Frequently Asked Questions

In this section, we provide answers to the most frequently asked questions about the ITER Project.

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Fusion and the ITER Project

What is ITER?

ITER (the Latin word for "The Way") is a large-scale scientific experiment intended to prove the viability of fusion as an energy source. ITER is currently under construction in the south of France. In an unprecedented international effort, seven partners—China, the European Union, India, Japan, Korea, Russia and the United States—have pooled their financial and scientific resources to build the biggest fusion reactor in history. ITER will not produce electricity, but it will resolve critical scientific and technical issues in order to take fusion to the point where industrial applications can be designed. By producing 500 MW of power from an input of 50 MW—a "gain factor" of 10—ITER will open the way to the next step: a demonstration fusion power plant.

On-site construction of the scientific facility began in 2010. As the buildings rise at the ITER site in southern France, the fabrication of large-scale mock-ups and components is underway in the factories of the seven ITER Members. The shipment of the first completed components began in 2014 and will continue for at least five years. Machine assembly will begin as soon as the giant Tokamak Complex is ready for occupation.

ITER is one of the most complex scientific and engineering projects in the world today. The complexity of the ITER design has already pushed a whole range of leading-edge technologies to new levels of performance. However, further science and technology are needed to bridge the gap to commercialization of fusion energy.

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What questions will be answered by ITER that have not already been answered by research to date?

ITER is the experimental step between today's fusion machines, focused on plasma physics studies, and tomorrow's fusion power plants.

The plasma physics community will have access, in ITER, to a one-of-a-kind device capable of plasma pulses of a much longer duration than those achieved in other fusion machines. ITER will be twice as large as the largest tokamak fusion experiment currently operating (JET in the UK), with ten times the plasma volume. This unique experimental machine has been designed to:

- produce 500MW of fusion power ($Q \geq 10$)
- confine a deuterium-tritium plasma in which alpha-particle heating dominates

- demonstrate the integrated operation of technologies for a fusion power plant
- test components required for a fusion power plant
- test concepts for a tritium breeding module
- demonstrate the safety characteristics of a fusion device

Today, fusion research is at the threshold of exploring a "burning plasma," in which sufficient heat from the fusion reaction is retained within the plasma and sustains the reaction for a long duration. Such exploration is a necessary step toward the realization of a fusion energy source. Scientists are confident that the larger ITER plasmas will not only produce much more fusion power, but will remain stable for long periods of time. The scale of ITER is necessary to break new ground in fusion science.

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Is there consensus in the scientific community about the ITER Project?

In a project of this unprecedented scale, involving worldwide cooperation and billions of euros of expenditure, it would be naïve to believe that there could be unanimity in the scientific community on the aims and the scientific and technical basis of the project. A scientific consensus may be possible while discussions remain at the abstract level, but in a world of intense competition for research funding it is inevitable that scientists from various fields will criticize the decision to spend money on a large project, arguing that they would prefer to spend the money elsewhere.

What can be said about ITER is that for the scientific community working in the energy field, this project is considered by a strong majority as a major step that may provide a future energy alternative for all humankind. The present political and scientific approach to this project has not suddenly appeared out of lobbying by a few influential individuals. It is the result of decades of painstaking, step-by-step research by fusion scientists all over the world as well as intense discussions in the scientific administrations of involved governments who debated the options, the costs and the risks before deciding that ITER was a worthwhile investment in our common energy future. The proportion of papers directly concerned with ITER presented at leading international scientific conferences on fusion as well as in fusion journals has been steadily increasing for a number of years. The fact that research aimed at ITER is now such a dominant topic in these papers demonstrates how essential the project is to the advancement of fusion towards energy production.

Fusion research, and the role of ITER, has been subject to serious scrutiny by panels of independent experts established by funding agencies in Europe and most of the other ITER partners. The results of these investigations provide the most reliable measure of consensus in the scientific community. A few examples:

- In 2004 during the early stages of ITER negotiations, a high-level panel chaired by Sir David King (Chief Scientific Advisor to the UK government) concluded that the time was right to press ahead with ITER and recommended funding a "fast track" approach to fusion energy. In 2013 the European Fusion Development Agreement (EFDA) published a **roadmap** to the realization of fusion energy by 2050.

- The French Academy of Sciences organized a detailed review of the state-of-the-art and the remaining challenges of fusion both by magnetic confinement (including ITER) and using laser-driven systems. The review was published in a book in 2007 which emphasised the arguments supporting the construction of ITER.
- The United States went through a long process to decide to re-enter the ITER collaboration, after leaving it in the late 1990s. The US National Academy of Sciences convened a panel which included both fusion scientists and senior scientists from related fields such as nuclear fission power, high-energy physics and astrophysics. The non-fusion scientists were empowered to make the key recommendations. The panel strongly endorsed the renewed membership of the US in the ITER Project as the best path forward to fusion energy.
- China announced in 2011 that it is planning to train 2,000 skilled experts over 10 years to carry out research and development in fusion.
- In 2016, the US Department of Energy made a report to the US Congress in which it recommends that the US remain a partner in ITER, through a re-assessment in 2018. Noting that "the management of the ITER Organization and the performance of the project have improved substantially," the report concludes that despite accumulated delays, "ITER remains the fastest path for the study of burning plasma."

