FIVE YEAR ASSESSMENT REPORT

RELATED TO THE

SPECIFIC PROGRAMME:

NUCLEAR ENERGY

COVERING THE PERIOD 1995 - 1999

The Panel:

Nuclear Fusion

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Foreword

The specific EURATOM Programme comprises two key action, "Controlled Thermonuclear Fusion" and "Nuclear Fission, generic research on Radiological Sciences and Support for Research Infrastructures". This programme is being implemented through indirect research and training actions as provided for in Annex III to the 5^{th} Framework Programme. The strategic goal of the specific programme is to continue the implementation of the established EURATOM Programme in line with the requirements of the EURATOM Treaty, which aims to help exploit the full potential of nuclear energy, both fusion and fission, in a sustainable manner.

The historical background and activities within the Nuclear Fusion and Nuclear Fission Programmes are very different in nature. The Fusion Programme embraces all the research activities undertaken in the Member States (plus Associated countries) aimed at harnessing fusion, to enable the joint creation of prototype reactors for power production to meet the needs of society. The overall objective has been to establish the scientific and technological base the "next step", meaning the next generation of machines after JET. Whilst the Fission Programme provides a more broadly based support to a range of scientific and technical projects aimed at enhancing the safety of Europe's nuclear installations, improving the competitiveness of Europe's industry, ensuring the protection of workers and the public from radiation and helping to solve waste management and disposal problems.

Due to the very different nature of these key actions, it was decided by the European Commission to constitute separate 5 year Assessment Boards for the Nuclear Fusion and Nuclear Fission areas. These Boards have worked independently and the results of their assessment are presented as two separate self-contained reports. The Executive Summaries of these reports are presented in the following two sections.

Executive Summaries and Recommendations

Specific Programme: Nuclear Energy - Nuclear Fusion

- INTRODUCTION

Future long-term energy scenarios show a steady increase in world-wide energy demand, driven by the increase in the global population and the rapid growth in energy consumption per capita in the developing economies. In parallel, there is an increasing awareness of the environmental impacts of energy such as the climate change impacts arising from the burning of fossil fuels. Consequently, the need for new non-polluting and sustainable forms of energy is growing. The harvest of renewable energy is already partly developed but there are issues associated with its availability, location and integration into the network; nuclear fission is another available option although there are concerns about its safety and the long-term issues of waste disposal. Fusion still requires further research and long-term development but appears to have the potential to provide a CO_2 emission-free, sustainable, safe and clean high-density energy option.

- OBJECTIVES

The long-term objective of the European Fusion Programme is to embrace all the research activities undertaken in the Member States (plus Associated countries) aimed at harnessing fusion, and to enable the joint creation of prototype reactors for power production to meet the needs of society. During the past 5 years, activities to establish the scientific and technological base for the ‘Next Step’, a machine demonstrating a burning plasma under reactor conditions, have been a major focus of the programme. In the 4th and 5th FPs this has centred on ITER, and Europe has been an active participant in the engineering design activities together with Japan, the Russian Federation and the USA.

- MAJOR ACHIEVEMENTS

The Fusion Programme is probably the best example of European Added Value in the Community’s R&D Programme and can be considered as a model for the European Research Area. The good co-ordination and co-operation between the Community and national research programmes has enabled far greater achievements to be made than would be possible at a national level. During the last 5 years, the Programme has produced a wealth of high quality results in line with its objectives. The major European activity at JET and in the ITER Project has brought world visibility and has established Europe in the leading role in fusion activities world-wide.

The JET Programme has met all the objectives defined in the 1978 Council Decision and those of subsequent extensions and has exceeded original expectations; JET remains the most relevant machine for supporting reactor-orientated fusion research world-wide and is currently the only tokamak capable of D-T operation. The work on JET is complemented by the studies on concept improvement, long-term technology and safety and environmental studies, undertaken within the national research institutes in Europe, using a range of fusion machines. Together, these activities have enhanced the level of understanding in fusion science, demonstrated a number of the key features of the technical design for a ‘Next Step’ machine and enabled the development of a detailed and fully integrated design for such a machine.

Major achievements towards the ‘Next Step’ during the period include:

- Successful D-T campaign resulting in the production of record fusion power at JET (>16 MW for about one second, and 4-5 MW for about 4 seconds, generating 22 MJ of fusion energy) and the demonstration of alpha heating, a pre-requisite for the ‘Next Step’.
- Demonstration of ‘Next Step’ relevant technologies such as remote handling complex in-vessel components and closed cycle tritium handling.
- A substantially increased level of involvement by European industry, both in the assessment of ITER design reports and in the construction of components. For example, the fabrication of a large superconducting model coil (scale 1:3) for ITER.

The programme has contributed to the development of a strong and competent scientific, technological and industrial community. During the past 5 years, the programme has directly employed around 2000 scientists and engineers (including about 250 PhD students). It has directly contributed to Community policies on training and has the highest level of mobility of researchers of any European Programme at around 500 person-months per year.

European industry has grown in competence together with the fusion programme and can provide all the manufacturing and technical support required by the programme. The high level of technical sophistication and exacting requirements of the programme in areas such as superconductors, remote handling, vacuum technology, power electronics and brazing and welding, has enhanced the skill base and the quality of standards found in European industry. This has led to substantial developments in their specialised capabilities, personnel enhancement and the quality of their products.

Europe now has by itself all the required technical, engineering and industrial capabilities to proceed to the ‘Next Step’ and take the fusion programme forward.

- LESSONS LEARNED AND CONCLUSIONS

Many lessons have been learned from the Fusion Programme of which the following three are of particular importance:

- Large, long-term R&D projects require strong and constant sponsorship and high profile and competent leadership. In the past, the European Union (and some Member States) have given such sponsorship to the Fusion Programme and, in particular, to JET. This allowed the programme management to exploit the Programme very effectively.

  ITER, in its highly international configuration (which has inevitably introduced complications both at the strategic and management level), seems to have progressively lost sponsorship, despite the excellent work done by the entire ITER team. The US withdrawal from ITER (1998) and the financial crisis in the Russian Federation has led to the requirement to redesign a lower cost New-ITER with less ambitious objectives. Moreover, international uncertainty still exists.

- Such long-term, challenging and costly programmes require a firm, stable and powerful legal framework within which to be managed. Again, the JET experience is meaningful and, with the obvious adaptations to the new context, a legal framework with greater management responsibilities coherent with the requirements of the Next Step will have to be adopted.
- The fusion community has always stressed the differences between fission and fusion in terms of safety and environmental impact, and all the studies done in the recent years confirm this point. Nevertheless, the general public still tends to view the two technologies in the same light. More attention is required on this issue.

During the last 5 years, the programme has achieved very important results, confirming fusion should now be considered as a credible option in the search for clean, large-scale power generation systems. Nevertheless, there are still a number of important scientific, technological and engineering issues to be addressed before a commercial power plant can be realised. At least two more generations of machines are envisaged before building a prototype reactor and, based on present planning, large-scale electricity would be produced in around 50 years. Recent history has shown how sensitive the Programme is to delays in the decisions. The postponement of the construction of ITER has already introduced a delay of almost 10 years.

From the organisational and programme point of view, the last 2 years have been particularly complicated for the Fusion Programme due to the need for new organisational structures and framework agreements and due to the high level of uncertainty regarding the ‘Next Step’. The Board’s impression is that, in spite of this situation, the programme has been well co-ordinated and efficiently run by the Commission as shown by the results obtained.

- RECOMMENDATIONS

1. The European Fusion Programme has helped to place European science, technology and industry at the leading edge of development in this sector and this advantage should be defended and possibly increased.
2. The European Fusion Programme should continue to be reactor orientated and the construction of the 'Next Step' should be started in FP6. This should be the first priority and some of the budget should be specifically earmarked for the Next Step. The budget should be at least at the present level, although a constant budget may lead to a reduction in the funding available for the other activities. If the budget continues to remain at the same level in FP7 and FP8, the Board believes it will still be possible to finance the completion of the construction of the Next Step, provided there is a reorientation of the activities in the national research institutes.
3. To proceed with the ‘Next Step’ in the international collaboration perspective of the New-ITER, the European Union should within the next 2 years:

- Conclude negotiations on the legal and organisational structure of the future venture

- Actively seek a European site for the New-ITER, since this is the best option from a European viewpoint.
- Conduct a thorough review of the financial issues, including the different financial costs and benefits of siting it in Europe, Canada or Japan, and establish the extent to which Japan would support the construction of New-ITER outside Japan.
- Examine in detail the recent interesting expression of interest received from the Canadian Consortium.

4. In the same 2-year period, due to the uncertainty over the outcome of the international negotiations, Europe should study an alternative to New-ITER, which would be suitable to be pursued by Europe alone. For example, a copper magnet machine which would still achieve the required objective of demonstrating a burning plasma under reactor conditions even if this would delay the integration of the superconducting technologies. Europe would then be ready by mid FP6 to drive forward the development of fusion even in the event of a further lack of positive decision on the construction of the New-ITER.
5. In the meantime, in FP5, limited investment on JET should be allowed to exploit the full value of the machine. This will also enable the fusion community to further prepare for the operation of the 'Next Step'.
6. The Fusion Programme, as part of a long-term sustainable energy policy, is highly demanding from a political and operational viewpoint and requires renewed support from the political authorities with an explicit endorsement of the tight timescale suggested for the 'Next Step'.

   In view of the Programme's evolution to a more managerial phase, a more innovative operational solution should be studied, to be approved together with FP6. There are several alternatives, such as an agency in charge of the entire fusion programme (and EFDA could be considered as a first step) or a legal entity belonging to Euratom, to be responsible for the implementation of the Next Step including the management of the money earmarked for this specific objective. In any case, the Committee structure governing the fusion programme should be streamlined.
7. Following a positive decision on the construction of the Next Step, a refocusing of the European Programme will be required. For this purpose, a critical assessment of the different European machines and their funding should be undertaken.
8. A Materials Research Programme is necessary to develop high performance, low activation materials for machines after the 'Next Step'. This programme should be run in parallel with the 'Next Step' to ensure the materials are ready when required and should include new materials concepts. It is recommended that international discussions on a 14 MeV neutron source Materials Testing Facility or alternative testing solutions are brought to a decision on a timescale consistent with reactor development.
9. The public acceptance of fusion is a key factor in its development as an energy option. Concern on this point has been expressed in several of the recent annual monitoring reports for the fusion programme despite increased effort on the safety and environmental aspects of fusion. Environmental issues should be considered as a full programmatic action, using a broader and more structured approach, in parallel to reactor development (Figure 6 in the report). The programme should

continue to address issues such as fuel cycle management, waste management and recycling and all the safety aspects. In the short-term, a small Working Group could be set up to review the safety and environmental results obtained to date and to actively promote the benefits of fusion power to a broad range of political and public stakeholders.

10. There are various examples where there has been the transfer of technologies, skills and experience from the fusion programme to other areas of science and technology, and evidence for the transfer of know-how and experience to European industry. Such transfers should be exploited in a more structured and entrepreneurial way in response to market demand.

Specific Programme: Nuclear Energy - Nuclear Fission and Radiological Sciences

This report covers the 5 years assessment of the research performed in the period 1995-1999 under Nuclear Fission Safety in Framework Programme 3 (FP3) (1990-1994), Framework Programme 4 (FP4) (1994-1998) and Key Action 2: Nuclear Fission and Research of a Generic Nature in Radiological Sciences in Framework Programme 5 (FP5) (1998-2002) under the heading of Research and Training in the Field of Nuclear Energy. It is presented in the format of FP5. The overriding objectives of this field of activity are to enhance the safety of Europe's nuclear installations and improve the competitiveness of European industry. Within these broader objectives, the more specific aims are

- to contribute to the protection of workers and the public from radiation and the safe and effective management and final disposal of radio-active waste,
- to explore innovative concepts that are sustainable and have potential longer term economic, safety, health and environmental benefits,
- to contribute towards maintaining a high level of expertise and competence in nuclear technology and safety and
- to contribute towards the safe and competitive use in other industries and medicine of ionising radiation and towards the safe management of natural sources of radiation.

This area of research has been developed over many years and these objectives are to be seen in the light of continuous progress towards a coherent but evolving body of knowledge. The achievements of the programme during the past five years are many and diverse and are summarised below. Overall we believe that the standard of scientific quality has been maintained at a high level and that much European Added Value has been achieved through joint projects, networking, information dissemination and a general improvement in understanding of common problems. The research has been of value to a number of end users, including Industry, Regulators, Research Institutes and more generally to people involved in the use of or exposure to radiation However, we note that the resources available to this important area of research have been reduced during the evolution of FP3 - 4 - 5 to the point now that some of the basic objectives for operational safety, radiation protection and waste can no longer be achieved. In addition this could threaten the essential continuity of research in an area which depends on long term development.

The processes of management of the programme are improving, but are still heavily bureaucratic and cumbersome. This could be improved by giving more authority to Commission staff to manage once agreement has been reached on the overall objectives and content of the programme. In a similar vein, project co-ordinators need to be able to show more flexibility and leadership once projects have been awarded.

Major Achievements. There have been many significant achievements from the diverse and comprehensive coverage of research topics in this area. These are highlighted below according to the headings of FP5. More detailed descriptions are available in the main text under the same headings.

Operational Safety of Existing Installations.
Plant Life Extension. This area of Research was not identified separately in FP4, but a number of projects of relevance were carried out. These have lead to a much better appreciation of the interacting aspects of materials performance which have to be drawn together to optimise plant life management. Thematic networks have been very successful in this area, leading to, for example, laying the ground work for qualification and industrial validation of methods for the non-destructive examination techniques for aged material. Future work should be focused on the needs of Regulators.
Severe accident management. Research in this area has made an important contribution to an international effort over many years to develop an understanding of severe accident (core melting) phenomenology. Whilst an area as complex and diverse as this is never likely to be "closed", it is clear that a degree of maturity has been achieved and this has lead to the direct use of the research results in developing severe accident management schemes, both preventative and mitigative, and in providing a sound basis for innovative new designs. Specific results in severe accident research that underpin these conclusions include:

- The improved understanding of the coolability of corium ex-vessel.
- The reduction in the estimated likelihood of a major in-vessel steam - explosion.
- The improved understanding of the deflagration of hydrogen leading directly to better methods of control.
- The minimisation of the threat to containment from Direct Containment Heating (DCH).
- A better understanding of the leakage of aerosols through micro-cracks in concrete leading to a reduction in the expected fission product release following a severe accident.
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Safety of the Fuel Cycle. This area covers a very diverse range of issues. Questions of spent fuel management and disposal are often dealt with at a national level, but there are a number of common issues, such as repository performance assessment. The balance of research has shifted from waste management (which are relatively near term issues) to Partitioning and Transmutation (which is increasingly seen as being very long term). This is reflected in our recommendations.

In waste and spent fuel management and disposal a number of projects have been particularly successful. These include:

- Experiments in underground Research facilities have been the focus of international collaboration. Eventhough the EC funds only a small fraction of these major long term projects, it gets good added value through encouraging team work and sharing results.
- The Spent fuel Performance Assessment Project (SPA) covered all elements needed to come to a total system analysis of spent fuel disposal in various host rock

formations. Major achievements were made in the linking of laboratory work, data from field experiments and modelling. This showed clearly where there were still deficiencies in knowledge and challenges for strategy. Progress was also made through the input of natural systems studies.

- Many uncertainties remain that need to be clarified through continued basic studies. Studies on basic phenomena such as natural analogue projects (e.g. the Palmottu and Oklo projects) were very successful; progress was also made in other areas, such as migration and corrosion.

Partitioning and Transmutation. A re-appraisal of the possibility of separating and/or transmuting long-lived radioactive species has lead to a new interest in research in the area. In contrast to some other important areas the EC budget for research in P&T has increased considerably during the past five years. This priority is controversial. Research to date in transmutation strategies has shown that any plan to "burn" plutonium or other minor actinides will require a very long time and will require the investment of very large sums in the technology. It is not clear which technology will prove the most attractive (ADS[1] or LMR[2]) and further strategic studies including safety and waste management are needed before any significant investment decisions are made. Because of the long-term nature of this work, on balance we believe it would be more appropriately placed in the area of Safety and Efficiency of Future Systems. In partitioning there has been specific progress in the separation of trivalent actinides (americium and curium) from lanthanides which could lead to a process with a single cycle allowing direct extraction of the minor actinides from the very high level liquid waste which results from reprocessing.

Safety and Efficiency of Future Systems. This is a new area established for FP5, although related topics were included in FP4 under the heading of Innovative and Revisited Systems. Its aims include assessing new or previously discarded reactor concepts that would be potentially cheaper, safer, more sustainable, producing less waste and reducing the risk of diversion. The development of nearer term evolutionary plant is seen as being the responsibility of national or multi-national programmes. Results from the previous programmes have demonstrated the technology of some passive safety systems.

Radiation Protection. In FP5, this area was introduced as an end user oriented part of the key action 2. It contains a number of sections that overlap to some extent, each of which is covered below. It is intimately related to the following section on Generic Research in Radiological Sciences and we shall recommend that these two sections be considered together in future.

Risk Assessment and Management. Tools for risk assessment and management have been further developed. There has been an appreciation of the need to better understand how acceptance of risk at a social level can be achieved and the project TRUSTNET is an important contribution to that, and is continuing in FP5. The ETHOS-project was particularly successful in showing how the involvement of the local populations is vital in the rehabilitation process.

Monitoring and Assessment of Occupational Exposure. Progress in optimisation of occupational
exposure in a variety of applications resulted in recommendations to the EC, national authorities

[1] ADS; Accelerator Driven Systems
[2] LMR; Liquid Metal Reactors

and utilities on the use of the ALARA-principle.

Off-site Emergency Management. The RODOS system for assisting in off-site emergency management is now available for operational use. It represents the work of 40 Institutes in 20 different countries (in both the East and the West).

