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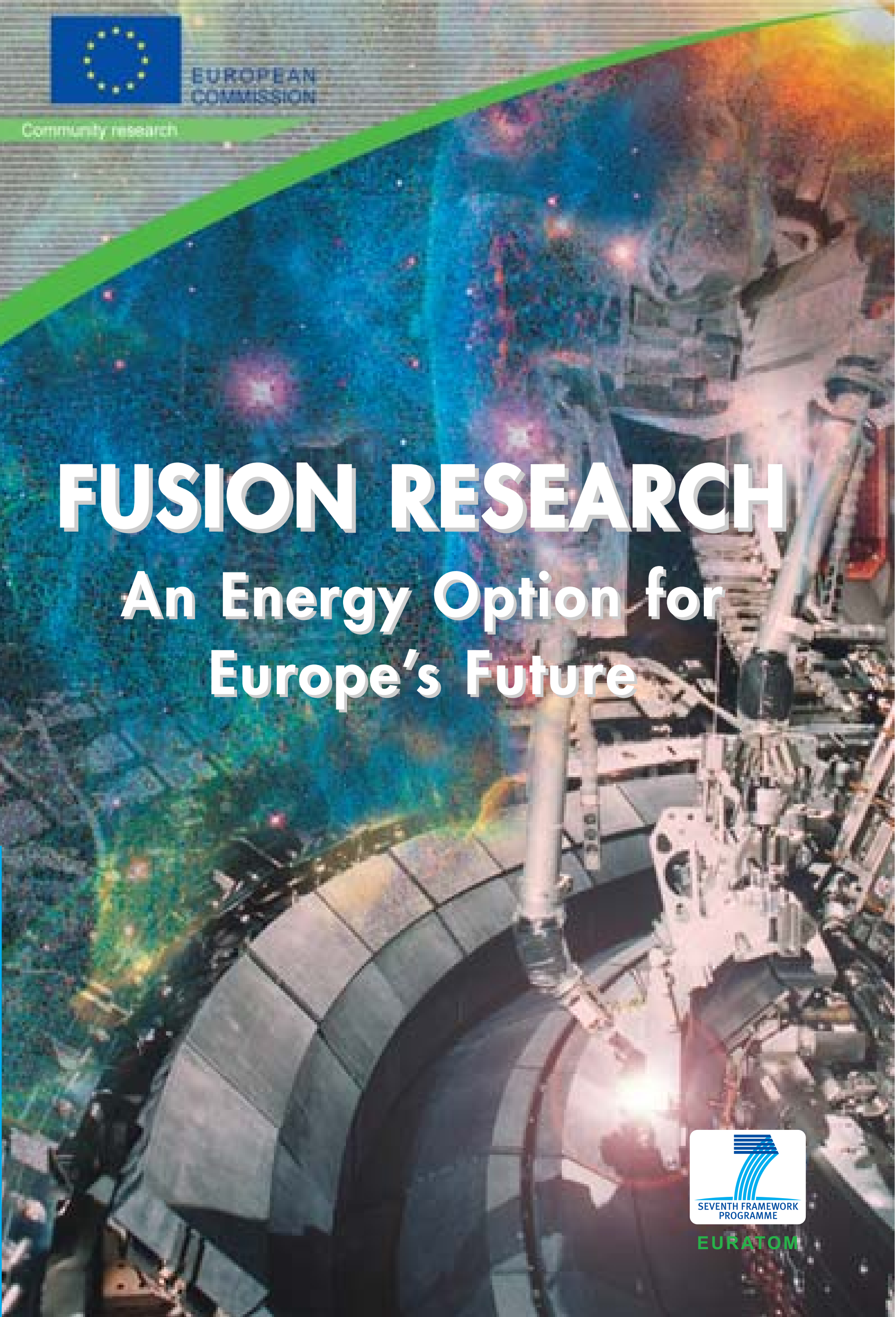

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An Energy Option for Europe's Future

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Directorate-General for Research
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Directorate-General for Research
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2007

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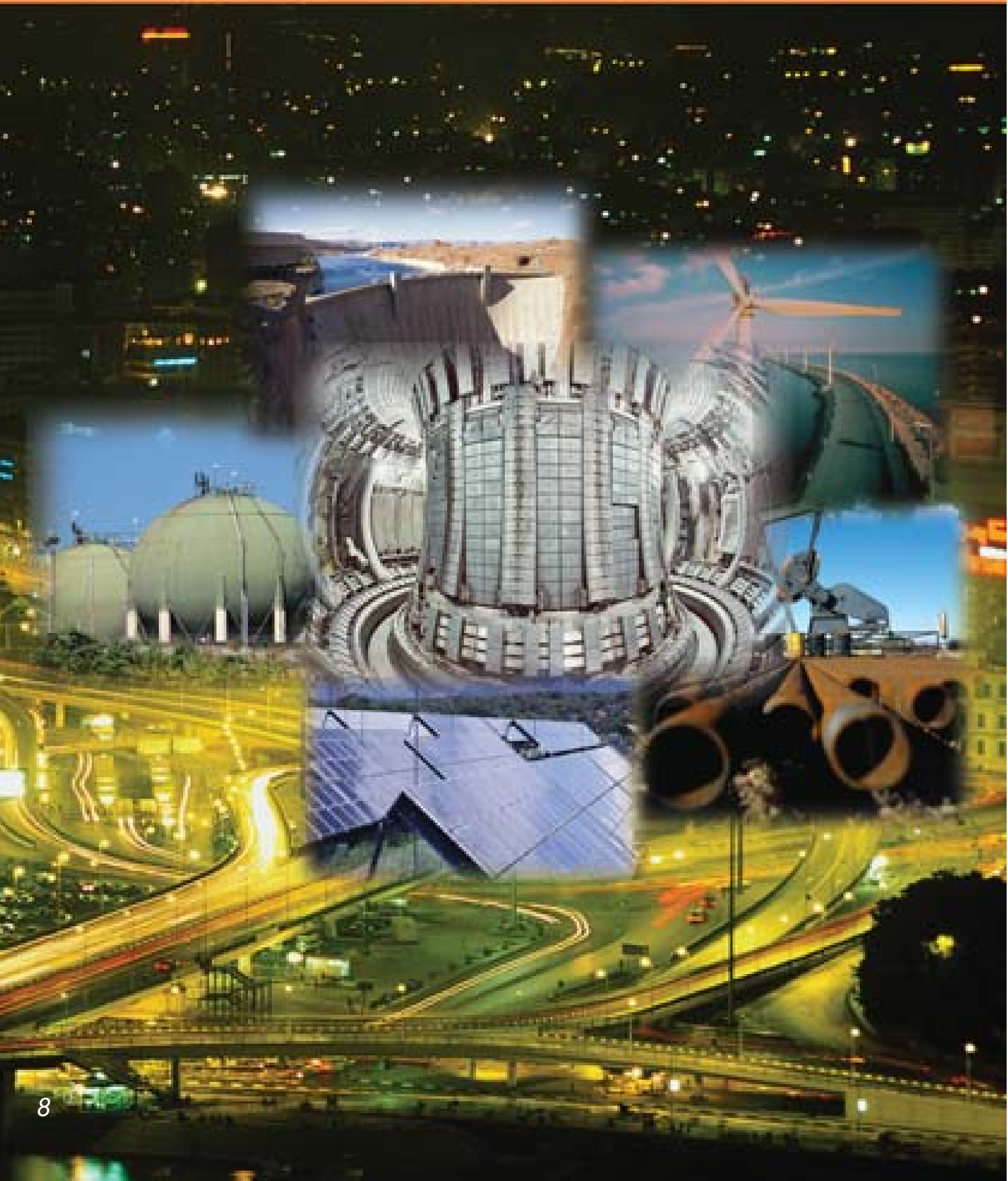
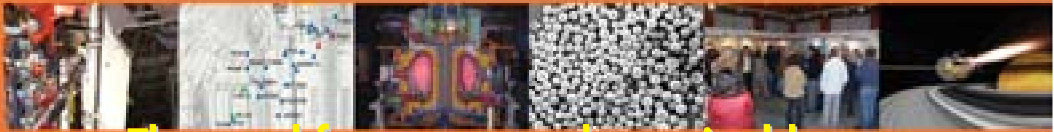