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What has been accomplished in 60 years of tokamak research?

The first small-size tokamaks (1950s-1970s) were basic devices without sophisticated control systems and technology, but they demonstrated that high temperature plasmas could be generated and that energy could be confined. New plasma phenomena such as anomalous transport, instabilities and disruptions were uncovered during these first experiments. Scaling laws indicated that energy confinement could be increased in larger devices with higher magnetic fields.

The second-generation, medium-sized devices in the 1980s introduced the extensive use of auxiliary heating techniques. The addition of the divertor demonstrated improved confinement; wall conditioning techniques were also introduced. The ASDEX Tokamak achieved high confinement mode for the first time in 1982.

A new generation of larger tokamaks—JET (Europe), JT-60 (Japan), TFTR (US) and T-15 (Soviet Union)—were built to study plasmas in conditions as close as possible to those of a fusion reactor, and regularly upgraded based on advances in fusion science. New features such as superconducting coils, deuterium-tritium operation, and remote handling were introduced. The experience accumulated on these machines contributed to the design of ITER.

Today, fusion research is at the threshold of exploration of a "burning plasma" in which sufficient heat from the fusion reaction is retained within the plasma and sustains the reaction for a long duration. Such exploration is a necessary step toward the realization of a fusion energy source; it must be done to establish the confidence in proceeding with demonstrations of practical fusion energy. Construction of ITER and implementation of the ITER research program would provide for such exploration.

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What are the advantages of ITER compared to the alternative approaches under development such as the W7-X Stellarator in Germany, and the inertial fusion programs in the US and France?

Of the magnetic confinement concepts for fusion (mainly tokamaks and stellarators) the main advantage of ITER and its tokamak technology is that, for the time being, the tokamak concept is by far the most advanced along the road to producing fusion energy. It is consequently pragmatism that dictated the choice of the tokamak concept for ITER. Stellarators are inherently more complex than tokamaks (for example, optimized designs were not possible before the advent of supercomputers) but they may have advantages in reliability of operation. The W7-X Stellarator, which celebrated its first plasma in 2015 in Greifswald, Germany, will allow good benchmarking against the performance of comparable tokamaks. These results will be incorporated in decisions about how DEMO, the next-generation fusion device after ITER, will look.

The inertial fusion concepts are something quite different. These technologies have mainly been developed to simulate nuclear explosions and were not originally planned to produce fusion energy. The inertial fusion concept has not demonstrated so far that it offers a better or shorter path than magnetic confinement to energy production. In Europe, the Euratom Framework Programs do not fund research on inertial fusion, but the program maintains a "watching brief" on developments.

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What is the ITER model for collaboration and cooperation?

The choice was made from the beginning to share the manufacturing of the most strategically important components among the seven ITER Members. This has considerably added to the complexity of the project, but the reasons for this decision were clear—by participating in ITER, each Member is preparing its industrial infrastructure, its scientific base, and its physicists and engineers for the next step on the road to fusion power: the construction of a demonstration fusion power plant.

It seems clear that no one Member has the financial and technical resources to build ITER alone. In this sense, by contributing only a portion of the project's costs, each Member benefits from the totality of the development program (where, already, there have been discoveries in technology, materials, science and even the first applications for patents) and, later, the totality of the 20-year experimental program.

Collaboration and coordination between the different entities of the project are improving all of the time. What is remarkable about fusion research is that, for a very long time, it has been an international, collaborative venture where discoveries in one area of the world immediately benefit other research programs. This is true every day at ITER, where the project benefits from the diverse experiences of its Members, including research underway on operational tokamaks in different parts of the world.

If ITER were only a construction project, its model would certainly have been organized differently. But as the world's largest and most challenging energy research project, the collaboration between seven ITER Members—all with decades of experience in fusion—has been most profitable in terms of pooling resources to solve the difficult challenges that remain on the road to fusion.

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ITER schedule

When will ITER be operational?

ITER is under construction now in Saint Paul-lez-Durance, southern France. Once the most important buildings are ready for occupation, the assembly of the machine and plant will begin. First-phase assembly, which will end with First Plasma, will be closely followed other assembly phases during which the in-vessel components (blanket, divertor, in-vessel coils ...) will be installed and the entire facility prepared for Deuterium-Tritium Operation.

Under the new Director-General Bernard Bigot, the ITER Organization and the Domestic Agencies conducted an eight-month, project-wide internal assessment in 2015 that scrutinized every detail of the ITER components and systems (from design, through manufacturing, delivery and assembly). The result—the best technically achievable project schedule and associated resource estimates—was presented to the ITER Council in November 2015 and subsequently reviewed by an independent group of Council-appointed experts.

