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

E-mail: Barry.green@cec.eu.int

Abstract. The EURATOM fusion research and development programme is a well integrated and coordinated programme. It has the objective of “developing the technology for a safe, sustainable, environmentally responsible and economically viable energy source.” The programme is focussed on the magnetic confinement approach and supports 23 Associations which involve research entities (many with experimental and technology facilities) each having a bilateral contractual relationship with the European Commission. The paper will describe fusion reactions and present their potential advantages as an energy source. Further, it will describe the EURATOM programme and how it is organised and implemented. The success of the European programme and that of other national programmes, have provided the basis for the international ITER Project, which is the next logical step in the development of fusion energy. The paper will describe ITER, its aims, its design, and the supporting manufacture of prototype components. The European contribution to ITER, the exploitation of the Joint European Torus (JET), and the long-term reactor technology R&D are carried out under the multilateral European Fusion Development Agreement (EFDA).

1. Fusion reactions and reactors

Fusion reactions [1] are those between the nuclei of light atoms which join together (or “fuse”) to form heavier nuclei. In the process, large amounts of (nuclear) binding energy are liberated. The conditions for such reactions to occur are that the reacting nuclei (positively charged on account of the protons they contain) approach each other sufficiently closely for the short-range attractive nuclear forces to dominate the electrical repulsion arising from the like electrical charges. This situation can occur if the gaseous mixture of reacting atoms is brought to very high temperature, which means that the atoms themselves have high energy and so can approach each other more closely. In fact, at temperatures where such reactions become significant (in excess of 100 million degrees Celsius), the atoms are fully ionised, that is the electrons and nuclei formerly associated as atoms are completely disassociated and form “interpenetrating liquids” in a state of matter termed a “plasma”. Fusion reactions are the ones provide the energy of the Sun and the stars.

In such a reaction between two light nuclei, the resulting nucleus has less binding energy than the sum of the binding energies of the reacting nuclei and the “surplus” energy is liberated as the kinetic energy (energy of motion) of the particles produced. The reaction which is “easiest” to establish is that between the isotopes of heavy hydrogen; deuterium and tritium (see figure 1).

Deuterium is an isotope which occurs in abundance (in water), and can be extracted by well-known, economical methods. Tritium is a non-naturally occurring, radioactive isotope (half-life 12.3 years) and therefore it needs to be generated. For example, the neutrons produced in D–T reactions can be made to interact with Lithium (a light metal, readily extractable from its significant concentrations in the earth’s crust and oceans) to produce tritium. The reaction product Helium is non-radioactive.
Figure 1. The Deuterium –Tritium fusion reaction. The products of the fusion reaction involving a nucleus of deuterium (a deuteron, D) and the nucleus of tritium (a triton, T) are a Helium nucleus (an alpha particle $^4$He) and a neutron (n). The kinetic energies of the product particles are given in MeV ($1.6 \times 10^{-13}$ J)

The aim of fusion research has been to develop a “reactor” inside which such reactions can take place, and to extract the energy produced for useful purposes e.g. electricity generation and/or the production of high grade heat for use in chemical processes (e.g. the production of hydrogen which may be used, in future, as an energy carrier, in particular for powering transport). The main type of “reactor” which is being developed to contain the reacting plasma is based on magnetic fields which, in the case of D–T reactions, influence the motion of the electrically charged reacting deuterium and tritium nuclei and the electrically charged Helium nuclei which are produced. The energetic neutrons resulting from the fusion reactions are electrically neutral and can escape the magnetic confinement of the “fusion reactor”. If a lithium-containing blanket surrounds the reactor chamber, then the kinetic energy of the neutrons can be converted to thermal energy and extracted by flowing a coolant through the blankets, as well as producing tritium to inject into the reactor to maintain the “fusion burn” with injected deuterium. This then is the concept of a D–T fusion reactor, the development goal of the European fusion research and development programme.

2. The Potential Advantages of Fusion as an Energy Source
The potential advantages of fusion as an energy source are tabulated as in table 1 (see also [2]).
Table 1. 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 considered 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). |

3. The European fusion R&D programme

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.
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 (a 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) [3], constructed as the largest project in the Community fusion R&D programme, and the largest tokamak (special fusion research device [1]) in the world.

As a result of this European 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 tokamak (performance closer to that needed for a reactor), ITER, which is described in section 4.

