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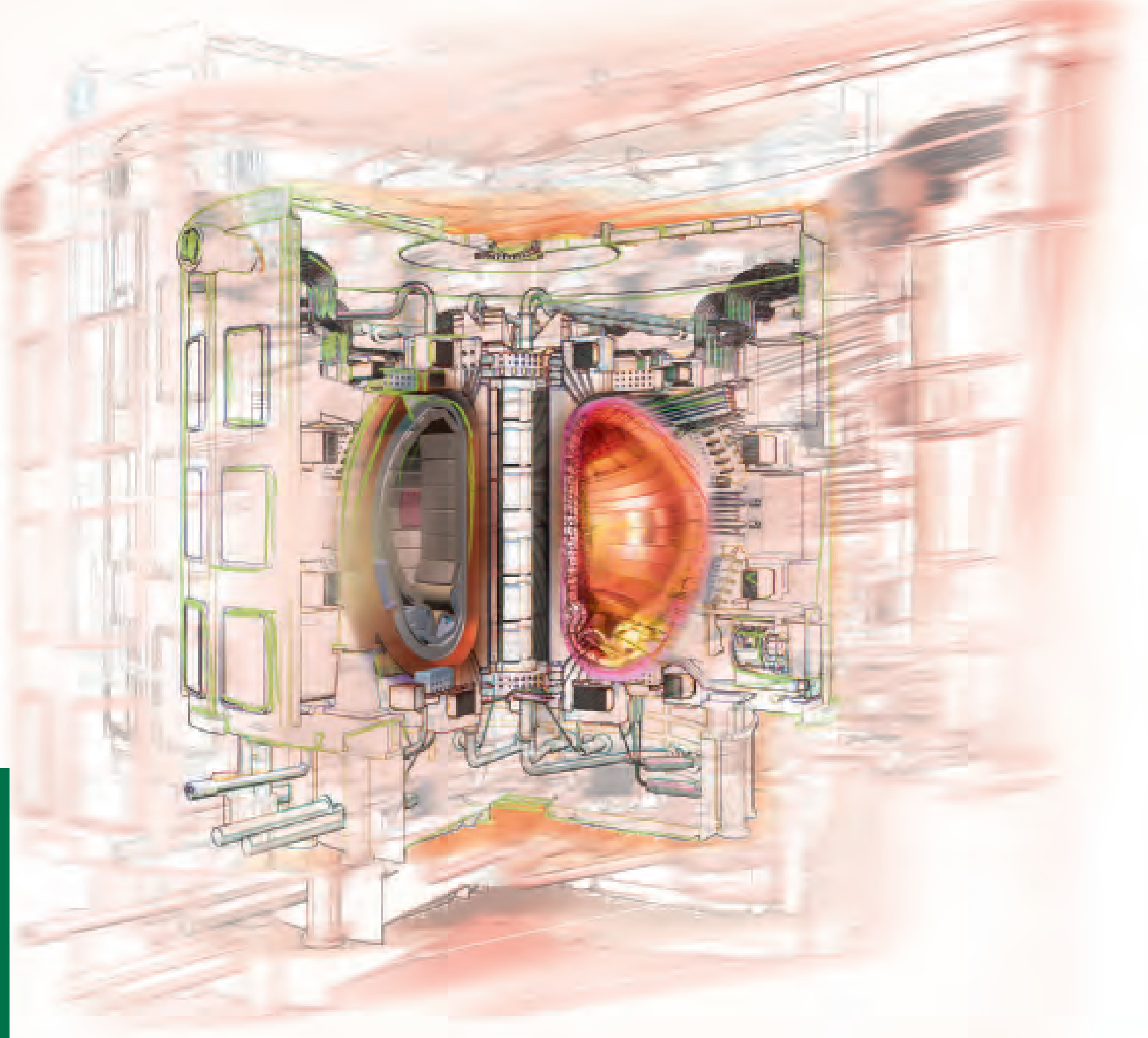

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2007

Directorate-General for Research
Fusion Energy Research

Cataloguing data can be found at the end of this publication.

Luxembourg: Office for Official Publications of the European Communities, 2007
ISBN 978-92-79-05548-5

Printed in Belgium

PRINTED ON WHITE CHLORINE-FREE PAPER

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FOREWORD

With the agreement to build the international ITER experimental fusion reactor in Europe, the EU is to host one of the largest scientific undertakings ever conceived by humanity. The ITER site at Cadarache, in southern France, will become the focus of world research on fusion energy. This project's outcome could have a profound impact on how future generations live, by showing that energy from fusion is a practical possibility.

Fusion research offers the prospect of a future energy source of unlimited scale that is safe, environmentally responsible and economically viable. It will benefit from an almost limitless supply of raw materials for fuel, widely distributed around the globe. Fusion already powers our world as it is the energy source that gives us sunlight - our Sun is a massive fusion power station. Replicating on Earth the processes at work in the Sun and other stars has been a dream and a subject of research for several decades. ITER will be a major step towards making that dream a reality.

If current trends continue, Europe will have to import an even greater proportion of its energy needs in the coming decades and thus compete with rapidly developing countries for dwindling fossil fuel resources. One way to ensure the security of our future energy supply is to develop new energy sources that can be produced in the European Union. Security of supply will be enhanced by having a portfolio of technologies, both conventional and new, and by improving the efficiency of our energy use. We need fusion to be ready to play an important role in this energy mix by contributing a large and cost-effective base-load supply.

The results of research within the European fusion programme, including the Joint European Torus (JET), and from other programmes world-wide mean that we are now able to make the next big step towards realising the potential of fusion power. ITER is that next step.

The ITER Agreement brings together more than half the world’s population to co-operate in the development on this major technology that will be of potential benefit to all. The challenges of the ITER project require the highest levels of technological and scientific expertise, which is being harnessed by pooling resources globally. But ITER is not only a large international research project: it also demonstrates how the EU can muster support for worldwide co-operation on major global issues. As an example of international scientific collaboration at an unprecedented level, it will also show how important scientific challenges, which require investments beyond the resources of most individual nations, can be tackled by collective global action.

By hosting ITER, the EU exercises a special responsibility at the forefront of fusion research. The European Joint Undertaking for ITER has a major role in procuring the components that Europe is committed providing to ITER. Hosting such a cutting edge research facility will bring considerable benefits to EU industry. We have seen before that such challenging projects attract the best and brightest young scientists and engineers, and have led to the development of highly innovative ideas that stimulate industrial growth.

This brochure presents the essentials of fusion science. It explores the world of European research that has brought us to ITER, within a successful international collaboration, and it explains the 'what, why and how' of the device itself. ITER will be a tremendous scientific adventure exploring and pushing back the frontiers of our knowledge, promoting international collaboration with the goal of safe, clean and abundant energy for the world - it truly represents one of humanity's best aspirations and endeavours.

Janez Potočnik

THE NEED FOR SUSTAINABLE ENERGY

Society today depends on energy: for transport, for industry and commerce, for health and wealth, and for our homes and leisure activities. Abundant and relatively cheap energy sources fuelled the improvement in the quality of life enjoyed by Europe's citizens during the 20th century.

Over the next 50 years, the global demand for energy may double as developing countries, such as China and India, need increasing amounts of power for their growing economies and as their citizens improve their standards of living. In Europe, too, it is likely that energy demand will continue to rise.

Supply issues

Entering the 21st century, the vast majority of the energy that Europe and the whole world depend upon still comes from fossil fuels such as coal, oil and gas. Looking forward, some existing energy sources will become scarcer as known reserves are used up. This, in turn, will make energy more expensive. The global competition for fossil energy supplies will be dramatically increased by the rapid growth of emerging economies.

Today, the European Union imports more than 50% of its energy, mostly in the form of oil and gas, from outside the Union. The European energy bill amounts to a negative trade balance of € 240 billion every year. Many of the regions of the world that supply our energy are geographically remote and some may be politically unstable. With current trends, it is predicted that by 2030 the EU will depend on imported energy for 70% of its total needs.

