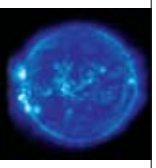


Mastering, on Earth, the fusion of light nuclei, such as deuterium and tritium, for power-generation purposes would open up virtually boundless resources. This is the goal of research work embarked upon by the major industrialized nations, and particularly by the European Union. The state of development reached by such investigations should allow the "fusion" community presently to take up the challenge of building the experimental device designed to demonstrate the scientific and technological feasibility of fusion power: ITER. While not itself generating electricity, ITER will serve as a basis for the next stage: a demonstrator electricity-generating reactor.

Magnetic-confinement **fusion**

CEA/DRFC

The ITER experimental reactor facility, as it would appear at the Cadarache site (Bouches-du-Rhône département, southern France), as proposed by he European Union. In the foreground, the existing facility, built around Tore Supra.

Basic principles of fusion

To achieve a **fusion** reaction, two **nuclei** must be brought together with sufficient force, when, both being positively charged, their natural tendency is one of mutual repulsion (see Box D, ***Nuclear fusion reactions***). A certain amount of energy is thus called for, to get through this natural barrier and reach the region, very close to the nucleus, where the nuclear forces that have the ability to prevail make themselves felt.
Fusion thus requires high temperatures in the reactant medium, typically over 100 million degrees (10 keV), to allow optimization of the numbers of reactions generated. At such temperatures, electrons are stripped from the nuclei, and matter then takes on its fourth state, the "**plasma**" state. Plasma is to be found in the Universe in a great variety of forms, having highly diverse temperature and density characteristics.
The fusion reaction most accessible in practice is the reaction involving **deuterium** (D) and **tritium** (T), two **isotopes** of **hydrogen**, which has been the focus of research work on controlled fusion for energy purposes.

Conditions required for fusion reactions

Apart from high temperatures, further conditions are required, if there is to be a chance of using fusion as an energy source. Hot plasma is subject to a variety of thermal losses, through radiation but equally through **convection** and **conduction.** Generally speaking, all such losses may be covered by a suitably-defined, ove-

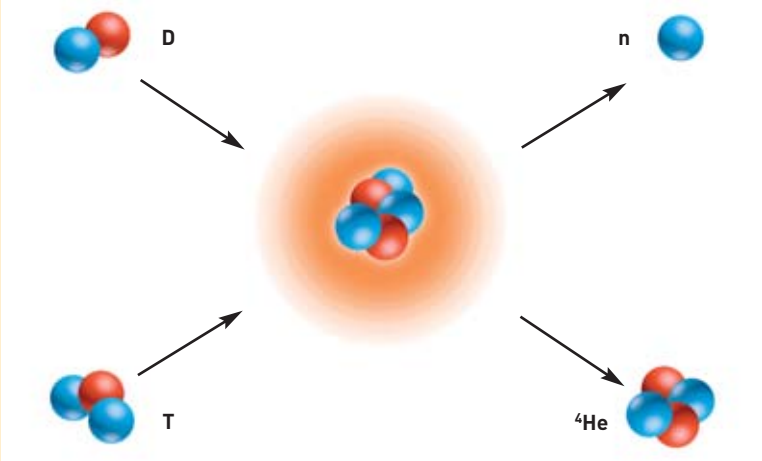
D Nuclear fusion reactions

To achieve the fusion of two light atom nuclei, they must be brought in close proximity to each other, whereas they naturally repel one another, since they both bear a positive electric charge. If the energy this fusion releases is to be recovered, the required energy must first be supplied, to break through this barrier, and allow each nucleus to reach the region, very close to the other nucleus, where the nuclear forces make themselves felt, that are able to overcome this electrostatic repulsion, or Coulomb barrier. Once this outcome is achieved, the most energetic reaction are those yielding the fused nucleus with the highest binding energy. In the event at hand, this is the case for helium isotope ^{4}H, which comprises four nucleons (two protons p and two neutrons n).

Of the fusion reactions that yield energy as well as generating, on the one hand, a new – helium (He) or tritium (T) – nucleus and, on the other hand, a nucleon, four are, at first blush, of particular interest.* The first two are attractive, since they only involve deuterium (D), the most abundant hydrogen isotope on Earth. Mastering them may be the ultimate goal for controlled fusion, however they are by far the hardest to bring about.

$D + D \rightarrow {}^3He + n + 3.27$ MeV

$D + D \rightarrow T + p + 4.04$ MeV



The two subsequent ones, yielding the very stable helium-4 nucleus, are particularly energetic:

$D + T \rightarrow {}^4He + n + 17.58$ MeV

$D + {}^3He \rightarrow {}^4He + p + 18.34$ MeV

The fusion reaction that is most easily achieved, exhibiting as it does the highest cross-section, is that involving a deuterium (D) nucleus and a tritium (T) nucleus, their fusion yielding a helium nucleus and a neutron, with respective energies of 3.5 MeV and 14.1 MeV. Thus it is on this reaction, the so-called D–T reaction, that research work on controlled fusion has focused, whether in the context of inertial-confinement fusion or of magnetic-confinement fusion.

Production of the tritium required is achieved through a fifth reaction, involving lithium and... the neutrons from the D–T reaction.

$6Li + n \rightarrow {}^4He + T + 4.79$ MeV

$7Li + n \rightarrow {}^4He + T + n - 2.47$ MeV

The primary fuels, i.e. the true raw materials for a reactor, are thus deuterium and lithium (Li).

* These reactions are known as *thermonuclear* reactions since only a temperature of the order of about a hundred million degrees, together with other density and confinement time conditions (see main article), make it possible to bring them about. See page 8 for the table of the main nuclear reactions occurring inside the Sun.

rarching time interval, known as the *energy confinement time* (τ): this is the time the plasma takes to void itself of its own heat, if the energy sources sustaining it are suddenly cut off. In a way, t characterizes the quality of the plasma's thermal insulation.

If fusion is to be energetically viable, the energy generated by the fusion reactions must be greatly in excess of these losses. This condition entails a lower limit for the product of density (n) × energy confinement time, as set by the so-called *Lawson criterion*: $n \cdot \tau > f(Q)$, where Q is the ratio of fusion-generated power over the power supplied to the plasma from outside to heat it. Factor Q is often designated as the *energy amplification factor*. Two typical values for Q are one, and infinity. If Q = 1, then power generated by the plasma is equal to the power coupled to it from outside. This state, know as **breakeven** state, can be approached in the current highest-performing experimental machines. The equation $Q = \infty$ implies outside power contribution to the plasma is nil. The plasma is then self-sustaining: it is said to be in *ignition*.

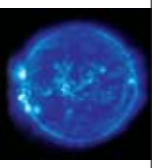
For a deuterium–tritium plasma, function $f(Q)$ has a value around 1 for Q = 1, tending rapidly to 5 for high values of Q. In such conditions, and at a temperature of 10 keV, the Lawson criterion may be written as: $n \cdot \tau \approx 10^{20}$ ($m^{-3}s$).

Fusion in the stars... fusion on Earth

In the Sun and in stars, the conditions required for fusion, in terms of temperature, density and confinement time, are sustained through gravity – a solution impossible to implement on Earth. Gravity-induced pressure may be substituted for here by pressure exerted by intense magnetic fields.