The need for secure and sustainable energy

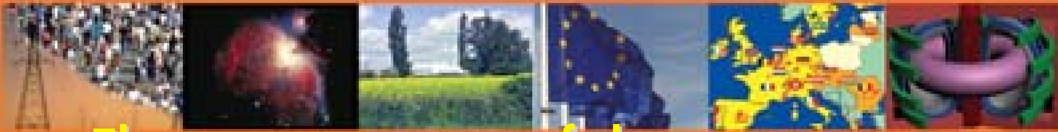
The European Union (EU) economy depends on a secure and sufficient supply of energy. Today this demand is mainly satisfied by fossil fuels (oil, coal and natural gas), which account for 80% of the total energy consumption. Almost 67% of the fossil fuels we use are imported. Overall, imported fossil fuels currently provide about 50% of the EU's energy needs, and by 2030 this is expected to increase to about 70%, in particular from oil.

Secure and sustainable energy sources are required to maintain our standard of living. European researchers are developing a range of environmentally acceptable, safe and sustainable energy technologies. Fusion is one of them.

For the long term, fusion will provide an option for a large scale energy source that has a low impact on the environment and is safe, with vast and widely distributed fuel reserves.

Fusion power stations will be particularly suited for base load energy generation to serve the needs of densely populated areas and industrial zones. They can also produce hydrogen for a "hydrogen economy".

This booklet describes the work being carried out by European researchers to realise the objective of making fusion energy available for the benefit of society.

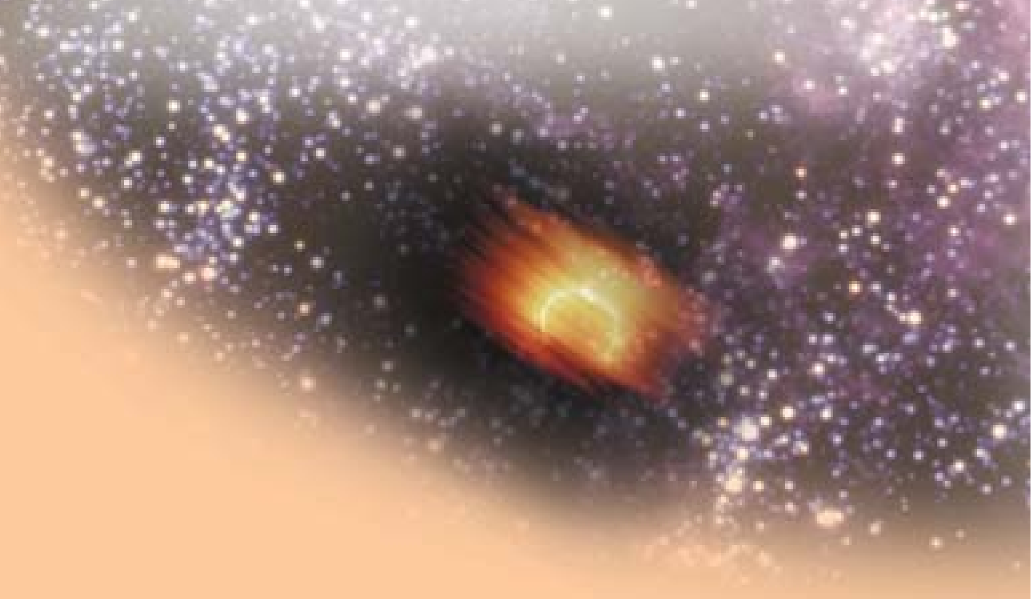


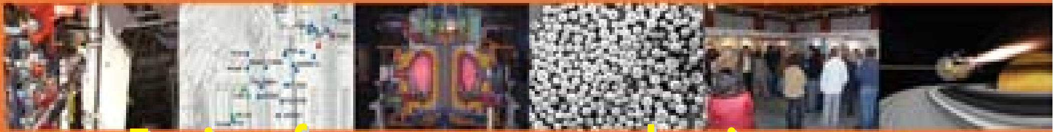
The energy source of the stars

Fusion is the process which powers the sun and other stars. Nuclei of low mass atoms “fuse” together and release energy. In the core of the sun, the huge gravitational pressure allows this to happen at temperatures of around 10 million degrees Celsius.

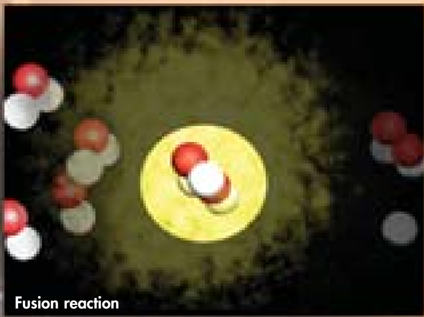
Gas raised to these temperatures becomes a “plasma”, where the electrons are completely separated from the atomic nuclei (ions). Plasma is the fourth state of matter with its own special properties. The study of these properties is the focus of plasma physics research. Although the plasma state is exotic on Earth, more than 99% of the universe is made up of plasma.

At the much lower pressures (10 billion times less than in the sun) that we can produce on earth, temperatures above 100 million degrees Celsius are required for fusion energy production rates of interest. To reach these temperatures powerful heating of the plasma is required and the thermal losses must be minimised by keeping the hot plasma away from the walls of its container. This is achieved by placing the plasma in a toroidal “cage”, made by strong magnetic fields, which prevent the electrically charged plasma particles from escaping: it is the most advanced technology and forms the basis for the European fusion programme and the international fusion experiment ITER.



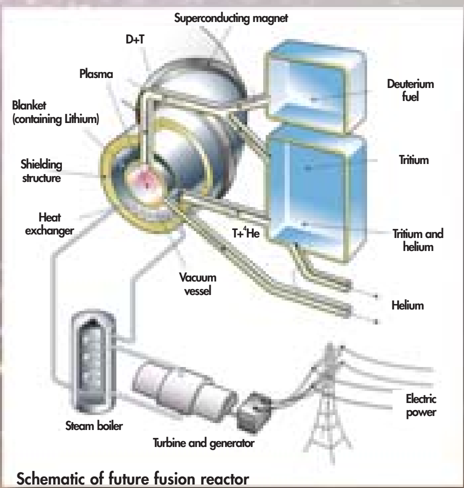


Fusion for energy production


Fusion reaction

$$D+T \longrightarrow {}^{4}He+n+17{,}6\ MeV$$

The fusion reactions between two isotopes of hydrogen – deuterium (D) and tritium (T) – provide the basis for the development of a first generation fusion reactor, as other fusion reactions require even higher temperatures. Deuterium is a naturally occurring, non-radioactive isotope and can be extracted from water (on average 35 g in every cubic metre of water). There is no tritium on Earth, but it will be produced from lithium (a light and abundant metal) inside the fusion reactor. Each fusion reaction produces an alpha particle (i.e. helium) and a high energy neutron.