Restoration and long-term management of contaminated environments. Models have been developed to identify areas with high transfer capacity of caesium. Significant progress was made in the development of more holistic countermeasure strategies by integrating issues of private and environmental costs and benefits, environmental management and consumer attitudes and behaviour into the countermeasure selection process.

Generic Research in Radiological Sciences. Estimates of the risks from exposure to ionising radiation are the basis of all radiation protection, thus they have to cover the wide range of radiation types and exposure conditions in the natural environment, the work place and the clinic to be of practical value. The following are some of the important achievements in this area.

Radiation protection and health. Co-ordination of work under FP3 and FP4 in this field has lead to a deeper understanding of the mechanisms by which radiation exposure leads to the induction of cancers and particularly on predisposition. Recent developments in gene research, molecular biology, irradiation techniques (single cell irradiation using soft energy microbeams) and computer modelling provided new possibilities to improve our knowledge of the effects of low doses of radiation.

Environmental transfer of radioactive material. The work has focussed on a better understanding of transfer mechanisms and developing of ecological models to predict the fluxes of radionuclides in different types of environment. For the future, a holistic approach to environmental protection including radiation protection is required.

Industrial and medical uses and natural sources of radiation. Progress has been made in the field of optimisation in intervention radiology (IR), paediatrics, Computer Assisted Tomography (CT) and fluoroscopy as well as developing image quality criteria. Because of the higher sensitivity of children to radiation a number of studies have focussed on developing guidance on paediatric radiology. For natural sources of radiation, studies on the risk arising from the inhalation of radon and its decay products, including lung modelling, epidemiology, and an intercomparison of passive radiation detectors, produced important results.

Internal and external dosimetry. Biokinetic and dosimetric models have been produced to improve estimates of dose from intakes of radionuclides by adults and children. An extensive database of dose coefficients was published to meet the needs of health physics practitioners and researchers in radiological protection. A real breakthrough was achieved in mixed neutron detection with important commercial possibilities.

Major Conclusions and key issues for the future.

Overall recommendations and conclusions are given in section 7 of the main report. Recommendations concerning specific issues are included in the appropriate sections of the main text. The following is an abbreviated summary of the main conclusions and issues for the future.

1. The five years assessment has shown that the specific programme in nuclear fission safety continues to provide results of high scientific value, which are relevant to the needs of Industry, Regulators and those concerned with radioactivity generally. It is seen as meeting most of its overall objectives.
2. The reductions in funding of FP3, FP4 and FP5 mean that sufficient funds are not available for important research needed to tackle key objectives of the programme.
3. The Commission staff should be empowered to be more pro-active in seeking research needed to fulfil agreed programme objectives.
4. Project co-ordinators should be given more freedom to manage the work, including financial flexibility once clearly defined responsibilities have been established and projects awarded.
5. The title "Nuclear Fission" no longer represents the current balance of the programme. We suggest that Radiation Protection be grouped with Generic Research in Radiological Sciences separately from Nuclear Fission.
6. The time frame for developing the technology for Partitioning and Transmutation is very long. We therefore believe that it should be considered in future along with "Safety and Efficiency of Future Systems" so that its funding and priority can be better judged as it is linked directly to the long-term needs of the Community.
7. European Centres of Excellence are supported in principle, but care is needed to guarantee the input of creative research activities and not to create monopolies.
8. Networking has proved to be a useful tool and should be further developed and given a higher priority in future.
9. A vision and strategy needs to be found in order to rationalise the training aspects of the programme as they make a potentially important contribution to the maintenance of the knowledge and skill base in the future.
10. Common strategic planning should be reinforced between FP and JRC programmes, and more co-ordination directed towards the needs of other concerned DGs, in particular to support horizontal actions.
11. Scientific dissemination is generally very good. Dissemination of research results is important for non-specialist end users, decision-makers and the public and should be done professionally.
12. Efforts should be made to make research data and tools available to other parts of the FP and to a wider technical catchment area. For example ESA where radiation effects are of importance.
13. A common theme emerging from many of the research areas is risk governance. Developing an understanding of such complex systems is not limited to nuclear activities and we recommend that very broad inter and multi disciplinary studies are undertaken by the Commission as a horizontal activity.

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FIVE-YEAR ASSESSMENT OF THE SPECIFIC PROGRAMME: NUCLEAR ENERGY: Nuclear Fusion

FINAL REPORT

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May 2000

1 Board Members

Board Member	Occupational and Professional Experience
Prof A Airaghi (Chairman)	Senior Vice President Finmeccanica. Chairman and member of the Board of various companies. Vice Chairman of the Italian Federation of Electromechanical, Electronics, Telecom and Informatics Industries (ANIE).
Prof H Condé	Professor Emeritus of Applied Neutron Physics at Uppsala University and former Senior Scientist in Neutron Physics at the National Defence Research Establishment. Former member of the Nuclear Data Committees of IAEA and OECD.
Prof C Matos Ferreira	Professor of Physics and co-Director of Centre for Plasma Physics at Instituto Superior Tecnico (IST), Lisbon Technical University. Presently, Chairman of the Scientific Council of IST and member of the COST Technical Committee for Physics. Former member of the Executive Committee and the Council of the EPS. Extensive experience in low-temperature plasma physics, plasma kinetics, and atomic and molecular physics of ionised gases.
Dr Ing G Newi	30 years experience in power engineering and utility management. Presently, Managing Director of CONSULECTRA, a consultancy subsidiary of Hamburgische Electricitats-Werke AG. Member of Fachbeirat for IPP Garching.
Dr P H Rebut	Member of the French Académie des Sciences. Advisor to the “Haut Commissaire à L’Energie Atomique” (France). Former Director of JET and ITER.
Prof A M Stoneham	Presently, Massey Professor of Physics and Director, Centre for Materials Research at University College London. Fellow of the Royal Society. Fellowships of the American Physical Society, Institute of Physics and Institute of Materials. Previously, Chief Scientist AEA Technology.
Dr J E Berry (Rapporteur)	20 years experience in energy and environmental work. Presently, a Department Manager at AEA Technology, based in Brussels.

2 Introduction

2.1 Fusion has long been recognised as a potential energy source for mankind. Against the current background of increasing world-wide demand for energy, finite resources of fossil fuels and international concerns over climate change issues, nuclear fusion is one of the few long-term energy supply options currently under investigation.

2.2 The long-term objective of the European Fusion Programme is to embrace all the research activities undertaken in the Member States (plus Associated countries) aimed at harnessing fusion, and to enable the joint creation of prototype reactors for power production to meet the needs of society. The Programme has developed to its present standing over the past four decades, starting with the original Euratom Treaty in 1957 and the first Association agreement with CEA, signed in 1959. Since that time the number of Associations has increased to 20, and most recently has extended to include agreements with CEE. Financed wholly by public funds from the Commission and Member State Governments, it represents itself as a single entity in its relations with other international fusion programmes. Collaboration with other non-EU nations (USA, Japan and Russia) plays a key part in the implementation of the Programme. At a European level, the overall expenditure for fusion orientated research has reached 10 billion Euros (1999 value) of which approximately 40% has been funded from the Community budget.

2.3 The specific objectives of the thermonuclear fusion programme have remained very consistent between the 3rd, 4th and 5th Framework Programmes (see Table 1). The overall objective has been to establish the scientific and technological base for the 'Next Step', meaning the next generation of machines after JET. In the 4th Framework Programme this 'Next Step' has centred on ITER. Overall, this has resulted in a scientifically and politically coherent programme.

Table 1: Objectives of the Framework Programmes

Programme	Programme Objectives
3rd FP (1990-94)	"The establishment of the scientific and technological base for the construction of an installation designed to achieve and study the ignition and prolonged combustion of plasma and related technological problems (Next Step)."
4th FP (1994-98)	"The objective of the Next Step activities will be to establish the engineering design of an experimental reactor, in the frame of the quadripartite international agreement ITER, between Euratom, Japan, the Russian Federation and the United States of America."
5th FP (1998-2002)	"To develop further the necessary basis for the possible construction of an experimental reactor. This key action should thus enhance the Community's preparedness, from a scientific, technical, financial and organisational point of view, to decide on and support such a future experimental reactor."

2.4 The European Nuclear Fusion Programme has been organised as a joint effort between the EURATOM and the Member States. This coordination of activities has been successfully achieved by a combination of bilateral contracts between the Commission and the relevant national research institutes (Association Contracts) in each EU Member State and Switzerland, and a series of joint European agreements which have enabled the programme to undertake activities which would have been impossible at a national level. The first major European research initiative was the construction and operation of the Joint European Torus (JET), which has been acknowledged worldwide as a major success and has reinforced Europe's position at the forefront of fusion development. This was established in 1978, as a Joint Undertaking (a solution foreseen in the Euratom Treaty to combine Community and Member States funds) and up until the end of 1999 has been managed by the JET Council, comprising representatives of the Commission and the organisations from Member States. Similarly, the NET Agreement (1983-1998) provided the framework for European collaboration in research and development in support of the Next European Torus and then in 1992 facilitated European participation in the International Thermonuclear Experimental Reactor (ITER) Project which was initially based on a quadripartite Agreement between the European Atomic Energy Community, and the Governments of Japan, Russian Federation and the USA. At the beginning of 1999, the new European Fusion Development Agreement (EFDA) came into force; it has been signed by the Commission and all the national research institutes and provides a framework for the continuity of European activities in the field of thermonuclear fusion. In particular, the EFDA Workplan now includes the technology work carried out by the national research institutes and by European industry, European contributions to international collaboration such as ITER and the exploitation of the JET facilities after 1999. The latter is specifically covered by the JET Implementing Agreement (JIA), between Euratom and the other parties of EFDA, and includes provisions relating both to the technical programme and the financing of the activities.

2.5 During the past 8 years, ITER has been a major focus of European activities. In July 1998, the ITER Engineering Design Activities were completed in line with the initial objectives. It was decided that the design phase should be extended for a further three years to enable the completion of technical tests, the exploration of a less expensive option with less ambitious objectives and the investigation of non-technical issues such as the licensing requirements. In July 1999, the US formally decided to leave the ITER Agreement. This decision has affected the world-wide fusion scenario and requires a new appraisal of the European Programme.

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2.6 The extensive European activities undertaken during the review period, both in direct support of ITER and in the development of concept improvements and longer term technology, have been reviewed against the background of international activities. The Board's activity and this report have been prepared in line with the Broad Guidelines for the 5 Year Assessment of the RTD Framework Programmes issued by the Commission. It has been undertaken in accordance with the legislative requirements as given in Article 5 of the Council Decision of

22 December 1998 on the Fifth EC Framework Programme and the Euratom Framework Programme, and with Article 4 of the Council Decision of 25 January 1999 adopting the Specific Programme in the field of nuclear energy (Euratom).

2.7 The Commission asked a Board of seven independent, external experts to review the implementation of the Fusion Programme over the period 1995-1999. The Board met 9 times in the period 28 September 1999 to 30 April. In order to review thoroughly the activities of the programme, the Board members undertook an extensive series of visits, meeting representatives from 16 national research institutes. This enabled them to discuss directly with the institutes' staff the activities being undertaken and their role within the European Fusion Programme. (Details of the activities at each of the national institutes are included in Annex 1). In addition, the Board has been provided with a large number of papers describing different aspects of programme.

3 Assessment of Implementation and Achievements

3.1 EFFICIENCY

3.1.1 Fusion is a highly challenging, long-term, scientific and technological objective. Its development requires permanent relationships and clear and stable mission definitions. The Fusion Programme provides a framework for a decentralised structure comprising a series of bilateral Association Contracts (between the Commission and national research institutes) and a number of specific fusion programme agreements (see Annex 2). The programme management in Brussels accounts for less than 1.5% of the community budget. This structure has provided a framework for the technical co-ordination and financing of European activities that is well accepted by the scientific, technical and industrial players in this field. It explicitly gives them responsibilities relating to the management, technical and financial direction of their work and, up to now, has proved to be satisfactory. This structure will need to be reviewed in light of the future development of the programme.

3.1.2 In the 4th FP, the European Fusion Programme was a separate programme but in the 5th FP, the Fusion Programme is a Key Action within the Preserving the Ecosystem Programme; this has increased the overall complexity of the management structure. In the 4th FP, the Fusion Programme was co-ordinated by the European Commission, advised by the Consultative Committee for the Fusion Programme (CCFP) and the STC Euratom. In the 5th FP, there is also an advisory body for the Key Action and in practice there is some overlap between the responsibilities of these groups.

3.1.3 The JET Joint Undertaking was a novel solution to combine EC and Member State funds. This solution proved to be a good framework with the exception of the statute concerning staffing. Staff were seconded to JET through two employers, namely the UKAEA and the Commission, which led to tensions and legal problems, and contributed to the termination of the Joint Undertaking with the loss of experience and some competent staff. It is hoped that the new European Fusion Development Agreement will continue to provide the required flexibility, at least in the short-term. The staffing issues have been specifically addressed, although the staff seconded under the new arrangements will take some time to become as effective as the previous staff.

3.1.4 Fusion, as a long-term programme, requires the highest level of continuity. Late adoption of the Council Decisions concerning the extension of JET and the successive FPs has made the continuity of the programme and investment difficult. The change in the legal framework from the Joint Undertaking to the new EFDA framework is creating difficulties for the operation of JET during the present transitional period. It is envisaged that the new arrangements under EFDA will enable the further exploitation and subsequent closure of JET; presently, there is only a legal framework for fusion activities up to the end of the FP5.

3.1.5 The Fusion Programme has been affected by the unavoidable break in the flow of funds between successive Framework Programmes. However, within the national research institutes, the “association contract formula” has ensured continuity between successive Framework Programmes. As a consequence, from the technical viewpoint, the transition between the FPs has been relatively smooth, and has enabled the programme of work to proceed without any major interruptions.

3.1.6 Due to the specialised nature of the Programme there has been only limited co-ordination with other Programmes under the FPs. The only exception has been the need for co-ordination with the fusion related work undertaken within the JRCs. This need has declined following the decision of the JRCs to withdraw from fusion work. At present there are a few 4^{th} FP projects nearing completion but no new activities under 5^{th} FP.

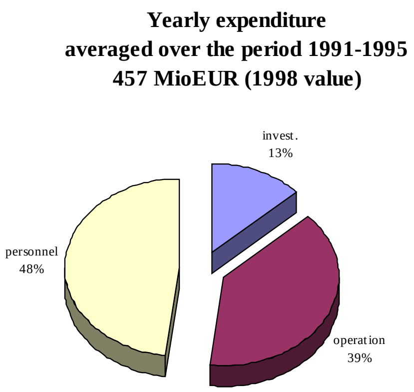
3.1.7 Potential opportunities for the cross-benefit of the Fusion Programme with other framework programmes, for example in the areas of materials and remote handling, have not been fully exploited.

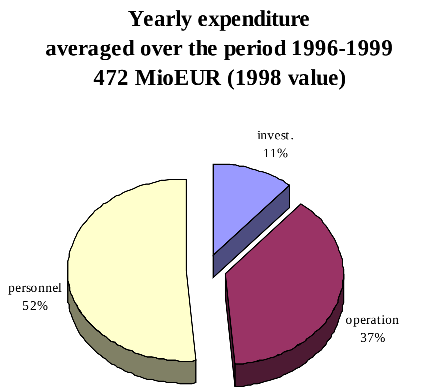
3.2 EFFECTIVENESS

3.2.1 The stated scientific and technical objectives of the Fusion Programme have been achieved and almost always met within budget. The total yearly expenditure on Fusion R&D, averaged over the period 1996-1999, has been around 3% higher than that in the previous 5 year period (Figure 1). Whilst the total level of investment has remained approximately the same, there has been a major shift in the nature of the investments. During the period 1991-1995, 34% of the investment was on JET whereas, during the last 5 years, this has dropped to under

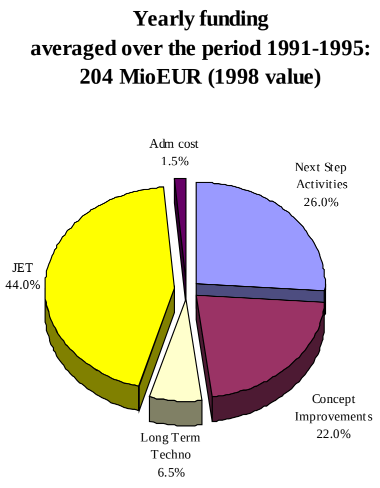
4% with substantial increases in ITER related activities and within the National research institutes. The 4% increase in personnel costs reflects, in part, the 'ageing' of the staff involved in the Fusion Programme.

Figure 1





3.2.2 The Community contribution to the overall budget has decreased from 44.6% (period 1991-1995) to 41.5% (period 1996-1999) as shown in Figure 2. There has also been a shift in the distribution of Community funding between the different areas of the programme (Next Step, JET, Concept Improvements, Technology and Administration). The level of funding for Next Step activities has increased, balanced by a decrease for Concept Improvements and Technology. This is in line with the increased emphasis on the Next Step activities during the past 5 years.



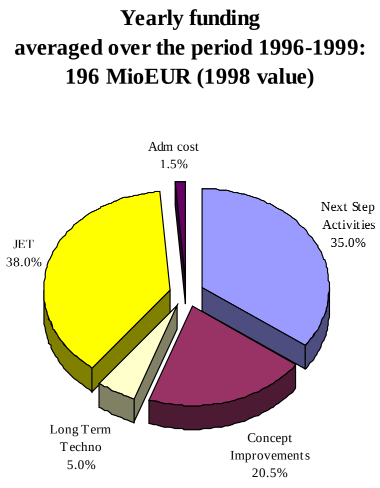


Figure 2

3.2.3 The European Fusion Programme has produced a wealth of high quality results in line with the objectives of the Programme (see Section 5.3). The major European activity at JET and in the ITER Projects has also brought world visibility, which in turn helps to promote high class European research capabilities and has established Europe in a leading role in fusion activities world-wide.

3.2.4 The Programme has been developing the technologies and improving the concepts required to develop nuclear fusion as a future energy source. It has concentrated effort on the use of magnetic confinement and mostly on tokamaks. The success of JET operations tends to support this decision.