In the 25 EU Member States, energy equivalent to 1 725 million tonnes of oil is consumed every year at a cost of € 500 billion — or more than € 1 000 per person per year. By 2015, European energy demand could grow to 1 900 million tonnes.

For a society critically dependent on energy, maintaining a reliable and secure supply is essential. This means that Europe must also develop new indigenous energy sources.

Environmental issues

Our use of fossil fuels also produces pollutants, including nitrous oxides and carbon dioxide. In particular, the increasing levels of carbon dioxide in the atmosphere due to burning fossil fuels are a significant contributor to global warming.

Continued and increasing use of fossil fuels, with the consequent increases in carbon dioxide and other greenhouse gases emissions, could have a profound effect on local climates.

Energy consumption results in 78% of EU greenhouse gas emissions. Europe has made commitments under the Kyoto Protocol to cut greenhouse gas emissions as part of the global effort to avert climate change. Reducing dependence on fossil fuels and diversifying our energy supply are at the heart of policies to achieve this aim.

Nuclear fission energy is a sustainable energy source which does not produce any greenhouse gas emissions and currently supplies a significant percentage of Europe's electrical power. However, there are political and environmental issues associated with fission energy, relating to the disposal of radioactive waste, safety, and nuclear material proliferation.

The international challenge

Current reliance on energy imports, high prices and climate change together represent a real threat to future European prosperity. Securing future sustainable energy supply is therefore a major challenge for Europe and the world.

Where will we find the clean, safe, affordable and secure energy sources that future generations need?

In addition to improving the efficiency of energy use, researchers around the world are developing a range of environmentally acceptable, safe and sustainable energy technologies. A balanced mix of energies, including renewable technologies such as wind power, hydroelectric and solar, will be necessary to satisfy future needs. But we must develop other new energy sources that can deliver continuous, large-scale power for the long term without harming the environment.

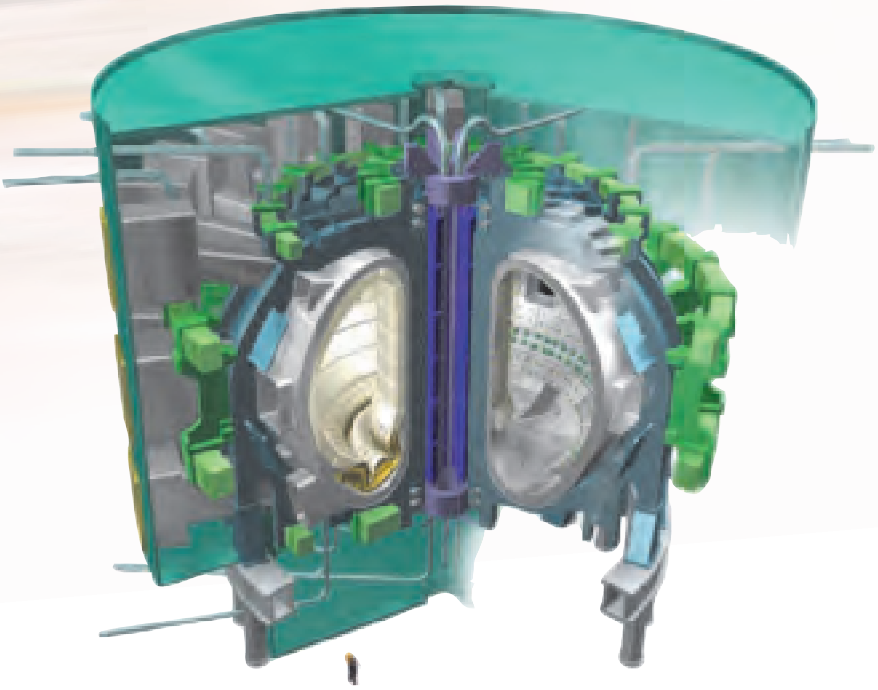
Fusion is such an energy source.

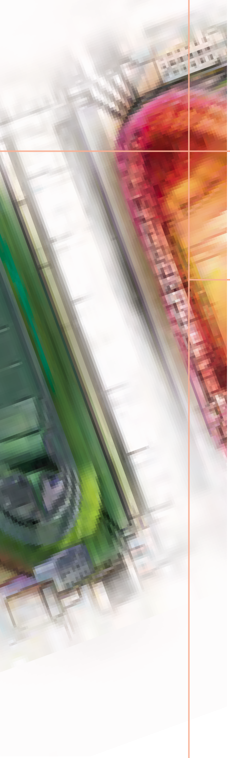
Fusion brings power producing processes like those of the Sun to work on Earth. Fusion has a low environmental impact, no long-term nuclear waste, is inherently safe, and uses a fuel derived from materials that have vast reserves and can be found almost anywhere on Earth.

However, making fusion work is technically very challenging. Such is the challenge and opportunity that the major world powers have decided to work together to take the next step towards making fusion power a reality. This next step is a fusion experiment called ITER.

ITER will prove the feasibility of fusion power and will enable a full exploration of the science relevant to fusion power, as well as testing key technology components for future power plants. It will be built in Europe, at Cadarache in southern France. The European Joint Undertaking for ITER, situated in Barcelona, manages the European contribution to the international ITER organisation.

This brochure describes the challenges for ITER; its aims, objectives and the international collaboration involved. It describes how fusion works, the technology that controls it on Earth, and looks to the future to see where the technology goes from here.





WHAT IS FUSION?

Fusion is the process that powers the Sun – it is fusion energy that makes life on Earth possible. Unlike nuclear fission, which involves splitting very heavy atoms to release energy, fusion releases energy as a result of the joining together of nuclei of two light atoms such as hydrogen to form a helium atomic nucleus.

Inside the Sun, fusion reactions take place at very high temperatures (about 15 million °C) and enormous gravitational pressures. At the high temperatures experienced in the Sun any gas becomes a plasma. Plasma is the fourth state of matter (solid, liquid and gas being the other three); it can be described as an 'electrically-charged gas' in which the negatively charged electrons in atoms are completely separated from the positively charged atomic nuclei (or ions).

Although plasma is rarely found on Earth, it is estimated that more than 99% of the Universe exists as plasma.

The Sun produces around 300 million billion billion watts (3×10^{26} watts) of power by consuming 600 million tonnes of fuel every second. On Earth, scientists are aiming to reproduce fusion on a smaller scale! A typical terrestrial power station produces about 1 000 megawatts, which would consume less than 0.01 grams of hydrogen per second. However, to achieve such a power output we have to find a way to confine the plasma and heat it to temperatures ten times higher than those in the Sun.

This is a significant scientific and technical challenge.

Terrestrial fusion will use the two heavier types (or isotopes) of hydrogen: deuterium – with a nucleus of one proton and a neutron (an atomic particle with similar mass to the proton but no electrical charge); and tritium (one proton and two neutrons).

When these two nuclei fuse together they produce a new helium nucleus (also known as an alpha particle) and a high-energy neutron. The energy of the neutron can be captured and used to heat steam to generate electricity just like in a conventional fossil-fuel power station.

Fusion energy has the potential to provide a sustainable solution to European and global energy needs. Scientists are about to embark on the next step towards realising this potential, in an international collaboration on an experimental facility called ITER. It will be the world's biggest energy research project.

THE ADVANTAGES

The fusion power concept is difficult to realise but it has a number of highly attractive advantages compared to other existing and future energy sources. For example, fusion power offers an energy technology that can provide a continuous baseload power supply which is sustainable, large scale and environmentally responsible.

Almost inexhaustible fuel

The raw fuels from which deuterium and tritium are extracted and generated are water and lithium, which is an abundant metal. Deuterium can be found everywhere on Earth. There are around 0.033 grams of deuterium in every litre of water. We all carry lithium around: it is a component of batteries in mobile phones and laptops. It is also plentiful and readily extractable. If used to fuel a fusion power station, the lithium in one laptop battery, complemented with half a bath of water, would produce the same amount of electricity as burning 40 tonnes of coal.