Schematic of future fusion reactor

The neutrons escape from the plasma and are slowed down in a "blanket" surrounding the plasma. Within this blanket lithium is transformed into tritium, which is recycled back into the vacuum chamber as fuel, and the heat generated by the neutrons can be used to produce steam which drives turbines for electricity generation.
To supply a city with a population of about one million with electricity for one year, a fusion power plant would require one small truck-load of fuel.

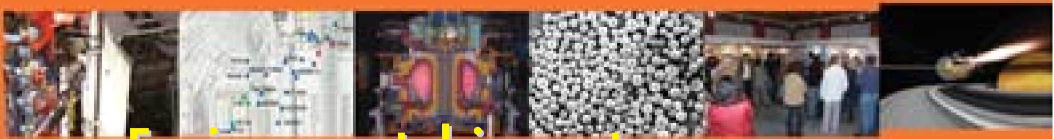
Safety

Tritium Handling Facility

A fusion reactor is like a gas burner: the fuel which is injected in the system is burnt. There is very little fuel in the reaction chamber (about 1 g of D-T in a volume of 1,000 m^3) at any moment and, if the fuel supply is interrupted, the fusion reactions last for only a few seconds. Any malfunction of the device would cause the plasma to cool and the reactions to stop.

The basic fusion fuels, deuterium and lithium, as well as the reaction product, helium, are non-radioactive. The radioactive intermediate fuel, tritium, decays reasonably quickly (it has a half-life of 12.6 years) and the decay produces an electron (beta radiation) of very low energy.
In air, this electron can travel only a few millimetres and cannot even penetrate a sheet of paper. Nevertheless, tritium is harmful if it would enter the body and so safety features to cope with tritium are designed and implemented in the facility.

Because tritium is produced as it is needed to maintain the fusion process in the reactor chamber, there is no need for the regular transport of radioactive fuel to a fusion power plant.



Environmental impact

The energy generated by the fusion reactions will be used in the same way as today, e.g. for the generation of electricity, as heat for industrial use, or possibly for the production of hydrogen.

The fuel consumption of a fusion power station will be extremely low. A 1 GW (electric) fusion plant will need about 100 kg deuterium and 3 tons of natural lithium to operate for a whole year, generating about 7 billion kWh. A coal fired power plant – without carbon sequestration – requires about 1.5 million tons of fuel to generate the same energy!

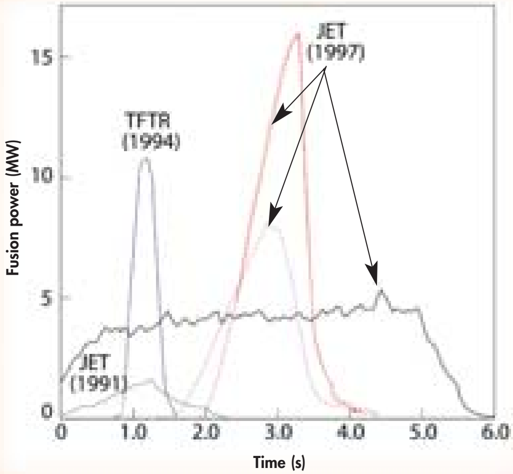
Fusion reactors do not produce greenhouse gases and other pollutants which can harm the environment and/or cause climate change.

The neutrons generated by the fusion reaction activate the materials around the plasma. A careful choice of the materials for these components will allow them to be released from regulatory control (and possibly recycled) about 100 years after the power plant stops operating. For these reasons, waste from fusion plants will not be a burden for future generations.

European Tokamak Facility JET (Culham-UK)

Advances in magnetic fusion research

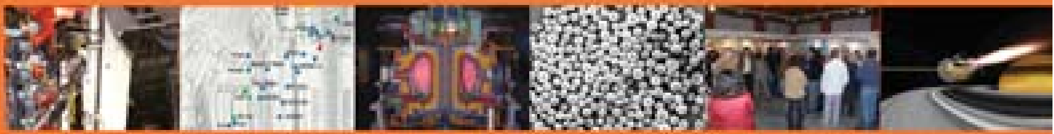
The European tokamak JET (Joint European Torus) located at Culham (UK) is the world's largest fusion facility and the only one currently capable of working with a D-T fuel mixture. JET has reached all its originally planned objectives, and in some cases surpassed them. In 1997 it achieved a world record fusion power production of 16 MW.



Fusion power achievements

All the laboratories participating in the European fusion programme and in the development of the science and technology for ITER share expertise and technical facilities: the Tore Supra tokamak in France – the first large tokamak to use superconducting magnets; the ASDEX device in Germany – with ITER-shaped plasmas; spherical tokamaks in the UK; and other magnetic confinement configurations including the reversed pinch device RFX in Italy and the stellarators TJ-II in Spain, and W7-X under construction in Germany.

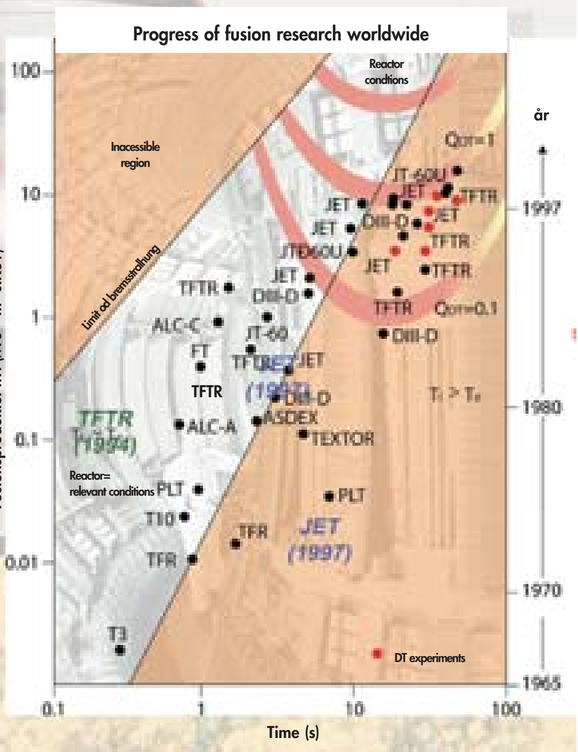
Tore Supra (Cadarache, F) high-performance plasma discharge of record duration



A simple measure fusion machines performance the figure of merit Q, the ratio of the fusion power produced divided by the heating power applied to the plasma. A fusion plasma reaches the condition of self-sustained "burn" (Q = ∞) when the energy being lost from the plasma is balanced by plasma self-heating due to fusion reactions. When this condition is reached, external heating is no longer required to maintain the high temperature conditions for fusion. Just like a fire, the plasma will continue to "burn", as long as it is fed with fuel. In future fusion reactors it will not be necessary to reach this condition while it will be sufficient to design power amplifiers.

JET has generated 16 MW of fusion power at Q = 0.65. The next machine, ITER, aims at Q = 10, while future fusion reactors may have Q values up to 40 or 50.

Since most current fusion devices do not use tritium fuel, their performance is characterised by the combination of plasma parameters which show how closely they approach fusion relevant conditions. The figure shows measured values of Q plotted against the plasma temperature, for a large number of tokamaks world-wide. The highest performance machines have achieved plasma parameters which are approaching those needed for a reactor.



