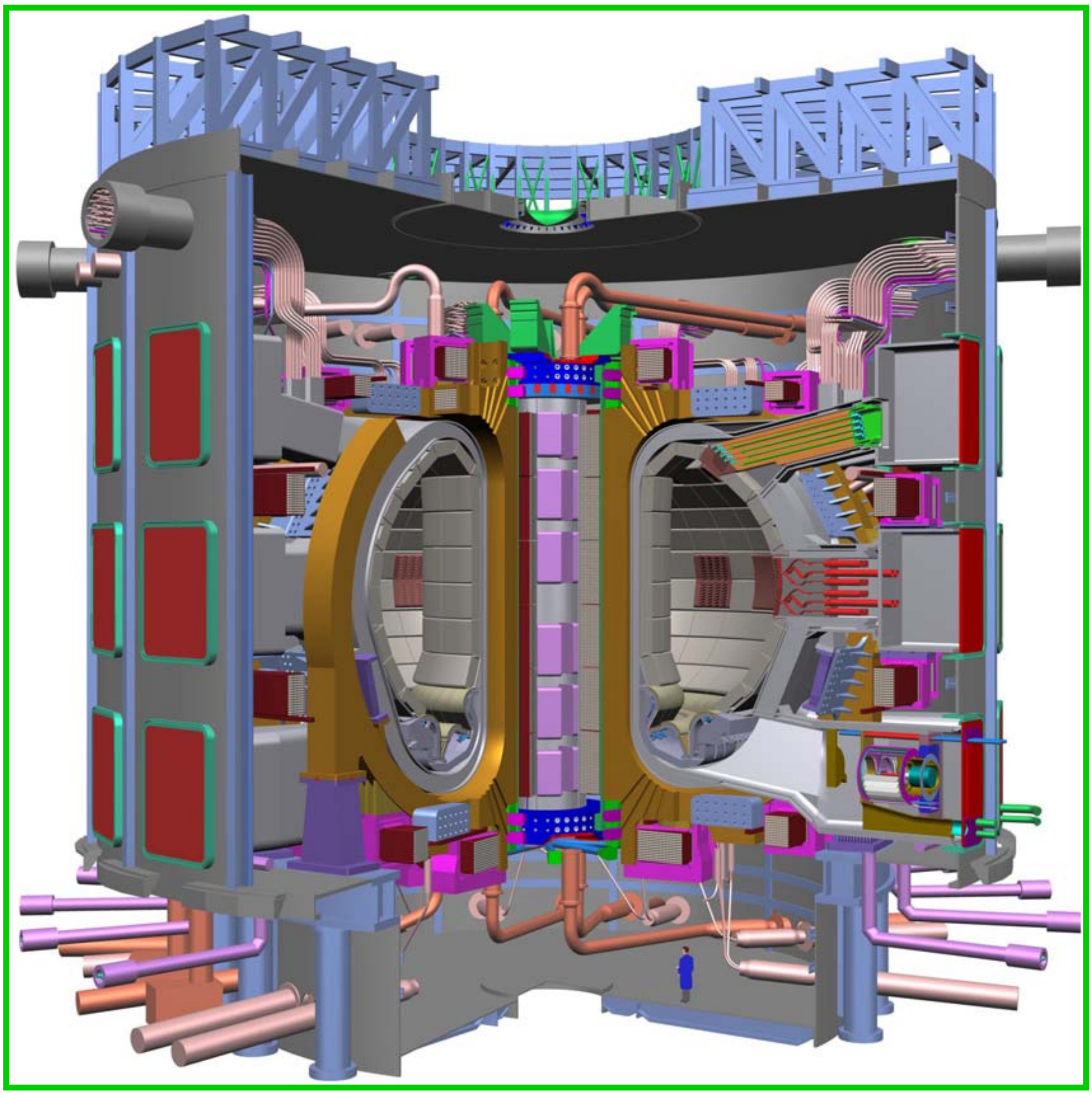
International Research Co-operation in the Field of

CONTROLLED THERMONUCLEAR FUSION

25[TH] REPORT COVERING 2002



ITER : International Experimental Thermonuclear Reactor

FEDERAL OFFICE FOR EDUCATION AND SCIENCE

(FEBRUARY 2003)

CONTENT

EN BREF

- Les ITER CTA (*Co-ordinated Technical Activities*) se sont achevées avec succès et les partenaires internationaux (Canada, Fédération de Russie, Japon et Union Européenne) se sont mis d'accord sur les ITA (*ITER Transitional Arrangements*) qui constituent, dès le 1er janvier 2003 et avant que ne soit créée l'ILE (*ITER Legal Entity*), la base légale pour la poursuite de la collaboration internationale préparant la prochaine grande installation de recherche.

- Le Japon a proposé officiellement de construire ITER à Rokkasho-mura, dans la partie nord de son île principale, ce qui porte maintenant à quatre le nombre (probablement définitif) des sites candidats ; à part le site japonais, il s'agit de Cadarache (France), Clarington (Canada) et Vandellòs (Espagne).

- Tout au long de l'année, la Chine et les USA ont exprimé une volonté croissante de s'associer au projet ITER et des déclarations officielles à cet effet sont attendues pour le début de l'année 2003 [1] ; il est intéressant de noter que le scénario "*fast track*", qui prévoit une commercialisation de l'énergie de fusion 20 ou 25 ans plus tôt que le calendrier actuel (50 ans), suscite un intérêt considérable aux USA.

- Le 3 juin 2002, le Conseil de l'Union Européenne a adopté le 6e Programme cadre de recherche et de formation de la *Communauté Européenne de l'Énergie Atomique* (Euratom) dans le domaine de l'énergie nucléaire et confirmé un budget de 750 millions d'€ pour la fusion ; sur cette base, la Commission Européenne a fixé à 20% (40% pour les activités prioritaires) le niveau du soutien communautaire aux activités de recherche effectuées dans les laboratoires nationaux associés au programme ; c'est là une diminution sensible par rapport aux niveaux du 5e Programme cadre (25% et 45%).

- Le 9 décembre 2002, le Conseil fédéral suisse a adopté la prolongation de quatre accords avec Euratom en matière de fusion : le *European Fusion Development Agreement* (EFDA), le *JET Implementing Agreement* (JIA), le *Contrat de mobilité* et le *Contrat d'Association*, assurant ainsi la poursuite d'une collaboration de longue durée.

- Le *Centre de recherche en physique des plasmas* (CRPP) de l'*École polytechnique fédérale de Lausanne* (EPFL) a été choisi comme chef de file responsable par les différents laboratoires nationaux auxquels seront confiés le développement et la construction du système de chauffage du plasma d'ITER par onde cyclotron électronique.

[1] Pour les USA, c'est chose faite depuis le 30 janvier 2003.

KURZER ÜBERBLICK

- Die ITER CTA (*Co-ordinated Technical Activities*) wurden erfolgreich abgeschlossen, und die internationalen Partner (Japan, Kanada, Russische Föderation and Europäische Union) haben sich auf die ITA (*ITER Transitional Arrangements*) geeinigt. Seit dem 1. Januar 2003 bilden letztere die juristische Grundlage für die Fortsetzung der internationalen Zusammenarbeit, die den Bau und den Betrieb der nächsten grossen Forschungsanlage vorbereitet, bevor die ILE (*ITER Legal Entity*) in Kraft tritt.

- Japan hat offiziell Rokkasho-mura im nördlichen Teil der Hauptinsel als Standort für ITER vorgeschlagen ; dadurch erhöht sich die (sehr wahrscheinlich definitive) Zahl der kandidierenden Standorte auf vier ; neben dem japanischen Ort handelt es sich um Cadarache (Frankreich), Clarington (Kanada) und Vandellòs (Spanien).

- Während des ganzen Jahres haben China und die USA ein wachsendes Interesse an einer Beteiligung am Projekt ITER signalisiert ; entsprechende offizielle Deklarationen werden für Anfang 2003 erwartet [2] ; bemerkenswert ist die Tatsache, dass der sogenannte "*fast track*"-Zeitplan, der 20 bis 25 Jahre früher als der herkömmliche Zeitplan (50 Jahre) eine Vermarktung der Kernfusionsenergie vorsieht, in den USA auf sehr grosses Interesse stösst.

- Am 3. Juni 2002 genehmigte der Rat der Europäischen Union das 6. Forschungs- und Ausbildungsprogramm der *Europäischen Atomgemeinschaft* (Euratom) im Bereich Kernenergie und bestätigte ein Budget von 750 Millionen € für die Fusion ; entsprechend setzte dann die Europäische Kommission die Höhe der finanziellen Unterstützung zu Gunsten von Projekten, die in den mit dem Programm assoziierten nationalen Institutionen durchgeführt werden, auf 20% (40% für Prioritätsaktivitäten) fest ; dies entspricht einer markanten Abnahme im Vergleich zum 5. Rahmenprogramm (25% und 45%).

