Report
of the

Fusion Programme Evaluation Board

prepared
for the

Commission of the European Communities

U. Colombo (Chairman), A. Jaumotte, E. Kennedy, C. Lopez Martinez,
M. Popp,C. Reece, H. Schopper, E. Spitz, F. Troyon

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PREFACE

The Fusion Programme Evaluation Board was set up by the Commission of the European Communities on 25th January 1990 and was requested by Vice-President Filippo Maria Pandolfi to produce a Report by July 1990. Its Terms of Reference were as follows:

- to conduct the independent evaluation of the Community's programme in the field of Controlled Thermonuclear Fusion;
- to appraise the environmental, safety-related and economic potential of fusion as an energy source, in particular for the Community;
- to analyse strategic options for the Community Fusion programme, with particular emphasis on:
  - the Next Step, its objectives and time schedule,
  - the role of international collaboration,
  - the balance of the programme between physics and technology,
  - the proposed prolongation of JET up to 1996,
  - the role of medium-size Tokamaks,
  - the role of alternative lines,
  - the role of industry;
- bearing in mind the appraisal of the environmental, safety-related and economic potential of fusion, to formulate recommendations on future strategy and on the necessary means for its implementation.

The 1990 Evaluation Board was chaired by Prof. U. Colombo. Its membership is given below. The Board held twelve meetings between February and July 1990. Visits were made to the principal European fusion facilities and private hearings were held in conjunction with Board meetings in order that the members might obtain first hand information on progress in the European effort. In addition to full meetings, sub-groups comprising a more limited number of Board members also travelled to other research centres, as guests of the Associations participating in the European Programme and of the JRC. Where as a result of the time constraint it was not possible for the Board to make an actual visit, arrangements were made for the Associations concerned to participate in hearings held elsewhere. The Board wishes to express its regret that it was unable to visit every site, and its thanks to members of the fusion community who dedicated valuable time to meet with the Board.

The Board also received oral and written contributions from various participants in the European fusion effort, and from other interested parties in government, industry and the universities. Substantial input was provided by the Fusion Directorate in Brussels, together with presentations from the Director of the Fusion Programme, Dr. Charles Maisonnier. The Board wishes here to thank the Fusion Directorate, and more generally the Commission services, for the invaluable and prompt assistance during the course of its work.

Meetings were also held with representatives of the Soviet, American and Japanese fusion programmes, who illustrated the state of fusion research in their respective countries and their strategies for the future, besides offering comments on the international dimension of fusion and cooperation in the ITER initiative. The Board herewith wishes to thank these distinguished visitors and to assure them of continuing European interest in their achievements in this field. The Chairman also met with leading officials of the American, Japanese and Soviet fusion programmes in Washington and Tokyo.

In addition, individual Board members had many occasions to talk with people with whom they came into contact during the course of their other activities, concerning attitudes to fusion, as well as particular aspects of the science or the technology. These informal contacts provided useful indications for the orientation of the Board's work. The Board would like to express thanks to all who contributed to the formulation of its position in this way.

The Board appointed Mr James Ruscoe as its Secretary. It wishes here to thank him for his skill and application in fulfilling a difficult drafting and editing task. His role in coordinating the acquisition of data also from individual experts proved very useful to the Board in identifying areas deserving its critical analysis.

The opinions contained in this Report are collectively subscribed by the members of the Fusion Programme Evaluation Board in their personal capacities. They are offered to the Commission in the hope that they can be used as input for the definition of new policies for fusion in Europe. The Board is firmly convinced that fusion has the potential to make a significant contribution to the world's energy supply, and hence living standards, without jeopardizing local, regional or global environments. Nevertheless, much still needs to be done to ensure that this potential is realized. Controlled nuclear fusion in reactor relevant conditions has become something of a moving target, achievement of which is said, every decade, to move yet another decade ahead in the future. This view ignores the outstanding progress achieved by research, particularly in the 1980s. It has to be corrected if public confidence in the eventual contribution of nuclear fusion to the world energy mix is to be strengthened. Thus, the Board believes that now benchmarks have to be set.

Many choices still have to be made on the road to commercial application of fusion energy. In the Board's view, some of these are likely to be dictated by environmental and safety criteria which hitherto have been accorded a perhaps secondary role in establishing the priorities in fusion research. If this Report leads to a reordering of priorities, in acknowledgement of the need to safeguard our environment by a more articulated approach to energy, in Europe as in the rest of the world, then it will have gone a long way to serving its purpose.

MEMBERSHIP OF THE FUSION PROGRAMME EVALUATION BOARD

Chairman: Prof. Umberto Colombo
Chairman, ENEA, Rome, Italy

Baron André Jaumotte
Honorary Rector, Université Libre de Bruxelles, Belgium

Prof. Eugene Kennedy
Head of the School of Physical Sciences, Dublin City University, Ireland

Prof. Cayetano Lopez Martinez
Rector, Universidad Autónoma de Madrid, Spain

Dr Manfred Popp
Staatssekretär, Hessisches Ministerium für Umwelt und Reaktorsicherheit, Wiesbaden, Germany

Sir Charles Reece
formerly Board Director of Research and Technology, Imperial Chemical Industries, London, United Kingdom

Prof. Herwig Schopper
CERN, Geneva, Switzerland

Dr Erich Spitz
Directeur Général Adjoint, Directeur de la Recherche et de la Technologie, Thomson S.A., Paris, France

Prof. Francis Troyon
Directeur du Centre de Recherches en Physique des Plasmas, Ecole Polytechnique Fédérale de Lausanne, Switzerland

Secretary:
Mr James Ruscoe
Rome, Italy

SYNOPSIS

Nuclear fusion has a great potential for the future of Mankind. It holds promise of becoming a virtually inexhaustible, environmentally acceptable and economically viable energy source, particularly suited for the generation of base load electricity. Europe is simultaneously heavily dependent on import for its energy supply and the world leader in R&D on magnetic confinement fusion. But, as an energy source, nuclear fusion is not around the corner. Our best estimate is that a prototype industrial reactor, that is a reactor which is environmentally and economically acceptable and that can be considered "first of a series", can be expected to operate only around 2040. Much has been achieved, there is now greater confidence than ever in its scientific feasibility and the very long time frame should not lead to undue discouragement. A long term strategy exists in Europe, comprising a sequence of machines backed up by a long term programme in technology and materials. Thus fusion can become a reality at a time in the future when the combination of the problem of energy supply and the need to preserve the quality of the environment and global climate mean that it is one of the few remaining practicable options.
The European Community should retain fusion as high priority in its R&D strategies.

On the basis of the scientific and technical progress achieved so far, the declared ultimate objective of the Community Fusion programme - the creation of safe, environmentally sound and commercially viable industrial reactors - appears to be realistic.
A stepwise strategy towards the prototype reactor should include, after JET, an experimental reactor (Next Step) and a demonstration reactor (DEMO).

An important role in ensuring the success of Europe in nuclear fusion research has been played by the twelve Associations under EURATOM.
The Associations will remain important, but the balance of their activities should change in the context of the evolving profile of the Fusion Programme.

A great part of Europe's present leadership is due to the outstanding success of JET. This machine, which has achieved world records over the last few years, has not completed its useful life and can still supply important data for realization of the Next Step machine.
The life of JET should be extended to 1996, with tritium operation in the last two years.

There is now need for a new device to go beyond the next threshold in fusion research. The Next Step machine must reach ignition and sustain it for long burn times. It must solve all outstanding problems of plasma physics and plasma technology. It must provide the basic data for building a demonstration fusion reactor (DEMO) capable of producing electricity with a capacity comparable to that of future commercial plants. Of the two alternatives before Europe, a European NET (Next European Torus) or a machine designed and built in cooperation with Japan, the USA and the USSR - ITER (International Thermonuclear Experimental Reactor) - the latter is to be preferred for technical and economic reasons.

Moreover, a long term research programme centred on ITER could become the symbol of what science and technology can achieve for Mankind if resources from the world's major industrial countries were pulled together.
Europe must express its full commitment to the ITER concept, together with a preference for a widely based ITER Programme rather than an agreement merely for a single device.

Negotiations for the siting of ITER, to start with its Engineering Design Activities (EDA), should get under way as soon as possible. Europe must select a candidate site. Given its outstanding international experience, as well as the presence of the NET Team and of JET, both important contributors to ITER, Europe has a good claim for assignation of EDA. There are several potential sites in Europe for both EDA and eventual construction.
Europe must advance its candidacy for the site of ITER Engineering Design Activities.

The fact remains that this international initiative is an R&D enterprise of unprecedented complexity, requiring the continuing commitment of four partners over a very long timespan. Europe would be well advised to retain capability to go ahead alone with NET, should undue delay or problems of a political nature arise that might jeopardize the ITER initiative.
Europe should retain the capability to proceed with NET, if the ITER initiative proves too difficult to continue.

It is essential to expand the effort on technology, not only for the Next Step, but also on longer term issues, particularly in relation to the new emphasis on environmental and economic constraints. Environmental and safety criteria should as of now be considered as essential elements in governing the evolution of the Fusion Programme. Problems concerning materials, the use of tritium, the maintainability of the reactor, should all be faced in time, avoiding freezing of design or engineering concepts which might lead to environmentally unacceptable fusion reactors, or make their design excessively complex.
Environment and safety must assume high priority in the European Fusion Programme and in its wider international extension.

Europe's effort in inertial confinement fusion for civilian applications has been very small up to now. It would appear to make little sense at this point to try to make up an accumulated gap vis-à-vis other major fusion programmes.
A watching brief on inertial confinement fusion should be maintained in Europe.

As the scale and scope of the Fusion Programme evolve, and the industrial implications of research become more significant, the organisation and management of the European Fusion Programme should also evolve to achieve a flexible, focused and effective structure. This may require an institutional change of status of the Fusion Programme within the European Community. This should be conceived to promote much greater industrial involvement and avoid formal obstacles.
Organisation and management of the European Fusion Programme will need to change as the programme becomes more international and its industrial implications become more significant.

The annual budget of the European Fusion Programme has settled since the late 1980s at about 450 MioECU. This level of expenditure is considered sufficient for the next 5-6 years, including both the extended JET programme and the engineering design phase of ITER. Thereafter, with the start of ITER construction, the budget level will increase, reaching about 750 MioECU towards the end of the 1990s. The total cost of the European Fusion Programme up until the production of electric power by the DEMO plant around 2025 can be estimated at around 30 billion ECUs. This must be regarded as an indicative figure, given the technical and political uncertainties pending on such a long term programme. The budget of the European Fusion Programme does not need substantial increase until start of construction of the Next Step machine after 1996.

The decision to build a Next Step as well as the choice of the framework, international or European, for construction will have major and long-lasting political, financial and technological implications.
A further Evaluation Board should be set up to report in 1995 before taking a firm decision on construction of the Next Step.

RECOMMENDATIONS

FUSION AS AN ENERGY SOURCE

1. In view of its potential as a virtually inexhaustible energy source possessing inherent environmental and safety advantages over all current alternatives for base load electricity generation, and its role as a leading edge technology in which Europe enjoys an advanced position worldwide, the Board recommends maintaining fusion as a priority in the Community's energy research strategy.

THE EUROPEAN FUSION STRATEGY

2. The Board supports continuation of the present concentration of the European fusion effort on magnetic toroidal confinement, with the Tokamak as the main line, supplemented by a significant programme on the Stellarator and Reversed Field Pinch, with maintenance of the current watching brief on activities in the field of inertial confinement.

On JET

3. The Board supports proposals to prolong the operational life of JET until 1996 and, subject to rigorous scientific, technical and safety assessment undertaken within the Fusion Programme, introduction of tritium into the machine after 1994. (See also Recommendation 19)

THE WAY FORWARD: On the Next Step

4. **The Board recommends that, for Europe, the minimum objective of the Next Step (be it ITER or NET) must be a machine able to reach ignition, and to sustain it for long burn times, as well as able to explore and solve related plasma physics and plasma technology problems in reactor-relevant conditions.**

5. Whilst recognizing the greater organisational complexity in any international collaboration, the Board recommends the quadripartite approach of ITER, given the prospect of shared investment and access to world technology.

