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port2004@ijs.si
www.drustvo-js.si/port2004
+386 1 588 5247, fax +386 1 561 2276
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The European Fusion Research and Development Programme and the Iter Project

B. J. Green
European Commission
Directorate-General for Research
Rue Montoyer 75, B-1050 Bruxelles, Belgium
Barry.green@cec.eu.int

ABSTRACT

The EURATOM fusion R&D programme is a well integrated and co-ordinated programme – a good example of a European Research Area. Its goal is "the joint creation of prototype reactors for power stations to meet the needs of society: operational safety, environmental compatibility, economic viability". The programme is focussed on the magnetic confinement approach to fusion energy and supports 21 associated laboratories and a range of experimental and fusion technology facilities. The paper will briefly describe this programme and how it is organised and implemented. Its success and that of other national programmes has defined the international ITER Project, which is the next logical step in fusion R&D. The paper will describe ITER, its aims, its design, and the supporting manufacture of prototype components. The European contribution to ITER, as well as the exploitation of the Joint European Torus (JET) and long-term fusion reactor technology R&D are carried out under the European Fusion Development Agreement (EFDA). Finally, the potential advantages of fusion as an energy source will be presented.

1 INTRODUCTION

Fusion research and development (R&D) has been part of the Community research programme since the inception of the EURATOM Treaty (1957). It has also been included in all six Research and Technological Development Framework Programmes.

The basis for the Community's interest in this R&D is that fusion power promises to be an attractive part of a future energy supply mix. The long-term objective of the Community programme is the "joint creation of prototype reactors for power stations to meet the needs of society: operational safety, environmental compatibility, economic viability." This long-term reactor orientation of the R&D programme is the basis for its unique nature, differing in its implementation from that of other Commission-supported R&D programmes. This will be described in section 2.

The Community programme involves the member states of the Community, plus some non-member states associated with EURATOM (Switzerland, Romania and Bulgaria). The R&D programme has been highly successful in investigating the confinement, heating and control of fusion fuel plasma of hydrogen isotopes) in conditions approaching those required in a reactor. This has been dramatically demonstrated by the production of about 16 MW (peak) of fusion power in the Joint European Torus (JET) [1], constructed as the largest project in the Community fusion R&D programme, and the largest tokamak (special fusion research device [2]) in the world.

As a result of this success, and of similar progress made internationally (primarily in Japan and the U.S.A.), the Community is involved in an international collaboration to design and construct the next-step (performance closer to that needed for a reactor) tokamak ITER which is described in section 3. Finally, the potential advantages of fusion as an energy source are presented in section 4.

2 THE EUROPEAN FUSION R&D PROGRAMME

This programme is fully integrated at the European level in terms of overall co-ordination and the extensive collaborations between the national research institutions involved, including the joint use of European facilities (e.g. JET). There is strong international collaboration e.g. on ITER, but also in terms of bilateral and multilateral agreements with other countries carrying out this type of R&D. In fact, the European fusion programme is, and has been for many years, a good example of a European Research Area and has a unique character within the research supported by the EU Framework Programme.

The budget for fusion R&D in the EURATOM Framework Programme 6 (2002-2006) is about 830 M€ including up to 200 M€ for ITER. This budget covers a 4-year spend programme. The overall annual expenditure on fusion R&D both from member states and from EURATOM is about 480 M€, so that the EURATOM share is approximately 40%.

There are about 2000 scientists and engineers involved in the programme including about 250 PhD students. Training and education is an important part of this programme (including fellowships) as they ensure that the staffing requirements of the programme can be met and maintained for the duration of this challenging work. Another particular feature of the programme is its support for mobility of researchers among all the participating laboratories.

The European Commission co-ordinates the fusion R&D activities and represents the programme to the outside world. It is advised by the Consultative Committee for the EURATOM Specific Research and Training Programme in the Field of Nuclear Energy (fusion). The fusion R&D programme is implemented through;

1. *Contracts of Association:* Each contract is a bilateral agreement between the Community (represented by the European Commission) and a national research institution or Government department. Contracts of Association exist in most of the 25 Member States of the European Union, Romania and Switzerland. These Contracts of Association allow for the continuous implementation of R&D with annual reviews and planning. Figure 1 shows the research centres of the Associated organisations.