3.2.5 To date, the JET Programme has met all the objectives defined in the 1978 Council Decision and those of subsequent extensions and has exceeded original expectations. The successful JET Deuterium-Tritium campaign, the development of an active gas handling system and the sophisticated remote handling facilities demonstrate the direct applicability of the science and technology activities to the overall objective of developing fusion as a long-term energy source.

3.2.6 The ITER machine has been conceived as an important step towards the development of a prototype fusion reactor. One of its defined objectives is to demonstrate ignition. The combined effect of the US withdrawal from ITER in July 1999, the economic problems in Russia, the moratorium on large-scale research investment in Japan, and the unwillingness within Europe to invest more money in the construction of ITER, necessitated a reappraisal of the ITER objectives, design criteria and the cost of the machine. The subsequent decision to extend the design activities until 2001 and proceed with the design of a new machine (New-ITER), with a less ambitious set of scientific objectives[3] and approximately 50% reduction in budget, has required additional design work. This work has been able to draw on the same scientific basis on which the original ITER design was based and a viable alternative has been designed. The relatively short timescale on which this has been achieved has demonstrated the overall efficiency and effectiveness of the ITER teams.

3.2.7 The delays in the decision process regarding the construction of ITER, and the entry of the programme into a new generation of machines, has encouraged the continued exploitation, and in some cases further development, of existing machines. This approach has helped to control the loss of highly qualified researchers and contributed to enriching the knowledge and databases. A reappraisal of the existing machines is recommended for the future.

3.2.8 The Thermonuclear Fusion Programme is probably the best example of European Added Value within the FPs. The only other research activity within Europe on a similar scale is CERN. The nature and range of activities/expertise and the large capital investments required in the fusion area would limit the level of activity that could be undertaken within the national budgets in any individual Member State Association. Good co-ordination and co-operation between the Associations (16 in 1996, but presently 20) has enabled far greater achievements to be made and, as mentioned above, has enabled Europe to be recognised internationally as leading research in this field.

[3] Originally known as ITER-RO/RC, but referred to throughout this document as New ITER since the ITER Council has still to decide on a name. Designed to achieve a Q gain of 10 rather than ignition and 30% of the original power production.

3.2.9 The Programme requires a highly multidisciplinary research effort drawing on a wide range of different disciplines and skills, (e.g. plasma physics, engineering, mathematics, computing, material science..). The success of the major experiments and the programme over the past 5 years has been largely due to the co-operation achieved within the multidisciplinary, multinational teams responsible for the work. Likewise, the ITER design has benefited from the transfer of experience from the European Programme.

3.2.10 European industry has grown in competence together with the fusion programme and can provide all the manufacturing and technical support required by the programme. The high level of technical sophistication and exacting requirements of the programme in areas such as, superconductors, remote handling, vacuum technology, power electronics and brazing and welding, has enhanced the skill base found in European industry and the quality of standards in industry. In addition, there are a number of examples where industry-based technicians, working in support of the programme, have benefited from the specialist training they have received. Eureka and COST type activities are not appropriate at this stage.

3.2.11 The long-term research and development nature of this Programme has meant that there have been no significant opportunities to contribute directly to other Community policies. Nevertheless, the orientation of the European Programme (see Section 4) towards fusion power production could offer a long-term, clean and safe alternative for the future large-scale production of electricity world-wide and could contribute to the reduction of carbon dioxide emissions. There is reasonable hope that in-depth studies undertaken on the safety of fusion technology during the past 5 years will lead to a wider acceptance of this energy option. Hence, it offers the opportunity for major impacts on future European energy, environmental and urban policies.

3.2.12 In the short-term the programme has provided substantial social benefits. It has contributed to the development of a strong and competent scientific, technological and industrial community. During the past 5 years, the programme has directly employed around 2000 scientists and engineers (including about 250 PhD students). It has directly contributed to Community policies on training and has the highest level of mobility of researchers of any European Programme at around 500 person-months per year. At any one time, around 40-45 young researchers are in receipt of grants for training. In addition, the programme has indirectly supported a considerable number of staff in related support and supply industries. In many cases this has led to substantial developments in their specialised capabilities, personnel enhancement and the quality of their products.

3.3 MAJOR ACHIEVEMENTS DURING THE PAST 5 YEARS

3.3.1 The Next Step activities have been a major focus of the programme, with Europe being an active participant in the engineering design activities for ITER together with the USA, Japan and Russia. The European contribution to ITER has been provided through:

- the European Home Team

- participation in the Joint Central Team.

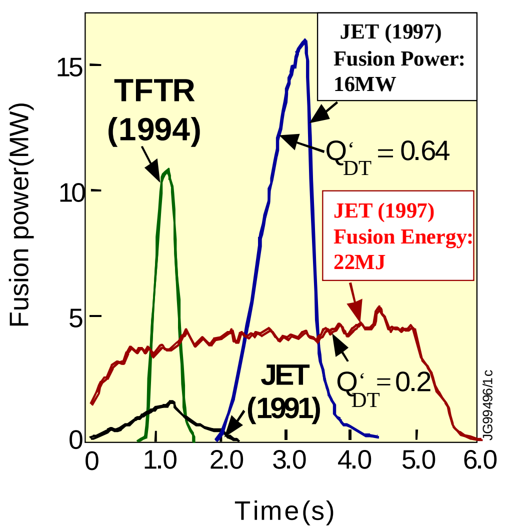
In addition, the majority of the work undertaken at JET during the past 5 years has been in support of ITER, together with a large proportion of the activities within the national research institutes.

3.3.2 Major achievements towards the ‘Next Step’ during the period include:

- Production of record fusion power at JET (>16 MW for about one second, and 4-5 MW for about 4 seconds, generating 22 MJ of fusion energy – see Figure 3) and the demonstration of alpha heating, a pre-requisite for the ‘Next Step’.
- Demonstration of ‘Next Step’ relevant technologies such as remote handling complex in-vessel components and closed cycle tritium handling.
- A substantially increased level of involvement by European industry, both in the assessment of ITER design reports and in the construction of components. For example, the fabrication of a large niobium-tin superconducting model coil (scale 1:3) for ITER.

3.3.3 JET remains the most relevant machine for supporting reactor-orientated fusion research world-wide and is currently the only tokamak capable of D-T operation. The work on JET is complemented by the studies on concept improvement, long-term technology and safety and environment undertaken using the range of European fusion machines (Table 2), as discussed below. Together these activities have enhanced the level of understanding in fusion science, demonstrated a number of the key features of the technical design for a ‘Next Step’ machine (Figures 4 and 5 and Box 1) and enabled the development of a detailed and fully integrated design for the ‘Next Step’ machine. The achievements of the European programme are well recognised world-wide.

Figure 3: Fusion Power Production in JET



Fusion power production in JET (in year 1991 and 1997) and in TFTR (in 1994)

The time traces of several experiments are super-imposed for comparisons.

The 1991 experiments in JET were the first ever using tritium, but at 10 % concentration.

The other experiments were performed at near optimum tritium concentration (50 %). The 1997 JET experiments resulted in record values of fusion power and, during a quasi steady-state pulse of 4 seconds, of fusion energy.

Q_{DT} , the fusion power gain, is the ratio between the output fusion power and the additional power injected into the fuel to sustain its temperature.

Table 2: Specialised Fusion Machines in Europe

Machine	Association EURATOM	Main objective	Ip [1] (MA)	Start of Operation
Tokamaks				
TORE SUPRA	CEA (Cadarache)	Long-pulse operation in Next Step relevant conditions	1.7	1988 -
ASDEX Upgrade	IPP (Garching)	Poloidal divertor, plasma purity control in ITER and reactor relevant topology	1.6	1991 -
FTU	ENEA (Frascati)	Confinement at high density and high field; current drive	1.6	1990 -
TCV	Switzerland, CRPP (Lausanne)	Physics of strongly shaped plasmas	1.2	1992 -
TEXTOR-94	FZJ (Jülich)	Plasma/wall interaction, edge plasma, confinement with additional heating	0.8	1981 (94) [2]
COMPASS-D	UKAEA (Culham)	High-beta and MHD stability studies in JET / ITER geometry	0.4	1989 (92) [2]
MAST	UKAEA (Culham)	Spherical Tokamak physics at parameters comparable to medium sized conventional Tokamaks	1	1999
CASTOR	IPP-CR (Prague)	Lower Hybrid Current Drive, fluctuations, diagnostic development, edge plasma polarisation	0.025	1977
ISTTOK	IST (Lisbon)	MHD activity, transport, diagnostic development	0.01	1992-
Reversed Field Pinches				
RFX	ENEA (Padova)	RFP physics, toroidal confinement and transport, performance prospects	2.0	1991 -
EXTRAP-T2	NFR (Stockholm)	Stabilisation, shell studies fluctuations, scenarios	0.3	1993 (99) [2]
Stellarators				
Wendelstein 7-AS	IPP (Garching)	Medium-size machine with modular coil system to investigate plasma behaviour in an optimised magnetic field configuration		1990 -
TJ-II	CIEMAT (Madrid)	Highly flexible medium-size machine with helical magnetic axis, e.g. confinement and high-beta studies		1996 -
Wendelstein 7-X	IPP (Greifswald)	Exploration of Stellarator operation at reactor-relevant collisionality towards steady state operation		1997 [3]

(1) Ip Plasma current
(2) Major refurbishment completed
(3) Start of construction 1997, expected to start operation in 2006

3.3.4 Following the recommendations from the previous panel, major effort has been dedicated to the assessment of the safety and environmental aspects of fusion, both in the short and long-term. The 1995 report on the Safety and Environmental Assessment of Fusion Power has been updated, confirming the intrinsic safety-environment advantages of fusion power. In addition, the EU made a significant contribution to the non site specific safety report for ITER which was well received by the ITER Council. Two major conclusions of these activities are:

- Most severe accidents would not require any public evacuation assuming appropriate design provisions are made.
- Almost all the activated material from the reactor could be cleaned or recycled (based on the use of presently available low activation martensitic steel or future advanced materials).

Figure 4: Fusion Performance of Several Machines

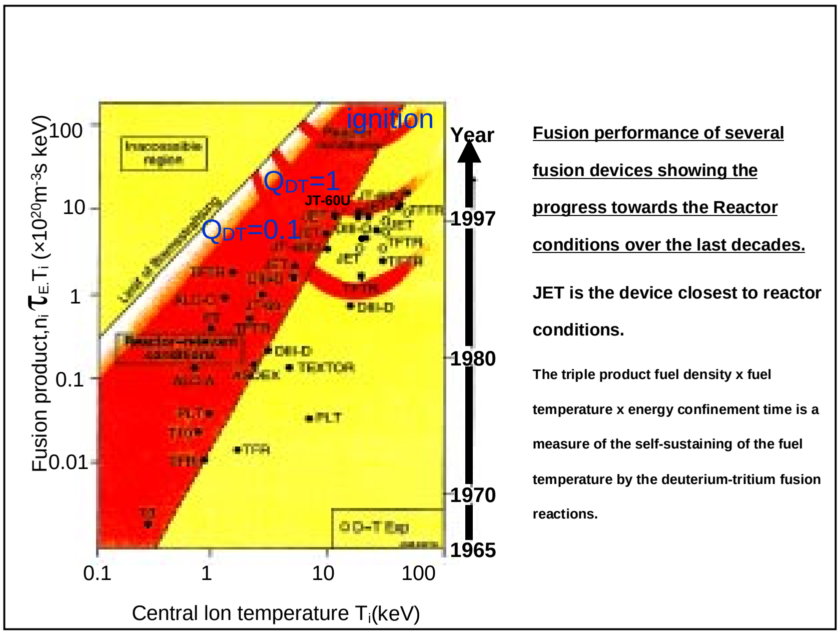
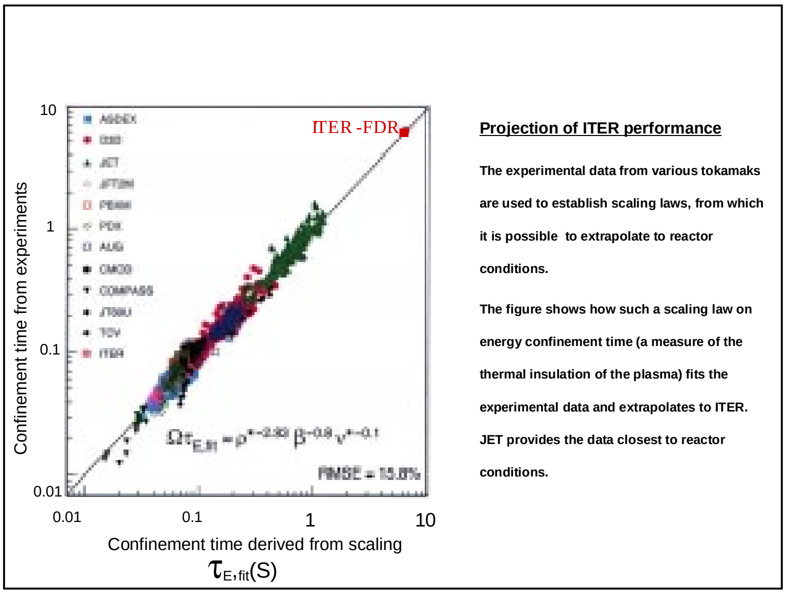


Figure 5: Projection of ITER Performance



Box 1: Major Achievements in Next Step Activities

Next Step Activities in Physics

- There is improved confidence in extrapolations to ITER from semi-empirical studies, in which dimensionless plasma quantities are kept identical (JET; ASDEX Upgrade, IPP; COMPASS, UKAEA), plus experiments showing clear evidence of alpha particle heating in JET D-T plasmas and a 25% lower additional heating power requirement to access the high confinement regime than in pure deuterium. This supports the design variants of the New-ITER developed by the ITER-JCT and the EFDA-CSU aimed at the lowest possible capital cost for a superconducting, ITER-class machine.
- Quasi-stationary high confinement modes with a large radiated power fraction and good power and particle exhaust have been achieved. High density divertor operation and baffling the divertor have been shown to reduce neutral particle flux back into the main plasma chamber, with a clear improvement of D and He pumping (ASDEX Upgrade, IPP).
- Operation in the high confinement "optimised shear" regime has been demonstrated (JET; ASDEX Upgrade, IPP; Tore Supra, CEA; FTU, ENEA), and the associated internal transport barrier sustained in long-pulse operation by plasma current profile control (Tore Supra, CEA).
- A new operational mode for optimising plasma boundary characteristics with respect to radiation level and heat transfer, the "Radiative Improved" or RI-mode has been developed (TEXTOR-94, Etat Belge – ERM/KMS & TEC; ASDEX Upgrade, IPP; JET), and previously established density limits have been exceeded by high field side pellet injection (ASDEX Upgrade, IPP).
- Theoretical models and codes have been developed for the study of: accessible operational space and regimes of Tokamaks (Conf. Suisse), control techniques for mitigating disruptions (UKAEA), improved ICRH and LHCD power coupling (TEKES), MHD effects (RISØ).

Next Step Activities in Plasma Engineering and Technology

- Further development of gyrotrons as sources for ECRH has resulted in world record operation of a 118 GHz tube for >10 seconds at 400kW power output (European industry with CEA, Conf. Suisse and FZK). RF ion sources have been developed for positive and negative ion NBI (IPP; CEA; DCU), and improved launcher design has eliminated arcing on LHCD antennas by (CEA; ENEA; TEKES; Czech Rep.).
- In order to operate Tokamak machines on prescribed trajectories in parameter space for optimised performance, hardware and real-time algorithms for feed-back control using online diagnostic signals have been developed (several National research institutes).
- Better determination of plasma parameters has been achieved by the development of a number of new diagnostics, such as high-resolution Thomson scattering (FOM), a laser fluctuation correlation diagnostic (RISØ), microwave scattering, neutron diagnostics (NFR; ENEA-CNR), reflectometers (IST), heavy ion beam system (IST), Li-beam edge plasma diagnostic (ÖAW; IPP), polarimetry (DCU), and a fast sweeping Langmuir probe (Hellenic Rep.).
- Superconducting strand and jacketing have been manufactured for the ITER toroidal field model coils and the coil has been fabricated (industry). Full size superconducting cables have been tested in the SULTAN facility (CRPP).
- Mock-ups (up to full size) of the first wall, blanket and divertor targets of ITER have been manufactured (industry), and divertor targets have been tested to heat flux levels in excess of the ITER requirement (FZJ; industry).
- Full scale ITER divertor remote replacement/refurbishment facilities have been built and tested (ENEA with participation of Canadian and the Japanese Home Team), and an ITER first wall/blanket remote replacement facility has been built and tested (ENEA). An in-vessel viewing system has been designed and constructed (ENEA; VVT).
- A tritium plant test facility has been realised (FZK supported by ITER Canada) and a torus exhaust cryopump test facility has been realised (FZK).
- A major contribution has been made to the ITER safety assessment.

3.3.5 Research on alternative concepts and new plasma configurations and regimes is an important component of the European Fusion Programme. New tokamak regimes have been studied on several different machines in the national research institutes (Table 2). The results of this work tend to complement those obtained using JET; they explore alternative configurations and broaden the parameter ranges. In addition, they have facilitated the professional training of staff in this field. Developments on these machines have led to improvements on JET, and to the design of the 'Next Step' machine (Figure 4). Major achievements using the tokamak machines during the past 5 years are summarised in Box 2.

3.3.6 Research on alternative configurations is also undertaken by the national research institutes using a range of machines, such as Stellarators and Reversed Field Pinch machines (Table 2). Special mention should be made to the Wendelstein 7-X Stellarator, which is under construction and expected to come into operation in 2006. This represents the largest investment presently being undertaken in the European Programme. Although this machine does not fit exactly with the 'Next Step' tokamak objectives, the decision to determine the potential of the stellarator was taken based on a number of criteria and was recommended in the previous 5 year assessment report.