In June 2016, the ITER Council endorsed the updated Resource-Loaded Integrated Schedule, through First Plasma; at its next meeting, in November 2016, it adopted the updated schedule through the start of Deuterium-Tritium Operation in 2035.

First Plasma is schedule for December 2025. This will be the official start of ITER operation.

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When will the first giant ITER components travel along the ITER Itinerary?

The first Highly Exceptional Load (or HEL) travelled along the ITER Itinerary in January 2015.

The roads, bridges and roundabouts of the Itinerary were modified by France to meet the needs of the exceptional convoys that will transport ITER components arriving by sea to the ITER site.

Between 2015 and 2021 (estimated), 250 exceptional convoys will travel along the ITER Itinerary with their extra-large cargo by night, at reduced speeds. The heaviest? 900 tons. The tallest? 10 metres. The widest? 9 metres. The longest? 33 metres. We're expecting each one of these exceptional convoys to be quite a local event.

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Is ITER running behind schedule?

For a first-of-a-kind project like ITER, challenges to the schedule along the way can be expected. It certainly took longer to build up the ITER Organization—and establish world-class systems for managing the project—than was originally foreseen.

A 2013 Management Assessment of the project identified a number of other root causes: a complex, multinational structure; inefficiencies related to the sharing of work among many parties; underestimated staffing needs; and lack of strong central management.

Because the ITER Organization and the Domestic Agencies all have equal stakes in completing the ITER Project, strong measures have been set into place to track schedule performance. For critical areas, specific recovery actions have been set into motion, for example measures to reduce delays in the signature of agreements and contracts, accelerate and optimize design review and design change processes, strengthen central engineering and configuration control, and improve collaboration in schedule-critical areas (vacuum vessel manufacturing, building construction ...).

A project-wide schedule updating exercise in 2015 has resulted in a new calendar for ITER that has been approved by the ITER Council through First Plasma (schedule for December 2025) and Deuterium-Tritium Operation (scheduled to begin in 2035).

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What are the Members doing to address the project's difficulties/schedule delays?

In March 2015, a new ITER Director-General, Bernard Bigot (from France) took over at the helm of the project. He is currently implementing a project-wide action plan that has received the support of all Members.

The ITER Project is entering a critical phase, as Tokamak Complex construction is underway and the fabrication of strategic ITER components (magnets, vacuum vessel, cryostat ...) has been launched. A new organization—centred on deliverables and strong project management—is being set up within the ITER Organization Central Team, and a new way of working in an integrated way with the ITER Domestic Agencies has been established.

A closer working relationship among the Members and between the Members and the ITER Organization Central Team will allow faster and more informed decision making and issue resolution. A new Executive Project Board associates the management of the ITER Organization Central Team and that of the Domestic Agencies.

Through close collaboration and close tracking of the schedule, solutions are being sought to improve manufacturing performance for the systems and components required for the first experiments. Close collaboration with industry, for example, has already resulted in the recovery of some delay.

Quality control is also essential—we have to make sure all the components will fit and work together. Within the ITER Organization, there is a team dedicated to quality assurance (QA) and quality control (QC). Its members help oversee and ensure that the proper QA/QC practices are implemented at companies manufacturing the reactor's components.

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We hear the project is delayed. Are the ITER Members prepared to contribute additional budget?

The updated schedule for the ITER Project identifies December 2025 as the "best technically achievable" date for First Plasma. Endorsed by the ITER Council in June 2016, the updated schedule comes with a revised estimate of the overall cost of the project, including increased staff resources.

In November 2016, the ITER Council approved the complete updated project schedule through Deuterium-Tritium Operation in 2035. The ITER Members will now go through their domestic processes of obtaining approval for the associated overall project cost.

The ITER partners are taking a number of actions to ensure that they have control over the cost of the project:

- By focusing now on the achievement of First Plasma, financial and human resources are concentrated in the near-term on core industrial elements and overall project risk is lowered.
- By implementing a staged approach (First Plasma followed by a number of progressive phases to equip the machine for Deuterium-Tritium Operation interspersed with operational phases), confidence is increased and risk is minimized.
- By closely monitoring project risks and opportunities, and tracking against agreed milestones, any potential deviation from optimum progress can be identified at an early stage and mitigated.
- By freezing the design of all interfacing First Plasma components, the risk of delay due to project change requests is averted.

The ITER Council is also considering a proposal for regular reviews in order to validate the project's step-by-step progress and also to have the benefit of expert independent counsel in implementing best-practice.

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Was the ITER Project schedule affected by the natural disaster in 2011 in Japan?

The earthquake and tsunami in Japan on 11 March 2011 affected some of the installations producing components for ITER. In particular, the buildings for superconducting magnet test equipment and neutral beam test equipment were seriously damaged.

The ITER Organization did everything possible within the scope of its mandate to minimize the impact of the Japanese disaster on the ITER Project schedule. With effort and ingenuity, and strong support from the ITER Domestic Agencies, the delay in First Plasma was contained to one year.