- Am 9. Dezember 2002 genehmigte der Schweizerische Bundesrat die Verlängerung von vier Abkommen mit Euratom auf der Gebiet der Fusionsforschung : das *European Fusion Development Agreement* (EFDA), das *JET Implementing Agreement* (JIA), den *Mobilitätsvertrag* und den *Assoziationsvertrag* ; dadurch wurde die Fortsetzung einer langjährigen Zusammenarbeit gesichert.

- Das *Forschungszentrum für Plasmaphysik* (CRPP) der *Eidgenössischen Technischen Hochschule* in Lausanne (EPFL) wurde von den verschiedenen nationalen Institutionen, die für die Entwicklung und den Bau einer Plasmaheizung für ITER auf der Basis von Zyklotronwellen verantwortlich sind, als führendes Laboratorium gewählt.

[2] Am 30. Januar 2003 haben es die USA getan.

IN SHORT

- The ITER CTA (*Co-ordinated Technical Activities*) have been successfully completed and the international partners (Canada, Japan, Russian Federation and European Union) have reached an agreement on the ITA (*ITER Transitional Arrangements*) which provide a legal basis as of 1 January 2003 for the continuation of the international co-operation on the next large research facility, until the ILE (*ITER Legal Entity*) comes into force.

- Japan has officially proposed a site for ITER : Rokkasho-mura in the northern part of the main island ; thus, the (most likely) final number of candidate sites amounts now to four ; besides the Japanese site, these are : Cadarache (France), Clarington (Canada) and Vandellòs (Spain).

- China and the U.S.A. have expressed throughout the year a growing interest in joining the ITER project and official announcements to that effect are expected for early 2003 [3] ; it is worth noting that the so-called "fast-track" scenario, which foresees a commercialisation of fusion power 20 to 25 years earlier than the current road map (50 years), is attracting a lot of interest in the USA.

- On 3 June 2002, the Council of the European Union adopted the 6th Framework Programme of the *European Atomic Energy Community* (Euratom) for research and training on nuclear energy and confirmed that 750 million € will be attributed to fusion ; on that basis, the European Commission set at 20% (40% for priority items) the level of support it will grant to research activities carried out in national laboratories associated with the programme ; this is a significant decrease from the level of support granted during the 5th Framework Programme (25% and 45%, respectively).

- On 9 December 2002, the Swiss Federal Council adopted the prolongation of four agreements with Euratom in fusion research : the *European Fusion Development Agreement* (EFDA), the *JET Implementing Agreement* (JIA), the *Mobility Agreement* and the *Contract of Association*, thus ensuring the continuation of a long-standing co-operation.

- The *Plasma Physics Research Centre* (CRPP) of the *Swiss Federal Institute of Technology* (EPFL) in Lausanne has been selected as the leading laboratory by the various national institutions in charge of developing plasma heating systems for ITER based on cyclotron waves.

[3] The USA have done so on 30 January 2003.

FOREWORD

In the field of controlled thermonuclear fusion research, the end of the 20th century was marked by a series of significant breakthroughs at a few large facilities, such as JET (*Joint European Torus*) in Europe, which demonstrated that fusion energy can be produced on Earth. The first half of the 21st century will see a new generation of devices which will definitely establish the technical feasibility and economic viability of harvesting fusion energy for commercial electricity production. So, in several respects, fusion research finds itself currently in a phase of transition characterised mainly by international negotiations and decision planning for the steps ahead rather than by scientific and technical highlights comparable to those of the preceding decade.

Thus, it seems a good opportunity to review past achievements and future challenges, to take stock of 40 years of fusion research and to assess the road map ahead. The occasion – and to a very large extent the material – for such an evaluation was given by recent developments within the *International Energy Agency* (IEA) of the *Organisation for Economic Co-operation and Development* (OECD). Two years ago, the *Committee on Energy Research and Technology* (CERT) of the Agency asked its *Fusion Power Co-ordinating Committee* (FPCC) :

« – When will fusion power be available ?
– What are the steps needed to get there ?
– Why does it take so long ? »

A drafting party of the FPCC then produced a two page summary, endorsed by the FPCC, which is meant to become the official position paper of the IEA on nuclear fusion. It also wrote a more detailed, ten page chapter which will be part of an IEA book devoted to the options available in this century for mitigating greenhouse gas emissions (*Energy Technology : Facing the Climate Challenge*). The short and the full reports together make up chapter 1 of the present report and give an overview of the current status of fusion research.

Against this background, the significant events of last year in the world of fusion research are reviewed in chapter 2 with an emphasis placed on the next large facility (ITER) and on the Euratom fusion programme. Chapter 3 then summarises the noteworthy events in Switzerland in 2002 and the report closes with the usual list of contacts for the interested readers who wish to have more information.

As it is sent to a large, multilingual readership, the report is published for the first time in English rather than in French or German, with only brief summaries in these two languages. Readers who have strong feelings about this, either for or against, are kindly asked to let us now. It will help us make a final decision on that issue in one or two years.

Like every year, the author is indebted to Prof. Minh Quang Tran, Director of the *Plasma Physics Research Centre*, *Swiss Federal Institute of Technology* in Lausanne, and to Prof. Peter Oelhafen, *Department of Physics* of the *University of Basle*, for most of the information of chapter 3 and for the figure on the cover.

Dr. Jean-François Conscience
Federal Office for Education and Science

CHAPTER 1

FUSION POWER : WHERE DO WE STAND ?

Prospects for Fusion Electricity

The **Short Report** was prepared by the *Fusion Power Co-ordinating Committee* of the *International Energy Agency* (IEA) for the *Governing Board* of the Agency.

The **Full Report** is adapted from a chapter on nuclear fusion which will be part of a report on energy supply for the 21st century prepared by the *Committee on Energy Research and Technology* of the IEA, to be published in late 2003 or early 2004 under the title *Energy Technology : Facing the Climate Challenge*. Authors of the original chapter are Ian Cook, *United Kingdom Atomic Energy Agency*, Gunnar Leman, *Swedish Research Council*, Masayuki Nagami, *Japan Atomic Energy Research Institute*, Serge Païdassi, *European Commission*, and Michael Roberts, *United States Department of Energy*.

Both texts have been revised to fit into the present report and full responsibility for the versions included here rests entirely with J.-F. Conscience

SHORT REPORT

When will fusion power be available ? The question is today of particular interest as the international community will soon be asked to invest 4’500 million € in the *International Thermonuclear Experimental Reactor* (ITER). Under the auspices of the *International Atomic Energy Agency* (IAEA), the milestone project, now in negotiation, will be a joint venture of many countries with, as main partners, Canada, China, the European Union (EU) − including Switzerland and several candidate countries −, Japan, the Russian Federation and the USA. The design of what will be the first fusion reactor producing significant amounts of energy was completed in June 2001, and sites for hosting the facility have been offered by Canada, the EU (in France and in Spain) and Japan.

The facts

Technical feasibility – Production of fusion energy has been demonstrated in experimental devices at levels of up to several megawatts for short time spans. Scientific and technological know-how, leading to an agreed design, is now available for the construction of the first experimental reactor, ITER, in order to demonstrate that harvesting power from thermonuclear fusion is indeed scientifically and technically feasible. Thus, fusion energy generation on a commercial scale is not dependent upon further scientific breakthroughs ; it is a matter of research and development to optimise existing concepts and technologies, and it requires both large international facilities and strong domestic programs of supporting research. As materials with high irradiation resistance and low neutron-induced activation are of particular importance for highly performing, environmentally benign and economically attractive power plants, an *International Fusion Materials Irradiation Facility* (IFMIF) is being designed to test materials for fusion.

Safety – Extensive studies have shown that fusion is inherently safe and environmentally friendly. Initiating and maintaining fusion reactions require a number of such highly uncommon physical conditions that failure of components or uncontrolled operation immediately leads to reactor shut down. Although a fusion reactor contains significant amounts of tritium – a radioactive isotope of hydrogen, which, together with non-radioactive deuterium, makes up the fusion fuel – the worst in-plant generated accident would result in limited hazards to the public. Similarly, the consequences of accidents caused by external events, such as a very large earthquake, would be far less severe than those of the event itself. Finally, fusion fuels or materials are not subject to non-proliferation treaties because none of them poses a security threat with respect to nuclear weapon development.