6. The Board supports the broadening of the ITER device to embrace an articulated ITER programme. In such a programme, the main functions in fusion reactor development would be shared among the partners in worldwide cooperation. Apart from the principal Next Step project, these should include a large neutron source for materials testing and a major investigation into the potential of alternative lines. The establishment of such an ITER programme might also prepare the ground for an extended worldwide cooperation after the ITER project. The Board therefore recommends that this possibility be actively explored during negotiations. (See also Recommendations 12, 13 and 14)

7. Even accepting that any decision to go ahead with ITER construction cannot realistically be expected much before 1996-1997, the Board believes that quadripartite negotiations for successive phases after engineering design, together with complementary preparatory R&D activities and test programmes for components, should commence as soon as possible.

8. The Board recommends that EURATOM formally present a European candidate site for ITER engineering design activities as soon as possible to the ITER partners and begin procedures to identify suitable sites for eventual construction of the device.

9. The Board recommends that moves be made towards a convergence of the NET and ITER designs in the belief that European preferences in concept and design, as represented by NET, are scientifically and technologically the sounder, as well as financially the more attractive.

10. The Board recommends a stepwise approach in realization of the ITER device, with later upgrading intrinsic to the design. The Board thus recommends that final agreement on the operating time of the machine should be reached after careful evaluation of the option of generating tritium with a breeding blanket, as compared to the option of external procurement, which the Board would prefer if feasible. Non-inductive current drive should be regarded as an important objective of the research programme of the machine, but be postponed to a subsequent stage of operation.

11. While recommending a full commitment to the ITER initiative, the Board is convinced that, at this stage, Europe should retain a fall back capability in case ITER cooperation beyond the design phase proves impossible. The Board envisages this fall back solution as a staged version of a final converged Next Step, conceived so as to be able to be built using the resources available in the European Programme alone.

On technology

12. The Board recommends that considerably more attention and resources must be devoted to technological aspects, especially where these aim ultimately at ensuring the economic, and above all the environmental, attractiveness of fusion as a commercial power source. The European technology effort can conceptually be divided into two parts : specific technology targeted for the Next Step and broader long term and generic technologies relevant for fusion. The Board believes that this distinction should be allowed for in the future planning of resources.

13. In recommending higher priority be granted to technology in the European Programme and accepting that specific technologies for the Next Step remain the responsibility of the Next Step director, the Board holds that the long term technology effort will best be reinforced through the establishment of a Long Term Technology Team, with the responsibility

of drawing up and directing a planned programme of activity to provide an articulated response to the long term technology demands of fusion.

14. The problem of the need for a powerful source for high energy neutrons for materials testing should be addressed with the utmost urgency. Such a source should be made an integral part of the ITER programme. The Board understands that - as a first step - an international agreement for the adaptation and use of an existing American facility might be possible, and recommends active consideration of how best to investigate this option.

On the safety and environmental aspects of fusion

15. Demonstration of the safety and environmental feasibility of fusion power must be considered a primary objective of the Fusion Programme, to be pursued in parallel with the demonstration of scientific and technological feasibility. Adequate funding and priority must be devoted to this issue.

16. The Board recommends adoption as a safety target that the worst possible fusion accident will constitute no major hazard to populations outside the plant perimeter that might result in evacuation.

17. The Board recommends that environmental and safety criteria should govern the evolution of the European Fusion Programme and be monitored by an Environment and Safety Team. Among such criteria, it would list:
    - greatest possible utilisation of low-activation materials to avoid any need for geological timespan disposal, to reduce residual heat and to simplify maintenance;
    - use of environmentally benign neutron multiplier materials;
    - reduction of tritium inventories;
    - development of materials specifically capable of resisting high neutron fluence so as to minimise component replacement, and hence both the volumes of radioactive wastes generated and the exposure of maintenance personnel;
    - development of reliable remote maintenance techniques suitable to the complex geometry of fusion reactors. In addition, long term development programmes in the fields of technology and system design must take into account environmental and safety prerequisites. In particular, the Board recommends that research efforts in materials or engineering be carried out only on suitable candidates of reactor relevance in terms of safety and environmental requirements.

18. The Board recommends the launching of a European reference design for a commercial fusion reactor. This design will require periodic updating as research progresses, in particular to incorporate safety and environmental protection features likely to ensure public acceptance and to take into account the requirements of utilities in operating such a reactor.

19. Decommissioning must be seen in the future as an integral element in the strategy of the Fusion Programme, starting from the design phase. In the case of JET, given the evolution of attitudes to the acceptability of the different forms of radioactive waste disposal, the Board recommends that decommissioning of potentially tritium-contaminated material should be regarded as part of the Programme, in order for the Community Fusion Programme to acquire experience in a key area of public concern.

20. The Board recommends that adequate funds be allocated immediately to ongoing studies of issues of social acceptability in order that the evolution of opinion finds reflection in the orientation of research.

On the role of medium-sized Tokamaks

21. Existing Tokamaks and Tokamaks about to come into operation should be fully exploited to address critical issues associated with the main line. Any proposed new devices should be subjected to in-depth examination similar in scale and scope to that undergone by IGNITOR in 1989-90.

22. The Board concurs with the conclusions of the Ad-hoc Group for the Phase I examination of the IGNITOR proposal and is unable to support construction of the device as examined within the European Fusion Programme.

On alternative lines and concepts

a) The Stellarator

23. Although less advanced than the Tokamak, the Stellarator line might offer advantages in terms of a commercial reactor, such as continuous operation and the absence of plasma disruptions which may lead to severe mechanical stresses in a Tokamak, thus improving the reliability and availability of such a plant. Given the long lead time to commercialisation of fusion reactors, the Programme should allow sufficient resources to be devoted to the line.

24. Because of its relatively high cost, the proposed new Stellarator, Wendelstein VII-X, should be subjected to an in-depth examination similar in scale and scope to that undergone by IGNITOR in 1989-90. The examination should attempt to establish the strategic role of the device, to assess the rate of progress being achieved, to establish plasma performance targets and the technical feasibility of the reference design, and to assess the flexibility of operation. Given the budgetary constraints on the European Programme, close review of costs and timing should also be undertaken.

b) The Reversed Field Pinch

25. The Board recommends that milestones be defined on the path to an adequate demonstration of a possible solution to the two crucial issues of the Reversed Field Pinch configuration, namely: retention of very pure plasmas at up to the highest current and improvement in confinement, both to be explored on RFX.

c) Inertial confinement fusion

26. The Board cannot recommend additional allocation of resources over the current level from the Community's Fusion Programme to support ICF research. At this stage, this line of development is not seen as competitive in Europe with magnetic confinement fusion. The Board believes that, together with results reported from other programmes elsewhere in the world, the nationally-funded exploratory research activities will provide adequate information to judge whether ICF has a real future for commercial power application. Progress should be monitored however and, in the event of any breakthrough, the Community's watching brief should be reviewed.

d) Cold fusion

27. As no evidence has yet emerged that nuclear fusion actually takes place in the so-called cold fusion experiments, though accepting that some hitherto unknown complex effects may have been found, the Board believes that this research is of purely scientific interest. There is no evidence that this work will provide a possible source of energy and the Board therefore recommends that should Community support be granted for basic research, it should be found from sources other than the Fusion Programme budget.

ORGANISATIONAL IMPLICATIONS

On management

28. **As the Programme's scale and scope evolve and the construction of the** Next Step device approaches, with the prospect of wider international cooperation, in the Board's view it becomes urgent to consider enhancing the organisational structure and management methods of the Fusion Programme to achieve a more focused and effective structure. The Board recommends that the Commission begin, as soon as possible, a consultative process involving the competent bodies in the member states, as well as the Associations and other interested parties, to consider ways forward.

29. The Board believes that it may be wise to consider in due course establishment of a specific new body to focus fusion management in a strategic frame as provided for in the EURATOM Treaty. Given the major organisational implications for the Commission, this will be especially urgent should the choice for the Next Step fall upon ITER, as the Boards recommends. In view of the complexity of any institutional change within the Community, the Board recommends that the Commission start to

consider a different, more distinct, management framework to ensure an evolving balance between the long and short term demands of fusion research.

On industry

30. The Board insists on a bigger role for industry in the European Fusion Programme, especially in view of the need to inject industrial expertise into realization of the Next Step.

31. The Board recommends that it is important for the success of the fusion effort that all the critical technologies be available in Europe. It is above all essential for European industry to acquire experience in manufacture and testing. In this pre-commercial phase, the Board recognizes that, among various measures, this will require pre-financing of selected suppliers to ensure their ability to develop the required components, sub-sets and sub-assemblies at the time these become critical.

32. The Board recommends that the Commission use all available flexibility in tendering procedures to ensure the desirable continuity in industrial commitment, accepting that open competition among all European firms who wish to tender for a fixed price contract may conflict with the Programme's over-riding requirement of quality as well as industry's need for continuity. This will involve concertation between the Commission, European industrialists, the Associations and other interested parties, and within the Commission itself, to establish modalities for the creation and management of pan-European consortia operating at the cutting edge of technology, several decades away from commercial exploitation of nuclear fusion and designed to place European industry on a level playing field with that in other parts of the world.

On the Associations

33. **The Board believes that the Associations' capacity for exploration of confinement concept improvements, for the development of diagnostics, heating systems, etc. and their role in the training of young scientists and engineers will remain important. The Board therefore recommends strengthening their links with the rest of the European scientific community, in particular with the universities. Continued effort should be dedicated to outstanding critical issues such as understanding confinement, current drive, disruption avoidance and power and particle exhaust physics.**

34. In acknowledging that the Associations have been the backbone of the European Programme and remain the reservoir of skills, the Board believes that the balance of activities within the Associations will need to change in the context of the demands of the Next Step and the long term technology objectives of the Fusion Programme. In particular, the Board recommends increased efforts on the safety and environmental aspects of fusion technologies and on the technical requirements of commercial

reactors. These activities should be carried out within a planned programme, coordinated by the Long Term Technology Team, in order to provide an articulated response to the long term technology demands of fusion. As the next phase of the Programme is likely to develop in the direction of greater internationalisation, the Board believes that the relationship between the Associations and Brussels will need to be reviewed. (See also Recommendations 13 and 37)

On finance

35. In the presence of financial constraints affecting the overall Community research programme and research priorities in member states, the Board feels that it is unrealistic for the Fusion Programme over the next five years to be planned around a significant increase in funding and recommends that this continue at the current 450 MioECU per annum. In fact, Next Step construction is not foreseen until some time in the second half of the 1990s and currently most work is in design activities, related research and testing and the operation of existing facilities. Should other new capital projects be contemplated, the existing financial constraints will demand a reassessment of priorities. (See also Recommendation 38)

THE NEED FOR FUTURE ASSESSMENT OF THE FUSION EFFORT IN EUROPE

36. The Board recommends appointment of a further Evaluation Board to report to the Commission not later than 1995, that is before a firm decision has to be taken to commit the amount of funds needed for the construction of a Next Step device. Such a Board should undertake a rigorous independent assessment of the prospects of fusion in the light of available evidence of real progress achieved toward the Programme's ultimate goal.

37. The Board recommends that the Associations be called upon to present their views on the relationship between themselves and the central effort directed from Brussels to the Evaluation Board established under Recommendation 36, and that the Fusion Directorate commission a detailed report analysing the Associations' contribution in terms of expertise, staff and financial resources, as well as related management and coordination issues, for submission to the Evaluation Board.

38. The mandate of the Evaluation Board to be established under Recommendation 36 should include a rigorous assessment of costs and spends for continuation of the European fusion effort, as part of a review of financial allocations prior to the major commitment represented by the construction phase of a Next Step device. By that time, harder data on the wider energy picture - both technical and environmental - should be available to assist in making a realistic evaluation upon which a major strategic decision for the future of fusion can be based.