Box 2: Achievements in Concept Improvements and Alternative Configurations

Concept Improvements on Tokamaks

- Possible improvements in the Tokamak line have been demonstrated by the stability of highly elongated plasmas (k ~ 2.5) near operating limits (TCV, Conf. Suisse), and the achievement of record average beta values of 40% in a Spherical Tokamak configuration (START, UKAEA), followed by the completion of the construction of the Meg-Amp Spherical Tokamak MAST (UKAEA). Repetitive breakdown by current reversal has been demonstrated (ISTTOK, IST).
- The experimental stabilisation of neo-classical tearing modes using ECCD and LHCD (ASDEX Upgrade, IPP; COMPASS-D, UKAEA) has been accompanied by the development of fundamental physics models of stability and transport phenomena (including so-called "first principle" models) into a valuable tool for understanding underlying physics (NFR).

Alternative Configurations

- The exploration of the Stellarator line has continued with the demonstration that the "island divertor" configuration in Stellarators can give access to regimes similar to the those in divertor Tokamaks (Wendelstein 7-AS, IPP) and the successful start of operation of the Heliac Stellarator TJ-II (CIEMAT).
- The superconducting toroidal field demonstration coil for Wendelstein 7-X has been successfully tested (TOSKA, FZK).
- Improvements have been made in the understanding and control of internal relaxation mechanisms in toroidal plasmas using the reversed field pinch (RFX, ENEA-CNR), while the reversed field pinch EXTRAP-T2 (NFR) has been re-constructed to assess different regimes of shell stabilisation, after completion of its first programme phase.
- The Free Electron Maser has been tested at high power (750 kW) in short pulses (FOM).

3.3.7 Specific work on long-term technology has been undertaken by the ITER European Home Team, in the National research institutes, at the JRC and in industry. The effort has been focused on 3 main areas:

- European Blanket Project which aims at designing and constructing relevant tritium breeding blanket modules for testing in ITER
- Assessment of advanced materials
- Socio-economic studies.

Major achievements during the past 5 years are summarised in Box 3.

Box 3: Achievements in Long-term Studies

- The European Blanket Project has been started. Two concepts are being investigated, and progress has been made on the critical technologies of fabrication and materials testing (CEA, FZK, ENEA, FOM-NRG, SCK-CEN).
- A programme of characterisation and testing of low activation ferritic-martensic steels is in progress, and fabrication by European industry of a reduced activation ferritic-martensic steel (EUROFER 97) has been achieved (FZK, CEA, CRPP, ENEA, TEKES, CIEMAT, NFR, FZJ, FOM-NRG, IST, RISØ). Advanced materials are being explored (ENEA, CEA, ÖAW, CRPP, Hellenic Rep., JRC, FOM-NRG, IST), while neutronics and nuclear databases are being further developed (FZK, CIEMAT, CEA, ENEA, ÖAW, UKAEA).
- Studies of the socio-economic aspects of fusion power have started (CEA, IPP, CIEMAT, NFR, ENEA, FOM-NRG, FZK, FZJ, ÖAW, RISØ, TEKES, UKAEA).

Further details of the work of the individual national research institutes are provided in the series of fiche in Annex 1.

3.4 LESSONS LEARNED

3.4.1 Many lessons have been learned from the Fusion Programme of which the following three of particular importance:

- Large, long-term R&D projects require strong and constant sponsorship and high profile and competent leadership. In the past, the European Union (and some Member States) have given such sponsorship to the Fusion Programme and, in particular, to JET. This allowed the programme management to exploit the Programme very effectively.

  ITER, in its highly international configuration (which has inevitably introduced complications both at the strategic and management levels), seems to have progressively lost sponsorship, despite the excellent work done by the entire ITER team. The US withdrawal from ITER (1998) and the financial crisis in the Russian Federation have led to the requirement to redesign a lower cost New-ITER with less ambitious objectives. Moreover, international uncertainty still exists.

- Such long-term, challenging and costly programmes, require a firm, stable and powerful legal framework within which to be managed. Again, the JET experience is meaningful and, with the obvious adaptations to the new context, a legal framework with greater management responsibilities coherent with the requirements of the Next Step will have to be adopted.

- The fusion community has always stressed the differences between fission and fusion in terms of safety and environmental impact, and all the studies done in the recent years confirm this point. Nevertheless, the general public still tends to view the two technologies in the same light. More attention is required on this issue.

3.5 RELEVANCE

3.5.1 The FP5 objectives continue to provide a scientifically and politically coherent fusion programme. No changes to the objectives are considered necessary for the remainder of FP5.

4 Conclusions

4.1 During the last 5 years, the programme has achieved very important results (see Section 5), confirming fusion should now be considered as a credible option in the search for clean, large-scale power generation systems that are going to be required to provide a future sustainable energy supply. Nevertheless, there are still a number of important scientific, technological and engineering issues to be addressed before a commercial power plant can be realised. At least two more generations of machines are envisaged before building a prototype reactor and, based on present planning, large-scale electricity would be produced in around 50 years. Recent history has shown how sensitive the Programme is to delays in the decisions. The postponement of the construction of ITER has already introduced a delay of almost 10 years.

4.2 From the organisational and programme point of view, the last two years have been particularly complicated for the Fusion Programme due to the need for new organisational structures and framework agreements and due to the high level of uncertainty regarding the ‘Next Step’. The Board’s impression is that, in spite of this situation, the programme has been well co-ordinated and efficiently run by the Commission as shown by the obtained results.

4.3 The European Fusion Programme has helped to place European science, technology and industry at the leading edge of development in this sector. The programme provides a good example of scientific development leading to the further development of industrial capabilities. Europe now has by itself all the required technical, engineering and industrial capabilities to proceed to the ‘Next Step’ and take the fusion programme forward.

5 Programme Specific Issues

5.1 FUTURE GLOBAL ENERGY SCENARIOS

5.1.1 Future long-term energy scenarios show a steady increase in world-wide energy demand driven by the increase in the global population and the rapid growth in energy consumption per capita in the developing economies. Although considerable savings in energy resources can be achieved by the development of more efficient supply and demand technologies, these alone are unlikely to be able to meet future requirements. Hence, it is essential that a full range of alternative energy options is investigated.

5.1.2 In parallel to the growth in demand for energy, there is an increasing understanding of the environmental impacts of energy such as the climate change impacts of the continued burning, globally, of finite fossil fuel resources. Consequently, the need for new non-polluting forms of energy is growing and substantial Community and national financial resources are being deployed to meet this challenge. Renewable energy is a reality but issues exist associated with its availability, location and integration into the network for the provision of large-scale power in major industrial cities. Nuclear energy, both fission and fusion, are CO_2 emission-free alternative energy options for the provision of high energy density. Nuclear fission is already available but there are concerns about its safety and the issues associated with the disposal of long-lived radioactive waste. Nuclear fusion still requires further research and long-term development but appears to have the potential to provide a safe and clean alternative. Future energy demand will not be met by a single source but will be met by a mix of sustainable energy resources. To achieve this will require a long-term energy policy and a substantial increase in our level of knowledge.

5.2 THE DIFFERENT STEPS TOWARDS A FUSION REACTOR

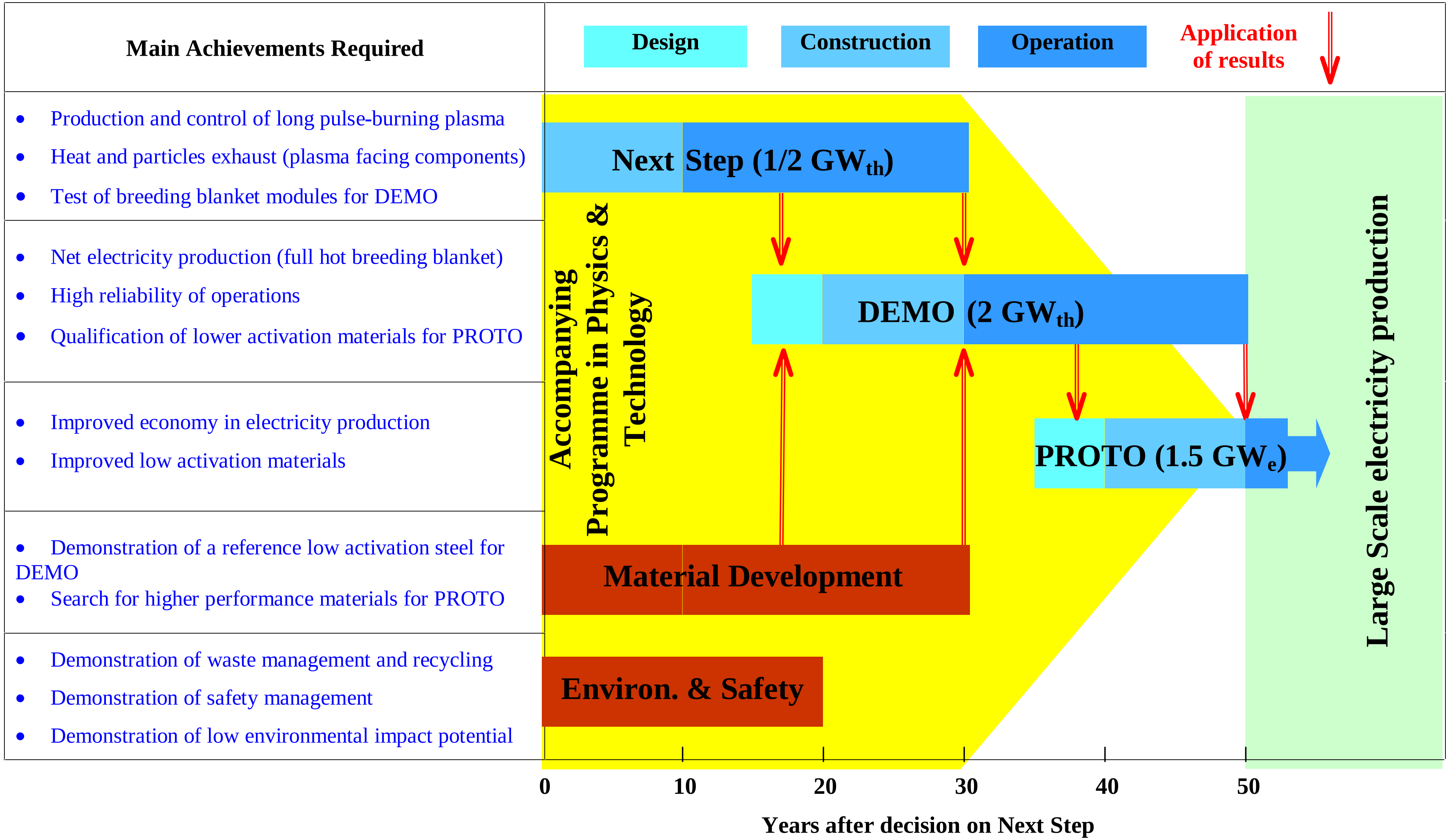
5.2.1 The European Fusion Programme is envisaging two major steps before a prototype reactor, as shown in the tentative roadmap in Figure 6. Each step should, at least, meet the specific achievements listed in the figure. It is envisaged that each step in the development will require at least one major machine, although ideally more than one would be built to provide supporting studies and confirmatory evidence.

5.2.2 Due to the level of public concern over nuclear power it will also be important to demonstrate as quickly as possible the waste management and sustainable recycling required by fusion power and to demonstrate safety management. Hence, this is shown as a separate activity on the roadmap, scheduled for completion before the construction of the DEMO machine.

5.2.3 In addition to the major steps, described above, a materials research programme is necessary to develop higher performance, low activation materials for DEMO and PROTO. This is likely to require a large-scale materials test facility. This was recommended in the previous 5 year assessment but as yet there is no commitment towards its construction either at an International or European scale.

5.2.4 The long time-frame (Figure 6) necessitates a long-term, coherent R&D programme. The programme must be based on sound management, with well defined milestones and decision points whilst maintaining sufficient adaptability to enable the programme to accommodate future uncertainties associated with the evolutionary process (scientific, technical and political).

Figure 6: Tentative Roadmap of Achievements starting from the decision to construct the Next Step



6 Recommendations for the future

6.1 The European Fusion Programme has helped to place European science, technology and industry at the leading edge of development in this sector and this advantage should be defended and possibly increased.

6.2 The European Fusion Programme should continue to be reactor orientated and the construction of the 'Next Step' should be started in FP6. This should be the first priority and some of the budget should be specifically earmarked for the Next Step. The budget should be at least at the present level, although a constant budget may lead to a reduction in the funding available for the other activities. If the budget continues to remain at the same level in FP7 and FP8, the Board believes it will still be possible to finance the completion of the construction of the Next Step, provided there is a reorientation of the activities in the national research institutes.

6.3 To proceed with the 'Next Step' in the international collaboration perspective of the New-ITER, the European Union should within the next 2 years:

- Conclude negotiations on the legal and organisational structure of the future venture
- Actively seek a European site for the New-ITER, since this is the best option from a European viewpoint.
- Conduct a thorough review of the financial issues, including the different financial costs and benefits of siting it in Europe, Canada or Japan, and establish the extent to which Japan would support the construction of New-ITER outside Japan.
- Examine in detail the recent interesting expression of interest received from the Canadian Consortium.

6.4 In the same 2 year period, due to the uncertainty over the outcome of the international negotiations, Europe should study an alternative to New-ITER, which would be suitable to be pursued by Europe alone. For example, a copper magnet machine which would still achieve the required objective of demonstrating a burning plasma under reactor conditions even if this would delay the integration of the superconducting technologies. Europe would then be ready by mid FP6 to drive forward the development of fusion even in the event of a further lack of positive decision on the construction of the New-ITER.

6.5 In the meantime, in FP5, limited investment on JET should be allowed to exploit the full value of the machine. This will also enable the fusion community to further prepare for the operation of the 'Next Step'.

6.6 The Fusion Programme, as part of a long-term sustainable energy policy, is highly demanding from a political and operational viewpoint and requires renewed support from the political authorities with an explicit endorsement of the tight timescale suggested for the 'Next Step'.

In view of the Programme's evolution to a more managerial phase, a more innovative operational solution should be studied, to be approved together with

FP6. There are several alternatives, such as an agency in charge of the entire fusion programme (and EFDA could be considered as a first step) or a legal entity belonging to Euratom, to be responsible for the implementation of the Next Step including the management of the money earmarked for this specific objective. In any case, the Committee structure governing the fusion programme should be streamlined.

6.7 Following a positive decision on the construction of the Next Step, a refocusing of the European Programme will be required. For this purpose, a critical assessment of the different European machines and their funding should be undertaken.

6.8 A Materials Research Programme is necessary to develop high performance, low activation materials for machines after the 'Next Step'. This programme should be run in parallel with the 'Next Step' to ensure the materials are ready when required and should include new materials concepts. It is recommended that international discussions on a 14 MeV neutron source Materials Testing Facility or alternative testing solutions are brought to a decision on a timescale consistent with reactor development.

6.9 The public acceptance of fusion is a key factor in its development as an energy option. Concern on this point has been expressed in several of the recent annual monitoring reports for the fusion programme despite increased effort on the safety and environmental aspects of fusion. Environmental issues should be considered as a full programmatic action, using a broader and more structured approach, in parallel to reactor development (Figure 6). The programme should continue to address issues such as fuel cycle management, waste management and recycling and all the safety aspects. In the short-term, a small Working Group could be set up to review the safety and environmental results obtained to date and to actively promote the benefits of fusion power to a broad range of political and public stakeholders.

6.10 There are various examples where there has been the transfer of technologies, skills and experience from the fusion programme to other areas of science and technology, and evidence for the transfer of know-how and experience to European industry. Such transfers should be exploited in a more structured and entrepreneurial way in response to market demand.

Programme of Visits/Meetings

Date	Place	Associations / Organisations	Participation
28 September 1999	Brussels (B)	• European Commission / DG Research	Full Board
12/13 October 1999	Abingdon Culham (UK)	• Euratom – UKAEA Association • JET Joint Undertaking	Full Board
2/3 November 1999	Cadarache (F)	• Euratom – CEA Association	Full Board
30 November 1999 afternoon	Brussels (B)	• European Commission / DG Research • European Energy Foundation – Dinner-debate	Prof. Airaghi Dr. Berry Dr. Rebut Prof. Condé
10 December 1999	Madrid (ES)	• Euratom – CIEMAT Association • Euratom – IST Association	Prof. Matos Ferreira Dr. Ing. Newi Prof. Condé
20 December 1999	Frascati (I)	• Euratom – ENEA Association	Full Board
10 and 11 January 2000	Garching (D)	• Euratom – IPP Association • Euratom – Greece Association • Euratom – ÖAW Association • ITER – Joint Central Team • EFDA – Close Support Unit	Full Board except Dr. Ing. Newi
17 and 18 January 2000	Jülich (D)	• Euratom – FZJ Association • Euratom – Belgian State Association • Euratom – FOM Association	Prof. Condé Dr. Rebut Prof. Stoneham
27/28 January 2000	Brussels (B)	• European Commission / DG Research	Full Board

18 February 2000	Helsinki (SF)	• Euratom - Ris∅ Association • Euratom – NFR Association • Euratom – TEKES, NTA Association	Prof. Condé Dr. Ing. Newi Dr. Rebut
2 March 2000	Brussels (B)	• Euratom – FZK Association • Euratom – Swiss Association	Full Board except Prof. Airaghi and Prof. Stoneham
3 March 2000	Brussels (B)	• European Commission / DG Research	Full Board
24 March 2000	Brussels (B)	• European Commission / DG Research	Full Board
14/15 April 2000	Rome (I)	• European Commission / DG Research	Prof Airaghi Dr Ing Newi Dr Rebut Dr Berry
27/28 April 2000	Brussels (B)	• European Commission / DG Research	Full Board

Glossary of Acronyms

CCE-FU	Consultative Committee Euratom-Fusion
CCFP	Consultative Committee for the Fusion Programme
DEMO	DEMOnstration reactor
EDA	Engineering Design Activities for ITER
EFDA	European Fusion Development Agreement
EURATOM	EURopean ATOMic energy community
FDR	Final Design Report of ITER
FP5	Fifth Framework Programme
FP6	Sixth Framework Programme
IEA	International Energy Agency
IFMIF	International Fusion Material Irradiation Facility
IAM	Intermediate Aspect ratio Machine
ITB	Internal Transport Barrier
ITER	International Thermonuclear Experimental Reactor
JET	Joint European Torus
JIA	JET Implementing Agreement
JOC	JET Operating Contract
JRC	Joint Research Centre
NET	Next European Torus
Q	Fusion power gain
RAFM	Reduced Activation Ferritic-Martensitic
RTD	Research and Technological Development
RTO/RC	Revised Technical Objectives/Reduced Cost of ITER
S&E	Safety & Environment
SERF	Socio-Economic Research on Fusion
SWG	Special Working Group
TAC	Technical Advisory Committee
$ß_N$	a dimensionless quality factor giving a measure of the plasma pressure which can be reached under stable conditions

ANNEX 1: National Research Institute Fiche

ASSOCIATION EURATOM/CEA - Commissariat à l'Energie Atomique

Contract Nr. : 344-88-1 FUA (F)ERB 5000 CT 910001
Period : 01/01/1988 - 31/12/2000

Research Unit : Département de Recherches sur la Fusion Contrôlée

Centre d'Etudes de Cadarache
Boîte Postale 1
F-13108 Saint-Paul-lez-Durance

History of Association/Laboratory

- Created in 1958 as Service de Recherches sur la Fusion Contrôlée.
- Operated the TFR Tokamak at Fontenay aux Roses for 11 years.
- PETULA and WEGA were constructed and operated at Grenoble.
- Research Unit moved to Cadarache in 1984-1986.
- First operation of TORE SUPRA in April 1988.