Environment – The fusion reactions produce no greenhouse gas and no radioactive or toxic products, but neutron-induced radio-activation of the inner reactor walls does occur. Almost all of the activated materials, however, can be disposed of as inert waste, recycled, or given shallow-land disposal a few decades after the end of operation. Further, it is reasonable to expect that future research on materials will optimise this aspect.

Security of fuel supply – Tritium is produced in the fusion reactor from lithium, an element which, like deuterium, is plentiful, widespread and available at low cost. It is recalled in this context that fusion reactions release huge amounts of energy : 0.1 ton of deuterium and 4 tons of lithium would be enough to fuel for one year a 1000 megawatt electrical power plant requiring today 2.1 million tons of coal, or 10 million barrels of oil, or 100 tons of uranium.

Economics – The estimated costs of ITER have been validated by industry. The final costs of fusion electricity are estimated by extrapolating from the ITER costs and will depend upon the extent to which fusion physics, technologies, and materials are further optimised in the next few decades. Despite these uncertainties, current evaluations show that fusion electricity would be competitive in the future energy market. This is all the more so if emission mitigation costs such as carbon sequestration or external costs (e.g., environmental damage, adverse health impacts) are taken into account, and the significance of these costs is expected to grow in the future. Under these conditions, the projected cost of fusion electricity is comparable to that of other, environmentally friendly sources, thus ensuring it a significant share of the market by the end of the century.

Social acceptance – Ongoing social studies indicate that no specific public acceptance problems are expected for fusion if comprehensive information is available and if the public is actively involved in the decision process at an early stage.

The questions

« *When will fusion power be available ?* » Despite significant progress, it is an acknowledged fact that the practicality and economical feasibility of harvesting fusion power remain to be demonstrated. ITER construction and operation are major steps toward that goal. The experimental reactor is designed to be a flexible test facility capable of producing a significant amount of thermal power (500 megawatts) under conditions mimicking those of a power plant. After about 10 years of construction, it will be exploited for 10 to 20 years, and, combined with the materials development programme, it will tell whether a demonstration power plant can be brought on line approximately 35 years from now. This would then lead to the first prototype commercial power plant toward the middle of the century. Stronger political will, leading to quicker decisions and heavier initial investments, could shorten markedly the development time ("fast track" scenario).

« *Why is it still so far away ?* » Since the 1960's, fusion research has often been perceived as an expensive, moving target, because the fusion community regularly had to revise its estimate of the time needed to bring the technology to maturity. With the benefit of hindsight, it is easy to understand why. The most important factor was the initial lack of knowledge in the state of matter to be reached in order to allow a fusion power plant to work. The construction of a series of experimental devices has enabled the building up of the necessary experimental data and the testing of theoretical models which allow now to undertake with confidence the development of fusion as an energy source.

« *Why invest in fusion ?* » The difficulties in solving the vital problem of providing energy for the future, with assurance of a secure supply while avoiding climate change, are universally recognised. No technological options can be ignored and, among these, fusion is a principal candidate for major contributions to the energy future, in particular for the centralised supply of base-load electricity. Indeed, socio-economic studies of long-term energy scenarios show that the cost, including externalities, of satisfying energy demand without fusion would be huge, dwarfing the cost of fusion development.

« *How is fusion research co-ordinated ?* » Worldwide co-operation on fusion is established primarily within the framework of the IAEA and the IEA. The IEA *Fusion Power Co-ordinating Committee* co-ordinates the activities of eight *Implementing Agreements* fostering international co-operation on many fusion-relevant topics. One of these agreements, devoted to fusion materials, is the technology incubator for IFMIF. Several countries have national fusion research programmes which, in Europe, are largely integrated into the Euratom fusion programme of the European Union.

FULL REPORT

Introduction

Energy supply must be geared to ensuring the uninterrupted physical availability of energy products, at a price that is affordable for all consumers, while respecting environmental concerns and looking towards sustainable development. Such considerations have recently highlighted the weaknesses of many of the major current energy sources. Sustained economic growth and the development of electricity consumption are contributing to the increase in greenhouse gas emissions and it is much more arduous to reverse this trend than it might have seemed some years ago. Climate change and the security of fuel supply are major challenges and a long-term battle for the international community.

The need for new non-polluting and sustainable forms of energy to reduce the energy dependency of developed countries, to promote economic development and to contribute to climate change minimisation is therefore growing. Key elements of a responsible energy policy include the following : (1) optimising the use of present technologies to minimise environmental impact ; (2) improving existing technologies, particularly in reducing pollutant emissions and increasing efficiency of energy production and use; and (3) developing a range of new technologies providing the options necessary to allow a gradual move to a radically different energy supply system and market.

Each potential technology for electricity production has pros and cons and all energy options have to be considered as potential contributors to an optimised future energy mix. Technologies for carbon sequestration are attractive options for possibly counterbalancing greenhouse gas emissions from fossil fuels, but their development is just starting. The harvest of renewable energy is already partly developed but there are issues associated with its availability, location and intermittence for a satisfactory integration into an electricity network. Nuclear fission is another available option although there are public concerns about its safety and the long-term issues of waste disposal.

Fusion, which would be particularly suited for the centralised supply of base-load electricity, appears as one of the most attractive long-term energy options because of the widespread distribution, abundance and low cost of its fuels and because of its significant favourable safety and environmental features. Thus, fusion energy would ideally complement renewable energy sources in the future energy mix. With the growth of the world population expected to occur in urban areas, concentrated energy sources that are not constrained with respect to where they can be located, such as fusion, may be particularly attractive.

As opposed to nuclear fission, fusion is a process that releases energy by joining together the nuclei of light elements, such as hydrogen and its isotopes, deuterium and tritium. It is the energy that powers the Sun and the stars, and the elucidation of the underlying scientific principles is one of the great achievements of 20th century physics. In so-called magnetic fusion [4], fusion reactions between deuterium and tritium nuclei take place in a

[4] This paper treats only magnetic fusion energy, reflecting the co-ordinated activities conducted by the IEA-FPCC. Inertial fusion energy represents a truly different scientific and technological approach. The direct funding for developing inertial fusion energy has been significantly less than for magnetic fusion, and much of the progress in this field has resulted from the investments made in some countries in inertial confinement studies for defence applications. Relative to magnetic fusion energy, only a small number of countries have formal inertial fusion energy programs. Additional information can be obtained from the book *Energy from Inertial Fusion*, International Atomic Energy Agency, Vienna, 1995 (see also page 22).

plasma [5] confined by a magnetic field and produce helium (an inert gas), neutrons and energy. The latter is used to heat the plasma and, thus, keep the fusion reactions going, and the excess is harvested to produce steam which can then be used to generate electricity according to well established technologies. In addition, neutrons react with lithium in the reactor wall to produce the tritium needed. Fusion reactions generate neither greenhouse gases nor radioactive or toxic products [6], and are inherently safe. Indeed, with enormous and widespread fuel resources, and the projection of viable economics, fusion represents a major and attractive option for future sustainable energy generation.

The long-term objective of fusion programmes in the international community is the creation of prototype plants for power stations to meet the needs of society : operational safety, environmental compatibility, economic viability. During the last decade or so, very important scientific and engineering developments have taken place, confirming that fusion is now a credible energy option having the potential for clean, large-scale power generation. This report summarises the findings of an assessment made by the *Executive Committee* of the *IEA Implementing Agreement on a Co-operative Programme on the Environmental, Safety and Economic Aspects of Fusion Power* and endorsed by the *IEA Fusion Power Co-ordinating Committee* (FPCC). The assessment aimed at determining when fusion power would make an attractive contribution to the future energy mix, and the steps needed to bring this about effectively. Main results of studies on safety and environmental impact issues, recent progress in developing the technology of fusion power and assessments of economic viability and social acceptance of fusion, in comparison with other energy sources, are outlined to substantiate these prospects.

Status of Progress in the Technology of Fusion

There has been great scientific and technological progress in developing fusion over the last decade. Fusion power production has been achieved in existing devices such as JET (*Joint European Torus*) at levels up to sixteen megawatts, though only for short time pulses (seconds). Whilst reasonable advances in physics are anticipated, no further technical or scientific breakthroughs are needed to produce fusion energy at power station scale.