Natural reserves of tritium do not exist on Earth, but it can be made easily from lithium. In fact, tritium can be made using the high-energy neutron released from the fusion reaction and offers the possibility of making tritium *in situ* in a fusion reactor. The neutron is absorbed by the lithium to produce tritium.

Inherent safety

A fusion reactor is like a gas burner with all the fuel injected being ‘burnt’ in the fusion reaction. The density of fuel in the reaction chamber will be very low at around 1 gram of deuterium/tritium fuel in a volume of 1 000 cubic metres. Any malfunction will cool the plasma and stop the reactions – a runaway situation is impossible.

The fusion fuels, deuterium and lithium, and the helium produced by the reactions, are not radioactive. Tritium is radioactive but decays quite quickly (a half-life of 12.6 years) producing a low-energy electron (beta decay). However, the tritium will be produced and used within the fusion reactor and appropriate safety features will be incorporated into any plant design to avoid its release. No transport of radioactive fuels would be needed for the day-to-day running of a fusion power plant, and even the ‘worst-case’ incidents would not require the evacuation of neighbouring populations. Because of its experimental character, ITER is not planned to be self-sufficient in tritium, but will use tritium produced in fission reactors.

Low environmental impact

The fusion process will not create greenhouse gases, other environmentally harmful pollutants or long-lasting radioactive waste. Its fuel consumption will be extremely low. A 1 000-megawatt electric fusion power plant would consume around 100 kg of deuterium and three tonnes of natural lithium in a year whilst generating 7 billion kilowatt-hour. To generate the same amount of electricity, a coal-fired power plant would need around 1.5 million tonnes of coal.

The neutrons produced during the fusion reaction will interact with materials close to the reactor. In future fusion power plants, careful choice of materials around the hot plasma will ensure that no long-term legacy of radioactive waste is produced by fusion power. However, in the case of ITER, the structural material will be conventional steels as used in nuclear technology and a limited amount of radioactive waste will be generated.

HOW FUSION POWER WORKS

To produce a self-sustaining fusion reaction, the tritium and deuterium plasma must be heated to over 100 million °C – this requires powerful heating devices and minimal thermal loss. To sustain such a temperature the hot plasma must be kept away from the walls of the reactor.

However, because the plasma is an electrically-charged gas it can be held or contained by magnetic fields. This allows the plasma to be held, controlled and even heated by a complex cage of magnets, whilst enabling the neutrons to escape as they have no electric charge.

'Toroidal magnetic confinement fusion' is the advanced technology that is the main approach for European fusion research and is at the heart of the ITER experiment. The reactions take place in a vessel that isolates the plasma from its surroundings it has a torus or 'doughnut-shape' – essentially a continuous tube.

The confining magnetic fields (toroidal and poloidal fields) are generated by electromagnets located around the reactor chamber and by an electrical current flowing in the plasma itself. This current is partly induced by a solenoid at the centre of the torus which acts as the primary winding of a transformer, the plasma being the secondary winding. The resulting magnetic field keeps the plasma particles and their energy away from the reactor wall.

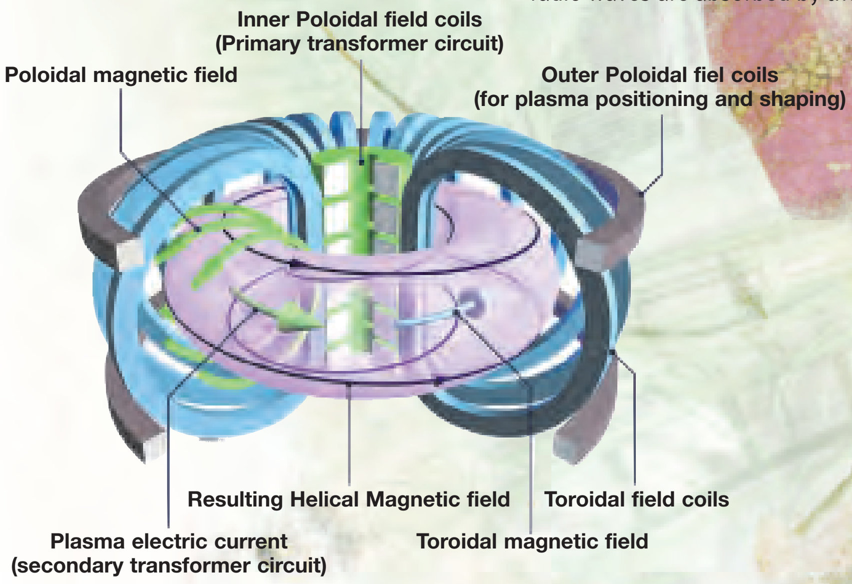
Several toroidal configurations have been studied. The most advanced of these is called the 'tokamak' — ITER will be the world's largest tokamak. The first tokamak was conceived in Moscow in the 1960s and has been the main line for European research in fusion since the 1970s.

Three conditions

To achieve net fusion power output in a deuterium-tritium reactor, three conditions must be fulfilled: a very high temperature greater than 100 million °C; a plasma particle density of at least 10^{22} particles per cubic metre; and an energy confinement time for the reactor of the order of 1 second. This latter quantity is a measure of the time that, if all sources of heating were removed from the plasma, the energy contained in it would dissipate.

To actively control the plasma we need to understand fully its properties, how it conducts heat, how particles are lost from the plasma, its stability, and how unwanted particles (impurities) can be prevented from remaining in the plasma.

One of the major challenges in fusion research has been to maintain plasma temperature. Impurities cool the plasma and ways must be found to extract them. Plasma is heated by the electrical current induced by the transformer arrangement, but additional heating is needed to reach the high temperatures required. This includes the injection of beams of highly energetic fusion fuel particles (deuterium and or tritium) which, on collision with plasma particles, give up their energy to them, and radio-frequency heating where high-power radio waves are absorbed by the plasma particles.



EUROPE AND FUSION

Europe has been a leader in fusion research for the last 20 years. The first practical experiments on fusion were conducted in Cambridge, UK during the 1930s, but real interest in the subject grew across European countries during the 1950s.

At the same time, interest was also being nurtured in the US with the formation of the Princeton Plasma Physics Lab and work at the Los Alamos National Laboratory. In the former Soviet Union, significant work was undertaken during the Cold War but no information was exchanged under normal scientific rules before 1956. In 1958, an 'Atoms for Peace' conference was held in Geneva, under the impetus of US President Eisenhower.

Almost ten years later, results from a Soviet tokamak gave fusion research a major boost. It achieved temperatures ten times higher than any other magnetic confinement experiment at the time. The Soviet success was confirmed by visiting European scientists a year later and led to the construction of many similar experiments around the world.

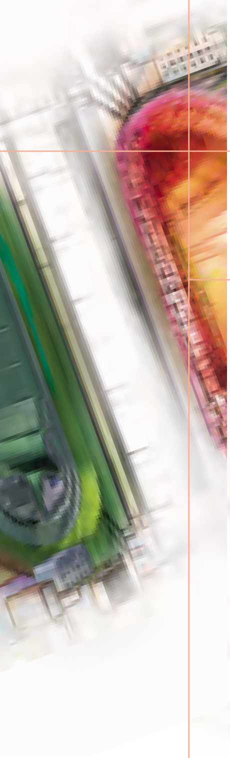
Precursor of the ERA

Fusion research in the EU is coordinated by the European Commission. Funding comes from the Community's EURATOM Research Framework Programme and national funds from the Member States and Associated States (Switzerland since 1979). Coordination and long-term continuity is ensured by ongoing partnership contracts between EURATOM (European Atomic Energy Community) and all the national bodies.

The long-term objective of fusion R&D in the EU is "the joint creation of prototype reactors for power stations to meet the needs of society: operational safety, environmental compatibility, economic viability".

Currently, the most successful and the largest fusion experiment in the world is JET (the Joint European Torus). The basic design of ITER is derived from that of the JET device. The European Fusion Development Agreement (EFDA) provides the framework for research, mutual sharing of facilities and the European contribution to international projects such as ITER.