CHAPTER ONE

NUCLEAR FUSION AND ITS POTENTIAL CONTRIBUTION TO THE WORLD'S ENERGY NEEDS

The first efforts to achieve controlled thermonuclear fusion in Europe date from the early 1950s. Fusion was soon recognized worldwide as a potential future energy source for Mankind and from the first Europe's scientific community made a major contribution to expanding our knowledge of the underlying physics. At that time, research in Europe was undertaken on a national basis, with little coordination. The EURATOM Treaty of 1957 specified fusion as an area of common European interest and joint effort between EURATOM and member states was commenced in 1959. Stronger central coordination with direct involvement of the European Commission came with the decision to proceed with the design of JET, the Joint European Torus, taken in 1973. By the late 1970s, Europe had developed a strategic path for a coordinated joint effort in fusion based on a sequence of three machines, JET, NET and DEMO, stretching into the next century. The Commission's Fusion Research Programme is now part of its Framework Programme for Science and Technology in Europe and is managed by DG XII.

Almost ten years have elapsed since presentation of the first Evaluation of the European Communities' Nuclear Fusion Research Programme by the panel chaired by Prof. K. H. Beckurts. The Beckurts Panel later revised its Report, issuing an update of progress together with a review of the state of application of its earlier recommendations in 1984. These ten years have seen the European Programme make rapid progress, at a time when the world energy situation has undergone substantial change.

1.1 The World Energy Picture

World energy demand continues to rise, a result of economic growth and of the population explosion in developing countries. Demand is currently matched by an abundant supply and, in real terms, energy prices have fallen to just above the level of the pre-energy crisis period in the early 1970s. World commercial energy consumption now exceeds 8 billion toe annually. About 88% of this derives from fossil fuels: oil (38%), coal (30%), natural gas (20%). Though now furnishing almost 6% of total supply, energy from nuclear fission has not penetrated the world energy market to the extent formerly anticipated. In several countries, public acceptance suffered a severe setback with, first, the Three Mile Island incident (1979) and then, more lastingly, with that at Chernobyl (1986). Moreover, continuing lack of a socially acceptable solution to the problem of very long term storage of radioactive wastes, in spite of technical progress made in this area, and the reduced economic competitiveness of nuclear power as a result of falling conventional fuel prices and increasing investment costs (determined by higher interest rates and more stringent safety criteria which impact on construction times), have led to current stagnation in the market for nuclear power plants. Meanwhile, big hydroelectric schemes have come in for increased criticism on environmental grounds and progress in renewable energy sources has been slower than anticipated. The latter is a result of both the depressed state of the energy market and of the poor economics of dispersed renewable sources in industrialised economic systems which already possess adequate energy infrastructure.

In recent years, environmental and global climatic issues, in particular the greenhouse effect and the potential danger of global warming, have come for the first time to dominate the energy debate. As a result of mounting scientific interest and the weight of public concern, industrialised countries may in the not too distant future be led to consider adoption of energy policies involving restrictions on the use of fossil fuels, ranging from stronger efforts in the direction of energy conservation, requiring the orchestration of a multiplicity of often unpopular actions, to the imposition of differential energy consumption taxes - the so-called carbon tax. If applied consistently, such measures might bring about a structural change in the energy mix.

The world energy system is also marked by a continually rising penetration of electricity, an energy carrier playing a determinant role in the emergence of a modern, energy-efficient society. Despite some evidence of decoupling of growth in GDP and total energy consumption since the energy crises of the 1970s and the induced economic recession, there has been a direct link between economic growth and the rise in the consumption of electricity. Technological change seems likely to increase reliance on the electricity supply. The development of non-fossil fuel energy sources for the generation especially of base load has thus a priority.

The historical pattern of one hegemonic energy source displacing its predecessor in a sequence of a less convenient source giving way to one easier and cheaper to use may be over. Future energy patterns may well be based on a plurality of sources, each with particular advantages in certain circumstances. Thus, the renewables may become appropriate as decentralized sources for use in climatically favoured areas, particularly where energy infrastructure is lacking (and hence in many developing countries), provided advances can be achieved in the economics and the technology. In the nuclear field, massive penetration of fission would most likely have to rely on fast breeders and reprocessing of spent fuel. It remains a viable alternative, but carries within it a degree of uncertainty. Should another major accident, however improbable, occur anywhere in the world, use of fission could suffer a further dramatic setback.

Nuclear fusion is likely to be an even more centralized and highly capital-intensive energy source than fission. It will rely on very sophisticated technology and on present knowledge it seems improbable that plants smaller than one gigawatt could be economic. The source will thus above all be suited to the generation of base load electricity in advanced industrialised countries.

Fusion, moreover, will have to earn its place in the world energy mix. Penetration will depend not only on the technical, environmental and commercial success achieved by fusion itself, but also on the extent of progress in other energy sources, including the renewables. Fusion will thus be assessed not merely on its merits, but also in comparison with whatever other energy options are by then available which can offer a solution to the needs and requirements expressed by the energy market as it will have evolved over the intervening sixty years. An additional element in any equation is that, by the time fusion approaches commercialisation, global problems may have dictated a new set of priorities.

1.2 The Case for Fusion in Europe

Fusion is not yet an energy source. It may become commercially available sometime around the mid-21st century. So far, enormous progress has been achieved in the basic research, much of this in Europe. The attainment of successive milestones has, however, been accompanied with a gradual realization of the existence of complex problems in both physics and technology, postponing planned subsequent stages on the path to achievement of the final goal of a commercial fusion reactor farther into the future.

It was always accepted that the development of fusion was going to be a long and arduous process. The aim is a source that is technologically reliable, environmentally acceptable and economically sound. Moreover, as already noted, it is clear that this latter must refer to the conditions that will reign in the energy market at the time in which nuclear fusion becomes available as a commercially exploitable source. In order reasonably to evaluate the priority to be assigned to fusion development, very long term trends in energy pricing must be considered. Given preoccupations with environmental and climate effects of energy production and use, attempts to assess the economic arguments in favour of fusion will have to take into account direct and indirect environmental costs, as well as a cost element linked to an assessment of the potential for serious accidents. Many of these aspects are design-dependent and must be taken into account during the phases of technological and commercial development. Other components in the economic equation are long term trends in the cost and availability of capital and the future organisational structure of the electricity industry, fusion's final customer, in the world and, in particular, in Europe.

The likelihood is of a generalized rise in the cost of fossil fuel derived energy in step with the exhaustion of the sources that are the simplest and cleanest to exploit and the more stringent codes governing their use. As we have noted above, burning these fuels may also be actively discouraged by government policies, including fiscal instruments. With regard to the renewables, these may play an important role above all where there are large tracts of otherwise unutilized land in geographically favoured areas. Such conditions are more frequent in the developing world, and are certainly lacking in Europe.

It appears clear that the competition between sources able to cover an important part of the base load in industrialised countries will have to be limited to coal and to nuclear energy from advanced fission and from fusion. Coal imported into Europe could be the most economic of these sources, as world reserves are presently estimated around 1,000 billion tons, sufficient for over two hundred years at current rates of consumption. In planning for the long term energy future, however, possible environmental and climatic constraints related to the use of coal, particularly with regard to its high emissions of CO_2 per unit of energy produced, may become important. In a strategy to reduce the effects of greenhouse warming, logic would indicate that the main alternatives for base load generation would be fission and fusion.

Arguments in favour of fission rest on the fact that the source is already available commercially, based on proven technology. New generations of reactors offer the potential for significant improvements in various operating parameters that could go some way to alleviating public concern about the safety of this source which is currently impeding greater penetration. Simpler reactor designs, and potentially modular systems, could significantly reduce capital requirements, once series construction is achieved. Fuel availability constraints now appear to be less than once thought. Commercially exploitable uranium reserves are estimated to be sufficient for about 60 years of operation of the current fleet of PWRs. With the use of fast breeders and reprocessing plants, both proven technologies even if open to further improvements, this figure could be multiplied by around fifty.

With adequate design, nuclear fusion does, however, offer environmental advantages over fission which might tip the balance in its favour. Fusion need not raise problems of long life radioactive waste, nor produce actinides. The potential for a catastrophic accident could be minimal. Environmental and safety-related benefits must be taken into account in costing the power produced by future commercial fusion reactors. The virtually inexhaustible reserves of the energy raw material also act in fusion's favour.

These arguments militate for maintaining fusion as a priority in the Community's energy research strategy. This strategy has been selectively in favour of fusion, anticipating the criteria of subsidiarity later enunciated by President Delors. Selectivity is shown by the difference in the ratio between Community spending on research and development for fusion and that on other energy R&D, on the one hand, and that for spending in these two areas by the member states on the other.

The European fusion strategy was conceived in its present form in the 1970s. It is clearly stated and has the benefit of simple logic. It has, moreover, been very vigorously followed ever since. It is thanks to this clear overall view that much of the progress so far achieved by the European Fusion Programme has been attained. Now, however, may be the right time to ask whether this strategy remains valid, or whether it has to be changed or corrected in response to events both in Europe and beyond over the last ten years. Given the fact that fusion is still a high hope, high risk, very long term undertaking, it might be wise to aim at wider collaboration. The seed for a broader international partnership already exists. The development of a potentially enormously important new energy source through pooling global efforts in science and technology could be seen symbolically as a commitment to a better future for all of humanity.

CHAPTER TWO

THE PRESENT STATUS OF FUSION RESEARCH

2.1 The Fusion Effort Worldwide

While several nations conduct research in the field of fusion, four programmes, broadly similar in objectives and content but with significant differences, are outstanding: these are the fusion programmes of the European Community (plus Sweden and Switzerland), Japan, the USA, and the USSR. The financial commitment worldwide in 1989 amounted to about $1,700 million; expenditure and professional staff as distributed among the four programmes are shown in Figure 1. In any comparison of these data, it should be recalled that statistics for the USA include a sizeable effort in inertial confinement fusion (ICF).

The evolution of the four programmes over the past twenty years is shown in Figure 2. In the US programme, the difference between the figure for magnetic confinement fusion and total expenditure corresponds to spending on inertial confinement. Corresponding funding for ICF in other countries is unknown, though some research is undertaken in both Japan and the USSR. In addition to the European Programme's watching brief, there is also other work on ICF in Europe, in particular in France, with significant activity also in Germany, the United Kingdom and Italy.

As Figure 2 shows, the budget of the US fusion programme peaked around 1983 and then dropped slightly, whereas the European Programme shows a steady increase until 1987, when it began to flatten off. This funding pattern has been to the European Programme's advantage in defining strategy. Nevertheless, the cut in US fusion programme has been relatively small compared to that in other energy programmes (fossil, solar, nuclear), which had been boosted dramatically on the heels of the 1970s' oil crises, peaking around 1980/81.

Magnetic confinement fusion research is an outstanding example of international cooperation. The argument for collaboration rests on the scale of the human and financial resources required, the very long time-scale, and the fact that fusion is still very far from the market place, being unlikely to generate large scale industrial competition for some time to come. Recognition of the potential benefits of sharing costs, risks and knowledge has increasingly led world fusion programmes to coordinate efforts in a spirit of collaboration rather than of competition. Collaboration now concentrates on the Next Step - the ITER project - which, if realized, will be the first major scientific and technological project ever constructed through worldwide cooperation.

2.1.1 The United States Fusion Programme

The US magnetic fusion programme is conducted under the control of the Fusion Office of the Department of Energy and executed in the National Laboratories, in a large number of universities spread across the country, and in some private corporations.

For long the world's largest programme, pursuing a broadly based magnetic fusion approach with major funding for Tokamak and mirror programmes, reorientation in the 1980s led to greater concentration on the Tokamak line. The American programme strategy aims at determining the potential of fusion as an energy option, centering on key areas in magnetic confinement: plasma confinement and heating, fusion materials and nuclear fusion technologies.

The major experimental effort in the US core programme is thus now on large and medium size Tokamaks. The largest device, comparable in size to JET, is the Tokamak Fusion Test Reactor (TFTR) at Princeton, which has almost attained breakeven conditions. Supporting medium size Tokamaks are located in San Diego (D III-D, General Atomics), MIT (Alcator C-Mod), Livermore (MTX) and the University of Texas at Austin (TEXT).

An additional important effort is carried out within the core programme on configurational improvements to the Tokamak concept in medium size installations: PBX (Princeton Beta Experiment), a Tokamak with a strongly shaped cross-section, ATF (Advanced Toroidal Facility), the largest operational Stellarator in the world at Oak Ridge; CPRF (Confinement Physics Research Facility), a Reversed Field Pinch under construction at Los Alamos, and MST (Madison Symmetric Torus), a large Reversed Field Pinch at the University of Wisconsin, Madison. The US programme also has a very strong theoretical and computational component, rooted above all in the academic environment.