Past studies have established the scientific and technical basis for the construction of an international device of the next generation. The engineering design activities of such a next step, ITER (*International Thermonuclear Experimental Reactor*), have been completed. The facility will demonstrate the scientific and technological feasibility of fusion energy through the achievement of long pulses of burning plasmas and the integration of key fusion technologies. Its cost is estimated at 3’500 million € to which approximately 700 million € must be added for personnel, research and development expenditures during the construction phase. Yearly operation costs are currently estimated at 240 million € and will cover personnel (about 33%), energy supply, tritium purchase, maintenance and waste disposal. Finally, after 10 or 20 years of operation, 430 million € will have to be spent on the dismantling of the facility.

Prototypes of most of the key components of a fusion power plant have been produced and successfully tested individually at close to the operating conditions. What is now needed are, firstly, the tests in ITER of tritium generation and energy extraction from blanket (plasma-facing inner wall of the reactor) modules prototyping the full size blanket of the

[5] A plasma forms when a gas is heated to such high temperatures (above 100 million °C) that atoms are stripped of their electrons.

[6] Activation of the reactor walls does occur, though : see p. 13.

future demonstration power plant and, secondly, the development of low activation and radiation resistant materials and their testing in conditions as close as possible to those of a fusion power station.

A materials research programme is of particular importance to provide solutions for a sustainable, environmentally benign and economically attractive fusion energy technology. In addition to the essential information provided by ITER on plasma facing materials, it is necessary to develop high performance, low activation materials for machines after ITER. This programme should be run in parallel with ITER, to ensure that the materials are ready when required, and should include new materials concepts. Low activation structural steels and vanadium alloys with good physical properties have already been produced, and irradiation testing in fission reactors has started. However, irradiation testing using appropriate high energy, high intensity neutron sources (such as the *International Fusion Material Irradiation Facility*, IFMIF, currently being designed under IEA auspices) is required to test and verify material performance when subjected to extensive neutron irradiation of the type encountered in a fusion power station. Before that, useful studies can be done using neutron spallation sources, in combination with modelling of radiation damage studies. The cost of IFMIF should amount to less than a fifth of that of ITER or well below 1'000 million €.

The main research thrust centred around ITER and IFMIF needs to be complemented by a strong accompanying programme carried out in national laboratories and facilities around the world. Such a programme will address questions of basic, experimental as well as theoretical, plasma physics, design novel materials and study alternative concepts, such as *stellarators* or spherical *tokamaks* [7], which might turn out in the end to provide a better basis for future commercial reactors than the current *tokamak* design on which ITER is based. In addition, several national fusion research centres have developed expertise in key auxiliary technologies that will be as essential for future developments as they were in the past; the accompanying programme also has the aim of maintaining and improving such expertise.

Thus, fusion power generation on a commercial scale is not dependent upon further scientific breakthroughs but is a matter of reasonable research and development including system optimisation through technological engineering advances and scientific innovation. This, in turn, requires a well co-ordinated international approach combining the use of large facilities (ITER, IFMIF) and adequate support for strong domestic research programs.

Security of Fuel Supply, Safety and Environmental Issues

Fusion power would enhance energy security and diversification as its primary fuels, deuterium and lithium, are plentiful, widespread and available at low cost. One tenth of a ton of deuterium and ten tons of lithium would be enough to fuel for one year a thousand megawatt electrical power plant requiring today two million tons of coal, or ten million barrels of oil, or one hundred tons of uranium. For example, the amount of deuterium that could be extracted from Lake Geneva would be enough to satisfy Switzerland's electricity

[7] The word "*tokamak*" is an abbreviation of the Russian phrase "toroidalnya kamera magnitnaya katuska" which means literally : toroïdal chamber magnetic coils. It is the most extensively studied concept for a magnetic fusion device, in which the plasma is heated in a doughnut-shaped chamber, and the most advanced facilities (JET, ITER, TCV, etc.) are based on that design; it is also a testimony to the important role played by Russian physicists, under the former Soviet Union, in the early stages of fusion energy research.

needs for several tens of thousands of years. Likewise, if the current total world electricity production was to be covered by fusion power stations, the amount of lithium needed (approximately 3.8 tons per GW-year) would only be 25% higher than the current pure lithium world production (6'000 tons per year), which represents a tiny fraction of world resources. Indeed, for all practical purposes, deuterium and lithium resources can be considered as quasi-unlimited.

There have been, during the last decade, many and extensive studies of the safety and environmental impact of possible future fusion power plants. These have convincingly shown that fusion has well-attested and attractive inherent safety and environmental features, as illustrated by the following points.

Fusion power stations will have only limited amounts of stored energy capable of driving accidents, as only a few minutes worth of fuel is present in the reaction chamber at any one time. It has been shown that the worst possible accident driven by in-plant energies would result in only very limited hazards to the public : maximal radiation doses would be comparable to those to which each individual is exposed every year from natural sources. Furthermore, the initiation and maintenance of fusion reactions requires such highly uncommon physical conditions that catastrophic spontaneous reactions are impossible and immediate shut down would follow a reactor failure. Finally, the consequences of a fusion plant accident caused by an external event such as a very large earthquake would be much smaller than the damages directly caused by the external event itself.

The operation of fusion power stations will make no adverse contribution to global climate change as no greenhouse gases are produced. The fusion process itself produces no radioactive or toxic reaction products. Although there is neutron-induced radio-activation of the machine structure during the plant operations, this would be sufficiently short lived that almost all, if not all, the materials in a fusion power station could be disposed of as non-radioactive waste, or recycled, or given shallow-land disposal a few decades already after the end of the plant life. There will not be a large waste burden for future generations.

Fusion power plants will make no use of uranium, plutonium or other fissile materials. None of the materials required are subject to the non-proliferation treaties, because none of them poses a security threat with respect to nuclear weapon development, a fact which also minimises the likelihood of a terrorist attack. Even small quantities of fertile or fissile materials illegally introduced into the plant could be readily detected since, as opposed to fission power station, these are not normal components of a fusion reactor.

One of the fusion fuels, tritium, an isotope of hydrogen which is produced in the fusion chamber by neutron-induced transmutation of lithium, is indeed a hazardous gas because of its radioactive nature. However, it has been the object of decades of study and, as a result, safe handling procedures are now well established. Furthermore, tritium is a short-lived radioisotope and, because of its continuous generation and consumption in the fusion reactor, it never accumulates to high levels and must not be stored and supplied from external sources.

The above safety and environmental advantages are already today a reality when power stations are designed using materials such as the reduced activation ferritic-martensitic steels that have been produced by industry for further qualification and which have been developed from experience accumulated with similar materials in nuclear fission technology. It is reasonable to expect that further safety and environmental advantages will be secured through the continuing development of these steels (e.g., micro-structural engineering) and through the development of advanced materials, such as vanadium alloys or silicon carbide composites.

Economics of Fusion Electricity

In the last few years, the economics of fusion electricity have been intensively studied and the main conclusions are summarised below. These investigations were performed in a way that was as independent of fusion programmes as was technically possible. The economic methodology, codes and calculations were standard, as recommended by several international agencies, including the IEA, and were verified by non-fusion experts. The components of economic performance fall into three areas : the internal costs of electricity generation; the associated external costs and the role of fusion power in total-cost-minimising future energy scenarios.

The term "internal costs" refers to the contributions to the cost of electricity from constructing, fuelling, operating, and disposing of, power stations. These direct costs of electricity generation by fusion, estimated currently by extrapolation from ITER costs, will eventually depend upon the extent to which fusion physics and materials are further optimised in the next few decades and this introduces inevitable uncertainties in making projections. However, the best available calculations show that, given only modest optimisation of fusion physics (which can be anticipated from current trends and would allow to achieve sufficient power plant availability) and use of materials currently in development, the direct costs of fusion electricity would be competitive in a future energy market.

Comparing the projected costs of electricity from energy sources producing base load power, the fusion costs are roughly comparable to those from clean (pollution abated) coal plants and about fifty percent larger than those from fission. They are also comparable to the published costs of electricity produced from typical renewable energy sources, even when a projected future decrease in the costs of renewable energy is introduced into the calculations. Furthermore, the same calculations show that the use of advanced materials, technology and physics would further decrease the direct costs of fusion electricity, approaching the costs from fission or unabated fossil fuels.

The internal costs of electricity generation do not include costs such as those associated with environmental damage or adverse impacts upon health. In the case of some of the present sources of electricity, these "external costs" are substantial and appreciation of their importance has become widespread in recent years. The external costs of fusion electricity – and the role of fusion in cost-minimising future energy scenarios – depend strongly upon fusion's safety and environmental characteristics. These issues can be assessed essentially without reference to any further developments in fusion physics or materials, since the full expression of the safety and environmental advantages of fusion can be gained with existing physics and only very modest and confirmatory materials development.