ITER and the European strategy for fusion

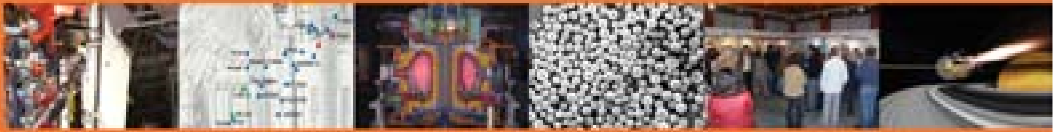
The long-term objective of fusion R&D in the Member States of the European Union plus Switzerland is "the creation of prototype reactors for power stations which are safe, sustainable, environmentally responsible, and economically viable".

The world and European strategy to achieve this long-term objective requires the development of the experimental reactor ITER which is pursued in the international collaboration. ITER is the world's biggest energy research project. Its overall programmatic objective is to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes.

ITER will be followed by a demonstration reactor ("DEMO"), which, for the first time, would be able to generate significant amounts of electricity and would be tritium self-sufficient. In parallel, durable and low activation materials will have to be tested and qualified in a International Fusion Irradiation Material Irradiation Facility (IFMIF) presently at the design stage.

Significant involvement of European industry, accompanied by physics and technology R&D activities in the fusion laboratories and universities will be needed towards the commercial exploitation of fusion power.

Schematic of ITER

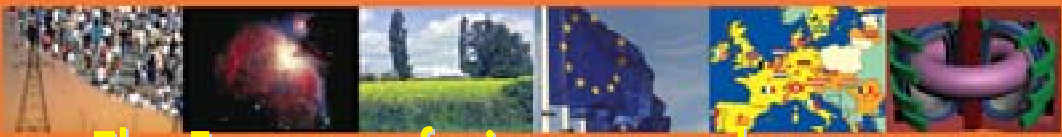


ITER is a joint international project hosted by Europe (in Cadarache, France) with partners, India, Japan, the People's Republic of China, the Russian Federation, the Republic of Korea and the United States of America. Negotiations taking place among the partners since 2001 on the joint implementation of the ITER have successfully ended in Paris in November 2006 with the signature of the ITER international agreement. This agreement, entered into force in October 2007, covers aspects like the establishment of the international organisation, the membership, the governance and the intellectual property rights.

The participation with international partners in the design of the ITER device has been an important element of the European fusion research programme in the recent years. The basic outline of this design follows that of the European JET. The extrapolation to ITER is undertaken by extensive modelling using the comprehensive experimental data base from European and international fusion experiments. The EU fusion laboratories and industry will play an important role in ensuring the success of ITER.

Artist impression of the European site for ITER at Cadarache - F

The EU contribution to ITER will be channelled through the EU Joint Undertaking for ITER and the Development of Fusion Energy established in April 2007 for 35 years in Barcelona (Spain). With a total budget of 4 billion euros over ten years the EU "domestic agency" 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.

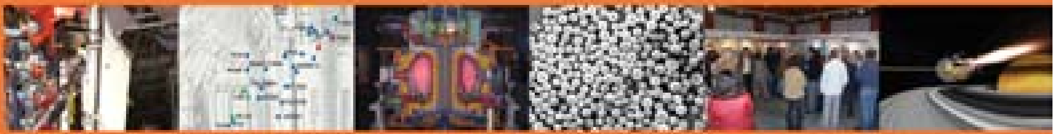


The European fusion research area

A key feature of the European fusion programme is its unique co-ordination which provides for an intensive use of all relevant R&D resources in pan-European collaborations on all the major research topics. Particularly important is the collaboration in the exploitation of JET and in the physics and emerging technology programme within the new European Fusion Development Agreement (EFDA), oriented to ITER, in complement to the EU Joint Undertaking which will provide the European contributions to ITER, but also including research for DEMO.

This single, co-ordinated fusion programme, with large and small laboratories working towards a common objective, is an example of a European Research Area and has brought Europe to the forefront of international magnetic confinement fusion research. Achievements in Europe's associated fusion laboratories have enabled the construction of JET and progress towards ITER, which none of the Member States or Associated States would have been able to achieve alone.

Besides the major international venture on ITER collaborations with non-European partners to pool the best world expertise on specific topics of common interest are also pursued with a number of bilateral and multilateral agreements between European and non-European laboratories.



Based on the Euratom treaty, the fusion research and development programme in Europe is co-ordinated by the European Commission and implemented through:

• Contracts of Association with research institutes or organisations in the Member States and countries associated to the Euratom Framework Programme (the laboratories of the Euratom Associations are represented on the map by red dots).

• The new EFDA agreement which, in complement with the EU "domestic agency" for ITER provides:
  - Co-ordinated activities in physics and emerging technology;
  - The collective use of the JET facilities;
  - Training and career development of researchers, promoting links to universities and carrying out support actions for the benefit of the thematic area of research "fusion energy";
  - The European contributions to international collaborations that are outside of the scope of the EU "domestic agency" for ITER.

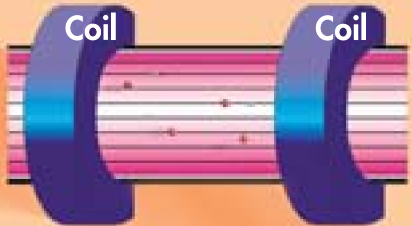
• Contracts of limited duration in countries which do not have a fusion "Association".

• An agreement for the promotion of mobility of researchers, and Euratom Fellowships maintain and further develop the knowledge base in fusion for scientists and engineers.

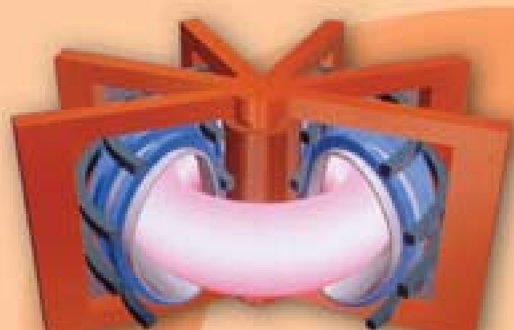
In the 7th EU Framework Programme (2007 to 2013) Fusion Energy Research is a Priority Thematic Area with a Community budget of €1947 million.
Behind the success of European fusion research stands the work of about 2,000 physicists and engineers in European laboratories and in European industry.

Magnetic confinement fusion

Magnetic confinement fusion makes use of strong magnetic fields to confine the plasma in a “vacuum vessel” which isolates the plasma from air. In an idealised situation electrically charged ions and electrons which make up the plasma cannot cross the magnetic field lines. They can however move freely along the magnetic field linesic cage.