Technological developments addressed inside the core programme include identification and qualification of new materials to minimise activation and extend the lifetime of structural components such as vacuum vessels and magnets, development of superconducting magnets, tritium handling, and blanket concepts. Emphasis is also placed on improving environmental and safety aspects. Overall, industrial involvement in these activities is not extensive, the national laboratories possessing large engineering staffs and even considerable manufacturing capabilities.

Progress in Tokamak experiments led the US programme to the design and development of a machine to be built at Princeton specifically to study the physics of burning plasmas, the Compact Ignition Tokamak (CIT). CIT design is, however, still not finalised and cost estimates have risen sharply. The request for funding has been deferred.

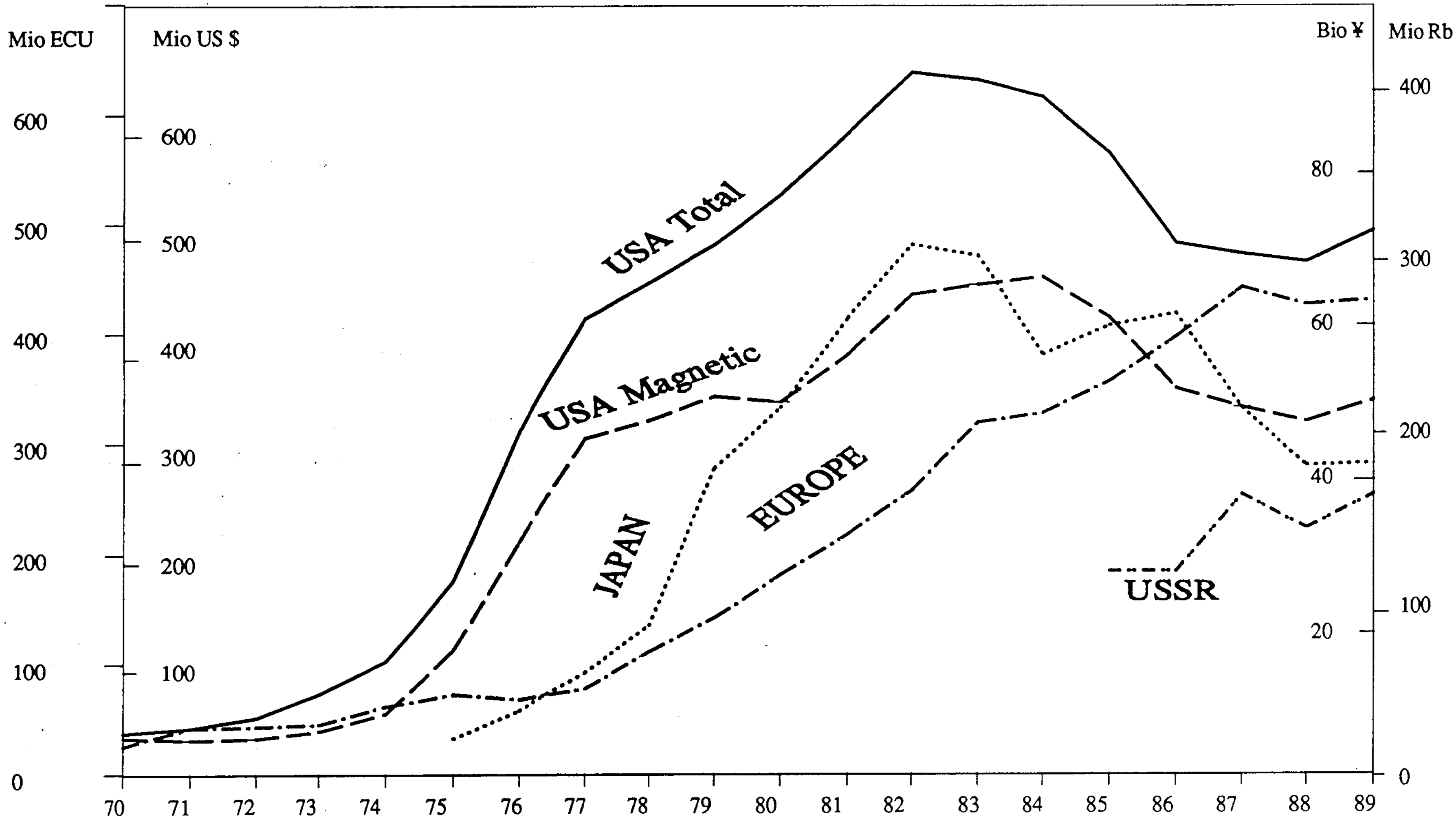
As already mentioned, a very strong ICF programme is being carried out in the United States. Currently, this amounts to about 50% of the funding for the magnetic confinement programme. The programme is linked to weapons research and is thus to a large extent classified. (See section 3.4)

Figure 1

EXPENDITURE + PROFESSIONAL STAFF 1989

Programme	*MAGNETIC CONFINEMENT*				*INERTIAL CONFINEMENT*		TOTAL	TOTAL
	Physics (Mio ECU)	Technology (Mio ECU)	Total Magnetic (Mio ECU)	Prof. Staff	(Mio ECU)	Prof. Staff	Fusion (Mio ECU)	Prof. Staff
EC	338	90	428	1735	3	15	431	1750
USA	285	54	339	1550	155	600	494	2150
JAPAN	237	33	270	1165	15	30	285	1195
USSR			203		51		254	1225
CANADA	8	8	16	80	-	-	16	80

Figure 2 **EVOLUTION OF EXPENDITURE IN THE WORLD'S FOUR LARGE FUSION PROGRAMMES**



For each programme, the expenditure is given in the national money of the year. Comparison between the programmes has been made by using the (constant) exchange rate of mid-1989 : 1 ECU = 1.03 US $ = 148 ¥ = 0.670 Rb.

The Department of Energy is currently conducting a strategic review of the US fusion programme which is felt to be suffering from a certain lack of orientation. This review is, in fact, the latest in an extended series of evaluation exercises and has also been called upon to address the issue of how best to manage the relations between the civilian and the military components of ICF. A final report is expected in the autumn of 1990.

2.1.2 The Japanese Fusion Programme

Fusion research and development in Japan is managed by several distinct ministries and administrations, coordinated by the National Fusion Council, under the Atomic Energy Commission and the Prime Minister's Office. Coordination is by consensus and the NFC exercises no executive authority. It does, however, conduct evaluations and brings together the Japanese fusion effort comprising:

(i) national and semi-national research institutions, such as the Japan Atomic Energy Research Institute (JAERI), which is the major organisation for realizing and funding the fusion programme, the Electrotechnical Laboratory (ETL) and the National Research Institute for Metals (NRIM), which are under the control of the Japan Atomic Energy Commission (JAEC) and the Government's Science and Technology Agency (STA);

(ii) universities, under the control of the Ministry for Education, Science and Culture, Mombusho (MBS), including the newly created National Institute for Fusion Science (NIFS);

(iii) industry actively involved in manufacturing equipment, engineering and R&D for the fusion programme.

Japan's fusion programme rose at the end of the 1970's to a level comparable to that of the other large programmes in the world. Japanese strategy embraces a comprehensive, strong national programme both in magnetic and in non-military inertial confinement. Fusion technology and materials research are also covered. There is considerable industrial involvement in technological R&D and in the design and manufacture of components. Japan has been participating strongly in international collaboration, especially with the United States (on D III-D and theory).

Again, the main emphasis is on the Tokamak, centred on JT-60 in JAERI, one of the world's three large Tokamaks. Currently the object of a major upgrade to be completed in March 1991, JT-60's aim is to achieve breakeven plasma conditions and to undertake a full programme into non-inductive current drive. D-T operation is not foreseen.

The JT-60 Upgrade programme is expected to provide input for a Japanese next step device, denominated FER, the conceptual design activity for which is well advanced. Engineering design permitting, it is understood that if authorisation is received construction of FER, a smaller machine but having design objectives similar to those of ITER, might be envisaged as early as 1995. Funding schedules could in fact permit the insertion of FER construction (costing something in the order of $2.2 billion, excluding R&D expenditure) in the Japanese nuclear research budget for the second half of the 1990s. Basic and supporting studies are undertaken on medium and small size Tokamaks in JAERI (JFT-2M) and in the university sector at Kyushu University (the superconducting Tokamak TRIAM-1M), Kyoto University (WT-3) and Nagoya University. Alternative lines are developed in MBS and ETL. The Stellarator programme, in particular, is very strong. The National Institute for Fusion Science, NIFS, has recently given support for a large superconducting helical device, LHD, on the basis of the encouraging results achieved by the Heliotron project at Kyoto University. LHD is a form of the Stellarator configuration and completion is expected by 1996. Studies on compact tori, such as Field Reversed Configurations, are also being continued at various universities and at the Electrotechnical Laboratory. A Tandem Mirror at the University of Tsukuba is investigating possible improvements in open mirror systems.

Supporting activities in theory and computation are relatively less important than in the other three major programmes. They are mostly carried out in the universities.

Japan is undertaking extensive work to establish a sound basis for such fusion technologies as plasma heating, high flux components testing, vacuum technology, superconducting magnets, tritium handling (a tritium processing laboratory is already in operation), blanket materials and the development of structural materials, with emphasis on first-wall and shield materials and on low activation.

The involvement of industry is organised via consortia with targeted objectives. Each consortium has a recognized lead firm and there is much pooling of information and expertise.

In inertial confinement, major implosion experiments are being conducted using a very large glass laser facility in Osaka University. (See Section 3.4, below)

2.1.3 The Soviet Fusion Programme

Fusion scientific work and R&D in the USSR is organised by the Main Department for Fundamental Issues of Nuclear Physics and Controlled Thermonuclear Fusion under the Ministry for Nuclear Power and Industry. It is notable that a large part of the effort is conducted within the scientific Academies.

There is a broad effort, including a traditionally strong theoretical component. The three main directions are:

(i) reactor design based on the Tokamak - the Tokamak was a Soviet concept - and this line retains its emphasis;

(ii) alternative magnetic confinement configurations;

(iii) inertial confinement.

The USSR's most important device is T-15, a superconducting Tokamak which began operation in Spring 1990. There is a large number of medium size and small Tokamaks, the largest being T-10 at the Kurchatov Institute in Moscow.

TSP is a compact high field Tokamak designed for adiabatic compression and final D-T operation.

Up until 1988, the main strategic goal of the Soviet programme had been the development of a fusion-fission hybrid system. The concept for OTR, the national thermonuclear test reactor, was along this line; OTR is now defined as a pure fusion device, with parameters close to ITER. Hybrid systems are no longer a major effort. As alternative lines, the Soviet Programme comprises small size Stellarators and a still significant mirror programme.

Technological research covers systems, reliability and quality control, materials testing and development in fields such as superconductors, plasma heating systems, vacuum technology, cryogenics, tritium handling and electrical engineering. Training of personnel for the programme is considered an important issue, as research takes place predominantly in the national laboratories. The most important institute is the Kurchatov Institute of Atomic Energy in Moscow and its Troitsk site.

In the place of industry, certain state institutes act as the main contractors for the development and construction of devices and components. An example is the Electrofisiks Scientific Industrial Corporation and its Efremov Scientific Research Institute of Electrophysical Apparatus in Leningrad. After its historic contributions to the development of the Mirror and the Tokamak, which influenced the whole direction of fusion research worldwide, the Soviet programme retains points of strength in gyrotron development, particle analysers, negative ion beam injectors, cryogenic steels and superconductivity, in the context of a still sizeable fusion effort. Considerable emphasis is also placed on analytic theory, relying on the work of many brilliant physicists.

An inertial fusion programme aims at energy production using laser and particle beam drivers or magnetic compression. It includes study of the conditions for ignition, target physics and connected problems such as energy concentration on targets and the reduction of pulse duration. (See Section 3.4)

2.1.4 Other Fusion Research Activities

Several other countries including Australia, Brazil, Canada, China and India have smaller, but significant, fusion programmes. They link through to the fusion activities in the rest of the world through bilateral and multilateral agreements, as well as through IAEA. IAEA also acts as a clearing house for information on fusion for other countries with activities in certain fields touching on fusion research. Canada participates in the ITER initiative through its link with the European Community.