2. *Cost-sharing actions:* These are limited-duration contracts between the Community (represented by the European Commission) and research institutions not covered by a Contract of Association. These institutions are in states associated with the EURATOM Framework Programme which, at present, are Bulgaria, the Slovak Republic and Slovenia.

3. *The European Fusion Development Agreement (EFDA):* This is a multi-lateral agreement between all those institutions having a Contract of Association and the Community (represented by the European Commission). It involves the joint implementation of the following activities within the European fusion programme:

a) ITER-related activities (technology design and R&D, physics R&D).

b) Long-term (reactor) technology and power plant studies, as well as socio-economic studies, and public information.

c) Exploitation of JET (from 1983 to the end of 1999, JET was operated by the JET Joint Undertaking which had designed the device in the period 1978-1983. EFDA assumed the responsibility for JET exploitation in 2000 while operation is ensured under a contract with the UK Associate (the UKAEA)).

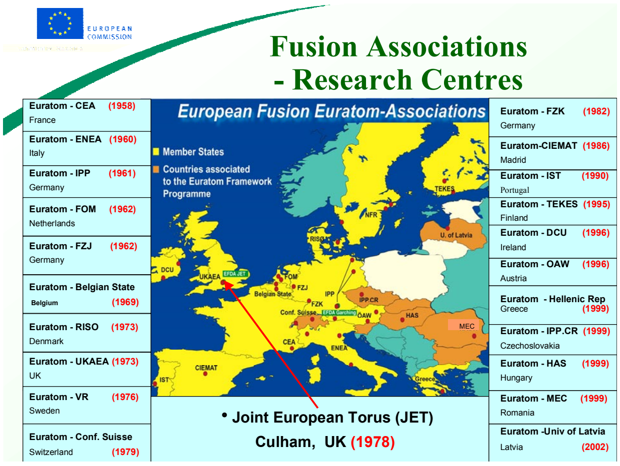

Figure 1: Research centres of the fusion Associations. Each Association is listed with the year of commencement of its Contract of Association.

These EFDA activities are jointly funded through a range of EFDA tasks with Community financing ranging from 20% to 100%. The latter case involves contracts with industry.

The main focus of the experimental work to develop an understanding of the plasma behaviour in regimes approaching those required in a reactor, is magnetic confinement and, in particular, the tokamak. This is a particular magnetic configuration for the production, heating and containment of hot plasma with which most success has been obtained so far [2]. However, other magnetic configurations are being studied, in particular stellarators, reversed field pinches, and a variant of the tokamak, the spherical tokamak.

The success of the experimental programme has led to the design of ITER, and investigations on the existing devices (especially the tokamaks) are required to contribute (in varying degrees) to the preparation of ITER operation, and in some cases (e.g. the stellarators) to identify magnetic configuration improvements.

The overall development strategy of the European fusion programme involves the experimental advance from JET to ITER and subsequently to a demonstration/prototype reactor (DEMO/PROTO) which, for the first time, would be able to generate significant amounts of electricity. There are two essential activities, which are included in this final step, and they are a) innovation and concept improvements, and b) technology and materials development.

2 ITER THE NEXT STEP TOWARDS A FUSION REACTOR

A tokamak generates and normally maintains its plasma by the change of vertical magnetic flux through the central hole of the (horizontal) torus container. The electric field, induced as a result of this magnetic flux change, ionises the gas inside the containment vessel, and the resulting plasma is then confined (thermally insulated) by a magnetic field configuration which is a superposition of fields resulting from:

a) the discrete coils which encircle (poloidally) the plasma containment vessel and are located at various toroidal locations. These are the so-called toroidal field coils since currents in them produce a magnetic field in the toroidal direction.

b) the discrete coils which are toroidal in form (co-axial with the toroidal plasma containment vessel) and are located at various poloidal locations. These are the so-called poloidal field coils since currents in them produce a magnetic field in the poloidal direction.

c) the toroidal current inductively driven in the plasma by the external change of vertical magnetic flux. This is primarily a poloidal field and so combines with that of b).