Present scientific and technical programme

- Operate the TORE SUPRA superconducting Tokamak
- Investigate long pulse operation of high-performance steady state discharges
- Prepare the next step :
  - superconducting magnet development,
  - plasma facing components,
  - (ergodic) divertor physics,
  - negative ion beam and ECRH development,
  - current drive and current profile optimisation,
  - tokamak system operation and control,
- Technology :
  - tritium breeding blanket,
  - structural materials,
  - high heat flux components, baffles, limiters,
  - electron gun tests,
  - remote handling
  - safety.

Achievements during the last 5 years

- Long energetic discharges: 280 MJ with 2.4MW injected and extracted power during 120s (world record).
- Non-inductive full current drive discharges: 70s with multiparameter feedback control (2.5 MW of LH power at 3.7 GHz).
- Enhanced Performance discharges by current profile control (LHEP mode).
- Demonstration of favourable properties of the ergodic divertor concept (low plasma edge temperature, high radiation rate mantle, impurity screening, edge confinement barrier).
- Developments of next step relevant technologies:
  - ❖ Superconducting cables and connexions for the ITER TF Model Coil.

- ❖ Actively cooled Plasma Facing Components developments for Tore Supra and ITER (10 to 20 MW/m^2 explored).
- ❖ Operation of a "single gap" negative ion based neutral beam injector at 950 keV.
- ❖ Successful test of a steady state LH launcher on Tore Supra.

Staff (CEA + Euratom) at Cadarache :	Professionals	161
	Support staff	143

Yearly budget (expenditure 1999) about 57 Mio EURO

Management Structure

Head of Research Unit: J. JACQUINOT, Deputies: M. CHATELIER, B. TURCK
STEP (Operation) Head: D. VAN HOUTTE Deputy: J. HOW
SIPP (Edge Plasma) Head: A. GROSMAN Deputy: G. REY
SCCF (Core Plasma) Head: B. SAOUTIC Deputy: C. LAVIRON

Status: February 2000

ASSOCIATION EURATOM/CIEMAT -
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Contract Nr.:	EUR 349-90-1 FUA (E)
Period:	1/1/1990-31/12/2000

Research Unit:	CIEMAT Avenida Complutense 22 E-28040 Madrid

History of Association
The Association EURATOM/CIEMAT was established on January 1, 1986.

Present scientific and technical programme
- Scientific exploitation of flexible heliac TJ-II
- Development of plasma diagnostics
- Theoretical studies
- Participation in technological programme and NET/ITER
- Participation in the exploitation of the JET facilities
- ICF “keep in touch” activities

Achievements during the last 5 years
- Successful construction of Stellarator TJ-II below budget.
- Measurement of vacuum flux surfaces in excellent agreement with theoretical predictions for TJ-II.
- TJ-II start up and experimental demonstration of TJ-II flexibility.
- Development and operation of a sophisticated set of plasma diagnostics.
- Development of theoretical tools for interpretation of 3D configurations.
- Transport and turbulence studies in different magnetic configurations.
- Development of understanding of radiation induced effects upon different materials.
- Specification and design of diagnostics for ITER.
- Cession of TJ-IU torsatron to University of Kiel.

Staff

Professionals:	70
Support staff:	50

Yearly budget (expenditure 1998): about 12 MioEURO

Management structure

Head of Research Unit: C. ALEJALDRE
(Director Laboratorio Nacional de Fusion por Confinamiento Magnetico)

Status: February 2000

ASSOCIATION EURATOM / Confédération Suisse

Contract Nr: 341-88-1 FUA (CH) (ERB 5000 CT 890018 007)
Period: 01/01/1989 - 31/12/2000

Research Unit: Centre de Recherches en Physique des Plasmas (CRPP)
Ecole Polytechnique Fédérale de Lausanne (EPFL)
PPB-Ecublens
CH-1015 Lausanne

History of Association/Laboratory:
•1961: created as a Plasma Physics Research Institute attached to the Swiss National Foundation
•1973: integrated in the Ecole Polytechnique Fédérale de Lausanne (EPFL)
•1979: became associated to EURATOM
•1993: integration of the group in fusion technology of the Paul Scherrer Institut, Villigen

Present scientific and technical programme
• Tokamak physics and gyrotron development
• Tokamak TCV started operation in November 1992 with the objective to study strongly non-circular and elongated plasmas
•Exploitation of 3.0 MW ECRH on TCV plasmas
•Installation of the remaining ECRH power (total power: 4.5 MW)
• Theory concentrated on the numerical study of the stability of toroidal configurations, RF heating, current drive and transport
• Plasma-wall interaction (with the University of Basel, Switzerland)
• SULTAN facility: superconductor development; superconducting magnet technology
• PIREX: low activation materials development and test

Achievements during the last 5 years

- TCV achieved a record plasma elongation of κ=2.64 for an ITER-like aspect ratio tokamak.
- TCV showed that the beta-limit decreases with high elongation, confirming our earlier ideal MHD predictions.
- TCV achieved a fully non-inductive plasma current of 123kA for 1.9 seconds using 1.5MW ECCD.
- TCV explored the shape-dependence of energy confinement in Ohmic and ECH plasmas, leading to better understanding of current profiles and sawtoothing over a wide range of plasma elongation and triangularity.
- We recorded a record energy output for a high frequency gyrotron, 400kW for 15.5s at 118GHz, developed in a European collaboration between Associations and industry.
- We developed gyro-kinetic codes capable of exploring the causes of anomalous transport in tokamaks and later in stellarators.
- We continued the development of numerical models for exploring novel 3-D magnetic confinement configurations.

- In our unique SULTAN facility we tested long cable lengths of high current 100 kA cable-in-conduit- superconductors developed world-wide and we used the experimental results for engineering code validation.
- We radiation tested OPTIMAX, a class of promising new material (ferritic martensitic steel) for future reactor construction, developed under a collaborative agreement with industry.
- We collaborated actively in many international partnerships, especially JET and ITER.

Staff Professionals: 54
Support staff: 54

Yearly budget *(expenditure 1998)* about 17 Mio Euro

Management structure
Head of Research Unit: Professor M.Q. TRAN
UHD (Unité Hors Département) of the Ecole Polytechnique Fédérale de Lausanne

Status: February 2000

ASSOCIATION EURATOM/DCU - Dublin City University

Contract Nr. : ERB 5004 CT 96 0011
Period : 19/08/1996 - 31/12/2001

Research Unit: Irish Research Unit consists of research groups at :

DCU-PS (School of Physical Sciences)
DCU-MS (Department of Mathematical Sciences)
UCD (School of Mathematics)
DIAS - (Dublin Institute for Advanced Studies)
UCC-P (University College Cork - Department of Physics)
UCC- EEM (Department of Electrical Engineering and Microelectronics)

History of Association/Laboratory

Co-ordinated fusion activities started in 1989 with the awarding of three contracts to conduct cost-sharing actions. The number of contracts and their work grew steadily from there leading to the setting up of an Association in August1996.

Overview of Scientific and Technical programme

- DCU-PS:	Negative ion source development (in association with CEA-Cadarache) Plasma diagnostics, computational physics and plasma surface interactions
- DCU-MS:	Mathematical modelling of resistive MHD instabilities (in association with Dundee University and CEA-Cadarache)
- UCD/DIAS:	Theoretical and computational work on: ion cyclotron harmonic mode excitation, nonlinear Alfvénic structures in MHD, cross-field diffusion and field-line wandering
- UCC-P:	Investigation of high Z impurity and MARFE spectra in JET Spectroscopy of the COMPASS Tokamak (at UKAEA-Culham)
- UCC-EEM:	Faraday rotation polarimetry for the RFX machine (in association with IGI-Padova) Extension of the FIR Interferometer on the TCV machine to a Faraday rotation polarimeter (in association with CRPP-Lausanne) Computation studies and numerical modelling of plasma diagnostic data (with IPP)

Achievements during the last 5 years

DCU –PS - Determined a resonant energy exchange between argon and hydrogen leads to an increase of vibrationally excited molecules in the argon/hydrogen mixture. An experimental run was carried out on the KAMABOKO source on MANTIS in CEA Cadarache to carry out optical emission spectroscopy on the filament driven discharge. Local measurements of the rf electric field and current density have been made and the plasma conductivity deduced which allowed the confirmation of the importance of the anomalous skin effect and collisionless heating.

UCC-ASL - Work has continued towards building up a database which will enable high Z elements to be identified promptly when they enter fusion plasmas. A SPRED survey spectrometer and a CCD^2 X-ray spectrometer have been prepared for use on MAST where they will be used to monitor impurities.

UCC-EEM – For the first time multichord FIR polarimetry measurements have been performed in the RFX experiment. Reliable results have been obtained for plasma currents between 0.5 and 1MA and a scaling of the measured faraday rotation angle with the average poloidal B field has been demonstrated.

UCC-P – CLISTE code: Successful identification of current density profile on ASDEX Upgrade high-performance discharges with Internal Transport Barrier. Fast Identification of Stellarator Equilibria on W7-AS: Database studies to identify limits of pressure profile identification using magnetics. EFIT-TRANSP consistency checks underway at JET.

UCD-DIAS - Study of strange kinetics in Hasegawa-Mima turbulent transport. Study of transport regimes in anisotropic magnetic turbulence.

Staff

Professionals :	about 18 MY in 1999	(Number of Professional Staff : 28)
Support staff :	about 6 MY in 1997	(Number of Support Staff : 22)

Overall expenditure :about 0.9 MioEURO/year

Management Structure

Head of Research Unit:	Prof. E.T. Kennedy,	Tel: (353) 1 704 5305
	Dublin City University,	fax: (353) 1 704 5384
	Glasnevin,	E-mail:eugene.kennedy@dcu.ie
	EI - DUBLIN 9	

Status: February 2000

ASSOCIATION EURATOM/ENEA -
Ente per le Nuove tecnologie, l'Energia e l'Ambiente

Contract Nr. : 343-88-1 FUA (I) ERB 5000 CT 880031
Period : 01/01/1988 - 31/12/2000

Research Units of ENEA :

Centro Ricerche Energia ENEA Via E. Fermi 45 I-00044 Frascati	Centro Ricerche Energia ENEA Brasimone I-40032 Camugnano	Centro Ricerche Energia ENEA Bologna Via Martiri di M. Sole 4 I-40129 Bologna

History of the EURATOM-ENEA Association
Started 1959 as a Subassociation to Euratom-CEA, which then became the Euratom-ENEA Association in 1960. It pioneered in the '60 very high density and inertial confinement fusion schemes. From the 70's the program was prevalently devoted to tokamaks research and related technologies.

Present scientific and technical programme
- Magnetic confinement studies, centered on the exploitation of the Frascati Tokamak Upgrade and JET facilities.
- Fusion technology, NET/ITER related programmes (Superconductivity, Remote handling, Plasma Facing Components, Safety, various tasks, etc.), and Long Term programs (Blanket, Materials, Neutron Source, etc.).
- Frascati Neutron Generator : 10^{12} n/s.
- Inertial confinement studies : Laser ABC system. Keep-in-touch activity with the international research programme on inertial confinement.

Achievements during the last 5 years
- Demonstration of high efficiency of Lower Hybrid Current Drive at high plasma density. Demonstration of temperature dependence of Lower Hybrid Current Drive.
- Investigation of global transport properties of ohmic regimes at density and magnetic field values relevant for ITER.
- Achievement of enhanced confinement regimes with deep pellet injection and weak/negative magnetic shear profiles. Analysis of the effect of the MHD activity on transport in these regimes.
- Investigation of plasma transport in very high electron temperature plasmas (Te of the order of 15 KeV) produced by Electron Cyclotron Resonant Heating.
- Influence of high Z wall materials on tokamak operations.
- Analysis of shear flow formation induced by Ion Bernstein Waves injection.
- Development of hybrid MHD/ Gyrokinetic codes and analysis of instabilities driven by energetic particles (TAE, Fishbones etc...).
- Development and characterisation of superconducting coils for ITER in collaboration with industry.

- Fabrication of the first European Nb3Sn, 12T, superconducting coil with an ITER relevant Cable-in Conduit conductor. Tests and demonstration of the dynamic response of the coil in ITER conditions.
- Development of high temperature superconducting cables.
- Frascati Neutron Generator: improvement of the nuclear data library and validation of the shielding performances of the ITER blanket design.
- Materials: development of joining, plasma spray, non destructive examination techniques for plasma facing components; development and characterisation of SiC/SiC fiber composites.
- Fabrication and operation of the Divertor Test Platform and Divertor Refurbishment Platform in order to validate the design and remote maintenance procedure of the ITER divertor.
- Inertial Confinement Studies:
  Experiment: stable acceleration of thin (a few micrometers) foils over distance about 70 times the in-flight-foil-thickness.
  Theory: formulation of new ICF schemes different from the standard ones.

Staff
Professionals : 150
Technical staff : 165

Yearly budget (expenditure 1999): about 60 MioEURO (including the Milano and Padova/ CNR Research Units)

Management structure
Head of Research Unit : R. ANDREANI
The Fusion Division of the ENEA's Energy Department includes three Units : Physics, Technology, Experimental Engineering subdivided in Projects, Sections and Special Units. Management is assisted by a special Support Unit. Universities and other ENEA Units are contributing to the programme through subcontracts.

Status: February 2000

ASSOCIATION EURATOM-ENEA Consiglio Nazionale delle Ricerche, CNR – Milano

Contract Nr.: 343-88-1 FUA (I) ERB 5000 CT 880031
Period: 01/01/1998 – 31/12/2000

Research Unit Istituto di Fisica del Plasma "Piero Caldirola"
Associazione Euratom/ENEA/CNR
Via R. Cozzi, 53
I-20125 MILANO

History of Association/Laboratory

-Laboratorio di Fisica del Plasma del CNR, date of foundation 29.1.70.
-Istituto di Fisica del Plasma: foundation 20.12.1979.
-Association EURATOM/ENEA/CNR: 1-1-1983 onwards.

Present scientific and technological programme

1) ECRH experiment on FTU Tokamak (ENEA Frascati) at high density, in collaboration with the ENEA, Centro Ricerche Energia, Divisione Fusione: the plasma will be heated at 140 GHz, 2 MW for 0.5 s by microwave power.
2) Fusion Technologies: Study of the effects of plasma-wall interaction, in fusion reactor, by metal surface analysis (XPS; SIMS). Study of the effects on different ion impurities by Radiofrequency produced ponderomotive forces.
3) Theoretical research on: Wave-plasma interaction and non linear wave phenomena, support to the ECRH experiment on FTU; Transport and MHD Physics; Advanced wave plasma-problems.
4) JET (EFDA) activity: studies on the development of compensation coils for "error field" control on JET. Participation to the activity of the S2 Task Force on JET on the study of heat pulses and thermal barriers. Participation to the Task Force M on JET on the study of neo tearing modes. Participation to the Task Force H on JET (RF Heating)
5) ITER Activity: Participation to Tasks for the development of ECRH system for ITER.

Achievements during the last 5 years

ECRH experiment on FTU Tokamak (ENEA)

- Installation and operation of a system of four gyrotrons at 140 GHz (2 MW total), for ECWH experiments.
- Experimental results: full stabilisation of sawtooth instability in FTU with localised off-axis ECRH, proof of the consistency of response of saw-tooth instability to localised ECRH/ECCD with a critical shear model, obtaining of neoclassical ion energy transport regime with ECRH at high density, ECRH induced destabilisation of isolated and coupled tearing modes, achievement of high Te, up to 14 KeV, in discharges with low/inverted central shear.
- Identification of kinetic effects in electron energy distribution function at very high Te, with strong central ECRH.
- Specific diagnostic and computational tools for the measure and analysis of residual EC radiation at the vessel walls.

- Operation of an equipment for a fully automatic pattern measurement of large-size ECRH launchers; development of test-sets and laboratory equipment for phase-amplitude measurements of components/systems in the millimetre wave frequency band; operation of high power calorimetric matched loads for millimetre wave beams; development of passive microwave components, for 140 GHz, high power.

Fusion Technology

- Tritium recovery from Tritiated water by use of getter alloys; design of getter Reactor for recovery of Tritium from tritiated water, (ITER); methods of cryogenic separation for exhaust mixtures of Fusion reactors.
- Plasma device for application of ponderomotive forces to ion plugging.
- Development of diffusion liquid sodium pumps for NET.