2.2 The European Fusion Programme

2.2.1 Outline

Integration of all magnetic fusion research conducted by the countries of the European Community, plus Sweden and Switzerland, into one Community Programme has been essential for optimum use of the available human and financial resources. It has provided the basis for partnership in wider international collaboration and success has shown that, by joining forces, Europe can achieve an outstanding position in this field. A focused approach to fusion by magnetic confinement along the Tokamak line accentuated over the last decade, following a strategy established originally in the 1970s. The major facilities in the European Fusion Programme are shown in Figure 3.

The European strategy for achievement of the ultimate goal of joint construction of a prototype electricity generating reactor of industrial capacity has been based on three major intermediate steps. Overall, the strategy comprises:

(i) the present large Tokamak JET together with other specialized devices, to prove main aspects of scientific feasibility of fusion;

(ii) the planned Next Step Tokamak, to complete demonstration of scientific feasibility and to establish a solid basis for the evaluation of the technological feasibility of fusion;

(iii) a DEMO reactor to complete demonstration of technological feasibility and to establish a solid basis for the evaluation of the commercial feasibility of fusion.

For the evolution of device parameters see Figure 4.

Within the Tokamak programme, a strong effort is directed to issues of plasma confinement, to the physics of impurity control and recycling, as well as to plasma-wall interaction, with particular emphasis on coatings for plasma-facing components. Heating methods have also been developed. All major devices are equipped with neutral beam injection heating as a standard. Wave heating systems in the multi-megawatt range have achieved substantial heating and demonstrated the possibility of current drive.

Alternative approaches in magnetic fusion have been supported in the Community on an almost constant scale of around 10% of the Community total budget. Two concepts of toroidal magnetic confinement, close enough to the Tokamak to envisage mutual transfer of advances, receive significant support: the Stellarator and the Reversed Field Pinch. Inertial confinement is funded at a level of about 1% of the budget, aiming - in conjunction with national activities - at merely keeping in touch with developments elsewhere. There is a strong theoretical and computational component in the European Programme, centred on the Associations.

The technology R&D which is part of the Fusion Programme has been increased from about 7% in the beginning of the 1980s to 21% of the budget by 1989, recognizing the importance of developing technical solutions specifically for the Next Step device. Only a small part of this funding is in fact devoted to long term issues.

The relationship between European fusion laboratories and industry has improved in line with the requirements imposed by the increasing size and technological complexity of devices. Industry has participated in several areas of advanced technology, with some spin-off from fusion research (see Section 5.3, below).

Figure 3

FUSION IN EUROPE

Fusion Facilities

JET (JET Joint Undertaking) Abingdon

Compass (Euratom - UKAEA) Culham

RTP (Euratom - FOM) Nieuwegein

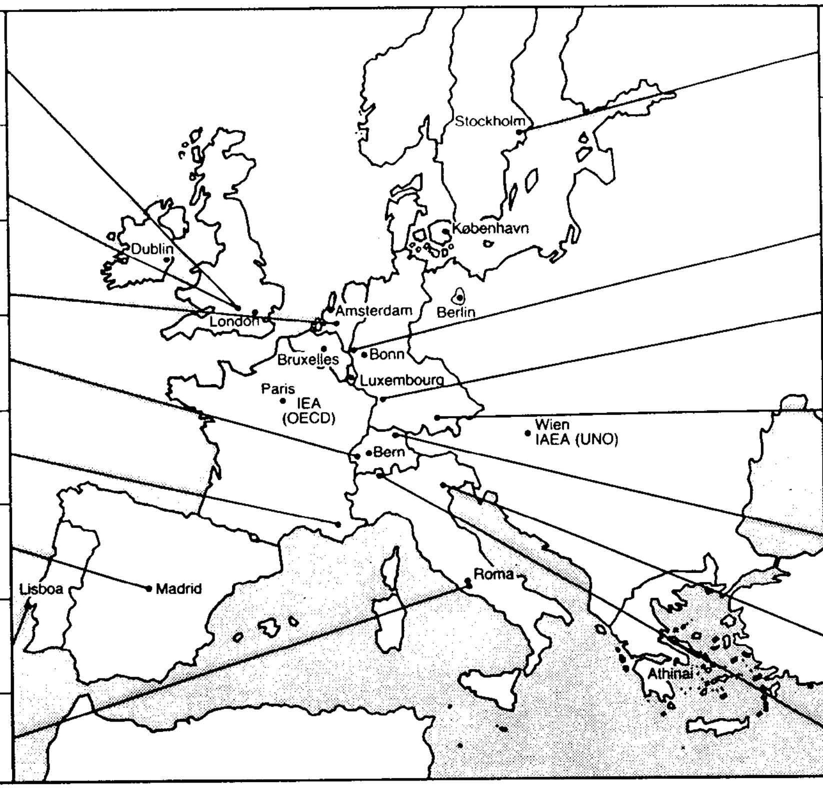
TCV (Euratom - Suisse) Lausanne

TORE SUPRA (Euratom - CEA) Cadarache

TJ - II (Euratom - CIEMAT) Madrid

ISTTOK (Euratom - IST)* Lisboa

FTU (Euratom - ENEA) Frascati



Extrap - T2 (Euratom - NFR) Stockholm

TEXTOR (Euratom - KFA, with support from Euratom - Etat Belge) Jülich

TOSKA (Euratom - KfK) Karlsruhe

ASDEX Upgrade
Wendelstein VII-AS (Euratom - IPP) Garching

SULTAN (Euratom - Suisse) Villigen

RFX (Euratom - ENEA) Padova

Tritium Lab (EC/JRC) Ispra

* Euratom Portuguese Association not yet established

The Associations

Euratom - CEA Association
Commissariat à l'Energie Atomique (CEA)
France (founded 1959)

Euratom - IPP Association
Max-Planck Institut für Plasmaphysik (IPP)**
Federal Republic of Germany (1961)

Euratom - FOM Association
Stichting voor Fundamenteel Onderzoek der Materie (FOM)
The Netherlands (1962)

Euratom - KFA Association
Forschungszentrum Jülich GmbH (KFA)
Federal Republic of Germany (1962)

Euratom - EB Association
Etat Belge (EB)
Belgium (1969)

Euratom - ENEA Association
Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energie Alternative (ENEA)
Italy (1972)

Euratom - UKAEA Association
United Kingdom Atomic Energy Authority (UKAEA)
United Kingdom (1973)

Euratom - Risø Association
Forskningscenter Risø
Denmark (1973)

Euratom - NFR Association
Naturvetenskapliga Forskningsrådet (NFR)
Sweden (1976)

Euratom - Suisse Association
Confédération Suisse
Switzerland (1979)

* Euratom Portuguese Association not yet established
** also hosting the NET Team and the Technical Site for ITER Joint Work

Euratom - KfK Association
Kernforschungszentrum Karlsruhe GmbH (KfK)
Federal Republic of Germany (1982)

Euratom - CIEMAT Association
Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT)
Spain (1986)

Euratom - IST Association*
Instituto Superior Técnico
Lisboa

JOINT ACTIONS

Joint Research Centre (JRC) — Ispra
Italy (1977)

JET Joint Undertaking
United Kingdom (1978)

Figure 4

EVOLUTION OF DEVICE PARAMETERS

	Before JET (1973)	*JET*	*NET (foreseen)*	*ITER (foreseen)*	*DEMO (foreseen)*	*Reactor (estimate)*
Major radius (m)		3	6.3	6.0	6.3	6.5
Minor radius (m)		1.3	2.05	2.15	1.8	1.8
Plasma volume (m^3)	~1	~140	~1,000	~1,000	~700	~800
Plasma current (MA)	0.4	4-7	25	22	20	22
On-axis toroidal field (T)		3.45	6.0	4.85	6.0	7.0
Pulse length (s)	<1	~25	>700	400-ss	s.s.	s.s.
Integral burn time (hrs)		~1	1,500	8,000	80,000	150,000
Wall loading (MW/m^2)		<0.2	~1	~1	2.2	3
Breeding ratio			tests	~0.7	>1	>1
Fusion product ($10^{20} m^{-3} keVs$)	0.03	8	50	50	50	50
Fusion power ($MW_{thermal}$)		(<30)	1,000	1,000	2,000	3,500

s.s. = approximately steady-state

International collaboration with countries not associated to the European Fusion Programme has also developed substantially during the past decade and now covers a large range of issues. After the end of the INTOR studies, a new initiative led to the present Conceptual Design Activities for an International Thermonuclear Experimental Reactor, ITER.

2.2.2 <u>Tokamak Line</u>

2.2.2.1 JET - The Joint European Torus

Since its commissioning in 1983, JET, the world's largest Tokamak, has been the principal actor in the European Programme and has provided significant contributions to progress in Tokamak physics. The size of the device, the large capabilities of the power supplies and heating systems, as well as the full array of diagnostic equipment and the dedicated team, allow JET to address issues of confinement physics and transport over a wider range and in more detail than any of the smaller devices.

The essential objective of JET is to obtain and study a plasma in conditions and dimensions approaching those required in a thermonuclear reactor. This has involved four main areas of work, defined as:

(i) the scaling of plasma behaviour as parameters approach the reactor range;

(ii) plasma-wall interaction in these conditions;

(iii) the study of plasma heating;

(iv) the study of alpha-particle production, confinement and consequent contribution to plasma heating.

During the early years of JET operation, emphasis was on scaling and plasma heating. The current programme aims at establishing effective control of impurities in operating conditions close to those of the Next Step and at a further improvement and better understanding of plasma confinement. D-T operation in JET, originally foreseen for 1989, has been postponed, following installation and testing of a pumped divertor, to study the possibility of impurity control in reactor relevant conditions. The JET programme in its new phase of operation is shown in Figure 8. D-T operation is now anticipated for the period 1995/96 should current proposals for an extension of JET operation be accepted, as this Report will recommend.

2.2.2.2 Specialized Tokamaks

Together with JET, the specialized Tokamaks aim to provide an additional basis for the construction and operation of the Next Step and to investigate long term generic problems. Specialized and medium size machines allow faster, more flexible operation and easier technical modifications, and they are a less expensive means for the investigation of many special issues. Figure 5 shows a list of the Tokamak devices that will be operational in the European Programme over the period 1990-1995, together with their main objectives.

TORE-SUPRA (Association EURATOM-CEA) at Cadarache, France, is the largest superconducting Tokamak in the world. IGNITOR, a compact Tokamak aiming at demonstrating D-T ignition, is presently in the detailed design phase (Association EURATOM-ENEA). The objective of this machine would be to achieve plasma ignition for a few energy confinement times (i.e. a few seconds). (See Section 3.3.)

2.2.2.3 Supporting Activities

A range of supporting R&D activities is necessary in order fully to exploit the potential of existing and future fusion devices. These include additional plasma heating, fuelling, development of diagnostics, plasma-wall interaction, plasma control, and theoretical and computational support.

Additional heating is achieved through the injection of energy into the plasma via high power neutral particle beams or electromagnetic waves. The neutral beam heating activity currently concentrates on improving efficiency of existing schemes based on initial positive ion acceleration and on developing high power, high energy, negative ion beams. At very high energies the neutralisation of negative ion beams before injection into the plasma is more efficient than for positive ions. Radio frequency heating has become a competitive alternative, with high efficiency of the wave generating and launching systems. Current R&D concentrates on developing high unit power sources in the very high frequency range suited to the direct heating of electrons in the plasma.

Fuelling by the injection of frozen deuterium pellets has become a favoured method. Multi-pellet high speed injectors are currently under development to enable deep refuelling of plasmas in large devices such as JET or the Next Step machine.

Diagnostic techniques for fusion plasmas have been developed to a high standard. Many of the important parameters can be measured with high accuracy. Of particular importance have been the development of laser and particle injection techniques, as well as the use of tomographic methods with multi-channel diagnostics. Further research is needed to measure the remaining parameters internal to the plasma.