Fusion external cost calculations have been performed only for Western Europe and may yield significantly different results elsewhere. Nevertheless, they show that fusion, along with wind, belongs to the class of low external cost sources. By comparison, the external costs of electricity from present European coal-fired plants are twenty times greater, and about half of them is attributed to climate change. Since external costs of a given technology increase broadly in proportion with levels of gross domestic product per capita, but internal costs are only weakly so dependent, the relative importance of external costs is expected to grow in the future.

Public Acceptance and Potential Share of Fusion in the Future Energy Mix

External costs associated with climate change are particularly uncertain. An alternative way of taking such issues into account is to investigate the consequences of imposing constraints on the amount of electricity production that is allowed to take place from specific sources, and this method can also be used to introduce constraints arising from social acceptance problems.

Exploratory studies on social acceptance of fusion technology were initiated a few years ago in some countries. Social science investigations and experiments were performed at local level including involvement of the public in the decision process on the installation of large energy facilities. Past experience with (fission) nuclear energy as well as with large fusion experimental plants were taken into account. According to preliminary results, no specific public acceptance problems are expected for fusion if (and this is a significant "if") comprehensive information is made available and the public is actually and meaningfully involved in the decision process at an early stage. Of course, fusion energy decisions could also become caught up in broader political issues over energy.

To assess its market potential, fusion power was incorporated into existing self-consistent economic models that determine the optimal energy and technology mix to minimise costs and emissions in a competitive market. In such models, constraints may be imposed on energy production from specific sources to take into account technology limits, investment capability, environmental policies and social acceptance problems.

In studies using this approach, fusion power was introduced into modelling of energy scenarios, up to the end of this century, for Europe, North America, the Asia-Pacific region, India and world-wide. The most important constraints applied in these studies were on greenhouse gas production. As the operation of fusion power stations does not produces such gases, it is not affected by this constraint. A range of constraints was applied to nuclear fission, to reflect possible social acceptance difficulties. Because of fusion’s favourable safety and environmental features, it was assumed not to be subjected to these constraints. On the other hand, an important constraint was applied to fusion relating to limits to the speed with which it could be deployed.

These studies show, broadly, that fusion could bring a contribution of about twenty percent of the electricity supply by the end of this century, mainly constrained by the assumed rate at which it could be deployed (essentially, whether it develops along a “fast track” or along the reference roadmap : see below). This result holds even when a major role is allocated to nuclear fission. However, fusion would capture little or none of the market if there were neither environmental constraints nor economic development. Since the environmentally-constrained scenarios were constructed to be economically optimal, satisfying the demand without fusion would be much more expensive : the sums involved are huge, dwarfing the costs of fusion development.

The results coming from all the economic studies indicate that completing the development of fusion would bring substantial economic benefits. The amount of further optimisation in fusion physics and materials needed to secure these benefits depends upon the expected external costs of other power sources and upon the constraints placed on their deployment arising from social acceptance factors and the need to control environmental degradations. In regions with high externalities, such as Japan or Europe, or if environmental impact and/or social acceptance become predominant constraints, the economics of fusion power would be attractive given only modest and readily anticipated further optimisation of the technology. Additional developments in fusion physics concepts and advanced fusion materials would then bring further economic benefits.

Road Map for a Practical Development towards Fusion Electricity

Although the achievement of commercial fusion energy has often been criticised in the past as being an unreachable moving target, it is fair and accurate to state clearly that the scientific basis for fusion is much more firm now than it was a decade or so ago. Today, there is a credible predictive capability based on key results, simulation models, diagnostic measurements and detailed comparisons between theory and experiment.

The current reference roadmap towards commercial fusion electricity production foresees three successive generations of devices : first ITER, then DEMO, a power plant to demonstrate the operational feasibility, reliability and economic attractiveness of harvesting fusion energy, and finally PROTO, a commercial prototype power station. According to the baseline timetable, DEMO could achieve net electricity production about 35 years after the decision to construct ITER, and large scale electricity production could begin in the second half of the century. This reference roadmap also assumes that the parallel development of fusion materials and the demonstration of environmental and safety cases supporting wide use of fusion power are completed in time for DEMO. A few key figures illustrate the progress to be made. Whereas JET produced 16 MW of fusion power for 2 seconds in 1997 (Q [8] = 0.65), it is expected that ITER will produce 500 MW for 400 seconds (Q > 10) and DEMO, 2 GW in continuous operation (Q = 20-50).

The major technical progress, in both the physics and technology of fusion, made during the last decade and summarised above, has brought about a realisation that a "fast-track" development of fusion is now possible, if this is desired, if the necessary political decisions are swiftly taken, and if the corresponding investments are made in a timely fashion. Eventually, the total amount of funding to reach the long-term objectives could be reduced substantially, but at the cost of increased short-term funding.

When looking towards energy production on such a faster road map, the ITER project remains the essential next step, and construction of the facility should start as soon as reasonably achievable. It is designed to be a flexible test facility to demonstrate fusion physics at power-plant relevant scale, to produce a large amount of thermal power (500 MW) and to test key technologies and components of fusion power plants. The engineering design has been finalised, and a modest upgrading could be readily achieved over the life of ITER, by fully exploiting the inherent flexibility of its present design. Technical feasibility of fusion power would then be demonstrated on a 20 to 25 year timescale. With ITER, the emphasis will be placed on demonstrating sustained fusion power production and extraction, and the facility will serve as an enabling research machine regardless of the design of later commercial power plants possibly derived then from alternative concepts, such as *stellarators* and spherical *tokamaks*.

Furthermore, earlier commercialisation of fusion electricity is regarded as possible if key steps are combined or taken in parallel. In particular, an attractive option would be to combine DEMO and PROTO into a single step that should be designed as a credible prototype for a power producing fusion plant, albeit in itself not yet fully technically and economically optimised. The feasibility of such an option depends strongly on the development of adequate materials. Thus, it is imperative, in a fast track scenario, to initiate the detailed engineering design activities of IFMIF in parallel with ITER construction and, once done, to build the facility without delay.

[8] Q is the ratio of the fusion power produced over the external heating power provided to the plasma; this ratio shows that ITER will be the first machine producing an excess of power; for a fusion reactor, Q should be in the range of 40.

Conclusion

Until roughly the past decade, the development of fusion was held back by several technical difficulties. The most important was the initial lack of knowledge of the state of matter to be reached in order to allow a fusion power plant to work. The construction and operation of a series of experimental devices, and the testing of theoretical models on these devices, has resulted in the building up of the necessary experimental data and a predictive capability that allow us now to undertake with confidence the development of fusion as an energy source.

Indeed, in the last ten years, the dominant factor delaying the development of fusion has not been scientific or technical obstacles but the lack of effective commitment and decision-making at all political levels. In addition, fusion budgets, which account for about 11% of the total spending on energy technology R&D in OECD countries, have been decreasing from 1’000 million USD to less than 700 USD between 1990 and 1999. Without these serious obstacles, ITER would be a reality now.

Today, fusion development is an international effort attracting an increasing number of highly motivated actors. The core partners who have brought forward the current ITER design (Japan, Russia and the European Union, including Switzerland and most of the candidate countries) will soon be joined by Canada, the United States, China, Korea and possibly other countries as well (India, Brazil). Continued and expanding international collaboration is indeed needed to bring effectively fusion forward to the market. The time scale of the endeavour will be critically dependent upon the degree of synchrony achieved in the realisation of the two main next ventures : ITER and materials development, including IFMIF. This, in turn, is a matter of political will and financial means; the promises of fusion and the challenge of meeting future energy needs deserve that both be strong.

CHAPTER 2

FUSION RESEARCH IN THE WORLD

Introduction

Throughout 2002, the renewed interest in nuclear fusion as a credible energy option for the second half on the 21st century continued to grow, in spite of the fact that no major scientific or technical breakthroughs occurred. Attention was largely focused on ITER, and the ongoing negotiations for the realisation of the project made good progress.

Within Euratom, the major partner of Switzerland in fusion research, the year was mainly characterised by the final decisions about the 6th Framework Programme (FP6) and the resulting renewal of the fusion research agreements.

ITER

Proposed almost 20 years ago by Ronald Reagan and Mikhaïl Gorbatchev at the 1985 Geneva Summit, the project led to a first concept finalised in 1998 which foresaw a 7'000 million € facility capable of achieving ignition, that is a burning plasma producing enough energy to sustain fusion reactions without external energy input. The United States, then, for a combination of scientific, political and financial reasons, decided to withdraw from the project, and the remaining partners (Japan, Russian Federation and European Union) launched a new EDA (*Engineering Design Activities*) phase which was concluded in 2001. The scaled down project now proposes to build ITER for roughly half the price of the initial concept. The revised machine will not reach ignition, but it will lead to the production of a ten fold excess of energy for up to several minutes. Furthermore, the facility will provide for ample testing of critical components for a future demonstration power plant.