Magnetic vessels to contain plasma

Plasma is an electrically-conducting fluid, though it is neutral overall, where **ions** and electrons move virtually independently from each other. Placed in a magnetic field, these particles will follow helical paths, winding round field lines, remaining "trapped" in them. This is the principle of magnetic confinement. The straight (or cylindrical) geometries initially investigated had the disadvantage that they allow the plasma to escape at the ends. To obviate this, the cylinder is closed back onto itself, yielding a torus configuration. However, in such a configuration, magnetic field curvature (and



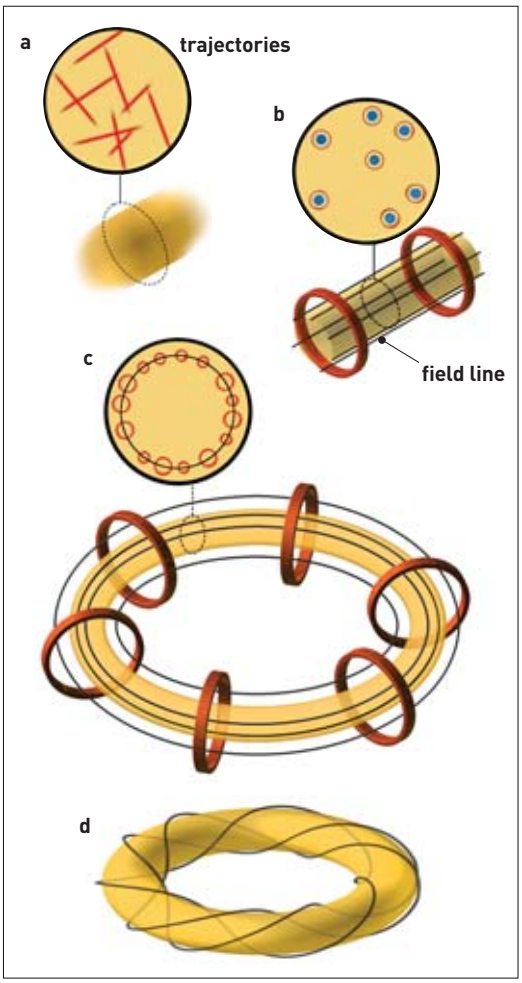


Figure 1.
The principle of magnetic confinement. In a free plasma (a), particles follow a random trajectory, and end up escaping. If this plasma is placed in a magnetic field (b), the particles wind round the field lines, and can no longer reach the side walls. To preclude losses at the ends, the vessel is closed upon itself, to form a torus (c). To further minimize particle losses, field lines must be made helical (d).

hence centrifugal force) and inhomogeneity (being higher on the inner face of the torus than on the outer face) result in migration of the charged particles. Ions and electrons tend to drift apart, the ones drifting up while the others go down, ultimately exiting the magnetic trap. To compensate for this drift effect, field lines are bent to make them helical (see Figure 1). Particles then successively pass to the top, then to the bottom of the magnetic configuration: the drift effect, always retaining the same direction as it does, is then compensated for on average. This is achieved by superimposing on the initial, "toroidal" field another magnetic field, perpendicular to it (the so-called "poloidal" field). In a "**tokamak**" device, a Russian design, the poloidal magnetic field is generated by an axial current, circulated in the plasma itself, which then acts as the secondary of a transformer. (Plasmas thus engineered are said to be "*inductive*" plasmas.) A tokamak is thus initially a *pulsed* device. It may be turned into a continuous device by generating the axial current in "*non-inductive*" fashion, by means of waves, or particle beams that transfer their momentum to the plasma's electrons. In a "**stellarator**," the magnetic configuration relies entirely on currents circulating in outside windings. This configuration, which is naturally continuous, though more complex in terms of the principles and geometry involved, has not reached as advanced a state of development as the tokamak configuration. Its inherent qualities, however, justify ongoing efforts in this area.

The plasma behaves as a gas, exerting an outward (kinetic) pressure rising with temperature and density. If the plasma is to remain confined, this pressure must be balanced by an inward pressure. This is the role assigned to the (magnetic) pressure exerted by the magnetic field. In practice, it can be shown that, to preclude the onset of hydrodynamic instabilities, kinetic pressure must be much weaker (by a factor 10) than the magnetic pressure. It can be seen this introduces a limit for density. At usual values for temperature (10–20 **keV**) and magnetic field intensity (5–10 teslas), this limiting density is of the order of 10^{20} m^{-3}. This also sets the value for the confinement time to be aimed for in magnetic fusion: of the order of a few seconds (Lawson criterion).

How is the plasma to be heated?

Initially, the plasma is never at the temperature required for fusion reactions. Aside from heating by the current passing through the tokamak (ohmic, or resistance heating), two methods are available, to heat a plasma:

- heating by injection of high-energy neutral particles (neutral-beam injection): this consists in generating, and accelerating an ion beam, outside the confinement vessel. The beam is then made neutral before it enters the plasma, where the particles become ionized once again, and are confined by the magnetic field. As collisions redistribute energy, the plasma's temperature rises;
- in heating by electromagnetic waves, at characteristic frequencies of the medium, wave energy is transferred to the plasma by means of antennas lining part of the confinement vessel. Choice of frequency allows to discriminate which particle species (ions or electrons) is to be heated, and the area where wave absorption, and hence heating, is to take place.

Further to heating the plasma, these methods allow current to be generated continuously, hence to consider implementing continuous tokamak operation, in "non-inductive" mode.

In a reactor, plasma temperature could be brought to the appropriate level by a combination of these techniques. Once fusion reactions occur in large enough numbers, energy carried by **helium** nuclei which remain confined in the plasma will take over as the dominant heating mode ($Q > 5$).

Reactor principles

The principle for the reactor is set out in Figure 2. The deuterium–tritium fuel mix is injected (at 1) into a vessel, where, by means of a heating and confinement system, it reaches plasma state, and burns continuously (2). This plasma yields ashes (helium atoms) and energy, in the form of radiation or charged particles (3), which shed their energy in the "first wall," the first material component they encounter beyond the plasma. Energy generated in the form of kinetic energy in neutrons, on the other hand, is converted into heat in the blanket (4), an element positioned behind the first wall, inside the vacuum vessel. This vessel is the component that encloses the region where the fusion reaction takes place. The first wall, blanket, and vacuum vessel, obviously, are cooled by means of a heat-extraction system. The heat is used to generate steam, fed to a turbine–alternator complex (5), which ultimately generates electricity.

The blanket fulfils a number of functions. Its first role is to recover the energy shed by neutrons as they heat up the materials. A heat-transfer fluid is circulated through the structure, transferring the heat generated to such conventional equipment as a steam generator, turbine and alternator. Its second role is regeneration of the tritium required for the fusion reaction. Tritium is in fact only to be found in very small quantities naturally. It will therefore be produced *in situ*, through neutron bombardment of another element, **lithium**, contained in the blanket, by way of the following reactions:

$$n + {}^{6}Li \rightarrow T + {}^{4}He + 4.78 \text{ MeV}$$
$$n + {}^{7}Li \rightarrow T + {}^{4}He + n - 2.47 \text{ MeV}$$

It is obviously advantageous to favor the first reaction, which releases energy. The blanket is thus host to energy-generating reactions, accounting for 20% of the reactor's energy balance. Lithium may be present in solid (ceramic) or liquid (metal alloy) form, according to blanket design.