Theory of plasmas and thermonuclear Fusion

- Development of the theory and codes for the propagation, power absorption, and non inductive current drive of Gaussian beams of EC waves in toroidal plasma confinement devices, including self diffraction effects.
- Development of codes for the design and interpretation of Collective Thomson scattering in tokamaks.
- Theory of the nonlinear interaction of intense short wavelength wavepackets with plasmas with results in the study of self channelling effects, ionisation instabilities and generation of high harmonics.
- Theory of electrostatic response of electron-ion plasma to ponderomotive effects of intense electromagnetic waves.
- Theory of nonlinear response to external fields and of the evolution of isolated and coupled rotating tearing modes in tokamaks, with identification of the role of the ion polarisation current and of the density scaling for the threshold of locked modes instability in presence of toroidal rippled field.
- Theory of the response of sawteeth and neoclassical tearing modes to localised E.C. Heating current drive, applied to the interpretation of tokamak experimental results and to scenarios of feedback control.
- Theoretical models of transition to stochasticity of magnetic configurations with singular lines.
- Development of interpretative models of nonlocal transient heat propagation, with sign reversal of heat pulses; identification of transport barriers in tokamaks.
- Development of interpretative tools for the diagnostic of the neutron emission spectrum in tokamak reactors.

Staff: Professionals: 20 Support Staff: 19 External professional Collaborators: 5

Management Structure: Head of the Research Unit: G. LAMPIS
Status: February 2000

EURATOM/ENEA (Consiglio Nazionale delle Ricerche, CNR - Padova)

Contract Nr. : 343-88-1 FUA (I) ERB 5000 CT 880031
Period : 01/01/1988 - 31/12/1999

Research Unit : Consorzio RFX
Corso Stati Uniti 4
I-35127-CAMIN PADOVA

History of Association/Laboratory

-Association Euratom/CNR : Contracts 46/76/I/FUAI; 54/79/I/FUAI; 102/82/I/FUAI.
-Association Euratom/ENEA (CNR) : Contracts 202/85/I/FUAI; 343/88/I/FUAI actual contract.

The activity of the Padua group for fusion research increased substantially in 1984 after the start of the RFX (Reversed Field Pinch eXperiment) project. The RFX construction was completed in 1991; the first RFP plasmas were obtained in 1992. Since then, the device was routinely operated by alternating experimental periods (for a total of 12.000 power pulses) and shutdown periods to install new or modified equipment.

Present scientific and technical programme

The present scientific program is mainly focused on the exploitation of the RFX experiment in a wide range of operational regimes, to perform studies on particle and energy transport, radiative losses, magnetic dynamics, plasma wall interaction. Plasma diagnostics are progressively improved to obtain higher accuracy and better time and space resolution. Technological developments are mainly oriented to increase the capability of actively control the plasma and the plasma - wall interaction phenomena. The Research Unit is also participating in the ITER Design and in JET operation.

Achievements during the last 5 years

- Extended range of plasma currents (up to 1.2 MA); clean discharges in the whole current range (Z_{eff} <1.5)
- Better space and time resolution of plasma diagnostics, giving a deeper understanding of transport phenomena
- New techniques to control the field configuration by fast amplifiers
- Rotation of tearing modes induced by external fields: experiments and modelling
- Improved confinement by pulsed and oscillating poloidal current drive
- Theoretical prediction and clear experimental evidence of quasi-single helicity states, both transient and stationary

Staff

Professionals : 60
Support : 55

Management structure

Head of Research Unit : F. GNESOTTO

Status: December 1999

ASSOCIATION EURATOM/Etat Belge-Belgische Staat
(Ecole Royale Militaire/Koninklijke Militaire School)

Contract Nr. : 346-88-1 FUA (B) ERB 5000 CT 920001
Period : 01/01/1988 - 31/12/1999

Research Unit : Ecole Royale Militaire/Koninklijke Militaire School
Laboratoire de Physique des Plasmas/Laboratorium voor
Plasmafysica
Association "Euratom-Etat belge"/Associatie "Euratom-Belgische Staat"
Avenue de la Renaissance 30
B-1000 Brussels

History of Association/Laboratory
The laboratory was established in 1961 as the research arm of the Chair of Physics of the Royal Military Academy and became a founding member of the EURATOM-Belgian State Association in 1969. It specialised in the study of the propagation of electromagnetic waves in plasmas and the design of appropriate launching structures, highlighted by the development, during 1976-1981, of ion cyclotron heating on ERASMUS, the first university-size tokamak in Europe. In a collaborative effort with the EURATOM-KFA Association, the laboratory conducts since 1981 heating (ion cyclotron) and confinement studies on the TEXTOR tokamak. This collaboration developed in 1996 into the Trilateral Euroregio Cluster of FOM-Rijnhuizen, ERM/KMS-Brussels and FZ-Jülich aiming at an integrated programme of core, edge and exhaust physics centred around the RI-mode, the enhanced confinement state at high radiation fraction discovered on TEXTOR.

Present scientific and technical programme
The programme concentrates on the one hand on the understanding of the influence on tokamak confinement of radiative mantles and edge electrical fields and on the other hand on the advancement of ion cyclotron heating as the heating method for fusion reactors. Theory, diagnostics and technology are developed wherever these aims demand so and support for JET and ITER (through Task Agreements) is of prime concern.

Achievements during the last 5 years
- Discovery of Radiative Improved Mode of tokamak operation in TEXTOR-94 (in close collaboration with the Association EURATOM-KFA).
- Elucidation of role of velocity shear in the suppression of turbulence.
- Further development of ICRH heating systems and codes for plasma heating.
- Development of tokamak start-up and conditioning techniques based on ICRH.
- Development of novel diagnostic techniques for poloidal flow measurements and for the detection of fusion products.

Staff

Professionals : 26
Support staff : 10

Yearly budget (expenditure 1998): 3.135 MioEURO (includes 0.25 MioEURO subcontract with Université Cath. de Louvain)

Management structure

Head of Research Unit : R. WEYNANTS (Director)
Assistant-Director: R. KOCH

Status: February 2000

ASSOCIATION EURATOM/Etat Belge (Université Libre de Bruxelles, ULB)

Contract Nr. : EUR 346-88-1 FUA (B) - ERB 5000 CT 920001 - ERB 5005 CT 99 0104
Period : 01/01/1988-31/12/2001

Research Unit : Unité de Physique Statistique et Plasmas
Université Libre de Bruxelles
Campus de la Plaine, CP 231
Boulevard du Triomphe
B-1050 Bruxelles

History of Association/Laboratory
The Association was founded in 1969: at that time it had two branches:
Ecole Royale Militaire and Université Libre de Bruxelles.
Later, the Centre d'Etude Nucléaire (SCK/CEN) joined the Association.

Present scientific and technical programme
- Theoretical problems of plasma physics in connection with fusion research.
- Transport processes in plasmas.
- Study of plasma turbulence, in connection with transport and heating.
- Numerical simulations of MHD turbulence.

Achievements during the last 5 years
- Development and testing of Hamiltonian maps for field lines and particle trajectories in a general toroidal geometry.
- Derivation of scaling laws for diffusion.
- Neoclassical transport in presence of strong electric fields.
- Implementation of a new numerical technique for MHD turbulence.

Staff
Professionals: 12
Support staff: 1 + 1/2

Management structure
Head of Research Unit: D. CARATI
Deputy: R. BALESCU

Status: January 2000

ASSOCIATION EURATOM/Etat Belge
(Studiecentrum voor Kernenergie/Centre d'Etude Nucléaire, SCK/CEN)

Contract Nr. : EUR 346-88-1 FUA (B) ERB 5000 CT 920001
Period : 01/01/1988 - 31/12/2000

Research Unit : SCK/CEN
Boeretang 200
B-2400 Mol

History of Association/Laboratory

An initial contract of collaboration, on thermonuclear fusion research, between the Association Euratom-Belgian State and the SCK/CEN was concluded on December 22, 1975. In 1982, the SCK/CEN became an associated laboratory.

Present scientific and technical programme
The fusion work at SCK.CEN focuses on *radiation tolerance of materials*: characterisation of neutron irradiated metals (vessel structure, plasma facing components), environmental tolerance of instrumentation for remote handling and diagnostics (ceramics, optical fibres, electronics). This cover also connected items related to safety aspects (reactivity of materials in accidental condition), corrosion (also in collaboration with KULeuven university) and waste management. In the future, SCK.CEN will continue along this main expertise field.
The BR2 material testing reactor and related facilities, as its hot cells equipped for material characterisation, are main assets in the SCK.CEN fusion research programme.
The SCK.CEN manages also the contribution of GRADEL-Luxemburg (divertor maintenance remote handling tools).

Achievements during the last five years
- Overall characterisation of radiation induced degradation of *beryllium*: mechanical toughness, surface reactivity in accidental conditions (hydrogen production), helium production and fracture mechanism modelisation, integrity after thermal annealing, etc. Results contributed to fusion database, and to the SEAL report.
- Characterisation of radiation induced degradation of *stainless steels* (fracture toughness, fatigue toughness), *inconel* (irradiation creep), contributing to the ITER database.
- Identification of several radiation-hardened alternatives to position and force sensors, and to motors, for remote handling units. Significant progress also obtained on *optical fibre* sensors for fibroscopy, strain sensing and optical data link. Preparation of a representative reactor testing of insulation ceramics for heating and current drive.
- More recently, characterisation of alternative reactor materials such as *chromium*, and study of *waste disposal* issues (intrusion scenario), as well as comparison of dismantling strategies on the basis of in-house PWR experience.

Staff

Many SCK/CEN agents participate on a part time basis in the SCK/CEN fusion research programme. The integrated yearly effort is between 10 to 15 professionals and about the same amounts of support staff.

Management structure

Head of Research Unit : M. DECRETON

Status: February 2000

ASSOCIATION EURATOM/FOM - Stichting voor Fundamenteel Onderzoek der Materie

Contract No.: 347-89-1 FUA (NL) ERB 5000 CT 900021
Period: 01/01/1988 - 31/12/2000

Research Unit: FOM Institute for Plasma Physics "Rijnhuizen"
Edisonbaan 14
NL-3439 MN Nieuwegein

History of Association/Laboratory
The Euratom-FOM Association was established in 1962.

Present scientific and technical programme
In the framework of the Trilateral Euregio Cluster (TEC), the Dutch Association concentrates its efforts on the study of the physics of Tokamak turbulent electron transport and non-linear electron dynamics. The experimental work is performed on the TEXTOR-94 facility at Jülich, in particular by means of ECRH/ECCD. Fluctuations are measured by high resolution diagnostics in particular Thomson scattering.
Technology: development of a 1 MW, tunable 130 - 250 GHz Free Electron Maser (FEM) for ECRH/ECCD application in fusion research.

Achievements during the last 5 years
- The development of high resolution diagnostics which made possible:
- The discovery of electron thermal barriers near (but not at) many rational q-surfaces in tokamaks (RTP) and stellarators (TJ-II).
- The interaction of these barriers with magnetic islands and zones with chaotic magnetic field and the influence of these phenomena on turbulent electron transport.
- The creation of filaments under intense ECRH in areas of the RTP plasmas with low magnetic shear as a manifestation of 'hot snakes' or 'positive' islands, i.e. magnetic structures closed on themselves with very good confinement.
- The occurrence of off-axis sawteeth relaxations in case of negative central shear discharges.
- ECW driven current leading to discharges with 55% non-inductive current.
- The demonstration that with only 5% ECW driven current in counter direction sawteeth can be suppressed as the central q-value is lifted just above 1.
- The demonstration that ECRH could be used to postpone and ameliorate high density disruptions.
- The demonstration that for determination of ECW current drive efficiencies it is necessary to take into account the existence of electron thermal barriers, filaments and islands.
- The direct confirmation in RTP of ASDEX-U observations that the high density clouds around ablating pellets are not in MHD equilibrium and therefore are pushed out of the plasma towards the low field side.
- The preparation for TEXTOR of 5 different microwave diagnostic systems (ECE and reflectometry), a high resolution Thomson scattering diagnostic, a collective Thomson scattering system (together with MIT) for fast-ion distributions and an

innovative ultra soft x-ray camera system for tomography of impurity line emission, this all as contribution to the TEC-programme.

- The preparation of a 110 GHz and a 140 GHz ECRH/ECCD system for TEXTOR as a contribution to the TEC-programme.
- The demonstration of the functioning of the Free Electron Maser as numerically predicted during short pulses(10 µs) of 700 kW at various frequencies between 165 and 205 GHz.
- The construction of a long pulse (hundreds of ms) version of such a FEM with a depressed collector to be tested in spring 2000.
- The education of Ph.D. students in high temperature plasma physics leading to about 20 theses in the period between 1996 and 2000 of which 60% have found a position in the European Fusion Programme.

Staff

Professionals:	30
Support staff:	45
Ph. D. Students:	10

Yearly budget (expenditure 1997): about 11 Mio EURO (about half of this is for NRG/Petten Research Unit)

Management structure

Head of Research Unit: F.C. Schüller

Status: January 2000

ASSOCIATION EURATOM/FOM (NRG-Petten)

Contract Nr. : EUR 347-89-1 FUA ERB 5000 CT 900021

Period : 01/01/1990 - 31/12/2000

Research Unit : NRG
P.O. Box 25
NL-1755 ZG PETTEN

History of Association/Laboratory

Long standing R&D research in nuclear energy since 1955 (since 1998 as NRG).

Present scientific and technical programme

In Fusion Technology :

- Irradiation and characterisation of fusion relevant structural materials;
- Post-irradiation and reference mechanical testing of various grades of austenitic stainless steel, ferritic/martensitic low-activation steels and advanced alloys;
- Post-irradiation and reference testing of mechanical and physical properties for various advanced ceramic composites;
- Investigation of the reweldability of irradiated stainless steel for ITER and (re)weldability of ferritic/martensitic low-activation steels;
- In-pile measurements of tritium-breeding materials and blanket submodules for ITER/DEMO;
- In-pile permeation measurements of barrier coatings and blanket subassemblies;
- Post-irradiation measurements of tritium retention and release;
- Material research for plasma facing components;

Staff

Professionals : about 10
Support staff: about 15

Management structure

Head of Research Unit : A.M. VERSTEEGH

Status:

ASSOCIATION EURATOM / FZJ - Forschungszentrum Jülich

Contract Nr.: 342-88-1 FUA (D) – ERB 5005 CT 99 0110

Period: 01/01/1988 - 31/12/2001

Research Unit: "Institut für Plasmaphysik" and "Projekt Kernfusion"
Partner in the Trilateral Euregio Cluster (TEC)
Forschungszentrum Jülich (FZJ)
D-52425 Jülich

History of Association/Laboratory

The "Institut für Plasmaphysik" was the first scientific institute of the Forschungszentrum Jülich, founded in the late fifties. The Contract of Association with EURATOM was signed in 1962. During the sixties the programme was focused on theta pinches. In the mid-seventies the activities were re-oriented towards plasma-wall interaction. The central facility for the experimental programme, the tokamak TEXTOR (Torus Experiment for Technology Oriented Research), became operational in 1983 and was upgraded in 1994 by a significant prolongation of the achievable pulse length ("TEXTOR-94").

Present scientific and technical programme

The joint research programme of the TEC-partners aims at developing a coherent concept for energy and particle transport/exhaust under quasi-stationary conditions. The Tokamak TEXTOR-94 ($R = 1.75$ m, $a = 0.5$ m) is equipped with a heating power of 4.0 MW ICRH and 4.0 MW NBI heating (providing a power flux density through the boundary of 25 W/cm²) and with a toroidal pump limiter (ALT-II). Fusion relevant plasmas can be produced and maintained for a duration of up to about 10 seconds. The experiments are accompanied by related modelling activities. Plasma facing materials and components are developed and tested using specific facilities for applying extremely high heat loads.
Highlights of the TEXTOR-94 programme: wall conditioning (boronisation/siliconisation), helium exhaust, edge radiation cooling, impurity transport, RI-mode, runaway electrons, sawtooth-physics, Dynamic Ergodic Divertor (under construction).

Achievements during the last 5 years

- Development and qualification of wall coatings (siliconization, boronization).
- Development and study of the radiative improved mode (RI-mode), which combines improved energy confinement (as good as that of ELM-free H-mode discharges in divertor tokamaks) at high plasma density (at or above the Greenwald density) with energy exhaust on large areas via boundary radiation from feed-back controlled neon or argon or from silicon sputtered from siliconized plasma facing components.
- Development of self-consistent transport code RITM for highly radiative discharges including an explanation for confinement improvements via suppression of ITG-modes. Modelling of poloidal asymmetries with a first fully self-consistent incorporation of drift motions (TECXY).

- Understanding of the trigger mechanism of the radiative instability phenomenon MARFE; with new techniques for suppression of MARFEs densities up to two times the Greenwald density were reached.
- Improvement in the understanding of the sawtooth phenomenon: incomplete reconnection, magnetic amplitude of the precursor mode, modulation of ion temperature and momentum.
- Erosion and deposition studies, in particular using a well diagnosed limiter lock system: prompt re-deposition, comparison of graphite/tungsten, penetration/screening and chemical erosion versus sputtering.
- Recycling and particle control: surface temperature dependence of the emission of H/H_2, dissociation of vibrationally excited H_2 into slow atoms (0.3 eV) and hydrogen (tritium) retention in co-deposited carbon.
- Development of new diagnostics: high resolution x-ray spectrometer, atomic beam for the plasma boundary, run-away detection via synchrotron radiation, recycling studies by laser induced fluorescence.
- Development of the Dynamic Ergodic Divertor as a novel tool to control particle and energy transport at the plasma boundary (to be installed 2000/2001).