The publication of the *Final Design Report* launched a phase of intensive negotiations between the partners, soon joined by Canada. Under discussion are the legal status and organisation of the future ITER management (the so-called *ITER Legal Entity* or ILE), the choice of the site and cost sharing issues. The negotiations have been ongoing throughout 2002 and significant progress has been achieved on a number of issues. The CTA (*Co-ordinated Technical Activities*) were completed at the end of 2002 and detailed planning of the facility will continue in 2003 under the ITA (*ITER Transitional Arrangements*) until the ILE enters into force.

As far as the site is concerned, assessments of the proposals made by Canada (Clarington near Toronto), France (Cadarache in Provence) and Spain (Vandellòs near Barcelona) were performed and extended to the Japanese site proposed in 2002 : Rokkasho-mura in the northern part of Japan's main island. Not unexpectedly, all sites have been found to meet the technical specifications, and the decision will now move to a higher political level. The prospect for a European site, in particular Cadarache, appears quite good. The current planning still foresees that all critical decisions (ILE, cost sharing, site) will have been taken by the end of 2004, thus allowing ITER construction to start in 2005 or 2006.

It is a fact that the redesigned ITER project is attracting a lot of attention and is largely responsible for the mounting political interest in fusion in many countries. Indeed, even if official declarations to that effect were still pending at the end of 2002, it was clear that the USA would rejoin the project, that China and Korea would also start negotiating a participation, and that a number of other countries (India, Brazil) would express interest as well. Thus, ITER is likely to become a truly international project, of importance not only to highly industrialised economies but also for developing countries. Furthermore, it is noteworthy that the "fast track" road map to fusion commercialisation, outlined in the preceding chapter, is gathering even more support from the newcomers than from the core partners.

In December 2002, the ITER International Team Leader, Prof. Robert Aymar, was appointed Director General of CERN and will take office in January 2004. It is planned not to replace him but to appoint the Co-Leader, Dr. Y. Shimomura, Acting Leader, until the ILE enters into force and the ITER Director General is chosen.

Euratom fusion programme

Within the European Union, the *European Atomic Energy Community* (Euratom) has been responsible for almost 50 years for R&D activities in the field of controlled thermonuclear fusion. Although the corresponding programme is now part of the framework programmes, it is still a separate chapter subjected to the rules of the *Euratom Treaty* of 25 March 1957. This implies, for instance, that final decisions regarding programme content and funding are not taken by the European Parliament but by the Council of the European Union.

Accordingly, on 3 June 2002, the Council gave final approval for the "*6th framework programme of the European Atomic Energy Community (Euratom) for nuclear research and training activities, also contributing to the creation of the European Research Area (2002-2006)*". The programme content includes the continuing exploitation of the large European *tokamak*, JET (*Joint European Torus*), in Culham (UK), the European participation in the design and planning of ITER, and a large fusion physics and technology section, including materials research and the investigation of magnetic confinement concepts other than *tokamaks*.

Two main instruments are used to execute the programme : (1) the *Contracts of Association* between the European Union and about twenty national fusion research institutions (the so-called "Associations" ; for the situation in Switzerland, see next chapter) and (2) the *European Fusion Development Agreement* (EFDA), which deals mainly with the centralised activities around JET and ITER. These two instruments exemplify the peculiar situation of the Euratom fusion programme which includes both joint activities managed centrally by the European Commission and the EFDA leadership, and decentralised projects carried out in the Associations with the financial support of the programme.

With the June 3rd decision, a budget of 750 million € was definitely attributed to fusion in the 6th Framework Programme (FP6). Not only is this a significant decrease from the 5th Framework Programme (FP5 ; 788 million €), but the support to the national laboratories will have to weather a disproportionate share of the shortfall, since 200 million € of the total budget are set aside for ITER. In fact, compared to FP5, 40% less funding is now available for the Associations. Consequently, soon after the decision, the European Commission decided to lower from 25% to 20% the level of its support to ordinary, approved national research activities, and from 45% to 40% its support to priority items (defined as activities directly linked to ITER, or having been given priority status in the past, or carried out by more than Associations in co-operation). This evolution is placing practically all Associations in front of severe funding problems which will have to be solved nationally.

Because of the transition from FP5 to FP6, the implementing agreements covering the execution of the Euratom fusion programme all terminated at the end of 2002 and had to be renewed. Besides the *Contracts of Associations* and EFDA, three auxiliary agreements were also renegotiated : the *JET Implementing Agreement* (JIA), which covers the common use of JET by the Associations under EFDA, the *JET Operation Contract* (JOC) with

UKAEA (*United Kingdom Atomic Energy Commission*), which pays for the operation of the facility by the British agency, and the *Mobility Agreement*, which, as in many other European programmes, encourages personnel mobility at all levels by granting travel and secondment allowances. By the end of 2002, all agreements had been renewed, the *Contracts of Association* for one year and the others for two years.

In 2002, a new Director responsible for fusion within the Research Directorate General ("DG Research") of the European Commission was appointed after a long vacancy. The Spaniard Pablo Fernandez Ruiz took office early in the year and has expressed since, on several occasions, a strong support for fusion. Finally, in 2002 Euratom negotiated successfully two co-operation agreements, one with Kazakhstan and one with Ukraine.

EFDA and JET

EFDA activities are very much focused on ITER and a whole range of supporting technologies (plasma heating systems, diagnostics, heat exchange, tritium generation, etc.). An important aspect of these activities is the exploitation of JET. Since the European *tokamak* is based on the same concept as the one which will be used for ITER, it has become an ideal test bed for ITER systems and components, and it has been widely used in 2002 for that purpose. The current arrangement, whereby UKAEA is operating the machine and the European Associations, under EFDA and JIA, are using it, has worked smoothly. Other activities under EFDA cover materials research, including the European participation in the design of IFMIF, and studies of alternative magnetic confinement concepts, such a *stellarators*.

In 2002, EFDA-JET has been an active member of EIROforum (*European Intergovernmental Research Organisations Forum* : www.eiroforum.org), a loose association of the major European research facilities (CERN, ESO, ESA, EMBL, ESRF and ILL) which, among other activities, promotes public information. Thus, EFDA-JET participated in the initiative « Couldn't be without it ! » which explains why many every day commodities would not be available without scientific and technological R&D.

Finally, at the end of 2002, the EFDA Leader, Prof. Karl Lackner, resigned to go back to his research activities, and the search for a successor is in full swing.

IEA and IAEA

IEA, an agency of OECD, plays an important role in co-ordinating worldwide various topics of fusion-related research via *Implementing Agreements* (IA's) between participating laboratories. Eight such agreements are currently in force and cover a broad range of fields including *tokamak* physics, materials for fusion (IFMIF), *stellarators* and other alternative concepts of magnetic confinement, plasma/wall interactions, socio-economic aspects, etc. (the site www.iea.org/impagr/imporg/impagpub/listof.htm#5 gives a list and a short description of current IA's in the field of fusion). Although the financial investment of IEA in those activities is modest, usually limited to administrative support, the importance of its co-ordinating role cannot be overemphasized. In 2002, the *Fusion Power Co-ordinating Committee* of IEA, which supervises the IA's, produced two interesting summaries of the current status of fusion research. This was in answer to a request by the *Committee on Energy Research and Technology* of the Agency and is the source of most of the information given in chapter 1 of the present report.

Besides providing administrative support to ITER, the **IAEA**, a specialised organisation of the United Nations, also has a number of activities related to nuclear fusion and steered by an advisory body, the *International Fusion Research Council* (IFRC). In 2002, the most visible event was the *Fusion Energy Conference* (FEC), which is organised every two years and which took place in October in Lyon, France.

Other international news

In the **USA**, as already mentioned, renewed interest for magnetic fusion made it practically certain, by the end of 2002, that it would rejoin ITER. The robustness of the current design did a lot to convince the Americans that the project is now scientifically, technically and financially sound, but the unwillingness of the Bush administration to impose significant penalties for energy wastage or to encourage seriously energy conservation measures was pulling at the same rope.