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Is there any danger that ITER will experience start-up difficulties as, for example, the LHC had with its array of magnets?

Once integrated and assembled, the ITER machine will go through a period of testing and commissioning. This is the equivalent of making sure that "all systems are go" before attempting the first experiment. Next, a several-year "shakedown" period of operation in pure non-nuclear fuels such as hydrogen, helium and deuterium is planned during which the machine will remain accessible for repairs and the most promising physics regimes will be tested. This phase will be followed by operation in deuterium with a small amount of tritium to test wall-shielding provisions. Only then, scientists will launch a third phase with increasingly frequent operation with an equal mixture of deuterium and tritium, at full fusion power.

The ITER superconductors have been the object of a particularly stringent development and qualification program. Conductor samples from every supplier undergo testing at the SULTAN installation, located at the Paul Scherrer Institute (PSI) in Villigen, Switzerland, before acceptance by the ITER Organization. At SULTAN, the samples are exposed to magnetic fields, current intensity and temperature conditions that are equivalent to those of the ITER operational environment.

In addition, for the 18 D-shaped toroidal field coils, the ITER Council has requested that a common set of specifications be developed for the cold testing at 77 K (minus 196°C) of the first three coils in each series of toroidal field winding packs as a risk mitigation measure.

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ITER cost

How is ITER financed?

ITER will be built collaboratively by the seven ITER Members.

During the construction phase of the project, Europe has responsibility for approximately 45.5 percent of construction costs, whereas China, India, Japan, Korea, the Russian Federation and the United States will contribute approximately 9.1 percent each. The lion's share (90 percent) of contributions will be delivered "in-kind." That means that in the place of cash, the Members will deliver components and buildings directly to the ITER Organization.

The in-kind contributions of the ITER Members have been divided into approximately 140 Procurement Arrangements. These documents detail the technical specifications and management requirements for the procurement of plant systems, components or site construction. The value of each Procurement Arrangement is expressed in ITER Units of Account (IUAs), a currency devised to measure the value of in-kind contributions to ITER consistently over time.

Procurement allocations were assigned among the Members on the basis of valuations of components. Upon successful completion of a component, the corresponding credit value is credited to the Members' account. Contributing 9.1 percent of the project, therefore, becomes a matter of adding up the IUA value of the different contributions.

For the operation phase, the sharing of cost amongst the Members will be as follows: Europe 34 percent, Japan and the United States 13 percent, and China, India, Korea, and Russia 10 percent.

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How much is France contributing as Host?

France contributes to the ITER Project as a member of the European Union. The country's commitment to ITER "at the level of EUR 1.2 billion through to 2017" was confirmed by French Minister of Research and Higher Education Geneviève Fioraso on the occasion of the ITER Headquarters inauguration (17 January 2013). Furthermore, France has contributed a number of in-kind contributions for a total of approximately EUR 260 million (ITER site preparation, the International School in Manosque and the realization of the heavy haul Itinerary). The French financial and in-kind contributions originate from the French government as well as from the local governments of the Provence-Alpes-Côte d'Azur region where ITER is located, who have pledged a total of EUR 467 million to the ITER Project over a period of 10 years.

This contribution is on par with the contracts and employment that have already been generated in the area by the ITER Project. (See section on Economic Benefits.)

For all Members, the potential benefits of participation are significant: by contributing a portion of the project's costs, Members benefit from 100 percent of the scientific results.

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Why have ITER costs risen?

Based on the 2001 design, the original cost estimate of ITER was EUR 5 billion for construction costs. This estimate, based on the best available information at the time, did not include some labour costs, escalation and contingency. It also did not properly estimate the time needed for the assembly and commissioning phases of the first-of-a-kind ITER Tokamak, or include some later-term matters such as component storage.

In 2008, a detailed design review called for modifications to the ITER machine based on advancements in fusion science; these modifications, such as the addition of vertical stability and Edge Localization Mode (ELM) coils, were incorporated into the 2010 Baseline and added to overall cost. The fact that the number of ITER Members passed from four to seven also contributed to cost increases by creating a much larger number of interfaces (and hence, complexity) within the design. The third important element of the cost increase is that building construction costs have increased significantly since the 2001 estimate. Raw material costs have doubled (steel) or tripled (concrete).

In 2015, the ITER Organization conducted an in-depth review and analysis of all aspects of manufacturing and assembly of the ITER systems, structures and components. The resulting updated schedule and overall cost estimate reflect a more advanced level of design maturity and a much-improved understanding of the scope, sequencing, risks, and costs of the ITER Project. The schedule exercise identifies December 2025 as the best technically achievable date for First Plasma and 2035 as the start of Deuterium-Tritium Operation. Both dates are contingent on resources.

With the new updated project schedule, the ITER Members now have all the elements needed to go through their domestic processes of obtaining approval for associated resources.

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Do we really know how much ITER will cost?