The tokamak is essentially a pulsed device. To sustain the tokamak magnetic configuration for longer pulses or in steady-state (relevant for a power reactor) the external coils must be superconducting to acceptably reduce the dissipative losses associated with conventional, resistive coils, and the plasma current must be maintained non-inductively. In order to provide the conditions necessary for the operation of the superconducting magnets, the whole device (containment or vacuum vessel and its internal components (e.g. the blanket and divertor), together with the magnets and their associated support structure) is enclosed in a cryostat. This is the basis of the ITER design.

The ITER vacuum vessel (the plasma container) is an all-welded, double-wall, water-cooled, steel torus which provides a high quality vacuum for the plasma and many ports for access of the following systems; plasma measurement, plasma heating, fuelling and pumping, inspection, remote maintenance and experimental tritium breeding blanket modules. It supports internally a blanket and a divertor. The vessel is made up of 9 toroidal sectors, and two, full-size, half sectors have been manufactured and the welding and cutting of the joints have been studied.

The ITER blanket consists of 421 modules which, in the initial phase of ITER operation, will act purely as a neutron shield. In a later phase of operation it could be converted to a tritium-breeding blanket. The modules have a detachable first wall of Be armour on a water-cooled, copper substrate attached to a steel shielding block. Prototype blanket models have been manufactured and subjected to extensive energy loading.

The ITER divertor consists of 54 cassettes located in the bottom of the vacuum vessel to provide the exhaust of particles (in particular non-hydrogenic ones (impurities)) from the plasma. The critical part of the design of this highly experimental component are the plasma-facing surfaces, and extensive R&D has been carried out on their ability to cope with the particle and energy fluxes to which they will be subjected.

Because both the ITER blanket and the divertor surfaces facing the plasma are subjected to high heat loads, allowance has been made for their removal and replacement in that special remote handling equipment has been designed and successfully tested.

The above “key” subsystems (magnets, vacuum vessel, blanket, divertor and the corresponding systems for their remote maintenance) were the subjects of extensive R&D programmes by the ITER Parties, all of which have essentially been successfully concluded. This has given a basis for significant confidence in the ITER design. It has allowed industry to master the new technologies involved, and the experience gained is now incorporated into the detailed engineering design and technical specifications of the time-critical components (e.g. the magnets). The scope of ITER supplies cover a large range of technologies and industrial fields and a widespread (direct and indirect) return to the constructing industries is expected, including small and medium-sized enterprises.

Aims

The programmatic objective of the ITER Project is to “demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes”. The four specific aims (see below) are made up of two which refer to ITER’s physical performance (numbers 1 and 2) and two which refer to its technological performance (numbers 3 and 4). These are:

1. Produce and study inductively-driven, burning plasma at Q $\geq$ 10 (where Q is the power amplification P_{fusion}/P_{input}) i.e. at powers of the order of 400-500 MW, for an “extended” time, ~ 400 s.

2. Aim at producing and studying “steady-state” burning plasma with non-inductive drive, Q $\geq$ 5.

3. Demonstrate the availability and integration of essential fusion reactor technologies.

4. Test components for a future reactor including tritium breeding module concepts (neutron power load $\geq$ 0.5 MW.m^{-2}, fluence $\geq$ 0.3 MW.year.m^{-2}).

Example of an ITER Subsystem

There are many subsystems required to operate ITER and a considerable R&D programme involving the construction of large-scale prototypes of key components by industry has taken place over the last 12 years. However, for the purposes of illustration, only one key subsystem (and its associated R&D) will be described here, the magnet system.

The cost of the ITER magnet system is estimated to be 29% of the total capital cost of ITER i.e. about 1,100 M€. System features are shown in Figure 2 and are given in Table 1.