In addition, the European fusion programme shares expertise and technical facilities across Europe, including: the Tore Supra tokamak in France – the first large tokamak to use superconducting magnets; the ASDEX device in Germany – with ITER-shaped plasmas; the MAST spherical tokamak in the UK; the high magnetic field FTU device and other magnetic confinement configurations including the reversed field pinch device RFX in Italy and the stellarators TJ-II in Spain, and W7-X under construction in Germany. These and many other smaller experimental fusion devices are all contributing valuable data to the development of the science and technology for ITER.



JET – THE JOINT EUROPEAN TORUS

The Joint European Torus (JET) is currently the world's largest fusion facility and is located at Culham near Oxford in the UK. JET is the only fusion device capable of running on the deuterium and tritium fuel mix that will power ITER.

The JET Joint Undertaking was launched in 1978 and the facility came into operation in 1983. It is a large tokamak device approximately 15 metres in diameter and 12 metres high and consisting of 32 'D'-shaped magnets generating a toroidal magnetic field in a plasma containment vessel almost six metres in diameter. The toroidal field combines with a poloidal magnetic field generated by the current flowing through the plasma to provide the confining magnetic field. In addition, other magnetic coils are used to 'fine-tune' the positioning and shape of the plasma in the reactor.

JET boasts an extensive array of plasma measurement systems (diagnostic systems able to measure a wide range of plasma properties). These include magnetic-based measurements of the plasma shape, position and current; measurement of plasma density and temperature; a full array of spectroscopic measurements (from microwave, through visible to X-ray) and neutron spectrometry; video imaging of the plasma, and many other techniques.

Record power

The JET facility has evolved and been upgraded over the years and the work undertaken with it has consistently led global fusion research. In 1991, JET was the first tokamak in the world to achieve a significant amount of controlled fusion power: 1.7 megawatts for about 2 seconds. And in 1997, running on deuterium-tritium fuel, JET established the current world record for fusion power of 16 MW for a limited duration, and 5 megawatts for 5 seconds. This record will not be beaten until ITER is built.

Since 2000, the JET experimental programme has been managed under EFDA with the UK Atomic Energy Authority (UKAEA) contracted to maintain and operate the facility. The programme itself is carried out by teams of visiting scientists from all the associated EU laboratories.

Recent upgrades to JET include new radio-frequency plasma-heating equipment that will enable high-performance operation getting closer to the plasma conditions expected in ITER. The main focus of current research at JET is to develop the scientific basis for ITER – a task for which JET is uniquely placed as it is closer to ITER in size, shape and plasma parameters than any other tokamak.

JET is also able to test much of the advanced systems technology, such as heating and control systems, new materials for plasma-facing components, and remote-handling devices that will be required by ITER in conditions close to power production.

Results from JET – together with other European and worldwide fusion experiments such as the Japanese tokamak JT-60 and the Tokamak Fusion Test Reactor (TFTR) in the US – have given scientists and engineers the confidence to design the next step in the story of fusion power: ITER.

THE OBJECTIVES

ITER will be an international scientific experiment that provides the link between scientific studies on plasma physics and future commercial fusion-based power plants. It is being built, financed and run by a truly international collaborative scientific partnership.

It will be a formidable scientific and technical challenge – a global challenge that has needed a global response. The project is expected to cost around €10 billion over its lifetime of 35 years.

Essentially, ITER will comprise a tokamak with superconducting electromagnets and other systems which make it capable of generating 500 megawatts of fusion power continuously for at least 400 seconds. The plasma volume will be ten times that of JET and will be close to the size of future commercial reactors. ITER needs to be this big in order to achieve the target fusion power: more volume means more fusion reactions taking place, and better thermal insulation of the hot plasma (corresponding to a large energy confinement time).

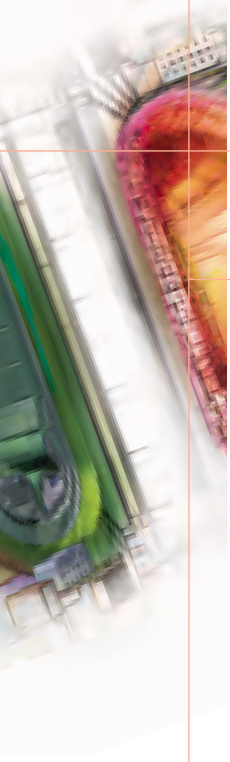
The ITER project will, for the first time, enable scientists to study the physics of a burning plasma – a plasma that is heated by hot alpha particles generated by the fusion reactions rather than by external heating. It will also demonstrate and refine the key technologies for developing fusion as a safe and environmentally benign energy source.

The ITER experiment will generate ten times more power than is required to produce and heat the initial hydrogen plasma – this is called the power multiplication factor (Q). In future power reactors, a Q factor of 30-40 will be typical. The heating, control, diagnostic and remote maintenance systems that will be needed in a real power station will be tested, and ITER will also investigate systems to refuel the plasma and extract impurities.

ITER will integrate the technologies essential for a fusion reactor, such as superconducting magnets and remote maintenance, and test other components such as the divertor mechanism and high-performance vacuum pumps to maintain low pressure in the plasma containment vessel. Although it will normally operate with externally supplied tritium, ITER will also test tritium breeding module concepts for demonstration power plant reactors.

ITER design parameters

Total fusion power (megawatt)	500 MW
Power multiplication factor (Q)	10
Tokamak diameter	24 m
Tokamak height	15 m
Plasma volume	850 m^3
On-axis toroidal magnetic field (tesla)	5.3 T
Operational life	20 years+



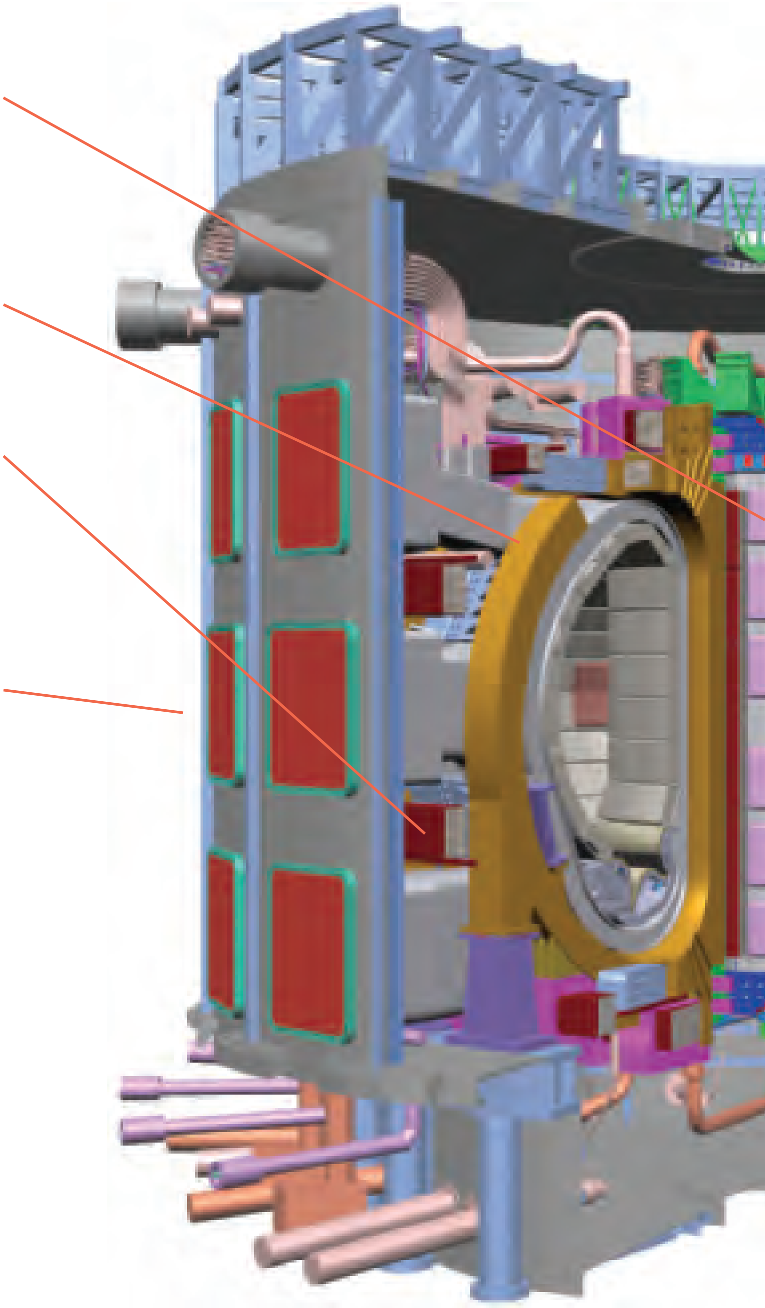
THE MACHINE

Central solenoid (1)
The primary circuit of a transformer – the plasma is the secondary circuit – that generates a poloidal magnetic field and electrical current in the plasma and heats it.