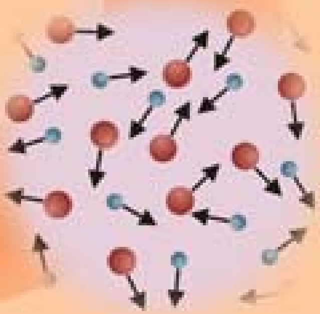


Plasma with magnetic field

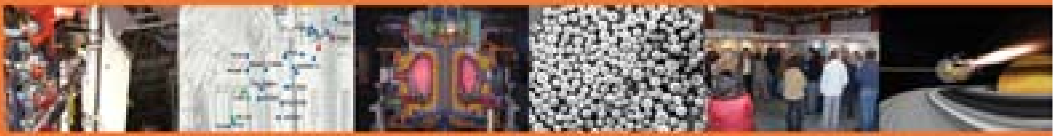


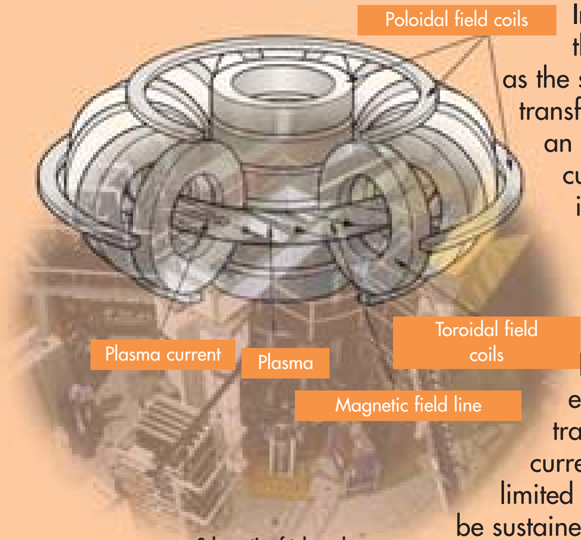
Magnetic confinement

By bending the field lines around to form a closed loop, the plasma particles are, in principle, confined. Particles and their energy are kept well isolated from the wall of the burn chamber, thus maintaining the high temperature. In fact, in a real toroidal magnetic system there are losses of energy through various processes, such as radiation, and by particle collisions which cause particles to escape from the plasma across the magnetic field lines as time goes by.



The magnetic fields are generated by large electrical currents flowing in coils located outside the reactor chamber. Frequently, currents generated in the plasma also contribute to the magnetic cage.



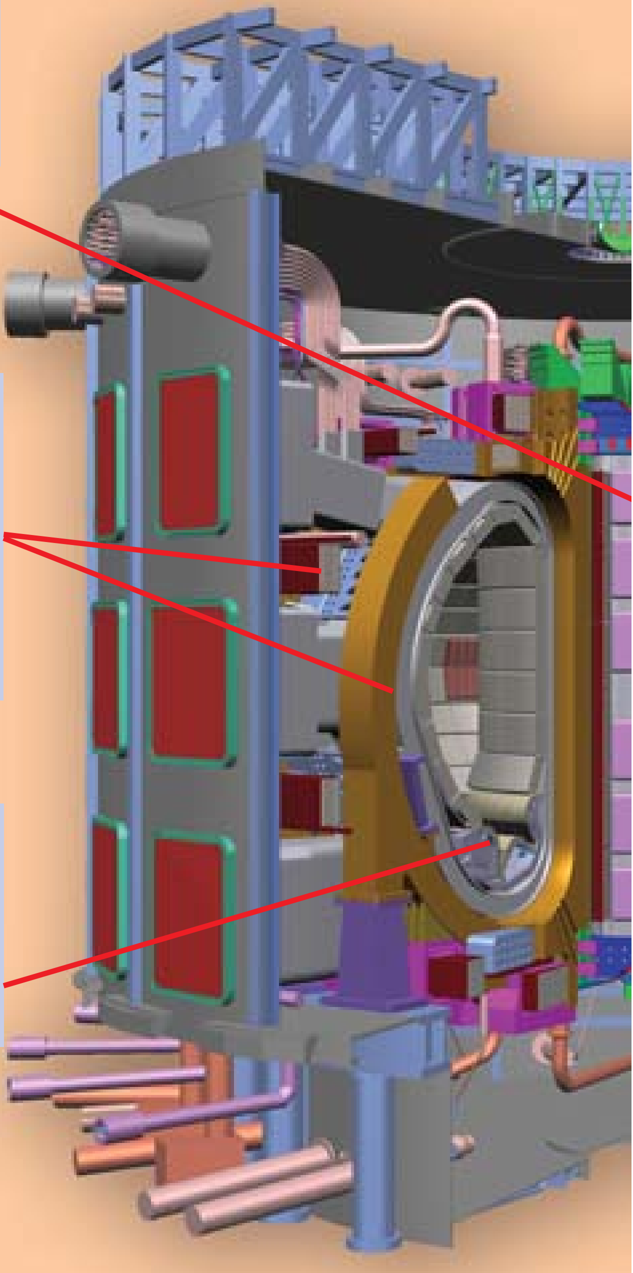


Schematic of tokamak

In the type of machine called the "tokamak", the plasma acts as the secondary winding of a transformer (the primary winding is an external coil) and a change of current in the primary winding induces a current in the plasma. As well as generating a magnetic field which plays a role in confining the plasma, this current also provides some heating, because of the plasma's electrical resistance. Since a transformer cannot generate a current continuously, the plasma has limited duration and steady state must be sustained by other means.

The type of machine called the "stellarator" uses the same principle of magnetic confinement, but with external coils of a complex shape and does not rely on a transformer effect to create a current in the plasma. Stellarators have therefore an inherent potential for continuous operation. The largest new facility currently being constructed is the stellarator W 7-X in Greifswald (D). Other magnetic configurations closely related to the above are the compact (or spherical) tokamak and the reversed field pinch.

Main tokamak components



Central solenoid

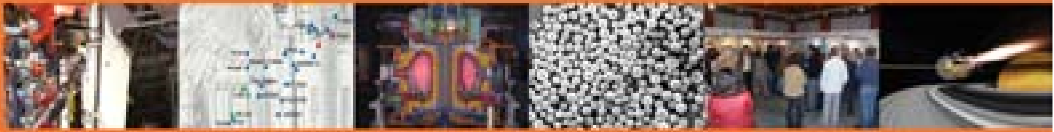
The primary circuit of the transformer. The plasma forms the secondary circuit.

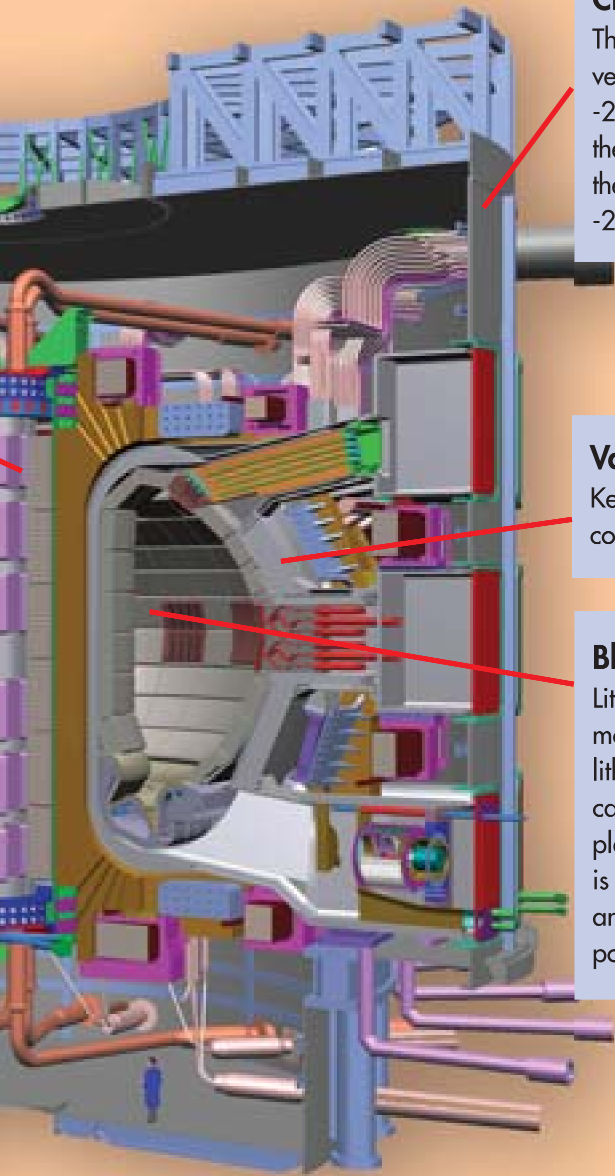
Toroidals and poloidal field coils

These generate the strong magnetic field (typically about 5 tesla, which is about 100,000 times the earth's magnetic field) that confines the plasma and stops it touching the walls of the vacuum vessel.