Because multiple Members are collaborating to build ITER, each with responsibility for the procurement of in-kind hardware in its own territory with its own currency, a direct conversion of the value estimate for ITER construction into a single currency is not relevant.

The European Union has estimated its global contribution to the costs of ITER construction at EUR 6.6 billion. Other Domestic Agency contributions depend on the cost of industrial fabrication in those Member states, which can be higher or lower, and their percentage contribution to the construction of ITER. Based on the European evaluation, the cost of ITER construction for the seven Members has been evaluated in the past at approximately EUR 13 billion (if all the manufacturing was done in Europe). As production costs vary from Member to Member, it is impossible to furnish a more precise estimation.

The costs associated with the resources estimated in the Updated Long-Term Schedule are not reflected in this estimation.

ITER is financed by seven Members: China, the European Union (plus Switzerland, as a member of EURATOM), India, Japan, Korea, Russia and the United States. In all, 35 countries are sharing the cost of the ITER Project.

For the other phases of the ITER Project the cost estimates have not changed. Operation of the ITER installation during its experimental lifetime (approximately 20 years) is estimated at 188 kIUA* per year. For the Deactivation (2037-2042) and Decommissioning phases, the costs have been established in euros at EUR 281 million and EUR 530 million respectively (EUR in 2001 values).

**The ITER Unit of Account was created as part of the ITER Agreement to equitably allocate the value of in-kind hardware procurement to each Member.*

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Is it worth spending billions on fusion or would the money be better spent in improving renewables like solar, wind and geothermal?
Are there risks of further cost increase?

Economic Benefits

Has ITER resulted in any positive economic benefits locally? Is ITER creating jobs?

What is the status of construction workers?

Some say that ITER construction will rely on migrant workers who are poorly paid and precariously housed. Is this true?
Doesn't ITER have a specific legal status ?
What hiring regimes apply?
How are the construction companies chosen?
How many levels of subcontractors are permitted?
How many workers are expected on the ITER worksite in the years to come? What percentage will come from outside of France?
I've heard that foreign workers on the ITER site are only paid EUR 300 per month. Is this true?
What controls are carried out by the French authorities on site working conditions?
Several construction companies have reported the late payment of invoices. What is the situation?
What are the plans for housing thousands of people involved with ITER construction and assembly works?
Will infrastructure modifications be necessary to absorb the increase in traffic flow around the ITER site?

ITER licensing procedure

What has been the licensing process for ITER in France?
Will the post-Fukushima nuclear safety stress tests apply to ITER? If so, is there any risk that these stress tests will lead to additional costs?

ITER and the environment

What kind of nuclear waste will be produced by ITER, and in what quantity?
What arrangements are foreseen for radioactive waste generated by ITER during operation and decommissioning?
What effect will ITER operation have on local electricity and water supplies?

ITER safety

Is the energy stored in a 100-million-degree plasma dangerously large?
What would be the danger of an earthquake occurring near ITER, or a double disaster like earthquake and flooding?

Disruptions : Everything you wanted to know

What are disruptions?
Physicists have been exploring the properties of plasmas within tokamak devices since the

Fusion as a sustainable energy source

Why has fusion science developed much more slowly than fission science, which provided [illegible] boundary conditions—for [illegible] their [illegible] both science and technology), there [illegible]

What about the issue of nuclear decay heat that was so serious at Fukushima?

A disruption is an instability that may develop within the tokamak plasma. [illegible] Disruptions lead [illegible]

[illegible] integrate all these technologies into a single [illegible]

[illegible] because of the large electric fields created during the disruptions, a relativistic electron beam (carrying "runaway electrons") forms [illegible] lost from the plasma.

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Is there any possibility that fusion opens a new way for the production of mass destruction weapons?

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What are the consequences of disruptions?

Unless mitigating action is taken, plasma-facing components can suffer local damage due to the thermal loads and to the deposition of runaway electrons during disruptions. In addition, in extreme cases, the mechanical stresses on the components during disruptions may cause some deformation.

Disruptions are not triggered randomly; they only occur when well-defined limits are exceeded. Disruptions have been observed, avoided and mitigated in most operating tokamaks. One of ITER's objectives is to perfect a stable operating scenario through experimentation so that disruptions become a relatively rare event. During the first years of operation, ITER operators will most likely deliberately provoke disruptive events. Their aim will be to analyze, and to learn to control, these events at reduced plasma parameters and low plasma energy so that disruptions cannot cause damage to the ITER components in experiments at the highest plasma current and energy.

By "pushing" the machine toward disruptions at modest plasma parameters, ITER operators will find its stability boundaries. Once these stability limits have been identified, there is no reason for plasmas in the ITER Tokamak to become disruptive spontaneously as the plasma current and plasma energy is increased, provided that this is done within the stability region identified.

There is abundant literature on the subject of disruptions (see, in particular, *Nuclear Fusion*) and on the operational strategies to avoid disruptions and to mitigate their effects when they cannot be avoided.