Toroidal field coil (2)
Eighteen large superconducting electromagnets generate the toroidal field.

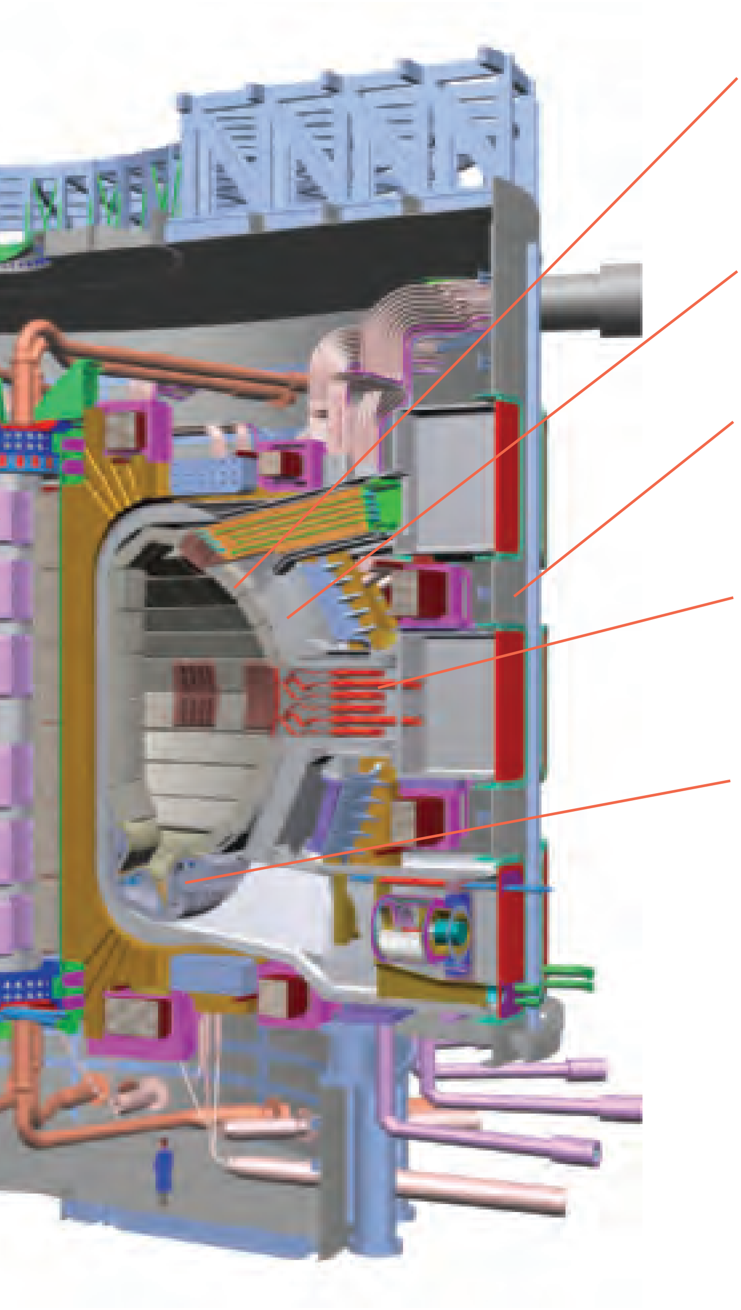
Poloidal field coil (3)
Six smaller superconducting magnets supplement the central solenoid in forming and controlling the poloidal field.

Diagnostics (4)
A wide range of diagnostics devices, measuring all the parameters of the plasma and of the tokamak, will provide real-time data to enable control of the plasma burn and to analyse plasma behaviour.



The overall ITER design comprises the tokamak itself, and associated systems for heating, fuelling, exhaust of waste heat and gas, control, diagnostic measurements, etc. ITER, like JET, will have a vertical 'D'-shaped plasma and a lower divertor system within the containment vessel. The **divertor (9)** is a critical component and the main area where plasma will contact the material wall. Testing this component and studying the processes involved in its behaviour is a very important part of the ITER experiments.

It will use low-temperature (-269°C, which is close to absolute zero) superconducting electromagnets for both its 18 **toroidal (2)** and six **poloidal (3)** coils and the **central solenoid (1)**. Together, these coils can generate a massive 5.3 tesla magnetic field – about 100 000 times greater than the maximum of the Earth's magnetic field. Control of the plasma is achieved using the poloidal field coils together with vacuum pumping, fuelling and heating systems linked to feedback from the **diagnostic (4)** sensors.



Blanket module (5)

Initially used to provide shielding from neutrons – later experiments will test tritium breeder concepts as well.

Vacuum vessel (6)

Built in nine sectors which are welded together, to provide a hermetically sealed plasma containment.

Cryostat (7)

The superconductors of the electromagnets need to be cooled to -269°C so the whole tokamak is in a huge cryogenic chamber.

External heating systems (8)

Up to 110 megawatts of external heating (neutral beam and radio-frequency heating) can be supplied to extend burn times and control plasma.

Divertor (9)

This is the main area where plasma will contact the vacuum vessel wall. The divertor controls the exhaust of waste gas and impurities from the reactor and is able to withstand very high surface heat loads.

The whole ITER machine is enclosed in a -203°C **cryostat (7)** which helps insulate the superconducting electromagnetic coils.

External heating systems (8) provide input heating power of about 50 megawatts using neutral beam injection and radio-frequency electromagnetic waves (electron and ion cyclotron frequencies). These systems are modular and an upgrade of this heating power is foreseen at some stage in the operation phase to 100 megawatts.

The heating systems, diagnostics and other equipment are located on three levels around the surface of the **vacuum vessel (6)** and can be accessed during remote maintenance. The inner surfaces of the vacuum vessel are covered with **blanket modules (5)**. These modules will initially provide shielding from the high-energy neutrons produced by the fusion reactions and some will also be used to test a variety of the most promising tritium breeding concepts during later experiments.

THE TECHNOLOGY

Many new technologies, from superconducting electromagnets to novel materials, have been, or are being, developed for ITER and future fusion power plants. Each technology area presents significant challenges resulting from scientific and/or technical issues. All must be overcome to produce an efficient and sustainable energy system.

Superconducting magnet technology

Very strong magnetic fields are required to confine the plasma in the ITER vacuum vessel. If conventional resistive electromagnets are used, a lot of energy is wasted in the form of heat. To limit the energy needed to produce the large magnetic field, superconducting magnets have been developed. The ITER magnet system consists of 18 toroidal field coils, six poloidal field coils together with a central solenoid and a number of correction or shaping coils.

The toroidal field coils and central solenoid are massive, weighing 290 tonnes and 840 tonnes respectively, and are made from a superconducting alloy material containing niobium and tin (Nb_3Sn). To achieve superconductivity, the coils must be cooled to liquid helium temperature (4 K or -269 °C). At this low temperature the resistance of the superconducting material falls to zero, thereby greatly reducing the energy required for the magnet.