Divertor

Removes the impurities and He from the vacuum vessel and is the only area were the plasma is deliberately allowed to touch the walls.





Cryostat
This encloses the coils and the vacuum vessel and is cooled to about -200 degrees Celsius to help keep the superconducting magnets at their operating temperature of -269 degrees Celsius.

Vacuum vessel
Keeps air from penetrating the containment region of the plasma.

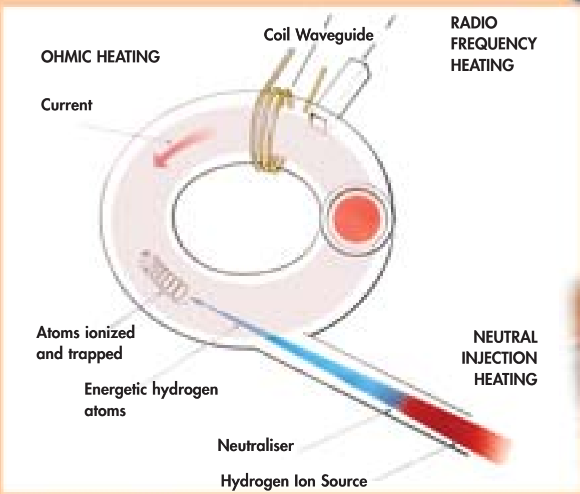
Blanket
Lithium is contained in the blanket modules. When neutrons react with lithium, tritium is produced which can be separated and fed into the plasma. The energy of the neutrons is removed to heat a water circuit and produce steam which will power the electrical generators.

Heating the plasma

The current flowing in a tokamak plasma contributes to its heating. As the plasma temperature increases, this ohmic heating becomes less effective and brings the plasma only to temperatures of a few millions of degrees, i.e. about 10 times too low for the fusion reactions to occur in large numbers. To go higher, further heating is supplied through external sources.

High-frequency heating uses high-power electromagnetic waves of different frequencies which transfer their energy to the plasma through resonant absorption.

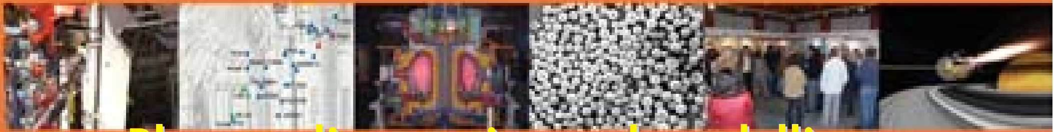
Three of these systems are being developed: Ion Cyclotron Resonance Heating (20 MHz to 55 MHz), Electron Cyclotron Resonance Heating (100-200 GHz, basically microwaves), and Lower Hybrid Heating (1-8 GHz).



Radio frequency antenna at Tore Supra (CEA, Cadarache - F)

Beams of energetic neutral particles are injected into the plasma, penetrate it, and transfer their kinetic energy to the plasma through collisions with the plasma particles.

JET Neutral Beam system

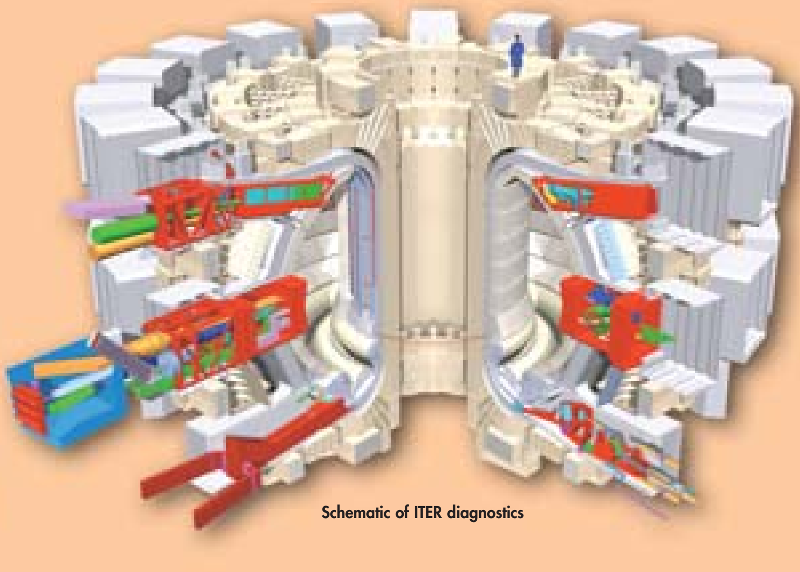


Plasma diagnostics and modelling

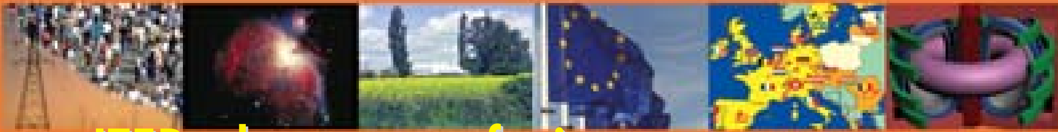
To understand how to design a fusion reactor it is necessary to understand the processes that are happening in the plasma. This requires sophisticated and complex measurement systems, which are referred to as diagnostics.

Diagnostics are being developed in European laboratories to monitor every aspect of the plasma from the temperature at the centre of the plasma, using very powerful lasers, to the amount of impurities in the plasma and where they are produced.

The data obtained from these diagnostics are used in the development of new computer codes that will ultimately be able to predict the performance of the device and ensure that the device is operating as expected.



Schematic of ITER diagnostics



ITER, the way to fusion energy

ITER is the world's biggest energy research project and the essential next step in the world and European strategy for the development of the fusion power. It is a joint international project hosted by Europe (in Cadarache, France) with partners: China, India, Japan, Russia, South Korea, USA. Its aim is to demonstrate the scientific and technological feasibility of fusion power.

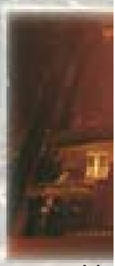
The ITER project is based on a successful international collaboration through a wide variety of technology R&D projects. ITER is based on the scientific achievements of many machines around the world.

ITER will have dimensions comparable to a power station and will be capable of generating 500 MW of fusion power for a duration of 6 minutes, to be extended later towards steady state. ITER will aim at demonstrating the controlled burn of deuterium-tritium plasmas, with steady state as an ultimate goal, and the technologies essential for a reactor in an integrated system.

ITER divertor full scale prototype

The capital cost of ITER amounts to about €5 billion. As host of the project, the EU will play a special and leading role in the ITER project and pay about the half of the total cost. The construction and licensing of ITER will require about 10 years and the device will then operate for a period of about 20 years.