Staff

Professionals:	50
Support staff:	70

Yearly budget: about 20 MioEURO

Management structure

Head of Research Unit: U. Samm

Status: February 2000

ASSOCIATION EURATOM/FZK - Forschungszentrum Karlsruhe

Contract Nr. : 350-89-1 FUA (D) ERB 5000 CT 900023
Period : 01/01/1989 - 31/12/2001

Research Unit : Forschungszentrum Karlsruhe (FZK) GmbH
Nuclear Fusion Programme
P.O. Box 3640
D-76021 Karlsruhe

History of Association/Laboratory
Since 1982 Forschungszentrum Karlsruhe participates to the European Fusion Programme as an associated laboratory. The main scope of the contribution is to address the important issues of fusion technology in view of the next experimental reactor to be built and, beyond, related to fusion power reactors. The FZK-Euratom Association, in development cooperation with the Max-Planck-Institute for Plasma Physics (IPP), contributes to the construction of the stellarator WENDELSTEIN-7X. FZK participates in the exploitation of JET.

Present scientific and technical programme:

- ITER related programme (EFDA technology)
  Test and component development for large superconducting magnets (i.a. test of the ITER TF model coil); advanced gyrotron and window development; cryogenic exhaust gas pumping development and prototypic tests; development and test in technical scales of an exhaust gas purification system (Tritium laboratory).
  Studies on high heat load effects and tritium permeation; design tasks with relevance to reliability and safety of the ITER systems and –plant.
- JET exploitation (EFDA-JET)
  Contributions to fuel cycle and first wall issues, waste management, active gas handling.
- Long term technology (EFDA)
  Breeding blanket development including test modules for ITER, qualification of low activation structural materials, reactor studies with aspects of safety, economy, and influence on the environment.
- Development and construction of the electron cyclotron heating system for WENDELSTEIN-7X in cooperation with University of Stuttgart and European industry.

Achievements during the last 5 years

- Successful test of large superconducting coils (poloial field coil, LCT coil at enhanced field, prototype W7X).
- Highest power (>2MW) and efficiencies ~50% achieved in gyrotrons (ITER, W7X).
- Solid breeder helium cooled blanket developed, engineering design of ITER test blanket.
- Plasma exhaust gas with 10^7 detriation factor demonstrated in technical scale (ITER).
- Qualification of EUROFER steel for low activation / good fracture mech. properties.
- Miniature specimen techniques developed for fusion neutron source (IFMIF).

Staff : 80 pmy/y + 70 support

Yearly budget: about 30 MioEURO/yr

Management structure: Project organisation, matrix structure (project, institutes)

Head of Research Unit : J.E. VETTER

Status: February 2000

ASSOCIATION EURATOM/HELLENIC REPUBLIC

Contract Nr.: ERB 5000 CT 99 0 100
Period: 22/06/1999 - 31/12/2001

History:
A Consultative Committee for Fusion Activities in Greece (CCFA-G) was set up in 1991 with the purpose to co-ordinate fusion activities, when these started being funded by Euratom via cost-sharing actions. In the meantime, fusion activities have developed so that an Association Contract between Euratom and the Hellenic republic was signed on 22 June 1999.

Laboratories, present scientific and technical programme and active collaborations
Physics Programme:

- National Centre for Scientific Research “Demokritos”, Institute for Nuclear Technology and Radiation Protection, Athens (N. TSOIS): SOL and divertor physics diagnostics, data base development and simulation (in collaboration with IPP).
- National Technical University, Department of Electrical and Computer Engineering (J. VOMVORIDIS) and University of Athens, Department of Physics (I. TIGELIS): high-power microwaves and plasma/electron beam instabilities, non-linear relativistic dynamics of charged particles, EM scattering (in collaboration with CRPP and FZK).
- University of Ioannina, Department of Physics (G. THROUMOULOPOULOS): negative-energy perturbations, stationary MHD states in magnetically-confined plasmas (in collaboration with IPP).
- FORTH, Institute of Electronic Structure and Lasers, Heraklion (P. LALOUSIS): vapour shield phenomena during hard disruptions, development of codes (in collaboration with IPP).
- University of Thessaly, Department of Mechanical and Industrial Engineering (N. VLACHOS), National Technical University of Athens, Department of Electrical and Computer Engineering (K. HIZANIDIS) and University of Athens, Department of Physics (C. POLYMILIS): MHD turbulent transport, stochastic modelling, transport and chaos and MHD instabilities in fusion plasmas (in collaboration with ULB).

Technology Programme:

- National Centre for Scientific Research "Demokritos", Institute for Nuclear Technology and Radiation Protection, Athens (S. MESSOLORAS): Fracture micromechanisms of ceramic composites and joints under irradiation, brazing with thermomechanical testing (in collaboration with CEA).

Achievements during the last 5 years (before the establishment of the Association)

- Design, construction, installation and operation of a Langmuir probe
- Assessment of radiation modes and beam instabilities in gyrotron beam tunnels
- Construction of equilibria with incompressible plasma flow and derivation of suitable sufficient conditions

Staff (Full-time equivalent, including both physics and technology)
7 Faculty members
7 Ph.D. researchers
10 graduate students, and technicians

Yearly budget (all funding sources): about 1.1 MioEURO

Management structure
Governing body for the administration of fusion activities in Greece: Administrative Committee
Administrator of the Contract of Association: Institute for Nuclear Technology and Radiation Protection of the National Centre for Scientific Research “Demokritos” (Director: M. ANTONOPOULOS-DOMIS)
Head of Research Unit: J. VOMVORIDIS
Participating Institutions: NCSR“D”, NTUA, UoA, UoI, FORTH, UoTh

Status: February 2000

ASSOCIATION EURATOM / Max-Planck-Institut für Plasmaphysik (IPP)

Contract Nr.: 339–88–1 FUAD
Period: 01/01/1999 - 31/12/2000

Research Unit: Max-Planck-Institut für Plasmaphysik
Boltzmannstrasse 2
D-85748 Garching bei München

History of Association/Laboratory

The "Institut für Plasmaphysik GmbH" (IPP) was established in 1960 as a shareholding of the Max-Planck-Gesellschaft (MPG) and Werner Heisenberg. In 1971 it became an institute of MPG. IPP has been a EURATOM association since 1961. – With the PULSATOR tokamak experiment (1973 - 1979) IPP succeeded for the first time in penetrating the high-density plasma regime, which is characterised by good confinement properties and low impurity density. The introduction of the new divertor concept in the experiment following, ASDEX (1980 - 1990), brought a further major improvement of the plasma purity which allowed, in 1982, the discovery of a plasma state with enhanced energy confinement (H-regime). This H-mode state is expected to form a sufficient basis for the energy confinement in ITER.

By using model plasmas IPP showed in 1964 that the confinement of a well-built stellarator (WENDELSTEIN Ib), in the collisional regime, is governed by classical losses only. At the same time the importance of resonances was discovered experimentally. In 1980 the WENDELSTEIN 7-A stellarator (1976 - 1986) demonstrated for the first time the possibility of confining a hot plasma just by applying external magnetic fields (without plasma current). A new, improved stellarator confinement concept was discovered and elaborated and forms the basis for WENDELSTEIN 7-X. – IPP hosts the EFDA group and is the European site of the ITER Design Activity.

Present scientific and technical programme

The research programme of IPP is aimed at developing and investigating the basic plasma physics required for a nuclear fusion reactor. For this purpose IPP design, construct, and conduct fusion experiments of the tokamak (ASDEX Upgrade) and stellarator (WENDELSTEIN 7-AS, WENDELSTEIN 7-X) types. The objectives of ASDEX Upgrade, which started operation in 1990, are to investigate divertor configurations suitable for a fusion reactor, to study the core physics and the relation to the edge behaviour (transport, operation limits, MHD phenomena), and to explore advanced tokamak operation. Thus, the results of ASDEX Upgrade will be an important input for the construction of ITER. The WENDELSTEIN 7-AS advanced stellarator, as the first experiment to adopt a modular coil system for magnetic field generation, has achieved clearly improved plasma parameters and confinement properties in comparison with its predecessor, WENDELSTEIN 7-A. These results together with detailed theoretical calculations form the basis for the WENDELSTEIN 7-X stellarator, which is to demonstrate under fusion-relevant plasma parameters and with an optimised magnetic field the physical qualification of a reactor based on the stellarator concept. WENDELSTEIN 7-X is being built in the branch institute of IPP in Greifswald. – Other investigations are concerned with basic plasma-wall interaction, material research, and surface physics.

Achievements during the last 5 years

- quantitative understanding of **ASDEX Upgrade** energy exhaust in different divertor geometries and achievement of strongly reduced target and wall loads due to divertor radiation fractions up to 50% of the input heating power
- progress in the clarification of the connection between core and edge transport; characterisation of different edge operating conditions and clarification of different nature of density limit phenomena in L- and H-mode
- demonstration of efficient pellet injection from the high field side
- formation of stationary internal transport barriers for ion and electron energies, particle and momentum combined with H-mode edge and weak shear for the duration of 40 confinement times and several internal skin times
- performance of weak shear internal transport barrier discharges extended to $H_{ITER-89P} = 3$ and $ß_N = 2.6$ at higher triangular plasma shapes, still limited by neoclassical tearing modes
- reactor-relevant $Te \approx Ti > 10$ keV operation achieved in internal transport barrier discharges with reversed shear ($q_{min} \approx 2$)
- identification of several new MHD phenomena in both conventional H-mode and advanced tokamak operation
- successful demonstration of feedback stabilisation of neoclassical tearing modes by electron cyclotron current drive (ECCD)
- in the **stellarator W7-AS** demonstration of neoclassical transport properties in the long mean free path collisionality regime; documentation of the role of the radial electric field; discovery of the H-mode in a non tokamak device
- achievement of stellarator plasmas with energy confinement times up to 60 ms, central ion temperatures up to 1.5 keV and central electron temperatures up to 6 keV in W7-AS with plasma radii less than 18 cm
- in high power neutral beam heated W7-AS discharges average beta values up to 2% obtained without indications of instabilities, but close to theoretical stability limit
- ion cyclotron resonance heating successfully applied to heat plasmas on W7-AS and also to sustain plasmas with ICRH only
- development of an island divertor
- development and design of the **stellarator W7-X** device, building construction, procurement of the coil system, preparation of vessel manufacturing, and developments for the power supply and plasma heating systems
- construction of an original-sized superconducting prototype non planar magnetic coil for the new stellarator W7-X device and successful operation in the background field of the European LCT (Large Coil Task) coil (in co-operation with FZK, Karlsruhe)
- investigation of the deposition mechanisms of hydrocarbon radicals and the incorporation of hydrogen isotopes leading to the understanding of layer deposition and hydrogen inventories in fusion experiments

- understanding of the transition from deposition to erosion of plasma facing materials under simultaneous hydrogen and impurity ion bombardment

Staff:	Professionals:	about 300
	Support staff:	about 700

Yearly budget (expenditure 1999 subject to Community support): about 109 Mio Euro

Management structure:

Directorate; Chairman: A.M. Bradshaw	Regulation and supervision of the research programme, internal and external representation
Board of Scientific Directors:	Definition of the research programme
Supervisory Board:	Consultation and supervision of the institute

Status: February 2000

ASSOCIATION EURATOM/IST - Instituto Superior Técnico

Contract Nr. : 418-90-1 FUA (PT)ERB 5000 CT 900029
Period : 01/01/1990 - 31/12/2000

Research Unit : Centro de Fusao Nuclear
Instituto Superior Técnico
P-1049-001 LISBOA

History of Association
Based on the experience acquired during fifteen years of research in fundamental plasma physics, the Centre entered the fusion field in 1986 (theory and reflectometry for ASDEX) and the Association EURATOM/IST was established in January 1990, based on the installation in Lisbon of a small tokamak (ISTTOK).

Present scientific and technical programme
The main projects are:
1) Operation of a fusion experiment in Portugal (ISTTOK)
2) Reflectometry diagnostics for fusion plasmas
3) Plasma engineering systems for fusion devices
4) Studies on non-inductive current drive
5) Studies on transport and MHD activity
6) Participation in the Fusion Technology Programme on materials
7) Keep-in-touch activity in inertial confinement

Achievements during the last 5 years
- Analysis of the electron density profile evolution on ISTTOK "sawtooth-like" discharges by heavy ion beam probing
- Enhancement of the ISTTOK plasma confinement and stability by negative limiter biasing
- Achievement of multi-cycle long duration flat-top alternating plasma current discharges without dwell time on ISTTOK
- Simultaneous measurement of the electron density and temperature in ISTTOK by a heavy ion beam deflection analyser with two species of ions
- Development of a reflectometry diagnostic for density profiles with high temporal as well as spatial resolution in both the high and the low field sides.
- Development of a reflectometry system combining AM and FM techniques for TJ-II
- Development of a "comb" transmitting/reflecting system to estimate the peak density of the JET divertor plasma
- Analytical calculation of the nonlinear frequencies for the unperturbed electrostatic lower-hybrid ray motion
- Development of a fast and accurate Fokker-Planck solver using non-uniform grids
- Development of VME and CAMAC distributed systems for fast timing and event management on MAST
- Development of a VME system for the monitoring of a laser in- vessel viewing system

Staff (in man-years)

Professionals:	53.8
Support staff:	9.4

Yearly budget (foreseen expenditure 1999): about 4 MioEURO

Management structure

Head of Research Unit :	C. VARANDAS
Directive Board :	C. VARANDAS, J. CABRAL, M.E. MANSO

Status: February 2000

ASSOCIATION EURATOM/NFR - Naturvetenskapliga Forskningsrådet

Contract Nr. : 345-88-1 FUA (S) ERB 5000 CT 900020
Period : 01.01.1988 - 31.12.2001

Research Unit/Laboratories :

The Alfvén Laboratory Royal Institute of Technology S-10044 Stockholm	Department of Physics I and II Royal Institute of Technology S-10044 Stockholm	Studsvik Eco Safe S-61182 Nyköping
Department of Electromagnetics Chalmers University of Technology S-41296 Göteborg	Dept. of Neutron Research University of Uppsala P.O. Box 535 S-75121 Uppsala	Dept. of Atomic Spectroscopy University of Lund P. O. Box 1703 S-22100 Lund

History of Association/Laboratory

After negotiations with Euratom during the years 1974-1976, the Swedish fusion research became formally associated with Euratom in 1976. The Swedish Research Unit consists of geographically separate sub-units, the largest one being the Alfvén Laboratory in Stockholm. The technology program is carried out in Studsvik.

Present scientific and technical programme

– Experimental and theoretical work on the reversed-field pinch and basic confinement physics.
– EXTRAP-T2 received priority status in 1990, operated 1994-8, rebuilt 1999, will start operation in Spring 2000.
– Fusion plasma theory on MHD stability, transport, confinement barrier, RF heating and fast particle physics, with applications to tokamaks and stellarators.
– Studies of plasma-surface interaction.
– Impurity and spectroscopy with fusion plasma physical applications.
– Neutron diagnostics.

Achievements during the last 5 years

- Studies of mode locking and wall locking in EXTRAP T2. Rebuild of T2 (new vacuum vessel, plasma facing wall, new shell with longer magnetic penetration time). Development of DEBS code for simulation of RFP dynamics.
- Studies of wall stabilisation, active feedback stabilisation, and operational limits in advanced tokamaks. Development of first principles models for drift-wave turbulence plasma transport in tokamaks: superior agreement with experimental results (ITER database). Models for L to H transitions and transport barriers. Theory of the global turbulent equipartition distribution in tokamak plasmas. Development of models and codes for ICRH and fast current drive: PENN and $\alpha\kappa$ - model (wave propagation), FIDO (ion velocity distribution), PION and SELFO (self-consistent simulations). Identification of RF-induced spatial transport. Development of models for turbulent transport at the plasma edge and simulation of plasma detachment in the divertor region. New models of sawtooth crashes and resulting fast-ion and impurity redistribution. Theory of alpha particle driven instabilities in tokamaks (TAE modes, fishbones, ion cyclotron emission).

- Measurements at TEXTOR and analysis of fluxes of D and impurities in the SOL, and retention of D and neon. Analysis of plasma facing components at JET.
- New analysis techniques and measurements of Z-effective electron temperature based on VUV spectroscopy in the RFP experiments. Measurements of impurity density radial profiles and impurity toroidal rotation velocity. Data base for low Z elements used for JET divertor modelling.
- MPR 14 MeV neutron spectrometer (priority support) on line in JET throughout 1997 including the tritium experiment: 3000 discharges recorded, neutron spectrum of triton burn up in D plasmas measured, measurements at the 10 ms resolution level in DT plasmas with NBI and ICRH heating, Doppler shifts in spectra corresponding to toroidal rotation velocities 600 km/s. TANSY 14 MeV neutron spectrometer on line (JET) during DT experiments: measurements of ion temperature anisotropy during ICRH. ToF 2.45 MeV spectrometer: measurements of T_i.
- The underlying technology programme is mainly focused on fusion safety and environment issues: modelling of loss of coolant accident transients; analysis of the behaviour of T and activation products in the environment; assessment of design and safety documentation for ITER and EU alternative concepts; assessment of plant safety and availability for a fusion reactor.
- The fusion technology programme includes research and development within: materials characterisation, T and activation products safety, waste management and disposal, development of plasma facing components, co-ordination of safety and environment tasks, and socio-economic research.

Staff Professionals: 58 my/y Support staff: 14 my/y
Yearly budget (expenditure 1999): about 8 MioEURO
Management structure: Head of Research Unit: Prof. M. LISAK, Chalmers University of Technology
The Natural Science Research Council (NFR) is the responsible Swedish funding authority.