Nb_3Sn is a brittle material and construction of magnets weighing a few hundred tonnes is not easy, but the material was chosen because it can support very high magnetic fields. Each toroidal field coil starts with some 1 100 wires about 0.7mm thick twisted together inside a 40 mm-diameter metal tube to form conductors 820 m long. When in use, supercritical helium flows within this tube and down a central gap to cool the Nb_3Sn.

The poloidal field coils will be made from a material containing niobium and titanium (NbTi) which is more commonly used than Nb_3Sn. These coils are located in a region where the strength of the magnetic field is low enough for this material to be used. However, the position also means that replacing poloidal field coils will be very difficult, so each coil will be designed with redundant turns so that any faults can be isolated to ensure that operation of ITER continues unhindered.

Once energised, the magnets can work continuously with very high efficiency, ideal for a steady-state fusion reactor. As these magnets run at liquid helium temperature it is necessary to operate them in vacuum to prevent heat in the atmosphere from boiling off the helium – hence the cryostat surrounding the central reactor.

The manufacture and test of large-scale superconducting electromagnets is one of the major engineering challenges for fusion, as they are the most expensive components of such a reactor. The successful construction of the ITER electromagnets will therefore be an important step forward for fusion.

Manufacturing reactor components

The ITER plasma containment vessel will be more than twice as large and 16 times as heavy as any previously manufactured fusion vessel. This raises issues of fabrication technology such as dimensional accuracy and welding distortion. The future construction of advanced fusion devices requires the development of a whole range of sophisticated processes and manufacturing techniques.

These include advanced welding processes, such as automated robotic welding and inspection techniques, that can improve quality and reduce manufacturing time and cost. Although these techniques are being developed within the fusion programme because of its specific needs, they have very wide-ranging applications. Improvements are also being made in the manufacture of superconductors (the superconducting material and its surrounding structures), which will increase their operating margins and reliability.

Remote handling

The internal structure of a fusion reactor will become radioactive during operation due to neutron radiation and the presence of tritium. Remote-handling systems are therefore vital to be able to replace components, such as the divertor and, eventually, breeder blanket modules, inside the machine.

For JET, engineers have mastered remote-handling technology with a combination of computer-controlled and operator-controlled systems. In ITER, very robust and reliable remote-handling equipment must be designed. This equipment must be capable of manipulating components weighing up to 50 tonnes. To start the design process, virtual prototyping uses a computer to model all the movements and mechanical behaviour of the robot in great detail so that the engineers can be certain that the equipment will perform first time. These remote-handling techniques have already been successfully demonstrated on full-scale mock-ups of ITER components – in particular, the basic feasibility for remote maintenance of the ITER divertor.

Cryogenics and vacuum systems

In a fusion power plant, cryogenic systems are used to remove the impurities from the plasma, cool the superconducting coils to allow them to operate, separate the waste gases into their different individual components for disposal or recycling for fuel, provide the cooling for the radio-frequency heating sources, and control the gas pressure of neutral beam systems.

Large-scale vacuum systems are required to ensure an ultra-high vacuum in the large reactor vessels that will be used by commercial fusion power stations, and to maintain the vacuum surrounding the superconducting magnets in the cryostat.

Plasma heating

Plasma heating systems are essential for obtaining a high-temperature plasma. For ITER, the fusion reaction would not continue if the plasma was not heated by an external source, and for both ITER and future power plant operation it is likely that the heating systems will be an essential tool to ensure stability and control of the plasma. Initially, three main types of heating systems will be deployed for ITER:

- Ion Cyclotron Resonance Heating – in this system, ions in the plasma are heated by electromagnetic waves with a resonance frequency of 30 to 50 megahertz. The main issues concern how to couple the intense radiation to the plasma and what effect this has on the performance of the plasma.

- Electron Cyclotron Resonance Heating – here the electrons in the plasma are heated by electromagnetic waves with a resonance frequency of 100 to 200 megahertz. This system is also being used to heat the outer surface of the plasma as a control mechanism for the build up of certain instabilities that lead to the cooling of the plasma. This radiation has the advantage that it can be transmitted through air which simplifies the design and means that the source can be far from the plasma, thereby making maintenance simpler.

- Neutral Beam Injection – in this system, charged fusion fuel particles are accelerated to a very high speed (kinetic energy of 1 mega electron Volt) and neutralised so that high-energy neutral particles can pass through the magnetic field and enter the fusion plasma. As a result, plasma is heated by the transfer of kinetic energy.

Diagnostics

In a fusion reactor, many instruments measuring a variety of parameters are needed to control the plasma performance, including temperature, density and the type of impurities present. Diagnostics must be developed to monitor every aspect of the machine. Plasma diagnostics fall into three categories: those necessary for machine protection or basic control; those needed for advanced performance control; and those desirable for physics studies. There will be about 45 different diagnostic systems deployed around the ITER tokamak and they will use a variety of measurements based, for example, on magnetic, optical, microwave techniques.

The most reliable way of measuring temperature is to shine a very powerful laser into the plasma. The photons in the laser beam scatter off the energetic plasma electrons and this scattered light can be measured. The Doppler shift in the wavelength of the scattered photons gives a direct measurement of the speed and hence the temperature of the electrons, whilst the intensity of the reflected light is related to the density of the plasma.

One method of measuring the level of impurities is to take measurements of the ultraviolet (UV) radiation from the plasma. Different sized particles will radiate differing UV wavelengths because they have different excitation energies. Therefore, knowing the UV spectrum of the plasma reveals the nature and amount of impurities present.

The divertor and wall materials

In order to remove heat, fusion products (helium) and other impurities from the plasma, the plasma will be allowed to touch its surrounding structure in a controlled manner. This is achieved by shaping the magnetic field lines in such a way as to enter the divertor. The divertor consists of two targets designed to withstand heat loads of up to 20 megawatts per square metre. Contact with wall materials elsewhere needs to be minimised as this will erode the vacuum vessel surface and reduce the lifetime of reactor components.

The material currently used as the target of the divertor is carbon reinforced with carbon fibre. In addition to this critical part of the divertor design, it is also important to design components that can withstand the high electromechanical loads experienced in the reactor chamber, allow high-vacuum pumping to remove the helium from the plasma, and tolerate long exposure to neutron radiation.

Breeding and shielding blanket technology

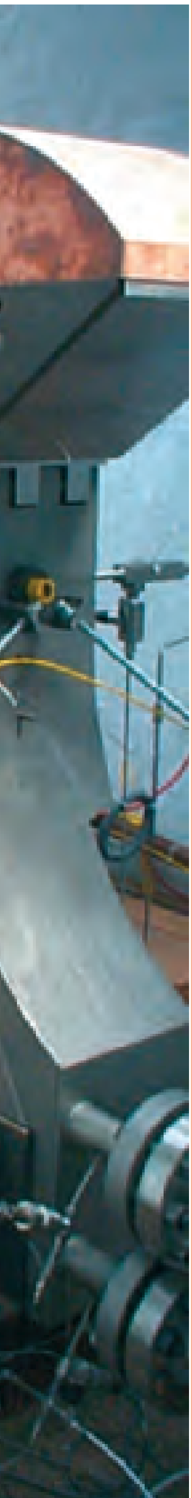
A reliable and efficient ‘breeder blanket’ technology is vital for heat transfer and fuel generation in future fusion power plants. The energetic neutrons released from fusion reactions do not interact with the plasma. The role of the blanket, which will surround a commercial reactor, is to slow the neutrons, recovering their energy as heat for industrial processing or electrical power production as well as using them to transform lithium into tritium. The tritium can then be extracted, processed and added to deuterium for refuelling the reactor. By capturing the neutrons, the blanket also shields other components, such as the superconducting coils, and protects them from damage.

A number of different concepts are being explored for breeder blankets. This technology will have to work at high temperatures in a commercial reactor to provide efficient heat exchange to raise steam for electricity generation, whilst continuing to breed at least one tritium atom for every fusion reaction in the plasma. Research in this area is concentrating on the use of liquid-cooled lithium-lead and helium-cooled solid ceramic breeder pebbles. Initially, ITER will use blankets for the shielding function and will demonstrate the most advanced tritium breeding concepts as part of its experimental programme at a later stage.