Plasma-wall interaction has become an active field of research and the achievement of present high purity discharges are a direct outcome of R&D over the past decade. Central issues now relate to handling the power flow and the radiation effects anticipated in the Next Step.

Plasma control (feedback control of position, shape and axial geometry) has been an active area of R&D both on JET and on the new devices with non-circular section plasmas. Standard operation closer to operational limits has been achieved. For the Next Step, further development will be of importance.

Theoretical and computational work has pioneered or supported progress in almost all areas of plasma physics, machine design, heating systems, etc. Further progress in the full theoretical description of transport and confinement is still necessary.

Figure 5

SPECIALIZED TOKAMAKS IN EUROPE

Device	*Institution/Place*	*Main objectives*	*Ip (MA)*	*Period*
ASDEX	IPP/Garching	plasma/wall interaction poloidal divertor	0.5	80-90
TEXTOR	KFA/Jülich	plasma/wall interaction pumped limiters	0.6	81-
TORE-SUPRA	CEA/Cadarache	long-pulse operation in Next Step relevant plasma conditions	1.7	88-
ASDEX-Upgrade	IPP/Garching	plasma purity control in reactor relevant conditions	1.6	90-
FTU	ENEA/Frascati	confinement at high density and current particles	1.6	89-
COMPASS	UKAEA/Culham	high-beta and MHD stability studies	0.4	89-
TCV	CRPP/Lausanne	high-beta studies and disruption control	1.2	91-
RTP	FOM/Nieuwegein	transport mechanisms studies	0.2	89-
ISTTOK	IST/Lisbon	MHD activity, ECCD	0.006	91-

2.2.3 Alternative Lines in Magnetic Confinement

Besides the Tokamak, two types of devices are being investigated due to their potential inherent advantages. For both, however, the state of the art is much less advanced than for the Tokamak.

2.2.3.1 Stellarators

Among the alternate approaches to magnetic confinement, Stellarators receive most attention. Their main advantage lies in the possibility of operating a reactor in a steady state and in their freedom from disruptions.

Wendelstein VII-A (Association EURATOM-IPP) was phased out in 1986. This device had demonstrated net current-free operation for the first time, an advantage for steady state operation in a reactor. A Stellarator (Wendelstein VII-AS) based on non-interlocked magnetic field coils has recently started operation, demonstrating the technical feasibility of such a design. Complementary information from a different Stellarator configuration is expected from TJ-II, now under construction in Madrid (Association EURATOM-CIEMAT).

A device aiming at plasma parameters in the range of the present largest specialized Tokamaks but without D-T operation - Wendelstein VII-X - is in the phase of conceptual design. No decision has yet been made whether to extend Community funding to this project.

2.2.3.2 Reversed Field Pinch

The advantage of Reversed Field Pinches is that high plasma pressures can be obtained. The operation of a large device, RFX, presently under construction in Padua (Association EURATOM-ENEA) should give information on the reactor prospects of RFP. Pilot studies on related toroidal pinch systems with multipole stabilization are investigated in the EXTRAP devices at NFR, Stockholm.

2.2.4 Inertial Confinement

Inertial confinement relies upon the very small time that a burning pellet of fusion fuel needs to cool down by unimpeded radial expansion. A high energy beam of photons (generated by a laser) or particles (ions generated by an accelerator) are used rapidly to heat the surface of a pellet containing the deuterium-tritium fuel, leading to ablation and implosion which compresses the fuel to extremely high densities and finally to ignition. The European Community programme has supported some inertial confinement studies (about 1% of the programme budget) at a level sufficient to maintain expertise in this field and keep in touch with major developments elsewhere. ICF is discussed in more detail in Chapter 3.4, below.

2.2.5 Technology

The European programme effort in technology has expanded over the past decade, the budget increasing from 12 MioECU in 1980 to about 80 MioECU in 1989. Dedicated predominantly to the needs of the Next Step, R&D is focused on seven main areas:

(i) Superconducting magnets for fusion have been developed within the 8 Tesla range (based on niobium-titanium). These were successfully tested (Large Coil Task). More advanced 8 Tesla technology is now used in TORE-SUPRA for standard operation. For the requirements of the Next Step and beyond, 12 Tesla technology (niobium-tin) and, as a back-up, super-cooled niobium-titanium conductors are under development.

(ii) Tritium technology continues to be a sensitive issue. For JET, the tritium handling system has been developed with help from the Associations, in particular CEA. For the Next Step, and the reactor, higher throughputs will require further development. Meanwhile, test facilities are in construction.

(iii) Blanket development has become a major activity in the technology part of the fusion programme, although the NET design no longer foresees a full breeding blanket and, if constructed, the device will be of only limited use as a materials test facility. Development is directed towards Next Step blanket test modules in view of the DEMO reactor.

(iv) At the beginning of the 1980s, materials research was directed toward the development of austenitic steels and later redirected toward martensitic steels. Martensitic steels and their low-activation modifications are the subject of some development work, along with vanadium alloys, in the framework of the currently small long term technology programme. An effort is being made to define possible goals of low-activation alloy development with the help of waste disposal, maintenance, and accident scenarios. Lack of an adequate source of fast neutrons is hampering this field of research, in Europe as elsewhere.

(v) Plasma-facing components technology has emerged as a major issue during the past decade. Detailed studies have led to the concept of cooled first wall austenitic steel elements protected by tiles made of low atomic number (low-Z) material. Production methods (including new brazing techniques) are being developed for the Next Step.

(vi) Remote handling has been developed for the tritium phase on JET. Developments (up to proof of principle testing) for the Next Step with more demanding equipment and speed requirements are underway in various laboratories. The maintenance of in-vessel components has been identified as a key area.

(vii) Safety and environmental studies have gained more momentum. The research programme is addressing the quantification of radioactivity source terms and waste production, pathways for dispersion of tritium and activation products in the plant, and the environmental analysis of accident sequences. With respect to the Next Step, this provides input for design-dependent safety aspects.

2.2.6 The Next Step Alternatives

A team was established at Garching near Munich for the Next European Torus (NET) in 1983 with the aim of defining the objectives, main design features, options and planning of NET, and of identifying the R&D needed for its design. Following this definition phase (completed by the end of 1985), a pre- , or conceptual, design phase has been started.

Following initiatives taken at the highest political level, the European Community, Japan, the USA and the USSR agreed in early 1988 to participate under the auspices of IAEA on an equal quadripartite basis in the joint development of a conceptual design for an International Thermonuclear Experimental Reactor (ITER) and supporting R&D activities. IPP, where the NET Team had already been established, was chosen as the site for joint work. Given the similarities between NET and ITER, the EURATOM contribution to ITER design work has been made mostly by the NET Team. It has required no specific funding.

Both the NET and ITER devices are intended to study the ignition domain, optimise operating conditions to control the plasma burn during long pulses, prove the technology of plasma-facing components, and validate exhaust and fueling systems. The Next Step debate is covered in detail in Section 3.3, below.

2.2.7 Organisation and Financing of the Community Programme

The Community Fusion Programme is a specific programme of research and training in the field of controlled nuclear fusion adopted by the Council of Ministers for periods not exceeding five years. The current programme covers the period 1st January 1988 - 31st March 1992. It embraces all work carried out in the member states in the field of thermonuclear fusion by magnetic confinement. Sweden and Switzerland are fully associated with the Programme.

The European Commission in Brussels is responsible for the overall management of the Programme and is advised by a Consultative Committee for the Fusion Programme (CCFP) with two sub-committees: the Programme Committee, concerned mainly with the physics programme, and the Fusion Technology Steering Committee, concerned with the fusion technology programme. The Fusion Programme is executed principally through the Associations in the member states, the JET Joint Undertaking and the NET Agreement. Specific aspects of fusion technology are also studied in the Community's Joint Research Centre (JRC).

The management structures of the European Fusion Programme have proven adequate and efficient for the scale of the fusion effort so far. By virtue of decentralized management, a small central staff in Brussels has managed to direct a large programme. A committee structure for project evaluation and coordination, basic and priority support schemes, mobility schemes, etc. has been created. Despite decentralization, coherence and coordination within the programme has been achieved and the quality of this management structure is acknowledged as a model internationally. Two non-Community countries have integrated into the programme: a third, Canada, is now considering joining - at least in part. For the ITER CDA, the committee structure has been modelled on the JET system.

Community participation in financing and staffing laboratories in the member states is ensured through Contracts of Association. Running costs are financed at 25% and a preferential support scheme allows for 45% funding of priority projects. In total, about 30% of the Associations' expenditures are financed by the Community. Each Association is managed by a Steering Committee with representatives of the national organisation and of EURATOM. There are currently twelve Associations in ten countries. A new Association is in the course of being set up in Portugal. Of a total of 1,360 professionals (including 40 EURATOM employees) in the Associations, 1,070 work in physics and 290 in technology. A list of the Associations is given in Figure 3; their role is discussed in detail in Section 3.6, below.

The Joint European Torus (JET), Joint Undertaking was set up with as members, EURATOM, all its associated partners in the frame of the Fusion Programme, Greece, Ireland, Luxembourg and Portugal. Responsibilities for the project are vested in the JET Council (consisting of representatives of the members of the JET Joint Undertaking) and the Director of the Project. The JET Council is assisted by an Executive Committee and is advised by the JET Scientific Council. It is financed 80% by the Community and 10% by the host institution (UKAEA). The remaining 10% is shared between all members having Contracts of Association with EURATOM. The JET Team, formed by staff drawn from all countries involved, is recruited by the Commission on temporary posting with guaranteed return to their home institutions, together with staff from UKAEA, which are directly seconded to the project. Additionally, staff are detached to JET under a variety of schemes for periods of usually between three months to one year. Currently, of a total staffing of about 600, over 270 professionals work at JET, of whom about 180 belong to the JET Team.

The work programme of the NET Team is supervised by the Fusion Technology Steering Committee (FTSC) which has recently been reorganised into FTSC-P (Planning, acting as a supervisory board for the NET Team) and FTSC-I (Implementing; coordinating the implementation of all technology activities). Of nearly 70 professionals of the NET Team, 30 come from industry. Support from the host laboratory to the NET Team is financed at 75% by the Community.

The Joint Research Centre's Ispra Laboratory performs work in specific areas of fusion technology. Its activities are covered by a separate decision of the Council of Ministers, currently for the period 1988-91.

There are two mobility schemes (Agreement for Promotion of Staff Mobility between EURATOM and the Associations, and Contract of Assignment from the Associations to JET). Each year, about 200 professionals are sent from their home institution to another site for periods of at least one month. More than 70 people work at JET for periods averaging 6 months. A major aspect of these schemes is to allow laboratories to assume full responsibility for a specific task on JET, or on one of the other specialized machines in the larger Associations.

Training is an integral part of the programme, and this assists the creation of competent teams in new Associations. Currently, there are about fifteen EURATOM Fellows in the Associations, plus seventeen at JET.

2.2.8 Role of Industry

Industry in Europe has participated in the development of technical know-how and in the construction of systems and components for fusion devices. Over 96% by value of all contracts for JET and the specialized devices have been placed with European industry. The gain in new technical expertise through such contracts is recognized by industrial companies. The role of industry in the fusion effort is analysed in Chapter 5.

2.2.9 International Collaboration

International collaboration is a main feature of European Fusion Programme strategy. There are bilateral agreements with Canada, the United States, and Japan covering joint planning, joint exploitation of devices, mutual supply of components or systems, joint development and staff exchange. Other, less comprehensive, agreements also exist. A bilateral agreement with the Soviet Union is in preparation.

Multilateral cooperation is conducted under agreements within the OECD International Energy Agency (IEA) and the International Atomic Energy Agency (IAEA). IAEA provides the formal framework for ITER Conceptual Design Activities. For a fuller discussion of international collaboration, and specifically of ITER, refer to Section 3.3, below.