Disruptions are an integral part of the official (and public) physics basis for ITER, which has been extensively refereed by the scientific community ("ITER Physics Basis," *Nuclear Fusion*, 47; 2007 complemented the initial 1999 report). Disruptions represent an active

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Will commercial fusion be available early enough to contribute to the energy transition needed to fight climate change and to replace fossil fuels?

The next decades are crucially important to putting the world on a path towards much reduced greenhouse gas emissions. Current and near-term technologies should be deployed [illegible] However, world population will continue to grow and the proportion of the population living in cities is expected to increase. Together with the need for a more equitable distribution of energy among the world's inhabitants, this means that even more large-scale, low-CO₂ sustainable energy will be needed later in the century. Fusion is a strong candidate.

Fusion is one of the few potential alternatives for large-scale energy production. ITER is a major step in this direction that will demonstrate the physics and technology on the way to fusion power plants. Achieving success in ITER will not lead immediately to the building of fusion power plants; another step, usually called DEMO (DEMOnstration fusion power plant) will be necessary. Building on the knowledge and know-how acquired within ITER and parallel research, DEMO will mark the transition to the deployment of fusion energy systems.

The timescale to commercial fusion therefore extends until at least the middle of this century, depending strongly on the political will to invest in this area of research. Lev Artsimovich, the famous Russian academician and one of the major figures in fusion history, used to say: "Fusion will be ready when society needs it."

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If successful, when would fusion be able to add power to the grid? What steps would be required after ITER?

ITER is the essential bridge between today's smaller-scale experimental fusion devices and the demonstration fusion power plants of the future. ITER is a scientific experiment that will open the way to industrial and commercial production of fusion energy.

Building on the knowledge and know-how acquired within ITER, as well as research carried out in parallel in other fusion devices, the next-step machine—an industrial demonstration (DEMO)—would demonstrate the large-scale production of electrical power and tritium fuel self-sufficiency. Several conceptual designs for such a machine are already on the table in the ITER Members; these designs will be refined as ITER enters operations.

field of research in the fusion community, in order to perfect the avoidance and mitigation schemes being developed for ITER.

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Will ITER be able to withstand disruptions?

The European tokamak JET and the French tokamak Tore Supra, as well as many others in the world, have been operated in a completely safe and satisfactory manner since 1983 and 1988 respectively. When exploring new plasma regimes, or during dedicated experiments to study disruptions and their mitigation, disruptions can occur several times a day in these two machines and others, but they have never led to the destruction or rupture of their vacuum vessels.

In 2012 the European Fusion Development Agreement EFDA, which reunites European fusion R&D laboratories, published *A Roadmap to the Realisation of Fusion Energy* that outlines its plan for bringing fusion electricity to the grid by 2050—a goal that it considers ambitious, yet realistic. It foresees a DEMO that will produce net electricity at the level of a few hundred Megawatts in the early 2040s. The EFDA Roadmap takes into account R&D currently undertaken by Europe and Japan within the framework of the Broader Approach activities.

Because disruptions are expected in ITER, they have been planned for. The ITER vacuum vessel and in-vessel components have been designed to withstand the forces produced by about 3,000 disruptions at full plasma performance over the course of their lifetime. ITER's resistance to disruptions is based on scaling laws ("engineering laws") that have determined the values chosen for ITER; these values have been validated by experiments on other tokamaks.

Japan, Korea, India and Russia have also stated their intention to begin building DEMO in the early 2030s in order to operate it in the 2040s.

China plans to first explore physics and technological issues in a test reactor built in the 2020s (the China Fusion Engineering Test Reactor, CFETR) before launching the construction of DEMO in the 2030s.

It is important to understand that disruptions are not a safety-class issue for ITER: there is absolutely no risk for the integrity of the vacuum vessel. But as the high energy loads during disruptions can, over time, damage the surface of plasma-facing components such as divertor targets and first wall panels, these components may need—and have been designed—to be replaced. This takes time and reduces the availability of ITER for experiments. It is therefore important to develop disruption mitigation techniques that [illegible] energy loads on ITER's components so that the time between interventions to replace these components is as long as possible, thereby optimizing the scientific exploitation of ITER.

Of course there are likely to be political and economic constraints that we cannot foresee. The final timescale to commercial fusion depends strongly on political and private sector will to invest in this area of research.

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How much power would a fusion reactor be able to deliver, and at what cost? Would it be competitive?

The power output of the kind of fusion power reactor that is envisaged for the second half of this century will be similar to that of a fission reactor, i.e. between 1 and 3 gigawatts. In theory, the larger the reactor, the more efficient it would be to operate and the more power it would produce, so it may be advantageous to go larger in the future. For the moment, it is envisaged that future fusion power plants would occupy buildings no bigger than those that presently house fission and coal-fired power stations.