WORKING TOGETHER

The idea of undertaking ITER has an international project was first proposed at summit level in 1985 and the technical work started in 1988 as a collaboration between the European Union, Japan, the former Soviet Union and the United States, under the auspices of the International Atomic Energy Agency (IAEA).

Today, the international consortium to implement ITER comprises the People's Republic of China, the EU, India, Japan, the Republic of Korea, the Russian Federation, and the USA.



Design and negotiation

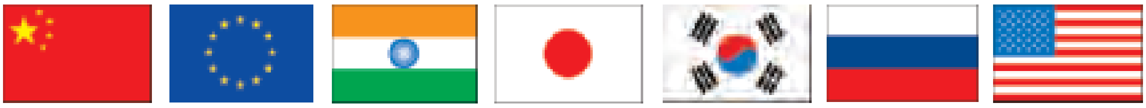
ITER is a multinational collaboration between countries involved in fusion research worldwide. It operates by consensus among its participants. In a way, it extends the European R&D model that has enjoyed success in the Euratom programme with JET.

Its design has passed through a number of phases. The first stage (1988-1990) developed the original conceptual design and was followed by a phase of engineering design activities (mid-1992 to mid-1998). However, when it was felt that it would be difficult to secure political support for the financial scale of the project, a further phase was required to design a smaller device that would be significantly less expensive. The USA did not participate in this phase.

This redesign was completed in July 2001 (ITER Final Design Report), including the cost, construction schedule, safety and licensing requirements. In late 2001, the EU, Canada, Japan and the Russian Federation embarked on official negotiations concerning the joint construction, operation and exploitation of ITER. Subsequently, the USA decided to rejoin the project. China, South Korea and, more recently, India have also joined as full participants, whilst Canada dropped out.

The ITER design was underpinned by a large research programme that has established its practical feasibility and involved construction of full-scale prototypes of key ITER components, including the magnets. This has provided the confidence that ITER can be built by industry. The successful testing of these components has continued in parallel with the negotiations and has helped maintain the scientific and technical momentum of the project while increasing confidence in the project's viability.

November 2006 saw the successful end of years of intense negotiations among the ITER parties on the Joint Implementation of the project. The official signing ceremony took place at the Elysée Palace in Paris, where ministers from the seven parties convened and saw the birth of the ITER international organisation.



INTERNATIONAL RESOURCES

As much and perhaps more than high-technology and cutting-edge science, ITER concerns human endeavour and our thirst for knowledge. ITER is about collaboration and co-operation across cultures and continents to meet a global challenge.

Although based in Europe, the ITER project is undertaken by the international ITER Organisation established following the signature of the ITER Joint Implementation Agreement. The parties to the ITER Agreement share the project costs. With respect to its construction, most components are contributed by members as contributions in kind. The European Joint Undertaking is the organisation -“domestic agency”- established in April 2007 that will manage the European contribution to ITER. Together, the EU and France will contribute about half of the total construction costs for ITER, with the other parties sharing the rest on an equal basis.

Hosting ITER enables Europe to maintain its position at the forefront of fusion research. The existence of such a high-technology, cutting-edge research facility will have considerable benefits for European and other Parties’ industry. It represents the commitment of Europe to the development of fusion and will ensure that the best and brightest scientific minds are attracted to ITER.

New way of working

The European experience with JET has demonstrated an excellent model for how to work together in ITER. Running experiments on a fusion device like ITER will not be the same as on other large scientific facilities such as telescopes or particle accelerators.
The experiments will not be run ‘on’ a machine which operates routinely for scientists – rather, the machine itself is the experiment. This demands a very high degree of coordination in planning, executing and analysing experiments by researchers from all the participating laboratories, as well as the machine operators.

European fusion researchers have been able to exploit JET efficiently because they have been working for a long time in a coordinated and integrated R&D programme. The experience gained and the management tools developed for the operation of JET demonstrate how the worldwide co-operation and collaboration needed for the operation of ITER can be organised.

The Cadarache site

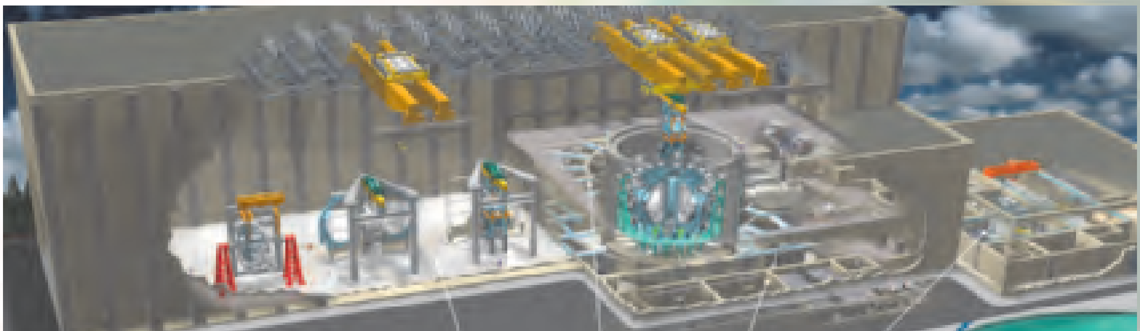
The ITER reactor will be built at the European site at Cadarache (near Aix-en-Provence) in southern France. This site is already a large-scale energy research centre for the French Atomic Energy Commission (CEA), housing 18 experimental nuclear installations including the Tore Supra superconducting tokamak.

The Cadarache site covers a total surface area of about 40 hectares with another 30 hectares available temporarily for use during building. Key requirements for the location include thermal cooling capacity of around 450 megawatts and an electrical power supply of up to 120 megawatts.

The region around Cadarache offers most of the social and technical infrastructures required for ITER and fulfils all the project requirements (technical - installation, seismic appraisal, water supply, electric power supply; safety and statutory licensing; socio-economic aspects; cost estimates).

Major components for ITER will be transported to the nearest sea port (Marseilles, the second largest city in France) which is located approximately 70 kilometres from Cadarache. The area has an associated social, cultural, industrial and academic infrastructure, an agreable, climate and pleasant natural environment.

Construction is ready to start at Cadarache and, if all goes to plan, the first ITER plasma will light up in 2016.



THE EU “DOMESTIC AGENCY”

The seven parties involved in ITER are to establish “Domestic Agencies” through which they will provide their contributions to the ITER organisation. The “European Joint Undertaking for ITER & the Development of Fusion Energy” (or *Fusion for Energy* for short) is the Domestic Agency created by the European Union for this purpose. It was established in April 2007 for 35 years.

Based in Barcelona, *Fusion for Energy* has a total budget of 4 billion euros over ten years. It will work with European industry and research organisations to develop and manufacture the components that Europe has agreed to provide to ITER – around 50% of the total.

Fusion for Energy aims to pool resources at European level. To this end, it will receive contributions from its members – EURATOM, the EU Member States and Associated countries (presently Switzerland).
Its organisation and internal rules will be adapted to its challenging tasks, particularly the procurement of high tech components from industry.

In the framework of the international agreement with Japan signed in February 2007, known as the “Broader Approach”, *Fusion for Energy* will also support projects to accelerate the development of commercial fusion power. These projects include the design of a fusion materials test facility (IFMIF), the superconducting upgrade of a Japanese tokamak (JT-60U) and the launch of an International Fusion Energy Research Centre. Their funding relies on the voluntary contributions from some Member states and Switzerland, mostly “in kind”. In the longer term, it should also implement a programme of activities to prepare for the first demonstration fusion reactor.

From an organisational point of view, a Governing Board will ensure overall supervision of *Fusion for Energy’s* activities. This Board will be composed of representatives from each of its members.

Human resources will be one of the most important assets for the success of *Fusion for Energy.* In particular, the organisation is recruiting top notch engineers and technicians to interact with industries, fusion laboratories and other organisations in order to ensure the effective delivery of Europe’s international commitments.