2.3 Review of Progress in Research

2.3.1 Strategic Changes in the 1980s

The strategy of development of magnetic confinement in the world, and in the EURATOM programme in particular, has evolved since 1980. The main points in this evolution are:

(i) a continuation of the trend already visible in the 1970s of a reduction in the number of lines pursued in the national programmes, with greater emphasis placed on the Tokamak. In the US, the open mirror configuration has been abandoned after disappointing results. The same focusing of the main effort on fewer options is also visible in the Japanese and Soviet programmes. The EURATOM programme was already focused on only three lines - Tokamak, Stellarator, Reversed Field Pinch - and here the evolution has been towards better coverage of these existing options;

(ii) diversification of Tokamaks to explore a wider range of parameters, with some conventional Tokamaks ceasing operation and several new Tokamaks being built. Stellarators and Reversed Field Pinches now are universally recognized as the main alternative lines;

(iii) while the 1970s were the years of ohmically-heated Tokamaks with very favourable empirical scaling, the 1980s have been the years of additional heating. The latter has revealed new difficulties: some already resolved, others still outstanding. In the early 1980s, the parameters of the international project INTOR and of its equivalent in the European strategy, NET, were based on ohmic scaling. The evolution from the INTOR/NET project to the ITER/NET project reflects the increased knowledge gained during the course of the decade from operating a variety of devices in regimes much closer to that of a reactor;

(iv) the INTOR/NET project proved very useful in helping to assess the status of knowledge and to identify the critical issues which need to be resolved before being able to build a reactor based on the Tokamak concept. The interplay between the various, frequently contradictory, physics constraints and an even more fundamental interplay between the physics and technology constraints, both emerged for the first time.

2.3.2 Milestones in Progress in Physics

2.3.2.1 Tokamaks

(i) Confinement

Discovery of the complexity of the confinement properties of a Tokamak plasma is one of the main results of the past decade. The main problem in the 1980s was energy confinement in the presence of auxiliary heating supplementing the basic ohmic heating inherent to the Tokamak configuration. At the time of the first Beckurts Panel, there was already some evidence of confinement degradation (that is, loss of thermal insulation) in Tokamaks heated with neutral beam injection. The data base was not sufficient, however, to decide if this degradation was an artifact of the type of heating used, nor to draw any real lessons. Now degradation is an accepted fact. While the various heating techniques each have their specific physical and technical limitations which do not make them fully interchangeable on any target plasma, evidence has accumulated that degradation of confinement is an intrinsic property of the magnetically confined plasma, only indirectly affected by the heating technique. This also applies to adiabatic compression, as demonstrated on TFTR.

There is still no generally accepted physical interpretation of confinement degradation. Many theories relying on very different models give degradation, and can explain some features of some specific machines, but experimental evidence has not allowed an unambiguous validation of any one of them. The extreme difficulty of diagnosing hot plasmas and the recognized difficulty of theorizing any turbulent state are the reasons for this. Lack of understanding has compelled plasma physicists to derive purely empirical laws to relate confinement time to engineering parameters (size, shape, magnetic field, current, pressure) from extensive experimentation using a large number of devices. These laws all identify as essential for good confinement large size, strong non-circularity of the plasma and high current (and thus indirectly high magnetic field, because of the operation limit on the current) - and all three of these conditions are technologically very demanding.

The discovery in 1982 of enhanced confinement on ASDEX in the presence of strong neutral beam heating opened the way to extensive experimental work to characterize what came to be termed the H-regime and, in particular, the conditions under which the transition from the fully degraded state to a higher confinement occurs. Evidence is accumulating that many, probably all, heating techniques can trigger the transition to the H-regime above a threshold power level in divertor or quasi-divertor configurations. Very recently the same sign of a transition has been seen in a limiter configuration on several devices but data are insufficient to draw definite conclusions. The improvement in confinement brought by the H-transition depends on operating conditions and can reach a factor of two. The scaling of confinement time as a function of basic design parameters does not appear to be different from the degraded state. There is no generally accepted interpretation of the physics involved in this transition. Other enhanced confinement regimes have been discovered, characterized by completely different conditions than the H-regime. Data are still scanty compared to those available for the H-mode and, as yet, do not allow any characterization of their potential.

The fusion product $n_i T_i \tau_E$ (n_i, T_i = central ion density and temperature; τ_E = energy confinement time) and the temperature T_i characterize the performance of a Tokamak. Figure 6 shows the performances attained by the major Tokamaks, including for comparison some older devices. The figure of merit Q is defined as the ratio of D-T fusion power (assuming a D-T plasma) to the total heating power needed to maintain the plasma temperature. JET has reached a fusion product only a factor of 7 away from the minimum ignition requirement.

(ii) Impurities

As more and more auxiliary heating has been applied to Tokamaks, impurities have become a dominant limiting factor on performance. In addition to the Tokamaks specifically built to study this area, all Tokamaks with auxiliary heating have had to devise ways to circumvent the problem. Some success has been achieved in controlling impurities by changing plasma-facing materials to low atomic number (low-Z) materials. In most Tokamaks, this has been done by using graphite tiles and/or a thin layer of graphite or boron carbide. Limiters are now mostly in graphite, sometimes coated with boron carbide or silicon carbide. In its last operating period, JET has used beryllium both as a coating and for limiters with success. The use of low-Z materials has provided some relief for, and in some cases cured, the problem of excessive impurity build-up on the short pulse length typical of the 1980s generation of Tokamaks.

A correlation between enhanced energy confinement and impurity build-up was first seen in ASDEX, then confirmed by many others machines. But D III-D in San Diego last year produced quasi-stationary H-discharges in which there is no impurity build-up. The data base is still insufficient to draw definite conclusions.

(iii) Operational limits

Tokamaks operate in a limited range of pressure and current. Attempts to exceed these limits cause either a rapid and complete loss of confinement, and disappearance of current, or massive and progressive loss of energy. The physics phenomena underlying these limits have been identified. The successful expansion of the range of operation achieved by elongating and shaping the plasma cross-section demonstrated on JET, D III-D and PBX in Princeton offers convincing evidence of the validity of these interpretations.

(iv) Plasma heating and non-inductive current drive

Neutral beam heating and the various forms of RF-heating have become standard methods, with multi-megawatts delivered for a few seconds. The underlying physics is well understood. Current drive with lower-hybrid waves and neutral beam injection was a speculative issue in the early 1980s. It has developed into a reliable and predictable tool with increasing efficiency as the size of the devices grows. Current drive remains a speculation for other schemes relying on different wave types. Full non-inductive current drive in a Tokamak was first achieved in PLT at low density. The main difficulty shared by all schemes is that the efficiency decreases inversely with the density, requiring very high power already at medium density. JT-60 has reached record efficiency with lower-hybrid current drive.

(v) Simulation of alpha-particle heating

The only possibility of creating a substantial population of alpha-particles is in D-T operation. It has nevertheless been possible to simulate such a population by accelerating a fraction of the particles in a D-H or D-^{3}He plasma to comparable energies. This enables study of the fate of these particles and of their effect on the rest of the plasma. Experiments on JET have so far not shown any anomaly in the behaviour of particles or plasma.

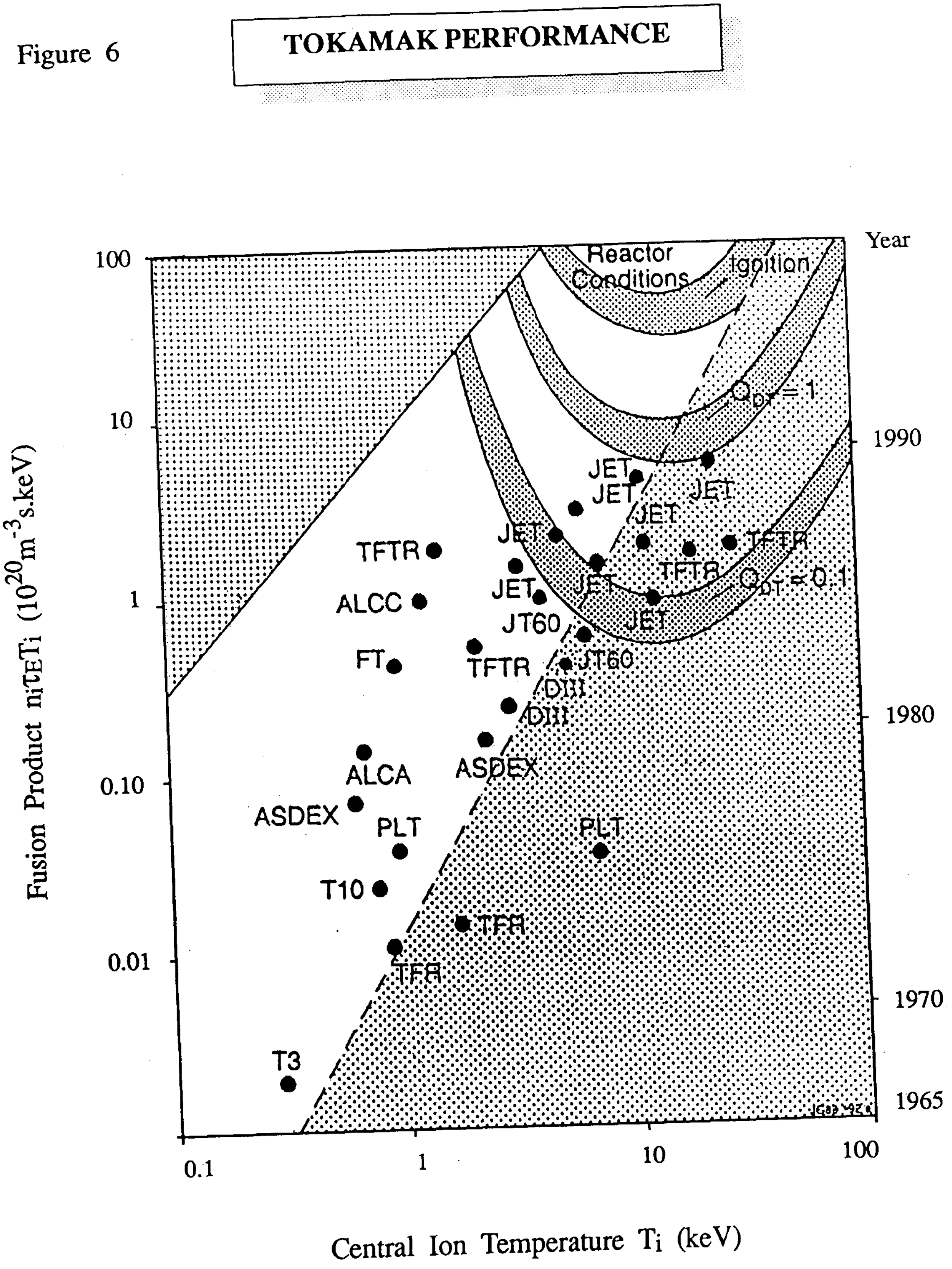
(vi) Theory and computation

Analytical theory has continued to focus on the issue of confinement, inventorying possible physical mechanisms which could explain transport anomalies in Tokamaks. Fluid simulations of Tokamak behaviour have reached maturity and have provided good understanding of operational limits. All the new devices of the late 1980s, as well as the conceptual designs for NET and for ITER, have incorporated these results. Good progress has been made in developing computational tools to design new plasma configurations. These have been essential for the design and realization of such complex devices as ATF, Wendelstein VII-X and LHD.

2.3.2.2 Stellarators

As noted elsewhere in this Report, the main contributions in the 1980s have come from Wendelstein VII-A in Garching and the Japanese Heliotron device. In a significant achievement, Wendelstein VII-A demonstrated in 1981 the possibility of operating a Stellarator with no net current and with a magnetic configuration maintained almost completely by external means. Heliotron achieved a pressure comparable to that obtainable in a circular cross-section Tokamak with the same magnetic field. Wendelstein VII-AS and ATF have just come into operation.

Figure 6


TOKAMAK PERFORMANCE
Fusion Product $n_i \tau_E T_i$ (10^{20}m^{-3}s.keV)
Central Ion Temperature T_i (keV)
Year
Reactor Conditions
Ignition
$Q_{DT} = 1$
$Q_{DT} = 0.1$
JET
TFTR
ALCC
FT
JT60
DIII
ASDEX
ALCA
PLT
T10
TFR
T3
100
10
1
0.10
0.01
0.1
1990
1980
1970
1965

Because of the complexity of these configurations, there has been an important supporting theoretical effort. A large portion of this effort has been concentrated on preparation for a new generation of devices - in the USA (Oak Ridge), in Europe (Garching, Madrid) and in Japan (Nagoya and Hiroshima).