The U.S.A. is one of the few countries in the world which has a significant inertial fusion programme. In this totally different approach to generate fusion energy, small pellets of deuterium and tritium are compressed to enormous pressures, thus forcing atomic nuclei to fuse. The approach, which has mostly been investigated in the shade of military research (because the technology is also used to simulate thermonuclear explosions), is generally regarded as far less mature than *tokamak*-based magnetic fusion and still has to pass through a number of critical milestones to demonstrate its feasibility and practicability. Nevertheless, the USA. is building (with huge delays and cost overruns) a *National Ignition Facility* (NIF) which will use intense laser beams to compress fuel pellets, whereas other US laboratories are investigating alternative approaches to compression, such as X-rays.

Finally, an article in *Science* magazine attracted some attention in the Summer of 2002. It was about an experiment at Oak Ridge National Laboratory in which fusion reactions reportedly occurred in solutions of deuterated acetone subjected to sound waves and neutron irradiation (so-called “table-top fusion”). To date, the results have not been reproduced though, neither by the original authors nor by any other laboratory, and it seems likely that table-top fusion will share the fate of "cold fusion" over a decade ago and fall into oblivion. Yet, the excitement it generated within a few days of publication is another sign of the very strong underlying eagerness to produce and harvest fusion energy.

In **Germany**, construction of the Wendelstein 7/X *stellarator* in Greifswald (Mecklemburg-Vorpommern) was considerably delayed by severe problems with the delivery of super conducting elements. As a consequence, the first operation of the facility is not expected before 2009-2010.

In **France**, the *Tokamak Tore Supra* at Cadarache produced in June 2002 a 3.5 minute long plasma discharge : this is the world record of duration.

Finally, the *Symposium on Fusion Technology* (SOFT) gathered over 400 researchers in Helsinki in September 2002.

CHAPTER 3

FUSION RESEARCH IN SWITZERLAND

Introduction

Research in the field of controlled thermonuclear fusion is hardly possible today without broad international co-operation, especially for smaller countries like Switzerland. Accordingly, the Swiss activities in this field are practically entirely integrated into the EURATOM fusion programme of which Switzerland has been a full member since 1978. Furthermore, some research projects are carried out within the framework of *Implementing Agreements* of the IEA and, finally, there are also a number of activities done within bilateral or multilateral collaborations with other fusion research laboratories. All this is financed by the Swiss Federal Institutes of Technology (including Paul Scherrer Institute), by the Swiss National Science Foundation and by the EU.

Major player is the *Plasma Physics Research Centre* (CRPP) of the *Federal Institute of Technology* in Lausanne (EPFL) with its two sites at the EPFL and at the *Paul Scherrer Institute* (PSI) in Villigen, near Zurich. In Lausanne, besides a strong theory group, the CRPP relies on its large facility, TCV (*Tokamak with Variable Configuration*) to study basic fusion plasma physics. In fusion technology; the centre has acquired international recognition notably for its expertise in heating systems using cyclotron-electronic waves. At PSI, the interest of the CRPP group lies in materials research with the proton irradiation facility PIREX, and in superconductors with the worldwide unique test stand SULTAN.

With the financial support of the *Swiss Federal Office of Energy* (SFOE), a unit of the *Department of Physics* of the *University of Basle* has been co-operating for many years with the CRPP in studying surface changes resulting from exposure to hot plasmas. The group capitalises on the expertise it has acquired in photoelectron emission spectroscopy and related techniques to analyse graphite tiles coming from the inner wall of TCV.

Energy research in Switzerland is co-ordinated – and partly financed – by SFOE, but fusion research is under the supervision of the *Federal Office for Education and Science*, for this is the administrative unit which manages the participation of Swiss scientists to EU programmes. This is why the author of the present report acts as head of project for controlled thermonuclear fusion in the overall energy research organisation of SFOE.

Agreements between Switzerland and Euratom

The *Co-operation Agreement in the Field of Controlled Thermonuclear Fusion and Plasma Physics* between Switzerland and the European Atomic Energy Community (Euratom) of 14 September 1978 remains the legal basis for an ongoing co-operation which has led to an almost total integration of Swiss fusion research activities into the European programme. It is a broad agreement of unlimited duration unless denounced by one of the two parties. The work programmes and the financial boundaries of the research activities carried out under the agreement are defined in implementing agreements of limited duration concluded between the executive branches of both parties, namely, the Federal Council for Switzerland and the European Commission for Euratom. Currently, four such agreements are in force :

- The *European Fusion Development Agreement* (EFDA : see page 20) ;
- The *Jet Implementing Agreement* (JIA : see page 20) ;
- The *Agreement on the Promotion of Staff Mobility in the Field of Controlled Thermonuclear Fusion* (Mobility Agreement, see page 20) ;
- The *Contract of Association* which deals specifically with the bilateral co-operation between the CRPP and the Euratom fusion programme; formally, the work programme is carried out by the so-called *Association Euratom - Confédération Suisse*, which, *de facto*, means the CRPP.

All four implementing agreements terminated at the end of 2002 and had to be renewed for the start of FP6. The decrease in the community support to national activities (see page 20), resulting from the lower fusion budget in FP6 and the priority given to ITER, led to some tough negotiations to agree on the financial ceilings of the *Contract of Association*, but, eventually, the Swiss Federal Council could adopt the amendments to all four agreements on 9 December 2002. Whereas EFDA, JIA and *Mobility Agreement* have been renewed for two years until the end of 2004, the *Contract of Association*, as requested by the European Commission, is only in force for one more year and a further renewal will have to be negotiated in 2003.

Under these various implementing agreements, the yearly contribution of Switzerland to the Euratom fusion programme amounts to almost 10 million Swiss francs and is likely to remain at a similar level for the coming years. On 6 June 2002, the Swiss Parliament approved the budgets requested by the Federal Council to finance the participation of Swiss scientists in FP6 between 2003 and 2006, and these budgets also cover the Swiss contribution to Euratom. However, because of the decreased EU support for the research activities of the CRPP, an increase in domestic funding for the Lausanne centre is needed in order to ensure an unchanged level of activity. Ways and means to secure such an increase are currently being explored.

The Association Euratom - Confédération Suisse

Except for a small unit dealing with industrial applications of plasma physics (and whose activities are not reported here because they fall outside the scope of the Association), the CRPP is fully integrated within the Euratom fusion programme and its research plan is defined, in particular, in the *Contract of Association*. In Lausanne, the main emphasis is put on the experimental and theoretical study of hot plasmas but, as it is also essential to master technologies required to build a fusion reactor, two groups of CRPP at PSI are actively involved in superconductivity research and in the development and test of low activation materials. Besides its own research activities, the CRPP also participates, through EFDA and JIA, in the scientific exploitation of JET, in the ITER project and in other European and international co-operative projects.

The scientific output of CRPP has been widely publicised throughout the year in major international conferences and in numerous articles in specialised journals. The CRPP organised in June 2002 in Montreux the *29th EPS Conference on Plasma Physics and Controlled Fusion* of the *European Physical Society* with over 700 participants. A detailed report on the research activities briefly summarised below can be found in the Annual Report of the CRPP which can be accessed through its web site (crppwww.epfl.ch).

From an academic point of view, 2002 saw the integration of the CRPP in the newly created *Faculty of Basic Sciences* of EPFL. Finally, in September, CRPP was host to the *Swiss Federal Commission for Energy Research* (CORE), an advisory body to the government; through a visit of the facilities and through presentations given by the ITER International Team Leader, Prof. Robert Aymar, the Head of the fusion programme in the European Commission, Prof. Hardo Bruhns, and the Director of CRPP, Prof. Minh Quang Tran, the Commission got a first hand and up to date report on the current status of fusion research.

Physics of **Tokamak** *on TCV*

Experimental *tokamak* physics research is performed using TCV, taking advantage of the unique capability of this state-of-the-art machine to produce hot plasmas with variable shapes. This is an attractive feature for the research programme which will accompany ITER construction and exploitation, and CRPP is thus well positioned to play an important role there.

In 2002, TCV was operated using its world most powerful cyclotron-electronic heating system at 3 MW (82.7 GHz) or 1.5 MW (118 GHz). Among the most salient results, mention is made here of :

- the extension of the operating range of TCV using cyclotron-electronic heating ;
- further studies on the influence of plasma shape on its physical properties from edges to core ;
- studies on the absorption of cyclotron-electronic waves at third harmonics ;
- further important observations relating to density limits, ITER relevant H modes, divertor physics and internal transport barriers.

Theoretical Studies and Numerical Simulation

Investigations in these fields rely heavily on numerical simulation models using the most performing massively parallel computers available in Switzerland (at EPFL and at the *Swiss Centre for Scientific Computing* in Manno) and in Europe (*Max Planck Institute* in Germany).