Finally, the blanket must play a protective role, by considerably attenuating energy and neutron flux, to shield the components behind it (vacuum vessel, magnetic system…).

To achieve an overall efficiency of the order of 35%, a reactor will have to be able to attain energy amplification factors Q higher than 25–30. This entails that fusion reactors must be large units, typically having the capacity to generate 1,000 MW of electricity, i.e. of the same order as the capacity of a fission reactor.

Advantages of fusion

Fusion power affords a number of major advantages. Its fuels are found in abundance, and evenly distributed geographically. Deuterium can be economically extracted from seawater (some 33 g per cubic meter). Deuterium resources amount to over 10 billion years' global yearly consumption! Tritium is to be produced *in situ* from lithium, which is found in the Earth's crust. Lithium resources are assessed at 2,000 years, a limit that can be pushed back to several million years, if this element is extracted from seawater.

Fusion presents advantages in terms of safety. The conditions involved in sustaining the fusion reaction allow plasma of very low density (a few grams of fuel in a volume of over 1,000 m^3) to be used. The amount of fuel present in the combustion vessel during the reaction is thus always very small. Any uncontrolled perturbation of this medium results in it rapidly cooling off, and fusion reactions terminate. A runaway reaction is thus inherently impossible.

Fusion power, like renewable energies and fission, generates through its operation no greenhouse gases or air pollution.

Neither the basic fuels, deuterium and lithium, nor the reaction product, helium (a rare gas), are **radioactive**, or toxic. Tritium will be wholly produced on site. This is a radioactive element, decaying into helium by way of the release of a low-energy (5.7 keV) **beta** radiation, with a relatively short **period** (12.3 years). Its radiotoxicity is low. Appropriate design of the reactor will be needed to allow taking on board extensive tritium **permeation** through the materials.

As in any facility subjected to a flux of high-energy particles (fission reactor, accelerator), the materials making up the reactor's structure will be **activated**. As regards environmental impact, selection, for such components, of materials with a short radioactive decay period should allow quantities of radioactive waste to be kept to a minimum. About a hundred years after final reactor shutdown, the greater part (or indeed the entirety) of such materials should either be classifiable as low-level waste, or be recyclable in the nuclear-generation chain.

Advances in research

Initial magnetic-confinement experiments were carried out in the United States as early as 1938. 1958 saw the declassification of research work in this area. A number of magnetic configurations were investigated: toroidal discharge [(1)] tubes, mirror devices… In order

(1) Discharge: this term refers to the presence of a plasma in the confinement vessel.

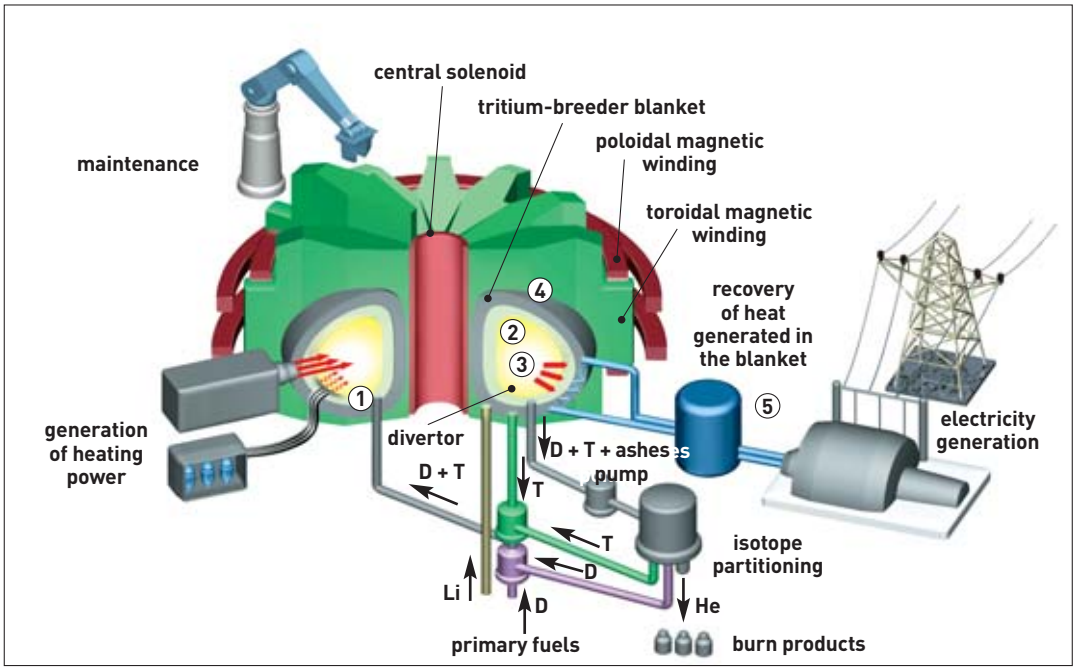
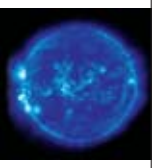


Figure 2. Schematic general layout of an electricity-generating reactor.



to secure the resources required to meet the scientific and technological challenges arising from the quest for mastery of fusion power, collaborations were set up on an international scale. On the European scene, such research efforts were coordinated, from 1957 on, by the Euratom Treaty. This fully-integrated organization, still extant, greatly contributed to European preeminence in this field.

In 1968, Russian scientists from the Kurchatov Institute reported greatly superior performances, compared with other experiments, using a highly specific configuration: the tokamak, which would soon supplant all other designs.

From then on, numerous tokamaks, though still of a modest size, were constructed in France, Germany, the United Kingdom, and Italy, but equally in the United States, in the Soviet Union and in Japan. It was with such devices that development proceeded of diagnostics and plasma heating methods, allowing rapid advances to be made concerning the physics of tokamaks.

Construction programs, as regards most of the large, modern tokamaks (European JET, JT-60 in Japan, TFTR in the United States), were launched in the late 1970s. France, having led Europe into the tokamak era with the TFR device, based in Fontenay-aux-Roses (the highest-performance machine in the world, in the years 1973–76), laid the groundwork, as early as the 1980s, on the technology and physics of continuous operation for fusion reactors, with the construction of a large toroidal-, superconducting-magnet tokamak, Tore Supra, this initiating operation in 1988.

Demonstration of basic principles

Since the early years of the tokamak era, at the end of the 1960s, considerable advances have been made in the understanding of the physical processes involved, and in the development of the technologies implemented in the construction of the experimental instruments.

Such results were arrived at on many facilities, of highly diverse sizes, designed and operated in the years 1970–90 (see Table). All major problems posed by fusion power were addressed, and, for most of them, solutions were put forward.