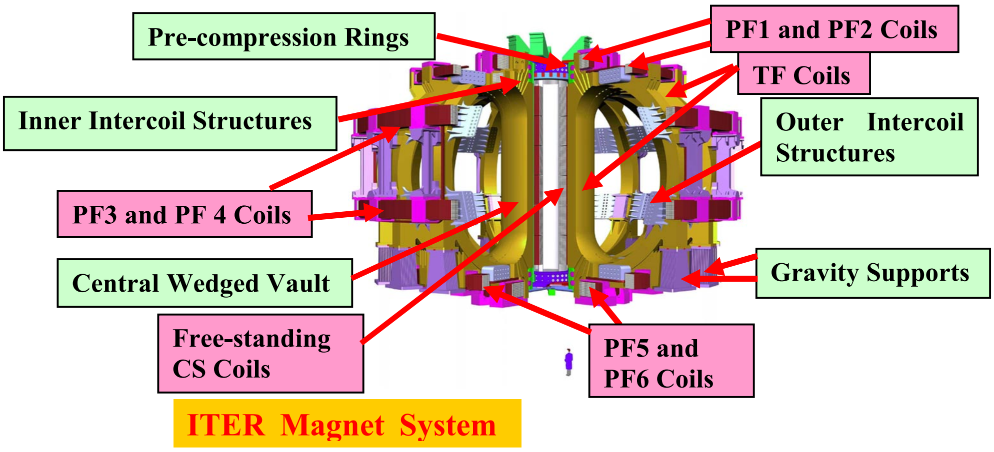

Figure 2: The ITER magnet system showing the toroidal field (TF) coils, the poloidal field (PF) coils, the central solenoid (CS) and associated structural features.

Table 1: The ITER magnet system – functions and design features of its components

Components	Main Function	Design Features
18 toroidal field (TF) coils (+ 1 prototype spare)	Produce the confining/ stabilizing toroidal field.	TF and CS coils use Nb_3Sn superconductor because of the large operating field.
Magnet structures	TF coil cases with their intercoil structures form the main support structure of the magnet system and the machine core (the PF coils and the vacuum vessel are linked to it).	Stainless steel coil cases. The inboard legs of the TF coils are wedged together along their sidewalls. Co-axial compression rings at the top and bottom of the TF coils prevent de-wedging of the TF coils. Intercoil structures resist the overturning forces on the TF coils due to the interaction of the poloidal magnetic field and the TF coil currents.

6 poloidal field (PF) coils + 18 correction coils (CCs)	Position the plasma and shape its poloidal cross-section. The CCs are required to correct error fields due to manufacturing/assembly imperfections, and to stabilise the plasma against resistive-wall instabilities.	PF coils use NbTi superconductor since the operating field is < 6 T, and are wound in double pancakes with square conductors.
6 central solenoid (CS) coils	Provides the inductive flux change to drive the plasma current.	CS coils wound in hexa- or quadru-pancakes with thick wall, square conductors. The ITER 6 coils are vertically stacked for operation.
Conductors for TF, PF and CS coils	Carry the electrical current.	As indicated above, Nb_3Sn and NbTi.
Magnet feeders and cryolines	Carry the electrical current from the power supplies and the cryogenic fluids necessary to cool the superconducting coils.	-

An extensive R&D programme has been carried out by the ITER Parties during the Engineering Design Activity (ITER-EDA) phase (1992-2001) for the qualification and fabrication of high field strands, large superconducting cables and joints, structural materials and coil cases.

Two model coils (see Figure 3) have been manufactured and tested, confirming the design of the ITER magnet system:

A. Central Solenoid Model Coil (CSMC) by the Japanese and US ITER Parties with involvement of the European and Russian Parties.

B. Toroidal Model Field Coil (TFMC) by the European ITER party.

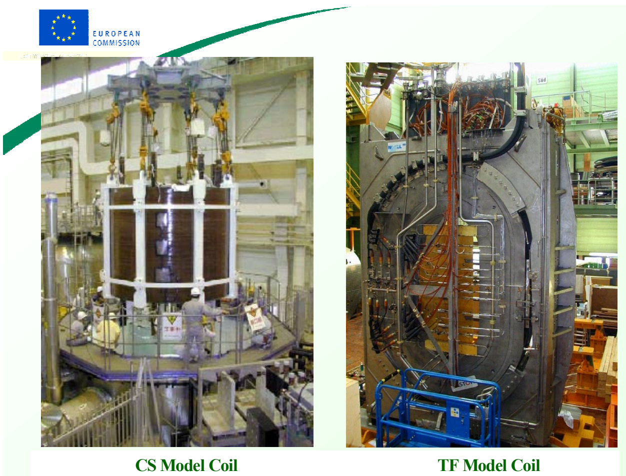

Figure 3: (left) The CS Model Coil is shown being installed in a cryostat prior to testing at Naka, Japan. (right) The TF Model Coil is shown being prepared for its testing in a cryostat at the Forschungszentrum Karlsruhe (Association EURATOM/FZK), Germany.