Ongoing studies are aiming at :

- improving our understanding of transport phenomena in magnetically confined fusion plasmas : emphasis here is on abnormal transport caused by micro instabilities such as waves that have become unstable because of ionic temperature gradients ;
- providing theoretical and interpretation support to experiments using TCV, JET or other *tokamaks* : here, plasma/cyclotron-electronic wave interactions, on the one hand, and neo-classical tearing modes, which can limit the performance of future fusion reactor, on the other hand, are main study topics ;
- exploring new optimised tri-dimensional confinement structures : these studies concern not only the magnetic configurations themselves but also heating of the confined plasma by absorption of electromagnetic waves.

Plasma heating technology

Over many years, CRPP has acquired an internationally acknowledged expertise in the field of heating systems for magnetically confined plasmas using electromagnetic wave absorption at cyclotron-electronic frequencies. This has led to an active involvement of the Lausanne centre in the development of the corresponding wave sources, so-called gyrotrons, for TCV and other European facilities, such as *Tore Supra* in France or *Wendelstein 7/X* in Germany. For the latter, in co-operation with the *Forschungszentrum Karlsruhe* and the industrial firm *Thalès*, a gyrotron capable of delivering 0.85 MW during 180 seconds was tested at 140 GHz. This is a world record for this type of device.

Contributions to international projects

Through the Euratom fusion programme and, in particular, EFDA, CRPP is participating in most projects which are part of the programme, such as ITER, JET and other European facilities. Accordingly, and in spite of heavy commitments linked to the exploitation of TCV, CRPP was fully involved in the exploitation of JET.

As far as ITER is concerned, several members of CRPP participate as experts in scientific committees. Most importantly, CRPP was selected in 2002 by the European Associations to co-ordinate and integrate all European activities related to the development and procurement of cyclotron-electronic wave systems on ITERs. This will cover two aspects : (1) the development and test of gyrotrons and (2) the design of an appropriate antenna to target cyclotron-electronic waves into ITER plasma. To this aim, a test stand for gyrotrons and antenna components will be built in Lausanne.

Finally, CRPP, through its Materials Group at PSI, continued to be an active participant in the *IEA Implementing Agreement on Fusion Materials*, the Executive Committee of which is chaired by a CRPP-PSI staff member, Prof. M. Victoria. In this way, CRPP is actively involved in the design of IFMIF.

Development and test of superconductors

The SULTAN test stand of CRPP is also located at PSI and its operation is supported by PSI [9]. As the only facility in the world suitable for testing the super conducting cables of ITER, it will play a crucial role throughout ITER construction, and it is the intention of the European Commission to offer the quality assurance testing of all the cables at SULTAN as part of the European, in kind contribution to ITER construction.

In 2002, activities in the field of superconductivity have been focused around the development of niobium- and titan-based cables and cable junctions for ITER. Detailed studies using SULTAN of Nb_3Sn threads isolated from cables led to a better understanding of the problems which arise when one extrapolates from the properties of individual threads to those of the full cable.

CRPP expertise in this field also includes high temperature superconductivity. In 2002, 70’000 A current leads for ITER were designed using high temperature superconductors and will be tested in 2003 at the *Forschungszentrum Karlsruhe*.

Materials R&D for ITER and fusion reactors

A critical milestone of the road map leading to fusion reactors is the development of materials which, under heavy neutron irradiation, undergo only weak and short-lived radio-activation while keeping their thermo-mechanical properties unchanged. The Materials Group of CRPP located at PSI has a considerable interest in studying this problem. Again with the support of PSI, a proton irradiation facility, PIREX, has been exploited for many years. Obsolescence and the costly investments needed to refurbish it led in 2002 to a decision to phase it out at the end of 2003. A new agreement with PSI now allows irradiation studies to be done at the Swiss spallation source SINQ. Indeed, a recent study carried out in the framework of the *IEA Implementing Agreement on Fusion Materials*

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[9] A formal research agreement in the field of fusion between EPFL and PSI defines the level of support the latter institution grants to the activities of the CRPP Materials Group and Superconductivity Group.

concluded that the use of such sources, combined with modelling studies, can yield useful results before IFMIF comes on line.

A unique feature of PIREX and SINQ is the fact that, at both facilities, the formation of helium inclusions in metallic alloys and their influence on thermo-mechanical properties can be investigated. As this is viewed as a critical problem of future fusion reactors, CRPP is well positioned to play an major role in the corresponding studies. In this respect, priority is now placed on thermo-mechanical properties of ferritic-martensitic steels, such as Eurofer, which are the currently favoured materials for fusion reactors.

To interpret correctly the results of future neutron irradiation experiments using IFMIF, it is essential to compare the data of mechanical tests performed on small samples with those obtained with normalised probes, and this is another focus of the CRPP Materials Group at PSI. Finally, further research activities in this field include physical metallurgy, modelling of irradiation damages, the physics of fractures and electron microscopic studies of model metals or alloys.

Research done at the University of Basle

Within the *Physics Department*, the group of Prof. Peter Oelhafen has acquired considerable expertise in the use of photoelectron emission spectroscopy and related techniques, which are particularly suited to study surface phenomena. For many years, the group has been analysing graphite tiles coming from the inner wall of TCV in order to characterise the surface changes caused by exposure to hot plasmas, indeed a critical question for designing future fusion reactors. These studies were continued in 2002 with greater detection sensitivity and extended to a surface depth of 10 micrometers, thanks to the use of proton induced X-ray emission and Rutherford backscattering, in cooperation with a group at the University of Freiburg-in-Breisgau (DE). Whereas previous results regarding carbon, boron and oxygen were confirmed, the use of the new techniques revealed a very low and previously undetected level of surface contamination with iron, nickel, copper and chromium.

In addition, 2002 has seen the initiation of investigations with high Z-materials such as tungsten and, in later studies, vanadium : deposition techniques have been developed and tested. Finally, contacts have been re-established, after several years of interruption, with the *Forschungszentrum Jülich* (DE) in view of a renewed participation of the Basle group in studies carried out in the framework of the *IEA Implementing Agreement "Plasma/Wall Interactions in TEXTOR"*.

ADDITIONAL INFORMATION

The following web pages provide much additional information on all the topics discussed in this report :

Energy in general

International Atomic Energy Agency IAEA : www.iaea.org

International Energy Agency IEA : www.iea.org

Switzerland : www.suisse-energie.ch

ITER

www.iter.org

Euratom

European Fusion Development Agreement EFDA : www.efda.org

Joint European Torus JET : www.jet.efda.org

European Commission : europa.eu.int/comm/research/fusion1.html

Framework programmes of the European Union : www.cordis.lu

IEA Implementing Agreements

www.iea.org/impagr/imporg/impagpub/listof.htm#5

Switzerland

Plasma Physics Research Centre CRPP : crppwww.epfl.ch

University of Basle : www.unibas.ch/phys-esca

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ABBREVIATIONS

CERN : European Laboratory for Particle Physics
CERT : Committee on Energy Research and Technology
CRPP : Plasma Physics Research Centre
CTA : Co-ordinated Technical Activities
DEMO : Demonstration fusion reactor
EDA : Engineering Design Activities
EFDA : European Fusion Development Agreement
EIROforum : European Intergovernmental Research Organisations Forum
EMBL : European Molecular Biology Laboratory
EPFL : Swiss Federal Institute of Technology in Lausanne
EPS : European Physical Society
ESA : European Space Agency
ESO : European Southern Observatory
ESRF : European Synchrotron Radiation Facility
EU : European Union
Euratom : European Atomic Energy Community
FEC : Fusion Energy Conference
FP5 : 5^{th} Framework Programme
FP6 : 6^{th} Framework Programme
FPCC : Fusion Power Co-ordinating Committee
GHz : gigahertz
GW : gigawatt
IA : Implementing Agreement
IAEA : International Atomic Energy Agency
IEA : International Energy Agency
IFMIF : International Fusion Materials Irradiation Facility
IFRC : International Fusion Research Council
ILE : ITER Legal Entity
ILL : Laue-Langevin Institute
ITA : ITER Transitional Arrangements
ITER : International Experimental Thermonuclear Reactor
JET : Joint European Torus
JIA : JET Implementing Agreement
JOC : JET Operation Contract
MW : megawatt
NIF : National Ignition Facility
OECD : Organisation for Economic Co-operation and Development
OFEN : Swiss Federal Office of Energy
PIREX : Proton irradiation facility
PROTO : Prototype fusion power plant
PSI : Paul Scherrer Institute
SINQ : Swiss spallation neutron source
SOFT : Symposium on Fusion Technology
SULTAN : Superconductor test stand
TCV : *Tokamak* with Variable Configuration
UKAEA : United Kingdom Atomic Energy Agency