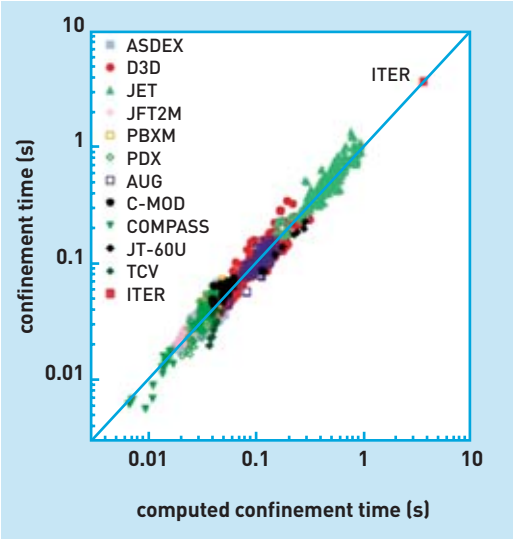
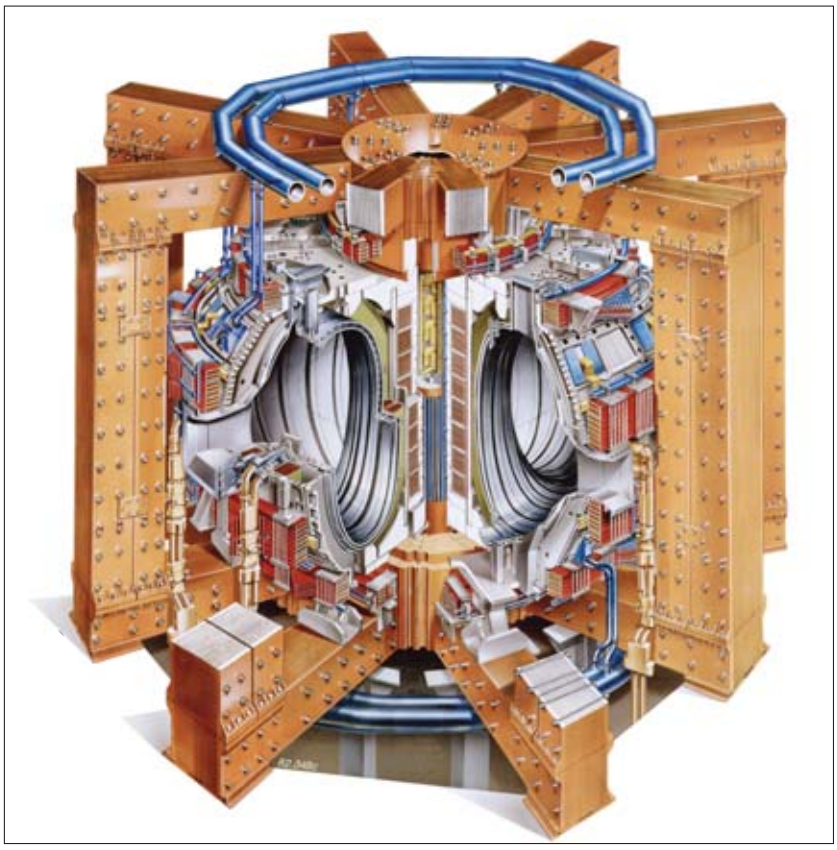


Figure 3. Scaling law for confinement (computation/experiment comparison). Analysis of experimental findings obtained on a variety of facilities allows an empirical scaling law to be derived, expressing confinement time in terms of the main plasma and device parameters. This scaling law, covering two orders of magnitude in parameter variations, is of prime importance for the extrapolation of present performance to that of a next-generation machine.

JET, the Joint European Torus, currently stands as the most powerful tokamak to investigate controlled thermonuclear fusion.



JET

Tore Supra, showing special ability for long-duration discharges, prefigures ITER, in particular with regard to its superconducting components and actively-cooled walls.