Gyrotron High Frequency Microwave Source



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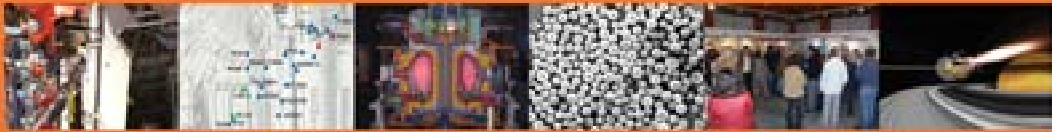
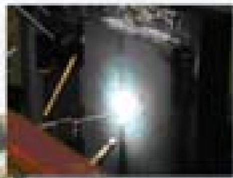




High power laser welding (11 kW) for vacuum vessel sectors

Testing on Toroidal Field model coil

Gyrotron High Frequency microwave source (1 MW)

ITER Divertor remote handling test platform

Blanket test facility

at flux test of protecting armour tiles

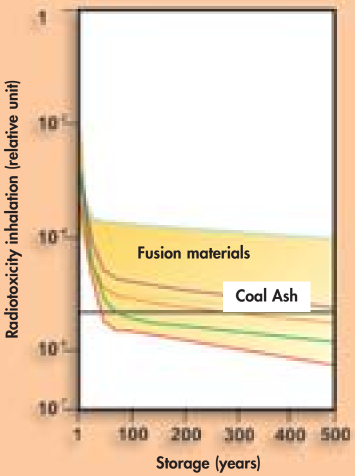
The full scale divertor vertical target mock-up tested at Framatome

Long-term technology activities

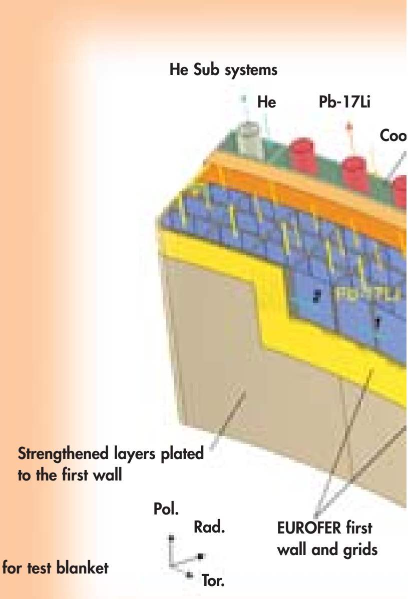
Apart from the work on ITER, there is much fusion technology research and development being carried out for DEMO. European breeding blanket studies concentrate on the use of helium-cooled lithium-lead and on helium-cooled ceramic breeder pebbles. This research is critical for the development of the fusion reactor tritium cycle.

European structural materials development concentrates on reduced activation ferritic and martensitic steels (EUROFER) and, looking further ahead, is investigating silicon carbide composites.

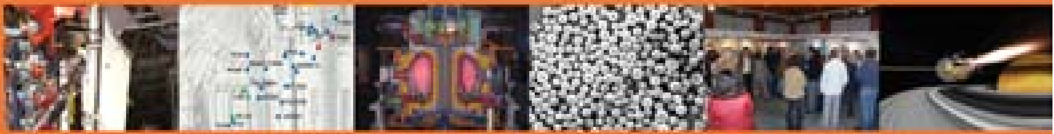
Safety and environmental questions are also tackled. These, mainly focused on improved concepts and the minimization of the activated materials, lead to the important conclusion that a fusion reactor can be designed in such a way that any in-plant accident will not require the evacuation of nearby population. Socio-economic studies analyse economic aspects and long-term scenarios for fusion.

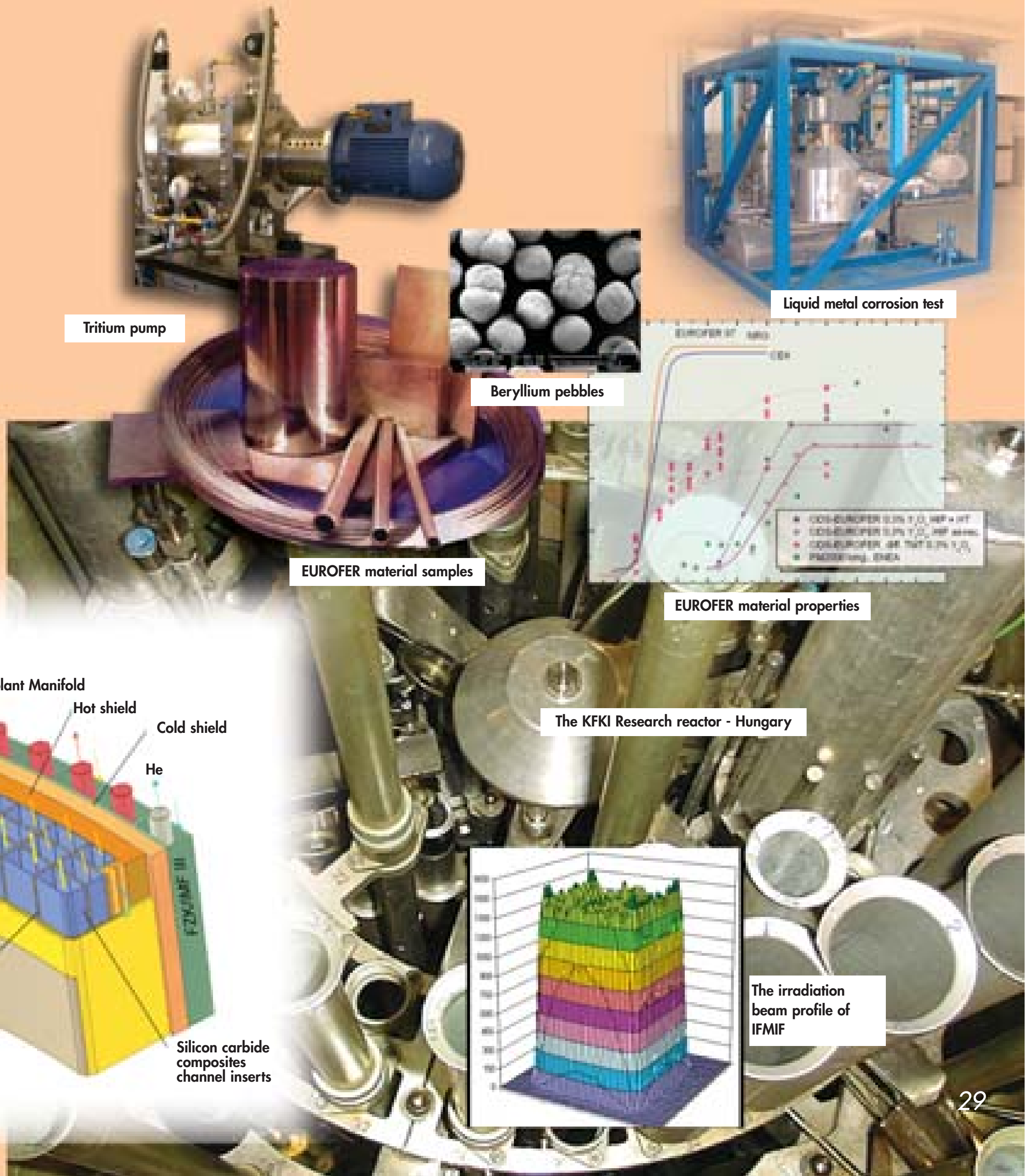


Calculated decay of radiotoxicity from different models of fusion power plants compared with the radiotoxicity of coal ash.