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.

The budget for fusion R&D in the EURATOM Framework Programme 6 (2002–2006) is 824 M€ including the contributions of Associated States and includes 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 500 M€, so that the EURATOM share is approximately 38%.

There are about 2,000 scientists and engineers involved in the programme including about 200 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 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 EURATOM (represented by the European Commission) and a national research institution or Government department. Contracts of Association exist in 21 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 2 shows the research centres of the Associated organizations.

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

3. **The European Fusion Development Agreement (EFDA)**: This is a multi-lateral agreement between all those institutions having a Contract of Association and EURATOM (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. In 2000 EFDA assumed the responsibility for JET exploitation, and the operation of JET is ensured under a contract with the UK Associate (the UKAEA)).

The Association and 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 [1]. 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 (see figure 3) 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.
4. 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, ionizes 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 a poloidal plane.

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 (liquid Helium temperature), the whole device (containment or vacuum vessel and its internal components (e.g. the blanket and a so-called “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 superconducting magnet system comprises; 18 discrete toroidal field (TF) coils, 6 discrete poloidal field (PF) coils and the central solenoid (CS) made up of 6 subcoils stacked one on the other for producing the change of vertical magnetic flux which inductively drives the plasma.
current in the toroidal plasma). Two model coils have been manufactured and tested to check the performance of the high-performance superconductors and the fabrication methods (see figure 4).

**Figure 4.** (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 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 beryllium (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 international R&D has had a volume of about 1,000 M€ for the period 1992 to the present. The EFDA Technology programme has been an integral part of this effort. Such work 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.

4.1. 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 \( Q > 10 \) (where \( Q \) is the power amplification \( P_{\text{fusion}}/P_{\text{input}} \)) i.e. at fusion 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 at \( Q > 5 \).
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 \( > 0.5 \text{ MW.m}^{-2} \), fluence \( > 0.3 \text{ MW.year.m}^{-2} \)).

4.2. Burning plasma physics
ITER will study, for the first time, a plasma in which most of the plasma heating comes from “self-heating”. This is the result of alpha particles (produced by the D–T fusion reactions (“fusion burn”)), which are confined by the magnetic field of the tokamak, which give up their energy to the plasma, thereby heating it. Such a plasma is called a “burning” plasma.

In addition, it will be possible to study:
i) the effects of high energy particles (the fusion reaction produced alpha particles, but also those particles which may be accelerated to high energies by other, external plasma heating means e.g. radio-frequency waves.
ii) the details of the balance in particles and energy between the hot plasma core and the cooler plasma edge. The understanding of this balance is of extreme importance and while aspects of both the physics of the core and the physics of the edge are studied in present-day devices and the results extrapolated separately to reactor conditions, ITER will provide the first opportunity to study the “self-consistent” situation.

Many detailed tokamak physics issues remain to be studied for the development of a reactor [4]. Some will be encountered on ITER for the first time (see above) but much information can already be obtained from experiments on existing devices. The issues involve: the details of the confinement of plasma particles and energy; the nature of plasma instabilities, their stabilisation or control; the control of plasma conditions to optimise plasma performance in experimental devices; the interaction of the plasma with the material walls of the containment vessel and its plasma-facing components; the study of the most efficient external means of heating the plasma and driving currents in it; the development of means of measuring the properties of the plasma (essential to be able to test theories of plasma behaviour); the development (and checking with respect to experiment) of numerical codes which model the plasma behaviour; the attainment of long-duration burning plasmas (up until now the duration of fusion plasmas has been limited); and the optimization of confining magnetic configuration (it is here that the stellarator, an alternative magnetic configuration to the tokamak, and the spherical tokamak, a variant on the more “conventional” tokamak like ITER, play an important role). The European fusion programme is actively pursuing research in all these areas in coordination with its direct involvement in ITER.
4.3. The status of ITER
On June 28, 2005 after several years of negotiations, the 6 Parties involved in the ITER Project (EURATOM, The Government of the People’s Republic of China, the Government of Japan, the Government of the Republic of Korea, the Government of the Russian Federation, and the Government of the United States of America) agreed that the site for ITER would be Cadarache, France. This declaration opens the way for the signing, by all parties, of the ITER Implementation Agreement, which, once ratified by all the corresponding governments, will allow the construction of ITER to start.

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.

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 [5].

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