CEA/DRFC

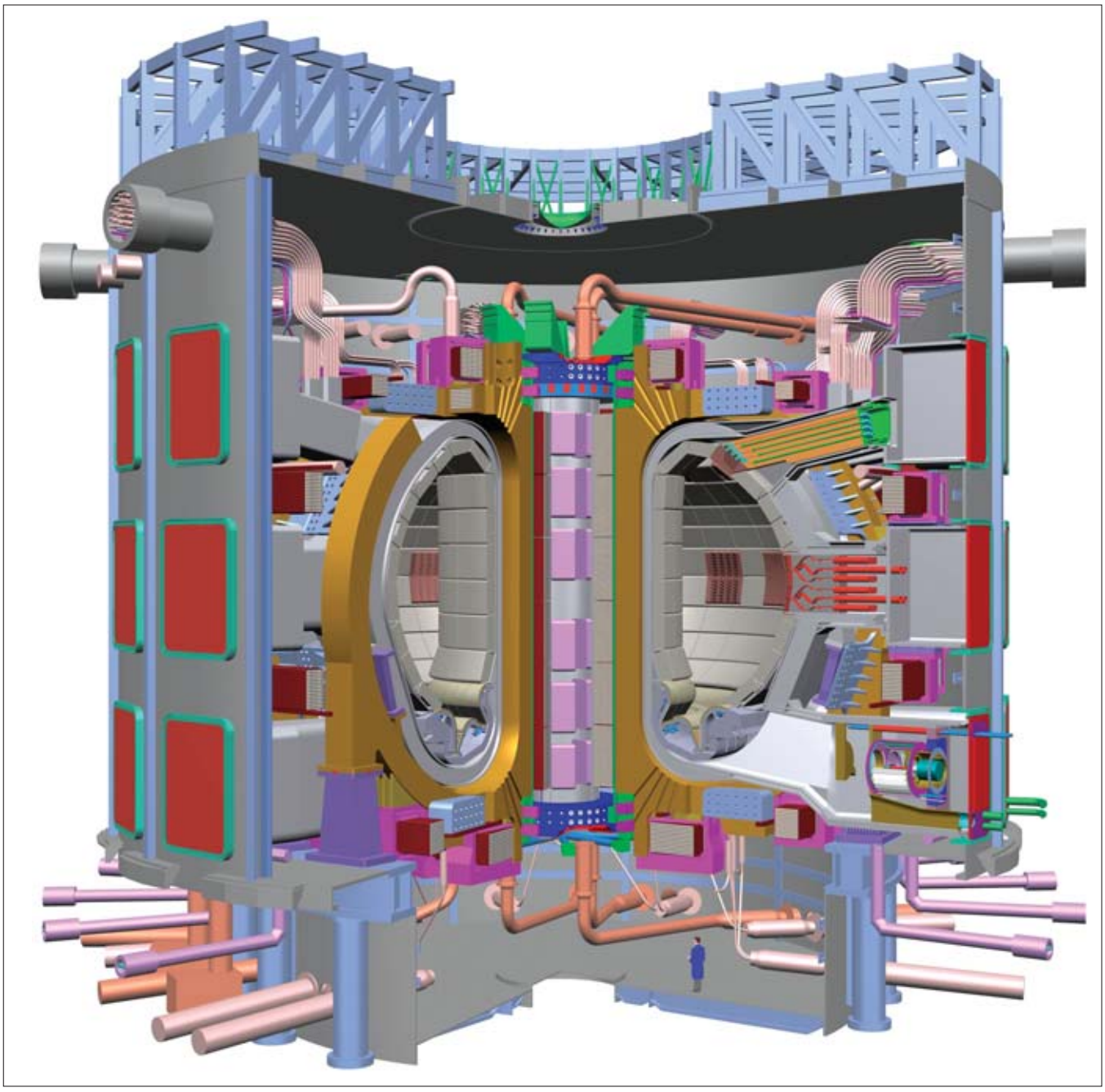
Improved plasma confinement

The many experimental investigations of confinement, carried out on machines the world over, clearly showed that confinement was enhanced as the device got larger, while it degraded with the coupling to the plasma of greater additional heating power. However, for certain conditions, a power threshold may be observed, beyond which confinement spontaneously improves: this regime, known as the H-mode (for High-confinement mode, as opposed to the mode prevailing below the power threshold, or L-mode, for Low-confinement mode), brings an enhancement in confinement time by a factor of nearly 2, mitigating the degradation effect observed in any event. Discovery of the H-mode, in the 1980s, which was made on the ASDEX device, was crucial. This mode, nowadays, stands as the reference scenario for the next-generation device, ITER (International Thermonuclear Experimental Reactor). The entire ensemble of findings has been brought together in a database, on the basis of which a scaling law was worked out, expressing confinement time in terms of the main device and plasma parameters (see Figure 3). While empirical, this approach is of prime importance for the extrapolation of present confinement performance to that pertaining to a next-generation device, close to reactor conditions. The figure emphasizes the significance of the European JET (Joint European Torus) device, currently the largest experimental fusion facility, alongside the Japanese JT-60U device.

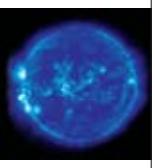
JET: high-performance discharges and associated technologies

Designed in the 1970s, JET represented, for its time, a major leap, considering the largest European machine, at the time, was TFR (Tokamak de Fontenay-aux-Roses), with a mean plasma volume of 1 m^3, i.e. some 100 times smaller than what was proposed for JET. JET remains currently the largest tokamak in the world. Its

Artist's impression of the ITER project.



ITER



magnetic system, comprising 32 copper coils ringing the confinement vessel, generates a 3.4-tesla (3.4 T) field at the center of the plasma. JET also implements the technologies required for tritium management (storage, injection into the confinement vessel, separation of hydrogens from extracted gases, isotope partitioning) and remote handling of its internal components.
The goals set for JET are essentially concerned with achieving good discharge performance, and qualification of the confinement scenarios being considered for the next-generation device. Aspects relating to plasma heating by **alpha particles** are also addressed. The 16 MW of fusion power achieved for about one second, in 1997, with an energy amplification factor Q of around 0.65, very close to breakeven conditions (Q = 1), stands as the most spectacular result to date. The unique ability to produce D–T plasmas on JET goes hand in hand, of course, with mastery of the associated technologies: tritium-cycle management, and remote handling capabilities. The latter system allowed every tile in the first wall to be replaced. The operation was carried out in 1998, on the **divertor** (the component ensuring continuous extraction of ashes from the reaction), which was replaced in its entirety by means of remote handling.

Tore Supra: long duration, superconduction and active cooling

Concurrently with research work on high-performance plasmas with JET, the problem of long-duration (several minutes) plasmas is also being investigated, within the European Union, on the Tore Supra tokamak, set up at CEA's Cadarache site (Bouches-du-Rhône *département*, in southern France).
Though having a plasma volume five times smaller than JET's, Tore Supra nonetheless ranks as the largest **superconducting**-magnet tokamak in the world. Such a characteristic, together with active water-cooling of plasma-facing components, allows investigation of plasmas in quasi-permanent regime.
Tore Supra features 18 superconducting toroidal coils. The chosen superconductor material is the niobium–titanium alloy, cooled in a bath of **superfluid** helium (1.8 K; 1 bar), whose remarkable heat-transfer properties ensure effective cooling of the superconductor with no fluid circulation. These magnets have been operated since 1989, with no major problem, thereby demonstrating the reliability of superconductor technology in a controlled-fusion device configuration.
The plasma-facing components are actively cooled, this being Tore Supra's second unique feature. These essentially consist in a toroidal pumped limiter (TPL), having the ability to extract a constant 15 MW of power, transferred by plasma particles, i.e. an average 3 MW/m^2, and at least 10 MW/m^2 continuous peak, values very close to those in a reactor. The limiter, positioned in the lower region of the device, comprises a stainless-steel load-bearing structure, on which are mounted carbon-fiber composite (CFC) and hardened-copper (CuCrZr) needles, or fingers, able to withstand intense continuous heat fluxes (several MW/m^2).
These technologies have made possible discharges of several minutes' duration. The record discharge achieved in December 2003, lasting 6 and a half minutes, sustained by a power of 3 MW, allowed over 1,000 megajoules of thermal energy to be extracted.

machine	country	minor radius a(m)	major radius R(m)	plasma current I (MA)	magnetic field B (T)
ITER	international	2	6.2	15	5.3
JET	EU	1	2.96	7	3.5
JT-60U	Japan	0.85	3.2	4.5	4.4
TFTR (shut down)	USA	0.85	2.5	2.7	5.6
Tore-Supra	France	0.8	2.4	2	4.2
T-15	Russia	0.7	2.4	2	4
DIII-D	USA	0.67	1.67	3	2.1
ASDEX-U	Germany	0.5	1.67	1.4	3.5
TEXTOR-94	Germany	0.46	1.75	0.8	2.6
FT-U	Italy	0.31	0.92	1.2	7.5
TCV	Switzerland	0.24	0.875	1.2	1.43
C-MOD	USA	0.22	0.67	1.5	8.07
MAST	UK	0.5	0.7	2	0.63
NSTX	USA	0.67	0.85	1	0.6

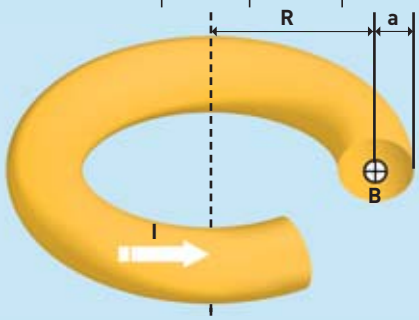
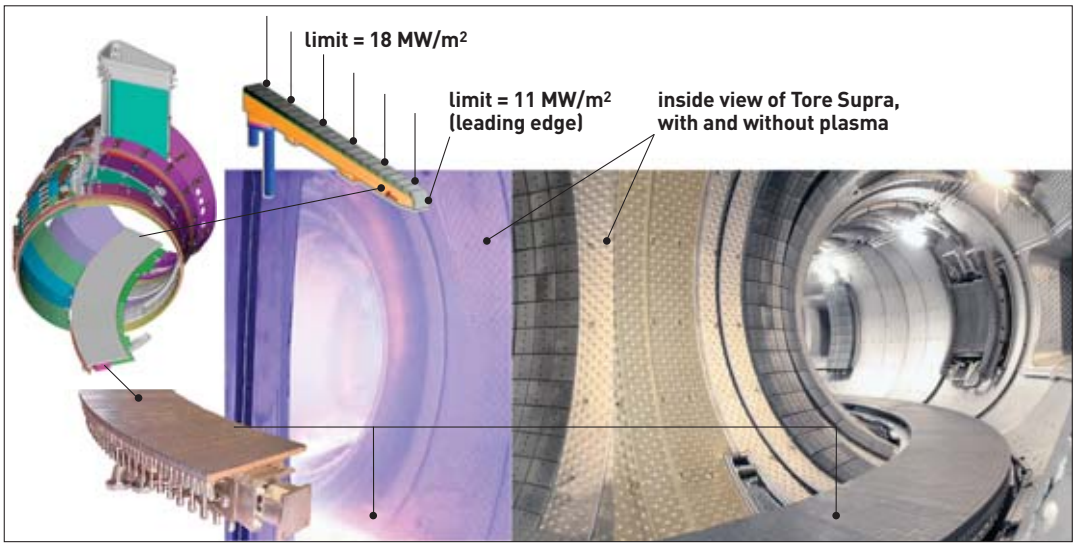


Table. Characteristics of the main tokamak-type fusion devices.