During the progressive commissioning of ITER, the machine will be tested with plasma currents and plasma energies lower than the nominal values required for fusion energy production. In this way, the potential damage of ITER's components by disruptions during this initial phase will be minimized. We will begin with low-current and low-energy plasmas to learn how to avoid and mitigate the effects of disruptions on ITER before moving on to more advanced operational scenarios with higher currents and higher energies (thus larger thermal and energy loads on components).

The main goal of ITER and future fusion reactor-based power plants is to develop a new, sustainable and virtually unlimited energy source. The average cost per kilowatt of electricity is expected to be similar to that of current fission reactors. It is likely to be more expensive at the beginning, when the technology is new, and less expensive as economies of scale bring the costs down.

The ITER strategy is not radically different from that already followed in the operation of the largest existing tokamak, JET, which achieved plasma currents of 6-7 MA (as compared to the 15 MA nominal plasma current planned in ITER).

In order to have a rapid market penetration, fusion will have to demonstrate the potential for competitive cost of electricity. Although this is not a primary goal for DEMO, the perspective of competitive electricity production from fusion has to be seen as a target. One way to do this is to minimize the specific DEMO capital costs (and that of fusion power

In summary, the ITER design allows for disruptions to occur at approximately 10 percent of plasma pulses. The early, low-energy/low-plasma-current phase of ITER will permit physicists to characterize disruptions in ITER without risk to the machine. Disruption mitigation is one of the major scientific missions of ITER, with direct plasma). The ITER Tokamak is a first-of-a-kind experimental machine, built with a vast array of diagnostic systems (over 40!) to learn as much as possible about what is happening in the plasma. A fusion power plant on the other hand would be conceived in quite a different way.

relevance to the future development of fusion power plants based on the tokamak concept.

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What disruption mitigation system is planned for ITER?

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on System (DMS) is currently in its design phase. In determining the best method, or combination of methods, for disruption mitigation, the ITER Organization is taking into account performance, reliability, flexibility, and cost. All the promising methods are on the table that will be further refined in the coming months and years for the ITER scenarios. Following years of development worldwide, shattered pellet injection—in which massive amounts (up to 5000) of particles are introduced into the plasma within 1 millisecond—has been chosen as baseline technique to disperse the energy of a disruption before it can concentrate its load on the wall of the containment vessel. Develpment work on a second approach, massive gas injection, will continue as part of risk mitigation.

Is there any assurance that there will be enough tritium available for commercial deployment of fusion? Are lithium resources sufficient to fuel future reactors in competition with other lithium usages?

Two conceptual power plant studies performed in the European fusion programme have shown that the commercial deployment of fusion would not be limited by the availability of fuels and raw materials. Deuterium and lithium (the raw material from which tritium is produced by fusion neutrons interacting with lithium in the blanket) are both widely distributed on Earth:

- deuterium is a naturally occurring isotope of hydrogen, available in water and easily extracted from it;
- lithium from proven, easily extractable land-based resources would provide a stock sufficient to operate fusion power plants for more than 1,000 years (each fusion plant would need only about 3 tons of lithium per year). Worldwide resources of lithium are presently estimated at 25 million tons and studies have shown that competition with other uses, such as batteries, will not be an issue. What's more, lithium can be extracted from ocean water, where reserves are practically unlimited (enough to fulfill the world's energy needs for ~ 6 million years).

An R&D program in disruption mitigation for ITER is currently underway. Experiments run on the ASDEX Upgrade (Germany), Tore Supra (France), DIII-D (US), and JET (EU), to cite a few of the tokamaks involved in this research, are contributing to the refinement of predictions for disruption mitigation in ITER. The ever-increasing capability for numerical simulation of disruptions is also being applied in the elaboration of the ITER disruption mitigation strategy.

The Disruption Mitigation System in ITER will function automatically, triggered as disruptions occur during plasma pulses by dedicated sensors and algorithms that can evaluate the likelihood of an impending disruption. With at least 10 pulses planned per day during operational phases, and disruptions expected in approximately 10 percent of these, it is accurate to say that the Disruption Mitigation System will operate routinely—probably daily—during operation, at least during the initial phases as the ITER operational scenarios are being developed.

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Is the concept of tritium breeding sufficiently robust to start the ITER Project?

Future fusion power plants will have to produce tritium; however, tritium self-sufficiency is not necessary in ITER. Rather, one of the missions for the later stages of ITER operation is to demonstrate the feasibility of one or more concepts of tritium production through the Test Blanket Module (TBM) program. The TBM program will build on tritium breeding studies that have been carried out for a number of years, in particular by the European Union which has substantial expertise in this field. The accumulated knowledge permits a high level of confidence that results from ITER will contribute to full tritium self-sufficiency in next-generation devices.

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I recently read that there was a shortage of helium in the world and this was unlikely to improve as stocks are used up. How will this affect plans for the fusion superconducting magnets?

ITER and future fusion machines based on present superconductor technology would require only a fraction of the present total world helium production.