INDUSTRIAL CONTRIBUTION

Clearly, achieving the goal of fusion power involves exciting and stimulating technological challenges. Existing technologies have been pushed to their limits and new technologies have been (and will be) developed. Industry has been a fundamental partner with academic research in achieving success in this area and has benefited in many ways.

Technology forward

One feature of the European fusion research programme is the knowledge transfer between the programme, industry and the wider scientific community. The ITER project adds an exciting new challenge, promising a wealth of additional opportunities for the industries involved. Large companies, many of whom may already have experience on the international stage, will be involved in ITER. Small and medium-sized enterprises (SMEs) will also be involved either directly, or indirectly as subcontractors, giving them the opportunity to demonstrate their expertise and widen their experience. Many companies around the world have already made significant contributions to the development of key ITER prototype components, such as the magnetic system.

This technology transfer process leads to many spin-off technologies, the formation of new companies and, in some cases, to whole new industrial sectors. Examples include high-heat flux components, superconducting magnets for imaging systems (MRI) – currently revolutionising medicine – high-power microwaves for industry, plasma physics software and diagnostics adapted for use in semiconductor and thin-film fabrication, new high-technology cloth-weaving machines, and carbon-composites for use in brakes and vehicle clutches. Moreover, the very demanding technical specifications imposed by fusion requirements have induced the industrial partners to improve fabrication processes and quality assurance. This is an important aspect of technology transfer even in cases of collaboration not necessarily leading to new products.

The fusion experimental devices and auxiliary facilities in the Euratom fusion research programme have been constructed almost exclusively by European industry. This has involved a high standard of engineering and frequently the development of subsystems and components at the cutting-edge of existing technologies.
The JET project is a classic example of industrial involvement. Up to the end of the JET Joint Undertaking in 1999, the total value of high-technology contracts for its construction and operation was € 540 million. Hundreds of companies were involved in projects covering the whole range of systems, including the plasma vessel, pumping and fuelling systems, cryogenic equipment, magnetic field systems, the mechanical structure, power systems, control and data acquisition, remote handling, diagnostics and additional heating systems.

This partnership with industry will increase as ITER takes shape, offering further opportunities and challenges.

AFTER ITER – THE ROAD TO POWER

The successful construction and operation of ITER will be a significant step towards sustainable energy production from fusion. The information, technology and experience that it will provide will be crucial to the development of a demonstration power plant (DEMO).

DEMO will generate significant amounts of electricity over extended periods and would be tritium self-sufficient.

Many of the components proven in ITER will be used in DEMO and, in parallel, advanced fusion materials research will contribute to the materials technology solutions needed for DEMO and the first commercial fusion power plants.

Advanced low-activation materials, which are resistant to the effects of high neutron fluxes, high surface heat loads and thermal cycling, will be required to ensure any structural waste from a fusion power plant will not be a long-term burden to future generations. These materials are being developed within the long-term fusion R&D programme. To assess the potential ‘life expectancy’ and accelerate testing of these materials it will be necessary to construct a test facility that can provide a similar neutron environment to that of a future fusion reactor. The realisation for such a facility called the International Fusion Materials Irradiation Facility (IFMIF) is being pursued through the co-operative agreement between Japan and the EU, the ‘Broader Approach’.

DEMO and beyond

ITER is planned to operate at a nominal fusion thermal power of 500 megawatts. Assuming that DEMO will be approximately of a similar physical size to ITER, its fusion thermal power level must be greater by about a factor of three in order to deliver (at current levels of turbine efficiencies) electrical power to the grid in the range of 500 megawatts electron. This increase demands a general level of heat flux through the reactor walls about three times higher than in ITER, and a consequent improvement in plasma performance. Scientists believe that this performance could be achieved with a 15% rise in ITER linear dimensions, and a 30% increase in the plasma density above those nominally expected in ITER.

A major challenge will be the performance and durability of breeder blanket technology and systems for refuelling/ replacement of modules during continuous operation.

If DEMO is successful in terms of systems and performance, the reactor itself can be used as a commercial prototype creating the so-called ‘fast track’ to fusion. This could bring forward the availability of fusion as a truly sustainable energy option by about 20 years.

This final step on the road to fusion power would be the construction of a first-of-a-series commercial-sized fusion power reactor. In order to double the electrical power of DEMO and achieve a 1 000 megawatt power station, the linear machine dimensions of DEMO would need to be increased by a modest amount.

Fusion power reactor economics

The economic viability for fusion power has been a subject of research in parallel to scientific activities and uses results from it.

Assuming plant capital cost scales with the tokamak volume, DEMO capital costs are expected to be of the order of €7 billion or €14 per watt (euro per watt electrical output) based on the cost estimates for ITER at current values. The cost of full-size prototype fusion power plant would typically be €8/W_e and, with the subsequent economies of series production of fusion plants, capital costs could fall to about €4 per watt. This should be compared to today’s fission and coal plants at about €3 per watt and €1.5 per watt respectively. However, the capital costs of today’s coal plants do not include the expense of mitigating environmental damage (the so-called externalities), nor do any of the above costs include the fuel, operating and decommissioning costs which, for coal, are typically comparable to the capital costs and should be lowest for fusion.

The story continues ...

The last 50 years of fusion research and development have continually thrown up new challenges to test the enthusiasm and skills of two generations of scientists and engineers. The story so far has been one of continuous progress as technology develops and our scientific knowledge grows.

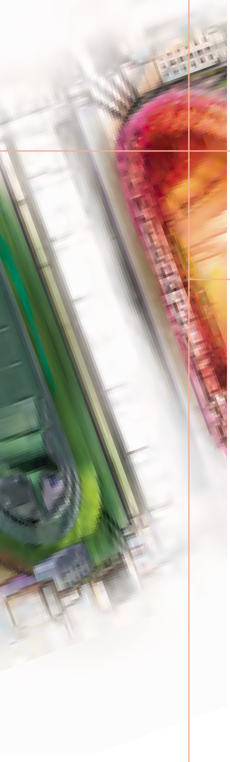
The development of fusion power has many unique aspects as a human activity. It has a very specific goal which will take a significant time to reach – beyond the normal economic perspective for commercial development. It demands continuity in investigation and transmission of knowledge between generations of physicists and engineers, requiring not only continuous levels of funding for the main research activities, but also funding to attract and train newcomers to the field in supporting experiments. However, energy is such a basic human need that in these circumstances it is government’s responsibility to make this long-term option available to society.

Fusion is the classic example of open research conducted on a global basis and able to bring scientists and engineers together from many different disciplines, backgrounds and political allegiances to share their knowledge freely.

ITER and its associated activities is the next step in this story.

In 1972, Lev Artsimovitch, the leader of the Soviet tokamak programme was asked: “When will fusion be ready?” His answer was: “Fusion will be there when society needs it.”

Looking at current energy trends and the proposed trajectory for fusion research and development it would appear that his prediction will be correct. ITER is the next step in fulfilling this promise.



FURTHER INFORMATION

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A glossary of fusion terms: http://www.fusion.org.uk/info/glossary/glossmain.htm

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ITER - Uniting science today global energy tomorrow

Luxembourg: Office for Official Publications of the European Communities

2007 -24 pp - 21.0 x 29.7 cm

ISBN 978-92-79-05548-5

KI-77-07-297-EN-C

Fusion has the potential to provide humanity with a sustainable, large-scale source of power relying on an almost limitless fuel supply. Attaining this goal has been the focus of intense scientific and technological efforts around the globe for several decades. The ITER Agreement brings together more than half the world's population to co-operate in the development on this major technology. The EU is to host one of the largest scientific undertakings ever conceived and one that could have a profound impact on how future generations live. The European Joint Undertaking for ITER has a major role in procuring the components that Europe is committed providing to the project. This brochure presents the essentials of fusion science. It explores the world of European research that has brought us to ITER and it explains the 'what, why and how' of the device itself. ITER will be a tremendous scientific adventure exploring and pushing back the frontiers of our knowledge, promoting international collaboration with the goal of safe, environmentally responsible and abundant energy for the world.

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ISBN 92-79-01532-X
9 789279 015328