Specific reactor technologies

Technologies more specifically intended for reactors are also being investigated. **Tritium-breeding** blankets are the focus of particular research, including both design studies and experimental assays (fabrication processes, mock-ups…). It has been shown, in particular, that self-sufficient production of tritium is feasible, with a variety of designs. European programs are investigating two of these, differing as to the tritium-breeder materials and heat-transfer fluids adopted. The first design uses a liquid material, taking the form of a lead alloy (LiPb) with pressurized-water cooling; the second one uses helium-cooled ceramics. A number of ceramics are being investigated (Li_4SiO_4, Li_2TiO_3), this also covering fabrication methods, which have reached the pre-industrialization stage. These studies are intended to lead on to the fabrication of complete blanket modules, to be tested in ITER.
The viability of fusion as a future source of energy will be determined in part by factors relating to safety and environmental concerns. In this respect, fusion can turn its relatively early development stage to advantage, to include at the earliest opportunity design solutions involving use of so-called low-activation structural materials. Development of such materials, affording the advantage of exhibiting rapid decrease in activation levels, has been particularly sustained in Europe, where efforts have focused on martensitic steels. [2] One specific grade (Eurofer) has been selected, and has already been cast in significant quantities (several ton-

(2) Martensitic steel: (from the name of German physicist A. Martens) carbon steel with a low nickel and/or manganese content, obtained by quenching, a treatment that distorts the centered cubic lattice in homogeneous fashion. Steels of this type form the largest group of stainless steels.



CEA/DRFC

Internal components of Tore Supra.

nes), allowing fabrication of samples that have been subjected to numerous tests (behavior with respect to irradiation, corrosion, welding…).
Development of such materials and validation of their performance when subjected to neutron fluxes typical of fusion conditions (14-MeV neutrons) are of paramount importance for the future reactor. These materials will make a decisive contribution to the internal components' thermal efficiency and lifetime, and, consequently, they will largely determine overall reactor efficiency and availability. Full validation entails availability of a 14-MeV neutron source, currently under development for the international IFMIF (International Fusion-Material Irradiation Facility) program.

ITER: the next stage

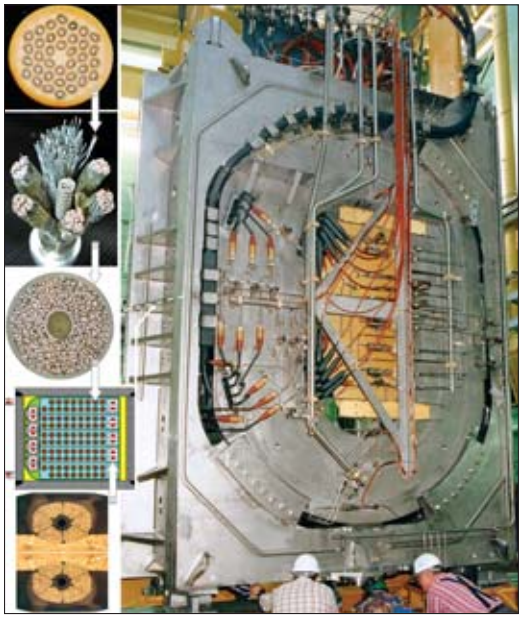
These examples illustrate the considerable advances made as regards the physics, the technology, or even the representation that may be presently entertained, of an electricity-generating fusion reactor. These results have been arrived at on a number of "specialized" experimental facilities: for the physics of high-performance plasmas over short durations (a few seconds), on JET, for the approach required by long-duration discharges (a few minutes), on Tore Supra – not forgetting the numerous breakthroughs achieved, in particular with respect to the principles of improved confinement, on all of the machines operated throughout the European and international community (see Table). Answers are being provided for the major part of the questions arising from the investigations, however still in disconnected fashion. The next stage needs must consist in integrating all these findings into a single facility: this is one of the aims of the international ITER program.

Origins of the program

During the 1980s, the success of such experimental work as that being carried out on JET, together with advances in the understanding of plasma behavior, achieved in smaller facilities, led the scientific community to the study of a "next-stage" experimental facility, dedicated to the investigation of plasmas close to those prevailing in a fusion reactor. At the Geneva Summit, in November 1985, President (then Secretary) Gorbachev suggested to President Reagan and President Mitterrand that the next generation of tokamak be built on the basis of a collaboration bringing together the four main protagonists in the fusion program. In September 1986, the United States, the European Union and Japan agreed to that proposal: the ITER program was born. It brought together, under the aegis of the International Atomic Energy Agency (IAEA), the United States, Japan, the Soviet Union and the European Union, in association with Canada. Thus, ITER is the first experimental facility to have been designed through scientific collaboration on a global scale. An initial version of the program, including construction of large-scale mock-ups of the main components, was presented in 1998. The United States withdrew from the program at this point. The remaining partners concentrated on designing a facility retaining the essentials of the initial scientific goals, while entailing lower costs. The detailed engineering phase for this new version was completed in July 2001.

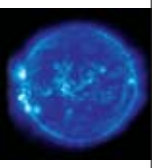
ITER goals

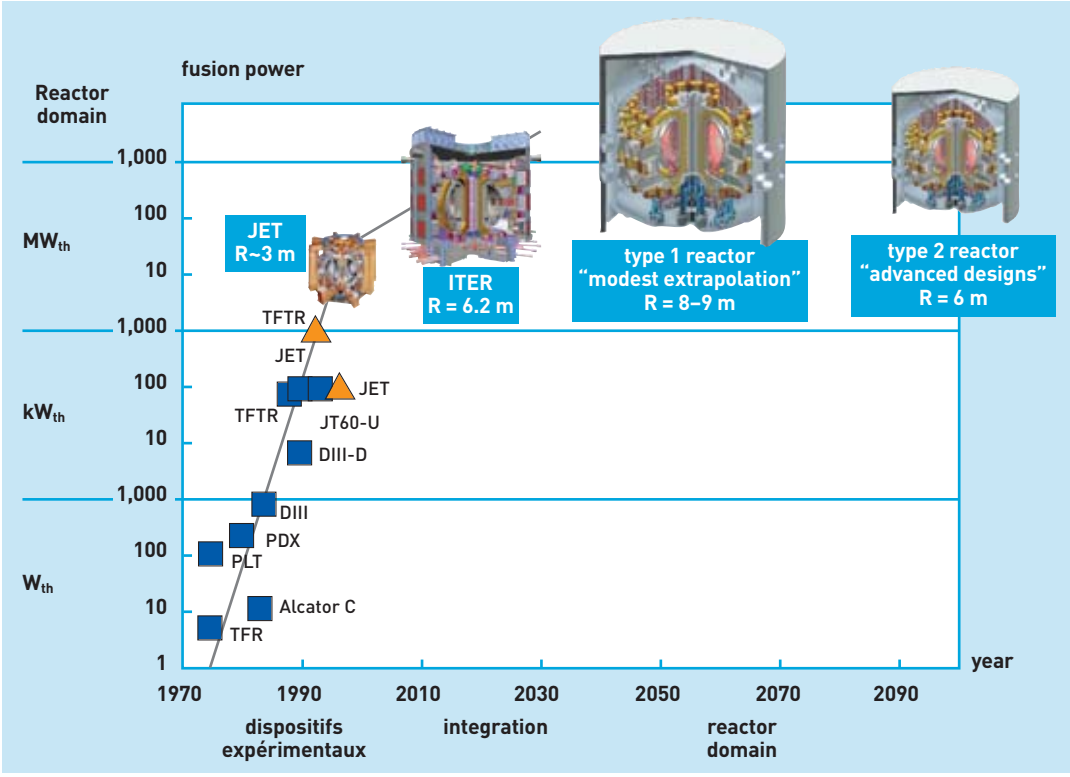
The essential goal set for the ITER program is to demonstrate the scientific and technological feasibility of magne-