One of the major helium reserves is the US strategic helium storage reserve; this was released for sale and quantities will reduce in the coming years but will be compensated with new helium sources going into production around the world at the same time. There are also several other untapped helium reserves that ensure sufficient production for party balloons and MRI magnets (some of the main users of helium).

While it is uncertain what the price of helium will be in the coming decades (it will depend on supply and demand), there shouldn't be any significant shortage for fusion.

In the future, fusion machines will have the capability to breed not only their own fuel (tritium) but also helium to preserve natural reserves.

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What are the benefits of pursuing fusion as compared to next-generation nuclear fission reactors?

Fusion and fission are totally different scientific and technological concepts, although both involve nuclear reactions. The fuel assemblies in the core of a fission reactor contain several tons of radioactive fuel which generates energy by the splitting ("fissioning") of atomic nuclei in a chain reaction. Fusion is not a chain reaction. The entire system contains a few kilograms of the radioactive fuel component (tritium) with only a few grams reacting at any given time in the reaction chamber.

Three very unique safety features make fusion technology an attractive option to pursue for future large-scale electricity production.

First, fusion presents no risk of nuclear proliferation. Unlike the fissile materials such as uranium and plutonium used in fission reactors, tritium is neither a fissile nor a fissionable material. There are no enriched materials in a fusion reactor like ITER that could be exploited to make nuclear weapons.

Second, nuclear fusion reactors would produce no high activity/long-life nuclear waste. The "burnt" fuel is helium, a non-radioactive gas. Radioactive substances in the system are the fuel (tritium) and materials activated while the machine is running. The goal of the ongoing R&D program is for fusion reactor material to be recyclable in less than 100 years.

Third, fusion reactions are intrinsically safe. A "runaway" reaction and the resulting uncontrolled production of energy is impossible with fusion. Fusion reactions cannot be maintained spontaneously: any disturbance or failure stops the reaction. This is why it is said that fusion has inherent safety aspects. Moreover, the loss of the cooling function due to an earthquake or flood would not affect the confinement barrier at all. Even in the case of the total failure of the water cooling system, ITER's confinement barriers will remain intact. The temperatures of the vacuum vessel that provides the confinement barrier would under no circumstances reach the melting temperatures of the materials.

Nuclear risks associated with fusion relate to the use of tritium, which is a radioactive form (isotope) of hydrogen. However, the amount used is limited to a few grams of tritium for the reaction and a few kilograms on site. During operation, the radiological impact of the use of tritium on the most exposed population is much smaller than that due to natural background radiation. For ITER, no accident scenario has been identified that would imply the need to take countermeasures to protect the surrounding population.

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Reliability of materials

Is it really possible to find materials which can cope with strong fusion neutrons?
Along the road to the successful development of fusion, one of the major challenges will be to develop materials that can maintain their essential physical properties and not remain highly radioactive for extended periods of time after exposure to the harsh thermal and irradiation conditions inside a fusion reactor.

Fusion R&D has already successfully developed reduced-activation steels. Further developments are foreseen for steel as well as for other materials with more advanced features for fusion reactor applications.

EURATOM and Japan signed a Broader Approach agreement in 2007 that aims to complement the ITER Project by carrying out R&D and developing some advanced technologies for future demonstration fusion power reactors (DEMO). Work is currently underway to complete the integrated engineering design of the International Fusion Materials Irradiation Facility (IFMIF) which will test and qualify advanced materials in an environment similar to that of a future fusion power plant.

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How often will the ITER first wall need to be replaced during operation?
The current operation schedule does not include the replacement of the ITER first wall. However, provisions have been made for the possibility of changing it once during the lifetime of ITER, if necessary. The component which receives most of the power load from the plasma (the "divertor") will need to be replaced more than once during the lifetime of the machine. It has been designed specifically to allow this operation by remote handling. Individual components may also need to be replaced from time to time for corrective maintenance.

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What are the procedures to dispose of the irradiated material contained in the first wall? Have safety risks been taken into account?
The irradiated material will be transferred within a confinement cask to enclosed, shielded compartments ("hot cells"). Inside the hot cells, several operations will be performed such as cleaning and dust collection, detritiation, refurbishment, and disposal. The waste, which

is classified as medium level, will be stored in the hot cells. All of these procedures are a part of ITER operation as presented in the Preliminary Safety Report, and consequently are also submitted to examination of the French Nuclear Safety Authority.

Remote handling technologies have been developed for fusion applications, for example they have been extensively used in the recent upgrade of the Joint European Torus (JET) facility to ensure that workers are not exposed to radioactive components.

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Is there any risk of damage in case of loss of superconductivity in the ITER superconducting magnets?

The fusion science community has an experience of more than twenty years operating large superconducting magnets, i.e., Large Helical Device (Japan), Tore-Supra (France).

Any loss of superconductivity is easily detected, and safety circuits place external resistors in series with the coils to absorb the stored energy. If the safety system and its backups were to fail the coils might suffer damage, but there is no possibility of threat to the integrity of the first confinement barrier.

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