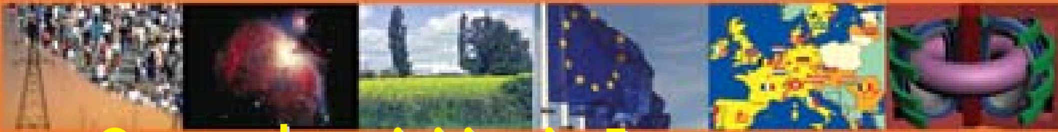


Concept for test blanket





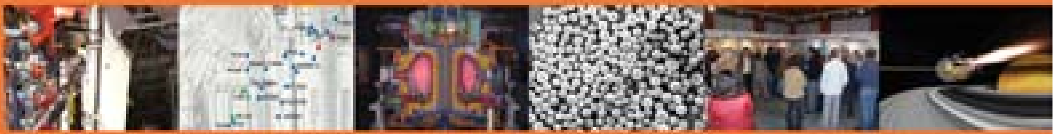
Tritium pump
Liquid metal corrosion test
Beryllium pebbles
EUROFER material samples
EUROFER material properties
lant Manifold
Hot shield
Cold shield
He
The KFKI Research reactor - Hungary
The irradiation beam profile of IFMIF
Silicon carbide composites channel inserts



Outreach activities in Europe

The European Commission undertakes activities to promote of public understanding of fusion within the 7FP. Each Association has activities in its own country, co-ordinated in a network managed by EFDA which also EFDA organises joint actions. The itinerant exhibition Fusion Expo has been created and successfully presented in many European cities to inform the general public and students about the fusion energy research activities in Europe. This exhibition about fusion is currently managed by the Association Euratom-ENEA (Padova). Since its inception more than ten years ago, the expo has typically been visited by 3000-5000 people at each of about 15 presentations per year and has been shown in almost all Member States and a number of other countries.

Fusion Expo at Berlaymont building (Brussels – Belgium) at the occasion of the initialling of the agreement for ITER (May 2006).



The fusion road show at the Berlaymont building (Brussels – Belgium).

The Fusion Road Show, developed by the Association Euratom-FOM (NL), provides a good example of successful outreach activities undertaken by the fusion community. The road show consists of a series of simple experiments to explain the basic principles linked together in an entertaining performance and accompanied by an explanatory presentation.

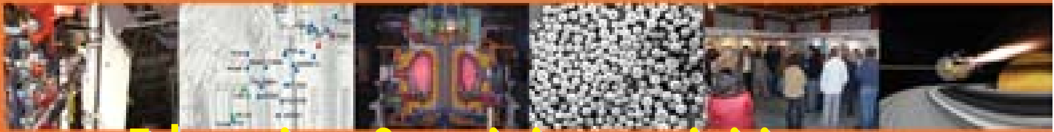
Eiroforum

Through EFDA, the European fusion programme participates in EIROforum, a collaboration between seven European intergovernmental scientific research organisations that are responsible for large infrastructures and laboratories. A primary goal of EIROforum is to play an active and constructive role in promoting the quality and impact of European Research. One specific aim is to co-ordinate the outreach activities of the organisations, including technology transfer and public education.

The seven EIROforum members are:

- **CERN** European Organisation for Nuclear Research (CH),
- **EFDA** European Fusion Development Agreement (GB, D),
- **EMBL** European Molecular Biology Laboratory (D),
- **ESA** European Space Agency (EU),
- **ESO** European Southern Observatory (D, CL),
- **ESRF** European Synchrotron Radiation Facility (F),
- **ILL** Institut Laue-Langevin (F).

Physics on Stage 3 – Teachers in action



Education & training activities in Europe

Education and training of young researchers is an important part of the work of the fusion community. A considerable number of PhD students (currently around 250) perform their research within the fusion laboratories. Several hold summer schools in fusion technology and plasma physics for graduate students and young researchers.

Within FP7 the European Commission has launched training schemes and career development initiatives in all fusion disciplines as well as coordination and support actions in the field of education to give universities and educational institutions better access to fusion infrastructures and careers in fusion energy research.

The main summer schools organised by the Associations are:

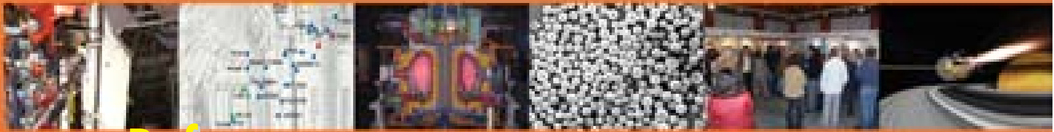
- Carolus Magnus Summer School – The TEC group of Associations (B, D, NL),
- Culham Summer School – Association Euratom-UKAEA (UK),
- Volos Summer School – Association Euratom-Greece (GR),
- IPP CR Summer School – Association Euratom-Institute of Plasma Physics, (CZ).

Fusion R&D spin-offs to other high-technology areas

Industry has been instrumental in helping to build devices and to develop the technologies needed in fusion R&D, and industry has benefited from this relationship by developing expertise and commercial products in various areas outside fusion. These spin-offs include plasma processing techniques, surface treatments, improved lighting, plasma displays, vacuum technology, power electronics and metallurgy.

Ion space motor

Knowledge transfer from fusion also occurs through researchers who move from the fusion research environment to other technology areas, bringing with them the skills they have developed in fusion. This kind of cross-fertilisation and inter-disciplinarity is one of the important forces driving European scientific and technological progress.



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http://www.iter.org
http://www.fusion-eur.org
http://www.eiroforum.org

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European Commission

Fusion Research An Energy Option for Europe's Future (update)

Luxembourg: Office for Official Publications of the European Communities

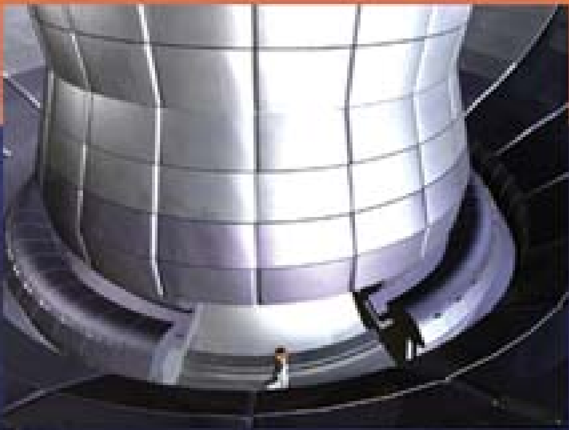
2007 — 37 pp. — format A5, 14.8 X 21.0 cm

ISBN 92-79-00513-8

“Starmakers”, a journey inside ITER

The 8 minute “Starmakers” film describes the ITER tokamak by offering a virtual reality visit to the audience with a visual appreciation of this challenging project. At the Fusion Expos around the world, the movie, when viewed through passive polarised glasses, takes the audience on a spectacular 3D virtual reality journey. The version distributed here is 2D and does not require special glasses.

The movie has been produced by the Centre de Recherches en Physique des Plasmas, Ecole Polytechnique Fédérale de Lausanne (CH) with financial support from the Directorate General for Research of the European Commission. The movie has been created numerically by Digital Studios SA (Paris – F) based on the computer aided design of the ITER device.



ENERGY FILM
FESTIVAL
LAUSANNE 2001

Grand Prix
du Festival

KI-60-04-256-EN-C

In its decision on the Euratom Specific Programme, the Council of Ministers underlines the objective of fusion energy research programme:
'Developing the knowledge base for, and realising ITER as the major step towards, the creation of prototype reactors for power stations which are safe, sustainable, environmentally responsible, and economically viable'.

This booklet describes fusion energy research and how it is co-ordinated and managed in Europe. The next generation fusion experiment, ITER, should pave the way in the second half of the 21st century for fusion to provide a significant contribution to the world's energy production.

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