CEA, ENEA, FZK

Designing and testing superconducting components for ITER.





CEA/DRFC

Figure 4. The way to the reactor: the goal should be reached in the latter half of this century.

tic-confinement fusion power. The device is to be able to generate 500 MW of fusion power for over 400 s, with the assistance of 50 MW of heating power, i.e. with energy amplification by a factor 10 (Q = 10). It will thus enable investigation of burning plasmas, in other words plasmas where heating by alpha particles generated in fusion reactions will be predominant. At over 60%, heating contribution from alpha particles will be increased sixfold, compared with the best discharges achieved on the JET machine. ITER will bring about a synthesis, in terms of performance, of Tore Supra (long-lasting plasma) and JET (energetic plasma). ITER will also be the first machine to include and combine most of the essential reactor technologies: very large superconducting magnets, actively-cooled plasma-facing components, tritium management, robot-operated maintenance, testing of tritium-breeding blanket modules.

With a major radius (distance from device axis to plasma center) of 6.2 m, plasma volume in ITER will be eight times larger than JET's. The wholly-superconducting cryomagnetic system is designed to deliver 5.3 T at the center of the plasma. Inside the vacuum vessel, the internal components (divertor cassettes, limiters, blanket modules…) will be fully replaceable by robotic maintenance. ITER's main components have been the subject of highly detailed studies, to the extent of building full-scale mock-ups, as was done for the vacuum vessel or divertor handling. The various superconducting cables and connectors were successfully tested in 2000 and 2001, in the guise of model coils (full-scale cables, 1/3-scale coil), further allowing validation of the various stages of industrial fabrication.

Cost of the project is estimated at some _4.7 billion, to be shared among partners. After eight years' construction work, operational status will be achieved gradually, starting with a hydrogen plasma phase, serving to test the machine, and allowing validation of the confinement scenarios for the deuterium and deuterium–tritium phases. Operational lifetime is estimated at 20 years.

ITER is a scientific and technological experiment, designed to demonstrate the feasibility of this novel power-generation option. All essential components of a reactor will be installed, except for dedicated tritium-breeding and electricity-generating components. These constituents, specific to the electricity-generating reactor, will have the special characteristic of being fabricated from low-activation materials; they will be involved in small-scale testing (blanket module) inside ITER.

After ITER: what extrapolations for a reactor?

The options to be considered for a reactor's operation are based on more or less far-reaching extrapolations of the options chosen for ITER (see Figure 4).

Reactors involving *modest extrapolations* require no technological leap. They do involve, however, controlling the power transferred to first-wall elements, on the basis of mastery of edge-plasma radiation. Overall efficiencies achieved are the same as are to be found with conventional nuclear reactors (30–40%). Size would be around 9 m for the major radius.

Advanced reactors entail *large extrapolations* relative to current knowledge, while remaining credible. Developing such reactors would as a whole go hand in hand with similar extrapolations in the technological sphere (silicium-carbide structure, for instance). Plasma topology and parameters are chosen to minimize recirculating power. It is assumed instabilities are fully controlled, as is edge-plasma radiation, with a radiative "mantle" being set up, with no impact on confinement or core-plasma performance. This results in heat fluxes on first-wall elements that are lower than for previous designs (by a factor 2, i.e. less than

10 MW/m^2), and a reactor size close to that of ITER (typically, 6 m). Such designs can potentially operate at very high temperatures (1,000 °C), and thus achieve efficiencies of over 60%. The current state of development, however, precludes considering their adoption in the short term.

Construction of an electricity-generating reactor (whether a demonstrator or a prototype) will require supporting programs, of a more "reactor-oriented" character. Such programs, in particular, are already on hand, concerning development of low-activation materials and tritium-breeder blankets. They are complemented by more general studies covering social and economic aspects. It may seem premature to go into production costs per kilowatt–hour, for an energy source that is still some tens of years away from commercialization. Such studies do nonetheless afford a number of benefits.

The first one is to highlight the impact of such and such a physical variable, or technological assumption, on costs. These conclusions, setting out relative orders of magnitude and directions of variations, have a direct bearing on development strategy.

The second benefit is verifying that the proposed device can meet market requirements. The economic models involved are directly derived from those used in the design, optimization, and computation of costs for present-day machines, or for ITER. In many respects, the latter machine is close to the reactor. Construction costs have been directly worked out by manufacturers in Europe, Japan, Russia and the United States. There is thus a sound basis for evaluation. Remaining uncertainties, important though they be, relate more to reactor availability than to the immediate cost of its components.

The studies show that, contrary to what has been claimed at times, the costs of fusion power are not such as to jeopardize its future. Taking in environmental impact, and conservative assumptions as to the physics and technological options involved, the cost per fusion kilowatt–hour lies somewhere between 1.5 and 2 times that for nuclear-fission power, intermediate between wind and solar power.

Making ready for the energy future

Civilian research work on fusion really took off at the end of the 1950s, with a major international cooperation drive. Progress ever since has been unflagging.

ENEA

Trial set-up for the robotic replacement of ITER divertor elements, at Brasimone (Italy). A full-scale prototype of the assembly robot intended for mounting of the vacuum vessel's internal shielding elements has also been completed in Japan.

Plasma energy balance, as measured by the product of density, temperature and energy confinement time, has increased 1,000-fold! Several megawatts of fusion power have already been generated, and discharges of several minutes' duration achieved. The scientific foundations are now sound enough to allow construction to be considered, of a machine that would validate the feasibility of fusion power: ITER. Insertion into the power-generation range of options could happen in the latter half of this century, at a time when exhaustion of conventional resources and the consequences on climate of our power consumption will be making themselves strongly felt. Fusion affords benefits such as to contribute to setting up power generation that would be environmentally friendly. It undoubtedly behoves to the present generation to ready the knowledge base that will enable decision-makers to give unbiased consideration to all possible energy options.