Status: February 2000

ASSOCIATION EURATOM/ÖAW - Österreichische Akademie der Wissenschaften

Contract Nr. : ERB 5004 CT 96 0020 001
Period : 15/11/1996 - 31/12/2000

Research Unit:
The Austrian Research Unit consists of research groups at:
ÖAW-TU (Technische Universität), ÖAW-U (Universität), Wien
ÖAW-U (Universität) Innsbruck
ÖAW-ÖFZ (Österreischisches Forschungszentrum) Seibersdorf
ÖAW-TU (Technische Universität) Graz
ÖAW-AI (Atominstitut der Österreichischen Universitäten) Wien
ÖAW-Böhler Edelstahl, Kapfenberg (1.1.98-31.12.98)
ÖAW-ARGE Wärmetechnik, Graz (3.7.97-31.12.98)
ÖAW-Plansee, Reutte (as of 1.1.99)
Erich-Schmid Institut für Materialwissenschaft (as of 1.1.99)

Present scientific and technical programme

1. Physics programme:
Edge Plasma Theory (U. Innsbruck), Edge Plasma Diagnostics and Modelling (TU Wien), Transport and Dynamics of Ignited Plasmas (ÖFZ Seibersdorf), Charged Fusion Product Confinement in JET (from 1/1/2000), Electrostatic Plasma Turbulence – Test and Development of Langmuir Probes (Univ. Innsbruck), Electron Impact Ionization and Surface Induced Reactions of Edge Plasma Constituents (Univ. Innsbruck), Studies of Cyclotron Heating and Current Drive (TU Graz), Basic Transport Theory of Fusion Plasmas via a Multiple Timescale Approach (Univ. Innsbruck)

2. Underlying Technology
Evaluation of Neutron Cross Sections for Fusion-Relevant Materials (Univ. Wien), Improvement of Materials and Testing Methods for Superconducting Magnet Components in a Radiation Environment (Atominstitut), Neutron Inspection of Fusion Relevant Materials - Influence of Hydrogen (Univ. Wien), Neutron Inspection of Fusion Relevant Materials - Neutron Micro-Radiography (Atominstitut), Advanced Characterisation Techniques for Ferroelectric Thin Films (Atominstitut) (from 1/1/2000)

3. Technology Tasks:
Next step: Electrical Properties of Magnet Insulation Materials in the Irradiated State (Atominstitut), Radiation Effects on Fusion Magnet Materials (Atominstitut), Materials for Superconducting Fusion Magnets (TU Wien), Thermal Desorption Measurements on First Wall Protection Materials (TU Wien), commitment for 1999, Investigation of D/T retention in N-irradiated PFC materials (Be, C, W) (TU Wien), Alternative Bolometers based on Ferroelectric Thin Films (Atominstitut).
Long term: SiC-SiC ceramic composites (Atominstitut), Chromium alloy development (Plansee and Erich-Schmid Institut), or Technology to start in 2000:

4. Socio-Economic Research on Fusion (SERF) :
Projects completed in 1999: Democracy and Autonomy in a Complex, Centralising Technology (Univ. Wien), Fusion Power as an Additional Vector in the WEC/IIASA World Scenario (ARGE Wärmetechnik).
Project started in 1999: Trust and Licensing Procedures for large Fusion Devices (Univ. Wien)

Achievements during the last 5 years

- Non-destructive inspection routines for actively cooled plasma-facing components (1997-1998)
- Remote handling – attachment of blanket modules to the back-plate (1997-1998)
- Mass spectrometry of hydrogen and helium (1997-1998)
- Reduced-activation ferritic / martensitic steel development (1998)

- Development of fusion edge plasma codes and diagnostics
- Fusion edge plasma relevant A&M data
- "Stochastic Mapping Technique" for plasma electron distribution functions
- Evaluation of neutron cross sections of fusion relevant materials
- Characterisation of superconducting materials for fusion experiments
- Influence of neutron irradiation on superconductors and superconducting magnet insulation
- Alternative structural materials for fusion reactors (SiC-SiC, Cr alloys
- Socio-economic research on fusion….

Staff : (1999) Professionals: 53.0 my
Support staff: 7.0 my
Overall expenditure : about 4.2 Mio EURO for 1999
Management Structure Head of Research Unit : H.-P. WINTER, TU Wien

Status: February 2000

ASSOCIATION EURATOM/RISØ - Forskningscenter RISØ

Contract Nr. : 348-89-1 FUA (DK)ERB 5000 CT 910002
Period : 01/01/1988 - 31/12/2000

Research Unit : Risø National Laboratory
Fusion Research Unit
OFD - 128
P.O. Box 49
DK-4000 Roskilde

History of Association/Laboratory
First contract of Association established in 1973

Present scientific and technical programme

- Theoretical and computational studies of electrostatic turbulence and turbulent transport in magnetised fusion plasmas.
- Research and development of new laser-based diagnostics with increased spatial resolution for studies of turbulent density fluctuations in fusion plasmas.
- Theoretical and experimental studies of plasma turbulence in Stellarators (in collaboration with IPP Garching).
- Effects of irradiation on physical and mechanical properties of materials such as copper- and iron-based alloys relevant to the Next Step and the Long-Term Technology programmes.

Achievements during the last 5 years

- Successful installation and operation on W7-AS of two-point laser diagnostic for measurements of turbulent density fluctuations
- Development of a fully three-dimensional, time-dependent numerical code based on first-principle physics for investigations of drift wave turbulence in the edge region plasma
- New theoretical model based on Turbulent EquiPartition (TEP) for description of inward transport, transport barriers and intermittency
- A new theory for void swelling and its verification by numerical calculations and specifically designed experiments
- A new model for radiation hardening and plastic instability (embrittlement)
- Identification of copper alloys for their application in the first wall and divertor of ITER-like machine

Staff

Professionals : 11.5 man-years
Support staff : 8.5 man-years

Yearly budget (expenditure 1998): about 3.0 MioEURO

Management structure
Head of Research Unit : J.P. LYNOV

Status: February 2000

ASSOCIATION EURATOM/TEKES - National Technology Agency, Finland

Contract Nr.: ERB 5000 CT 95 0000
Period: 13/03/1995 - 31/12/2001

Research Unit: The Finnish Research Unit consists of research groups at:
VTT Chemical Technology, VTT Manufacturing Technology, VTT Energy, VTT Automation, VTT Electronics, Helsinki University of Technology, Tampere University of Technology and University of Helsinki

History of Association/Laboratory
The Finnish Association was set up in March 1995, with the National Technology Agency Finland (TEKES). A programme has been established, which is carried out at various research institutes in the Technical Research Centre Finland (VTT), Universities and industry.

Present scientific and technical programme
The Association concentrates on work in a small number of areas, where existing expertise shall be developed in order to establish centres of excellence.

Fusion physics and plasma engineering are carried out at VTT Chemical Technology and at Helsinki University of Technology. The emphasis of this work is in theoretical and computational studies on rf-heating and current drive which are carried out in close collaboration with European tokamak experiments.

The work in fusion technology includes: research on **fusion reactor materials:** First wall materials and joining techniques at VTT Manufacturing Technology, fusion neutronics at VTT Energy and deuterium-tritium mobility and inventory in plasma facing materials at University of Helsinki and VTT Chemical Technology.

A second domain of fusion technology consists in **remote handling and viewing systems**: In-vessel viewing systems (IVVS) at VTT Automation, VTT Electronics and at Helsinki University of Technology and the development of water hydraulics tools and manipulators for the Divertor Refurbishment Plant at Tampere University of Technology.

Achievements during the last 5 years
- Transport and heating modelling (ICRF+NBI+LHCD) for high performance experiments of JET.
- Development of the multi-purpose Monte Carlo particle following code ASCOT for heating and transport
- analysis in tokamaks: L-H transition model based on ASCOT transport simulations in ASDEX Upgrade and JET.
- Particle-in-Cell (PIC) simulations of parasitic absorption and resulting heat loads in the LH-grill of Tore Supra.
- Design of the ICRH vacuum transmission line dielectric window including manufacturing tests.
- Molecular dynamics simulations showing the suppression of carbon erosion by hydrogen shielding.

- Concentration independent and dependent diffusion of hydrogen isotopes in diamond like carbon films
- Irradiation testing of high strength Cu-alloys showing the superiority of CuCrZr alloy at operating temperatures.
- Development Cu/SS joining techniques (explosion welding, HIP) and characterisation methods for Cu/SS joints.
- Neutronics calculations and nuclear analysis of ITER heating systems and equatorial heating ports.
- Development of water hydraulic tools and manipulators for ITER Divertor Refurbishment Platform.
- Design and feasibility demonstration of the ITER In-Vessel Viewing System based on linear array of optical fibres.

Staff : Professional : 30 my/y
Support staff: 2 my/y

Yearly budget : about 3 MioEURO

Collaboration with other institutions

JET, EFDA CSU-Garching, IPP, CEA, ENEA, FZK, Risø, CRPP Lausanne

Management Structure

Head of Research Unit: S. KARTTUNEN
VTT Chemical Technology / Industrial Physics
P.O. Box 1404, FIN-02044 VTT, Finland
Email: seppo.karttunen@vtt.fi

Status: February 2000

ASSOCIATION EURATOM/UKAEA - United Kingdom Atomic Energy Authority

Contract Nr.: 340-88-1 FUA (UK) ERB 5000 CT 90018
Period: 01/01/88 – 31/12/2001
Research Unit: UKAEA Fusion, Culham Science Centre, Abingdon, Oxon OX14 3DB, UK

History of Association/Laboratory
The Association dates from January 1st, 1973 when the UK joined the Community but co-operation between the UK Programme and European Programmes had existed for some time prior to the formal participation in Euratom activities. In the UK, work on plasma physics and controlled thermonuclear research was originally based at Harwell and Aldermaston. This work was transferred to the newly established Culham Laboratory in 1960-63. During 1973-76, Culham acted as host to the JET (Joint European Torus) Design Team and was then the host site for the JET Project from 1977. Since 1 January 2000, the Association has been responsible for the safety, maintenance and operation of the JET facilities (via the JET Operation Contract) to enable a collective European programme of experiments under the auspices of the JET Implementing Agreement. It also provides host support to the EFDA Close Support Unit at Culham. The UK Association's programme is presently centred on two experiments COMPASS (COMPact ASSembly), a small "ITER-like" tokamak which came into operation in 1989, and the MAST (Mega Amp Spherical Tokamak) facility, which commenced tokamak operation in 1999. MAST follows the successful START (Small Tight Aspect Ratio Tokamak) experiment, the world's first hot plasma spherical tokamak experiment, which operated 1990-1998.

Present Scientific and Technical Programme
The programme concentrates on the tokamak line and, in particular, support for JET and ITER. The programme also addresses concept improvements, notably the tight aspect ratio (spherical) tokamak, as well as the theory of fusion plasmas, safety, environmental and socio-economic assessments of fusion power, and the properties of materials in a fusion environment. The programme has an initiative to help industry benefit from fusion research, including identifying spin-offs into other markets, includes links to related areas of basic science, has an annual Plasma Physics Summer School, and participates in the European Programme's keep-in-touch work on inertial fusion via research at the Rutherford-Appleton Laboratory.

Achievements during the last 5 years - the Association has:
- Led experiments on COMPASS-D and JET which defined the requirements for the ITER error field correction coils
- Identified (on COMPASS-D) neo-classical tearing modes (NTMs), the main pressure-limiting phenomenon for ITER, and then showed how RF waves could be used to stabilise NTMs. Led related experiments on JET on scaling with plasma shape and current. Originated and developed the most successful theory of NTMs.
- Demonstrated, using RF heating and current drive, *sustained* high pressure tokamak plasmas (COMPASS-D)
- Improved understanding of enhanced confinement regimes and how they are accessed, through experiments on COMPASS-D and START, scaling comparisons with other devices, and model development via ITER expert groups

- Implemented the main JET current profile diagnostic (from the US), essential for understanding advanced regimes
- Pioneered the new, compact spherical tokamak concept through experiments on START and related theory ⇒ improved understanding of tokamak scalings, plus demonstration of world record normalised pressure in a tokamak system ($\beta \sim 40\%$), with resilience to disruptions and good confinement (including H-modes) and exhaust properties
- First experiments on the new MAST spherical tokamak facility, with Neutral Beam and RF heating
- Demonstrated that activation codes used for modelling ITER and conceptual power plants agree with (a) measurements of activation by D-T neutrons on JET, and (b) measurements from Japan's Fusion Neutron Source
- Helped develop ITER systems: heating & current drive, safety, neutronics, error field correction, etc.
- Took leading roles in safety and environmental assessments of fusion power (SEAFP and subsequent studies), and performed analyses which helped show how the potential safety and environmental benefits of fusion can be realised.
- Conducted integrated physics/engineering studies of conceptual power plants (conventional and spherical tokamaks), using system codes to identify key drivers for the most economic systems (advanced physics, good availability, etc.)
- Highlighted the key issue for fusion systems of tritium retention and its waste implications
- Organised 1998 Royal Society meeting on fusion, bringing together magnetic and inertial fusion communities plus key members of the UK academic community
- Co-ordinated the Associations' exhibition at the European Parliament, Nov/Dec 1999
- Launched initiative to help industry benefit from fusion research: contract opportunities and technology transfer
- Collaborated with many Associations, universities and other institutes, including an initiative to help maximise value of fusion research to other areas of science

Staff Professionals: 240
Support staff: 61
Plus many contractors and students

Expenditure in 1998 21.4 MioEuro.
The UK share of the funding is from the Department of Trade and Industry.

Management Structure
Head of Research Unit: D C Robinson (Director, UKAEA Culham);
Assistant Director: F Briscoe

Status: February 2000

JOINT EUROPEAN TORUS (JET)

Research Unit : JET Joint Undertaking
Abingdon, Oxfordshire
GB-OX14 3EA

History
From 30 May 1978 until the end of 1999 the JET facilities were operated as a Joint Undertaking of the European Community. Following the termination of the Joint Undertaking, the UKAEA was awarded the contract to operate the facilities. The EURATOM Associations, within the framework of the European Fusion Development Agreement (EFDA) are now responsible for the scientific and technical programme.

Scientific and technical programme of the Joint Undertaking
The original mandate of the JET Joint Undertaking was to: "construct, operate and exploit as part of the Euratom fusion programme and for the benefit of its participants, a large torus facility of Tokamak-type and its auxiliary facilities in order to extend the parameter range applicable to controlled thermonuclear fusion experiments up to conditions close to those needed in a thermonuclear reactor". For this aim, a plasma approaching reactor conditions was created and studied. The subsequent extension of the Project to 1996 and then to 1999 allowed additional objectives to be set: "to establish the effective control of impurities in conditions close to the Next-Step and to provide further data of relevance to ITER, especially for the ITER-EDA, before entering into a final phase of Deuterium-Tritium operation".

There were four principal areas of work: the study of scaling of plasma behaviour as parameters approach the reactor range; the study of plasma-wall interaction in these conditions; the study of plasma heating; the study of alpha-particle production, confinement and consequent plasma heating. A major focus was the study of divertor physics and the technology of divertors in order to provide key information for design of a Next Step fusion device and ultimate commercial systems. JET also developed two of the new technologies that will be required in fusion power stations: the use of tritium and remote maintenance and repair techniques.

Achievements of the Joint Undertaking in the 5 years to the end of 1999

- The JET deuterium-tritium experiments produced record fusion power of more than >16 MW for about one second, corresponding to Q=0.65.
- In quasi-steady state conditions (limited by external technical constraints) a record fusion energy of 22 MJ (from a power of 4-5 MW for about 4 seconds) was generated.
- For the first time on a fusion device, and under the constraints imposed by a radioactive environment, two of the technologies essential to the Next Step and a future reactor were demonstrated: remote handling of complex in-vessel components and closed-cycle tritium handling.
- Clear evidence of alpha particle heating was found in JET D-T plasmas, in line with theoretical predictions.
- The additional heating power threshold for access to the H-mode was shown to be 25% lower in D-T and tritium plasmas than in pure deuterium.
- Divertor concepts were further developed, with the original Mark I divertor being replaced by the Mark II, and finally the Mark IIGB ("gas box") configuration favoured for the next generation of fusion devices. A broad programme of divertor assessment in high performance plasmas was carried out, and experiments with the Mark IIGB divertor showed that helium exhaust in ELMy H-modes is compatible with reactor requirements.
- Scaling studies, in which dimensionless plasma quantities were kept identical gave, in conjunction with data from other experiments, improved confidence in the performance predictions for ITER.
- Operation in the "optimised shear" regime with high confinement due to the presence of an internal transport barrier (ITB) was demonstrated, and progress was made towards extending this mode of operation into steady-state.
- The factors affecting the onset and severity of neo-classical tearing modes (NTMs) have been investigated and the effect on plasma performance below q=3 has been demonstrated.
- Plasma regimes with high density, high radiated power fraction and small ELMs, which are key elements of the current ITER design, have been found to be associated with high ELM frequency, low pedestal pressure and correspondingly reduced global energy confinement time.

Status: end 1999

ANNEX 2: International Fusion Agreements

JET JOINT UNDERTAKING

JET was established in 1978, as a Commission Joint Undertaking (a novel solution to combine Community and Member States funds) and up until the end of 1999 has been managed by the JET Council, comprising representatives of the Commission and the organisations from Member States.

NEXT EUROPEAN TORUS (NET)

The NET Agreement (1983-1998) provided the framework for European collaboration in research and development in support of the Next European Torus and then in 1992 facilitated European participation in the International Thermonuclear Experimental Reactor (ITER) Project.

INTERNATIONAL THERMONUCLEAR EXPERIMENTAL REACTOR (ITER)

Quadripartite agreement between Europe (including Canada), the USA, the Russian Federation and Japan under the auspices of the IAEA for the development of the conceptual design (1988-1990) and subsequently the engineering design (ITER-EDA, 1992-2001) of the 'Next Step'. The US withdrew from ITER in 1999.

EUROPEAN FUSION DEVELOPMENT AGREEMENT (EFDA)

At the beginning of 1999, the new European Fusion Development Agreement (EFDA) came into force; it has been signed by the Commission and all the National research institutes and provides a framework for the continuity of European activities in the field of thermonuclear fusion. In particular, the EFDA Workplan now includes the technology work carried out by the National research institutes and by European industry, European contributions to international collaboration such as ITER and the exploitation of the JET facilities after 1999.

JET IMPLEMENTING AGREEMENT (JIA)

The JET Implementing Agreement (JIA), is between Euratom and the other parties of EFDA, and includes provisions relating both to the technical programme and the financing of the activities.