The main objectives of the model coil programme were:

i) to develop the manufacturing procedures for fabrication of large Nb_3Sn conductors (10 – 13 T), windings and structures, and

ii) to test the coils inside dedicated facilities at currents and fields similar to ITER.

The European ITER Party has contributed to the ITER magnet R&D as follows:

i) Qualification of short samples and manufacture of high current/field (80 kA, 10 T) Nb_3Sn superconductor.

ii) Jacketing of 6.5 km of CSMC superconducting cables.

iii) Manufacture and test of full-size conductor and joint samples.

iv) Characterisation of structural materials for the conductor jacket, radial plates and cases (base materials and welds).

v) Insulation systems and mechanical properties after irradiation.

vi) Manufacture, assembly and test of the TFMC winding, case and intercoil structure.

vii) Manufacture of three, full-scale models of the TF coil case.

viii) Manufacture of the PF conductor (NbTi) insert for the CSMC testing facility in Japan (in progress).

ix) Manufacture and qualification of high critical current density strands (in progress).

3 THE POTENTIAL ADVANTAGES OF FUSION AS AN ENERGY SOURCE

These are tabulated as in Table 2 (see also [3]).

Table 2: Potential advantages of fusion as an energy source

Aspect	Features	Comments
Fuels	Abundant, straightforward and "economical" to extract, geographically widespread.	For a first-generation fusion reactor, the basic fuels will be deuterium (extractable from water) and lithium (abundant in the earth's crust and also in the oceans). The fuel costs will be small relative to the reactor construction cost, and the fuel supply is "unlimited". In the sense of being unlimited on a time-scale of relevance to mankind, fusion is a sustainable energy resource. Because of the geographic distribution of fuel, security of energy supplies is assured.
Reactor components materials	No availability constraint even for an extensive use of fusion energy.	Studies show that appropriate materials are available and that no special (resource-limited) materials will be required. An extensive materials development programme is required to confirm that this is so and this is being actively pursued.
Environment	Small impact of fuel collection, no need for large land use, no need for long transmission paths (because it is safe to locate the reactor near the loads) or for large-scale energy storage, no environmentally-detrimental emissions (greenhouse gases, acid rain etc.).	The energy density of fusion fuel is typically at least a million times greater than that of other energy sources, and so for the same energy output correspondingly less fuel (earth "damage") is required. The actual power plant land usage is similar to conventional base-load power plants and because energy production is not intermittent there are no energy storage requirements. There are no emissions, which are harmful to the climate.
Safety	Favourable safety features (inherent safety, relatively low energy density).	The assessment that fusion is safe is based on the experience gained with actual systems and extensive theoretical and experimental studies. Detailed studies and experimentation are

		continuing to further consolidate this conclusion.
Waste	No radioactive ash but activation of the structure.	The radioactive waste will not be a long-term burden because, with the appropriate choice of structural materials, it will be possible to store the waste near the earth's surface for a duration of the order of 100 years after which recycling of material could commence.
Application	Large-scale, high temperature energy source not limited to electricity production, independent of geographical location.	Clearly appropriate for base-load energy production. Fusion power might be an attractive way of producing hydrogen for fuel cells (e.g. for powering environmentally friendly transport).

5 FINAL REMARKS

The construction of ITER, and later DEMO, will require the significant involvement of European industry and will need to be accompanied by complementary physics and technology R&D activities in fusion laboratories and in universities.

At present, the decision to build ITER has not yet been taken by the international Parties involved (China, the European Union, Japan, Korea, the Russian Federation and the United States of America), however, governmental negotiations are well advanced and an agreement of cost-sharing among the 6 Parties has been reached.

A leading position in the development of advanced sustainable energy systems could open a huge world market for European industry. R&D and innovation are pre-requisites for leadership towards a sustainable energy market. In fusion, European synergy and effectiveness has been achieved through a European Research Area, which brings together all players. ITER and the accompanying R&D programme will be a significant challenge for the public research players and industry.

Achieving a sustainable energy supply and demand is a major challenge, but fusion promises to make a substantial contribution to mankind's future energy supply. This promise is so attractive that many countries are actively pursuing fusion R&D programmes [4].

4 ACKNOWLEDGEMENTS AND DISCLAIMER

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Further information on ITER can be obtained from: http://www.iter.org.