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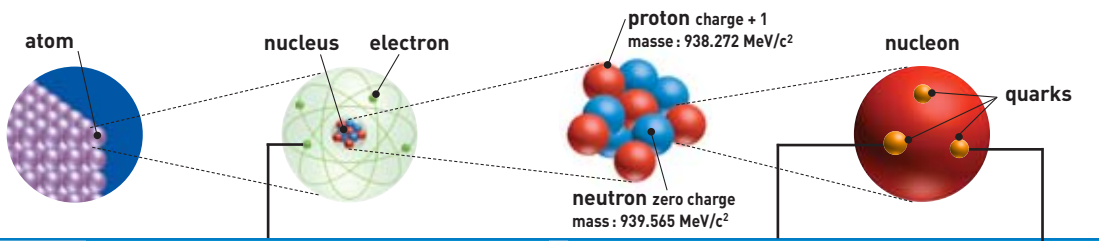
C Elementary particles and fundamental interactions

Neutrinos are the stealthiest particles in the **standard model of particle physics**, the theoretical framework describing all known **elementary particles** and the **fundamental interactions** they mediate (see Table).
The basic constituents of matter, **fermions**, are partitioned into two main categories: **leptons**, which do not respond to **strong interaction**, and **quarks**, which are subject to all of the interactions. The six quarks form three pairs (up/down, charmed/strange, beauty/top). In the lepton category, the **charged leptons** (**electron** e^-, **muon** μ, **tau** τ) are involved in the **electromagnetic interaction** and the **weak interaction**, while **neutral leptons** (**electron neutrino** ν_e, **muon neutrino** $\nu\mu$, **tau neutrino** ν_τ) are only subject to weak interaction. In the standard model, neutrinos have zero mass, however experiments have shown they do have some mass, though very small, the exact value of which is as yet unknown. Involvement



		leptons able to move freely		quarks held captive in larger particles, they are not observed separately	
Fermions Common matter is made up of particles from this group.	first family	**electron** Responsible for electricity and chemical reactions. Charge: – 1. mass: 0.511 MeV/c²	**electron neutrino** Has no electric charge, and interacts very seldom with the ambient medium.	**down** Electric charge: – 1/3. The proton holds one, the neutron two. mass: 5 – 8,5 MeV/c²	**up** Electric charge: + 2/3. The proton holds two, the neutron one. mass: 1,5 – 4,5 MeV/c²
Most of these particles were around just after the Big Bang. Presently only to be found in cosmic rays, and around accelerators.	second family	**muon** A more massive companion to the electron. mass: 105,658 MeV/c²	**muon neutrino** Properties similar to those of the electron neutrino.	**strange** A heavier companion to "up." mass: 80 – 155 MeV/c²	**charmed** A heavier companion to "down." mass: 1 000 – 1 400 MeV/c²
	third family	**tau** Heavier still. mass: 1 777 MeV/c²	**tau neutrino** Properties similar to those of the electron neutrino.	**beauty** Heavier still. mass: 4 000 – 4 500 MeV/c²	**top** Heaviest in the family (observed in 1985): 180 times the proton mass. mass: 174 300 ± 5 100 MeV/c²
Vector Bosons Fundamental particles carrying out transmission of all natural forces.		**photon** Elementary grain of light, vector for the electromagnetic force.	**gluon** Bearer of the strong force between quarks.	**W±, Z⁰** Bearers of the weak force, responsible for some forms of radioactive decay.	
Higgs Boson?		Responsible for "electroweak symmetry breaking."			

Tableau.
Constituants élémentaires.

of the various elementary constituents in the fundamental interactions is governed by their quantum numbers, or interaction charges (electric charge, color charge [1]...). To every constituent of matter is associated its **antiparticle**, a particle having the same mass and opposite charges. The **gravitational force**, which is not included in the standard model, acts on all fermions in proportion to their mass.
The table of elementary constituents of matter manifests another classification – independently from their involvement in fundamental interactions – into three generations, or families. From one family to the next, charged quarks and leptons having the same charges only differ by their mass. The electron, up quark and down quark, which all belong to the first family, are the lightest massive particles. They are stable particles, and the constituents of common matter. For instance, the **proton** is made up of two up quarks and one down quark; the **neutron**, of two down quarks and one up quark. Particles in the other two families are unstable, and rapidly decay into stable first-generation particles. This is why all the stable matter in the Universe is made up from constituents from the first family.
According to quantum mechanics, for an interaction to take place, at least one elementary particle, a **boson**, must be emitted, absorbed or exchanged. The **photon** is the vector for the electromagnetic interaction, the **W^+**, **W^-** and **Z^0** mediate the weak interaction, and **gluons** act as messengers for the strong interaction.
Quarks and charged leptons exchange photons, but conserve their electric charge after the exchange, the photon having no electric charge. Since the photon's mass is zero, the electromagnetic interaction's range is infinite. Having no electric charge, neutrinos are the only elementary fermions that are not subject to electromagnetic interaction.
In the electroweak theory (a unification of the weak and electromagnetic interactions), the weak interaction has two aspects: charged-current weak interaction, for which the interaction vectors are the W^+ and W^-; and neutral-current weak interaction, for which the mediator is Z^0. These two forms of weak interaction are active between all elementary fermions (quarks, charged leptons and neutrinos). The mass of these bosons being very large (80,000 MeV/c^2 for $W^\pm$, 91,180 MeV/c^2 for Z^0), the range of the weak interaction is tiny – of the order of 10^{-18} m. Since $W^\pm$ bosons have a non-zero electric charge, fermions exchanging such bosons undergo a change in electric charge, as of nature (flavor). Conversely, since the Z^0 boson has no electric charge, fermions exchanging one undergo no change in nature. In effect, neutral-current weak interaction is somewhat akin to exchanging a photon. As a general rule, if two fermions are able to exchange a photon, they can also exchange a Z^0. On the other hand, a neutrino has the ability to exchange a Z^0 with another particle, though not a photon.
Only those quarks that have a color charge exchange gluons, these in turn being bearers of a color charge. Thus, when a gluon exchange takes place between quarks, the latter exchange their respective colors. Gluons have zero mass, however, since they do bear a color charge, they are able to interact. The range of the strong interaction is consequently very restricted – of the order of 10^{-15} m.
The graviton, the vector for gravitational interaction, has not so far been observed.
Theory predicts that another fundamental interaction mechanism exists, responsible for the mass of elementary particles, for which the messenger is the Higgs boson, which remains as yet undiscovered. This boson makes it possible to assign a mass to elementary fermions of zero mass that interact with it.

(1) Color charge: a quantum number that determines whether a particle is involved in strong interaction. The color charge can take on three values: "red," "green," or "blue" – such colors bearing no relation to visible colors. Every quark bears one of the three color charges, every antiquark one of the three anticolor charges. Gluons bear double color–anticolor charges (eight possible combinations).

fundamental interaction	messenger	actions
gravitational	graviton?	responsible for the mutual attraction of any two masses and for the law of falling bodies
electromagnetic	photon	responsible for the attraction between electrons and atomic nuclei, hence for the cohesion of atoms and molecules
weak	W^+, W^-, Z^0	the root cause of **thermonuclear fusion** inside the Sun, ensuring its longevity. β^- and β^+ radioactivity, and reactions involving neutrinos are weak interactions
strong	gluons	ensures the cohesion of the atomic nucleus

Table.
Fundamental interaction and elementary constituents.