom.

…Fusion

While fission splits heavy atoms such as uranium, *fusion* does exactly the opposite: it fuses light atoms such as hydrogen into heavier ones. Both fission and fusion are mass-to-energy conversion reactions that generate considerable amounts of energy; both are spectacular illustrations of Einstein's famous equation $E = mc^2$.

More than 99 percent of the observable matter in the Universe is in a state of fusion. Fusion is the powerhouse at the core of the stars; it has caused our Sun to shine for the past five billion years, and is expected to continue to do so for an equivalent length of time.

It was not until the 1920s that physicists and astrophysicists (Jean Perrin in France, Arthur Eddington in the United Kingdom) began forming the notion that a fusion process was at work in the core of stellar bodies. In the decades that followed, the identification and clear understanding of the hydrogen fusion process (Hans Bethe) led to one ambition: if fusion reactions could be artificially created on Earth, a new, sustainable energy source would become available for the generation of electricity on a massive scale.

In the core of the Sun and stars, gravitational forces create the temperature and pressure conditions that make fusion possible. This process, which is efficient at the massive scale of the stars, cannot be replicated on Earth. But it can be imitated.

Physicists soon determined that an ultra-hot, ultra-low-density ionized gas (a plasma) – composed of equal parts of the hydrogen isotopes deuterium and tritium and confined by intense magnetic fields – would provide an environment in which fusion reactions could occur. "Low-density" is in fact a high vacuum – one million times less than the density of the Earth's atmosphere. "Ultra-hot" is a temperature in the range of 150 millions degrees Celsius, ten times that of the core of the Sun…

The advantages of fusion are many:
- The fusion reaction at the core of the process is intrinsically safe: the type of accidents that can occur in a fission plant – uncontrolled chain reactions, core meltdown, etc. – are physically impossible in a fusion installation;
- The fuel is virtually inexhaustible: deuterium is easily extracted from water and tritium will be produced inside the machine through the interaction of the fusion neutrons and lithium. A 1 GW fusion reactor (equivalent in power to an average fission reactor) will only require 100 kg of deuterium and three tonnes of natural lithium annually to generate 7 billion kilowatt hours;
- The impact on the environment is minimal: no CO_2 or greenhouse effect gases are generated;
- Fusion does not generate long-life/high-activity radioactive waste.

As early as the mid-1950s, "fusion machines" of various shapes, sizes and performance levels – such as pinch and mirror devices, stellarators, and tokamaks (a Russian acronym for "Toroidal Chamber, Magnetic Coils") – were operating in the Soviet Union, the US, the United Kingdom, Germany, France and Japan.

In that same decade, the veil of secrecy that had shrouded fusion research prior to World War II was lifted. Despite the Cold War tensions between East and West, Soviet fusion physicists, who were among the most advanced in the field, shared with their Western colleagues their data, hopes and frustrations. International collaboration became a staple of fusion research and has remained so to this day.

As they kept exploring the mind-boggling complexity of plasma physics and faced the technological challenges of building and operating fusion devices, physicists realized that in order to demonstrate the feasibility of fusion they would need a very large machine – one that no single nation, whatever its human, scientific and technological resources could design, build and operate alone.

The European JET (Join European Torus) was a first step in this direction. A very large tokamak, the machine achieved "First Plasma" in 1983 and was the first to implement the actual fusion fuels deuterium and tritium. Seven years later in 1991, JET produced a significant amount of power from fusion reactions. At about the same time, an American machine, the Tokamak Fusion Test Reactor (TFTR), was following the same route and obtaining similar results.
However, both JET and TFTR had required more energy to "light the fusion fire" than the "fire" had given back in return.

ITER

As JET was bringing fusion to the threshold of feasibility with a record power production of 16 MW in 1997, another project, immensely more ambitious, was taking shape, this time at a truly international level.

Chemistry will be central to ITER success

As a physical chemist by training, as President of the "Fondation de la Maison de la Chimie", and since 2015 a Director General of the largest and most ambitious energy project ever established, I am proud to say that chemistry will be central to ITER success. We will need to implement the most rigorous chemical processes to separate and recycle the isotopes we need, produce the purest materials, and the most efficient catalysts. The nature of ITER's demands, and the stringent requirements of our quality control processes will no doubt stimulate the field and offer large opportunities to both research and industry.

Initiated in the 1980s, ITER – the Latin word for "The Way" – received a decisive political and diplomatic push when President Reagan and Secretary General Gorbachev met for the first time in Geneva in November 1985 and agreed to launch "*the widest practicable development of international cooperation*" to develop fusion energy "*for the benefit of all mankind*."

Thirty-three years later, ITER progresses steadily towards its objective, demonstrating the technological feasibility of fusion as an energy source. The international collaboration brings together seven Members (China, the European Union, India, Japan, Korea, Russia and the United States) representing more than half the world's population and 85 percent of the planet's gross industrial product. Construction of the installation in Saint-Paul-lez-Durance, some 40 kilometers north of Aix-en-Provence (France), is now more than 70 percent complete.

ITER, whose construction began in earnest in 2010, is expected to produce its "First Plasma" in 2025 and commence full-power fusion operations in 2035. Over its fifteen to twenty years of operation, the project will explore the uncharted territories of "burning plasmas", validate the integrated operation of technologies for a fusion power plant, test materials, experiment tritium breeding technologies; and demonstrate the safety characteristics of a fusion device. ITER will be the first fusion machine to produce *net* energy, delivering 500 MW of fusion power from a heating power input of 50 MW ($Q \geq 10$).
The ITER machine will be the most complex ever built, which is both a huge challenge and a unique opportunity for the industries of the participating nations.

As Member contributions are provided essentially "in-kind" through the procurement of machine components and systems for the installation, industry has the opportunity to acquire competence and experience in areas as diverse as cryogenics, vacuum technologies, superconductors, cutting-edge robotics and remote handling, power electronics, ultra-high frequency signal transmission and more.

Building and operating ITER is an indispensable step towards fusion energy. The project marks both the culmination of six decades of research and development throughout the world, and the opening of a whole new chapter in the quest for unlimited energy – the beginning of a genuine industrial approach to fusion.

As the construction of the experimental ITER machine progresses, the ITER Members are already working on conceptual designs for a generic next-step machine, called DEMO. Whether the DEMO machine (or machines) will be built through international collaboration, through more restricted partnerships, or purely "nationally" remains an open question. By 2040, however, the DEMO concept – an industrial prototype founded on feedback from ITER operation – could enter the engineering design phase and open the way to large-scaled fusion development.

And just as DEMO will have succeeded ITER, industrial reactors will succeed DEMO. My conviction is that, depending on ITER's success, the first fusion plant will be connected to the grid early in the second half of this century. From then on, deployment will be rapid.

I hope to have a long life but, as mine began in the middle of the last century, I will most likely be gone when fusion-generated electricity becomes an everyday reality.

There has always been something of the cathedral builder in the fusion community: the generations that laid the foundations, built the first arcades, and raised the first buttresses knew that they would be long-gone when the highest towers were completed. Yet they had faith and determination.

Today, with ITER, fusion is nearing a historical breakthrough. Faith and determination are at last bearing their fruit.

Bernard BIGOT,
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