2.3.2.3 Reversed Field Pinches

The main result in the RFP area has been the demonstration that improved confinement, which translates into a reduction in loop voltage, can be obtained by exercising great care in eliminating field irregularities. Despite this, the loop voltage remains far higher than in a Tokamak with the same current. The predicted favourable effect of increased size and current on confinement has been verified so far in all devices.

2.4 **Outstanding Critical Issues**

2.4.1 Tokamaks

Because of its importance in fixing the parameters of the reactor core, energy confinement remains the crucial issue. While empirical laws have been established with those devices, especially JET, which are sufficiently close to reactor parameters to make the spread of performance as predicted by extrapolation to reactor size small, and thus relatively safe, improvement of confinement and identification of the factors which control confinement would have a crucial impact on all other issues. In particular, it would provide additional parameter space for optimisation of the engineering.

The effect of a large fraction of very energetic particles (that is, alpha-particles from D-T reaction or particles accelerated by auxiliary heating) on the confinement properties is central. Energy confinement and particle confinement of impurities (the helium ashes of the fusion reaction are also impurities) and of the hydrogen isotopes are intimately related and bring serious difficulties when the same system of exhaust is used both for energy and particles. The complexity and the interdependence of this problem is recognized and a strong European effort addresses the issue.

Non-inductive current drive offers the opportunity to transform the otherwise pulsed Tokamak into a steady state device or to assist the inductive drive in reaching high current where confinement is best. Important remaining generic issues include bringing schemes other than lower-hybrid and neutral beams to the same stage of development attained for these latter and establishing as wide as possible a data base on the range of plasma parameters accessible and on the behaviour of the plasma in the presence of non-inductive current drive.

While the application of known techniques for heating or current drive at the megawatt level no longer presents a problem, there remain two potentially useful techniques for which sources with the required performance and parameters suited to medium-size and large devices do not exist: very high energy neutral beams, which must be created by neutralisation of negative ion beams, and electron cyclotron resonance heating (ECRH), which requires the development of powerful and efficient microwave tubes.

At the current contemplated for the Next Step (20 MA or more), disruptions become very dangerous and must, if at all possible, be avoided. Identification of the causes of these disruptions and the development of control systems to prevent the plasma from approaching a disruptive state is a crucial problem.

According to present knowledge, the Next Step device will have to work relatively close to its operating limits and at an elongation of the plasma at the borderline of what has been achieved. Increasing the data base for such operation is vital. Operational limits are sensitive to the current density profile, so that the possibility of controlling this profile is also a key point.

2.4.2 Stellarators

Alternative lines - Stellarators and Reversed Field Pinches - are studied in the European Programme in the hope of improving on the Tokamak configuration by solving some of its crucial problems and the main generic problems of both lines are best defined by comparison to the Tokamak itself.

For the Stellarator, the main issues are to establish the upper pressure limit and to study confinement in regimes up to this limit. A scheme must be found to provide control of energy and particle exhaust, though this issue would appear of lesser importance, as a solution studied for Tokamaks may ultimately prove applicable. The main difficulty in finding convincing answers to such problems will be that of building these complex devices with sufficient flexibility to explore a reasonably wide range of parameters.

2.4.3 Reversed Field Pinches

Plasma confinement is the main issue in Reversed Field Pinches. While RFP has the potential to operate at higher pressure than a Tokamak, thus requiring a lower confinement time to reach ignition, its high current is difficult to maintain for long pulses because of the high load imposed on the transformer. The higher energy and particle densities make the exhaust problem very difficult.

CHAPTER THREE

STRATEGIES

3.1 Current Strategy and New Directions

The long term development of the European Fusion Programme has been conceived around the sequential attainment of three steps - scientific feasibility, technical feasibility and commercial feasibility. Each of these steps was associated with a separate machine, JET, NET and DEMO, for theoretical and practical demonstration. The programme structure was then complemented by a series of experiments carried out on different size specialized machines and by other activities conducted in the Associations. Specialized machines were to supply information and updates useful for the operation of the current main machine, for the design of the next, or for the investigation of solutions alternative to the Programme's reference development line of the Tokamak. The major facilities planning of the Programme is shown in Figure 7.

There is, however, an apparent delay in reaching the goals according to the timetable set by the Programme. Comparing the actual state of advancement with the previsions of the first Beckurts Report of 1981, the impression is of slower progress towards the final goal over the intervening decade. In 1981, it was anticipated that JET would complete its mission by 1990; consideration is now being given to prolongation of JET operation until 1996, in order fully to exploit the capability of the device. The Beckurts Report in fact forecast demonstration of scientific feasibility by the end of the 1980s, with the hope that construction in Europe or elsewhere of a machine designed to demonstrate technological feasibility could be started by the middle of that decade. The earliest date now foreseen in the European Programme for the start of NET construction is 1997. Estimates of the total world expenditure required before fusion can enter the commercial energy market range from $100 billion to $150 billion and this now spread over another fifty years of research and development, as opposed to an earlier timescale of only twenty five years to commercialisation. Fusion thus runs the risk of acquiring the reputation of being something of a mirage, a moving target that recedes as one tries to approach it.

It would be wrong, however, to believe that the European Programme has made little progress since 1981. Knowledge both of physics and of the engineering problems has greatly improved since then. The performance of JET has been good. The $nT\tau$ value attained is now over fifty times higher than the world best in 1980 and the device is less than a factor of two from breakeven conditions. The Board is convinced that much can still be expected from JET. As the largest Tokamak in the world, and the nearest to the Next Step device, the Board believes JET has a mission which extends beyond demonstration of breakeven in D-T plasma. Figure 8 gives an indication of the importance of the projected JET programme over the next six years. The decision to introduce tritium must be made only on scientific grounds. The Board therefore supports proposals to prolong the operational life of JET until 1996 and, subject to rigorous scientific, technical and safety assessment undertaken within the Fusion Programme, introduction of tritium into the machine after 1994.

Operation of JET and other devices has in fact shed much new light on issues at the basis of plasma physics and fusion power. Some of the results obtained in this period have, however, evidenced unforeseen difficulties. The problem of impurities in the plasma and the connected plasma-wall interaction, for instance, have proven far more critical than previously thought. Solutions often point to larger size and higher current, increasing both the technological and the financial challenge of fusion research.

Evidence of greater complexity points to the need for reconsideration of the European strategy. Specifically, the three consecutive steps in the demonstration of feasibility can no longer be directly identified with the three machines, JET, NET and DEMO. Although going a long way toward demonstration of scientific feasibility, JET is not expected simultaneously to attain all the required conditions, indeed ignition was not among its stated objectives. NET, initially intended as a device to obtain a range of results in technology areas of reactor relevance, will thus also have to operate as a research tool for aspects of the physics. Moreover, it is now not expected to supply definitive answers in all technological fields. Significant data will be lacking, for instance, in such important areas as materials endurance, a full hot tritium breeding blanket with provision for closing the fuel cycle, safety and environment. As a consequence, DEMO is in turn likely still to have a number of technological tasks to perform. It is thus highly improbable that DEMO will be able, by itself, to provide convincing demonstration of economic feasibility to Europe's electricity utilities. This will now require a fourth, commercial prototype, machine.

Pushing the analysis a little further, it would appear that the distinction between scientific, technological and commercial feasibility is itself blurred. The fact that long burning pulses may be limited by the build up of impurities, and that power densities for any given machine may be limited by plasma stability, makes the separation between scientific and technological feasibility less evident. Similarly, the need to avoid long down times due to maintenance and the replacement of components and to reduce the generation even of low level radioactive wastes to a minimum, as well as the operating characteristics deemed acceptable to utilities (among which probably steady state, as opposed to pulsed, operation), means that the distinction between scientific, technological and commercial feasibility is less marked today than it may have seemed in the past. Economic and environmental performance are both to a considerable extent critically dependent on the design choices, and interact with them.

One other factor originating outside the world of fusion has also to be considered. This is the enormously increased importance now given to safety and environmental issues since the Programme's inception. While this strong emphasis may favour fusion as a potentially safe and environmentally friendly source of energy, the true extent of the potential has to be plainly developed as early as possible in the Programme, and certainly not be postponed until the phase reserved for

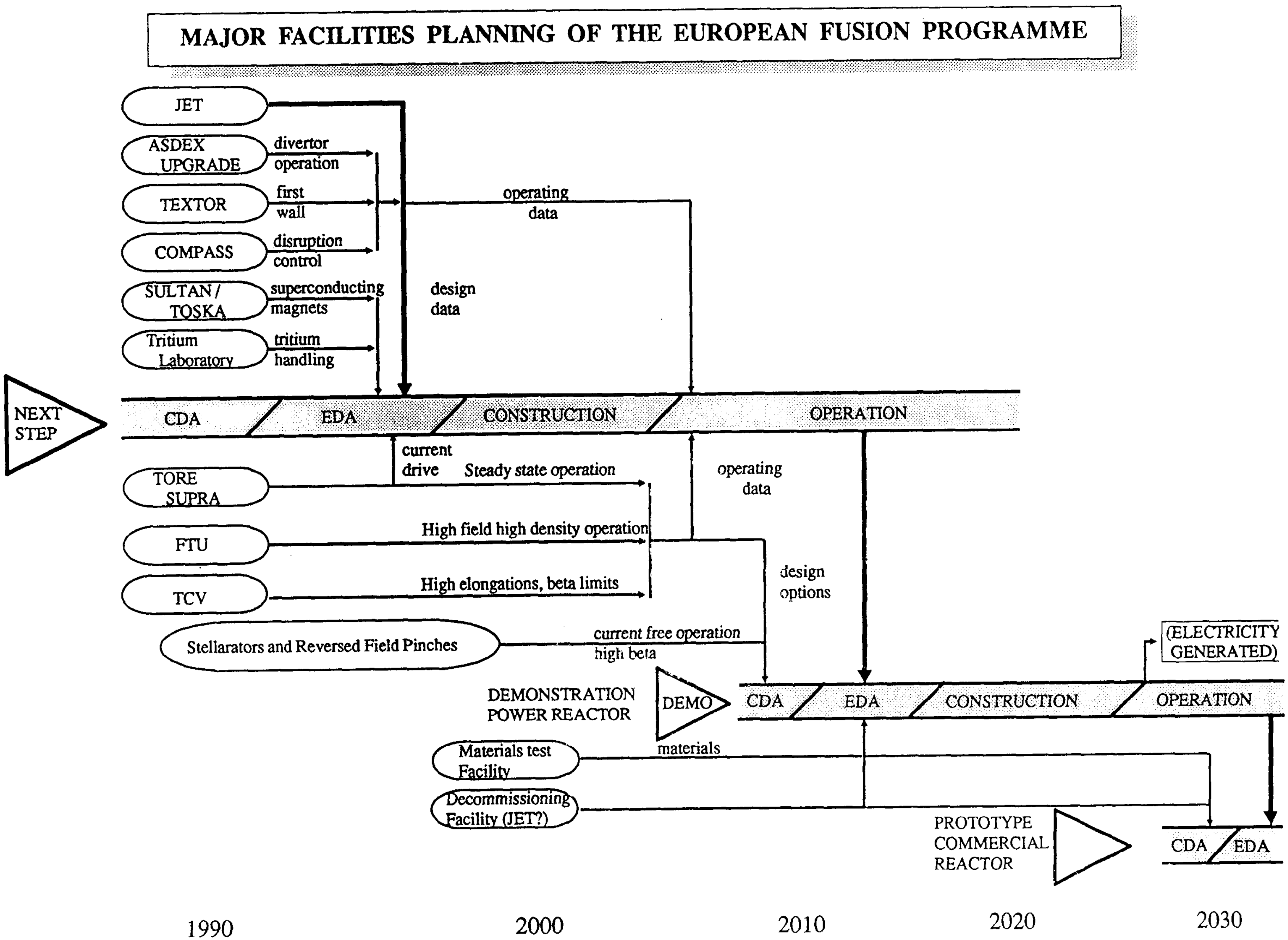
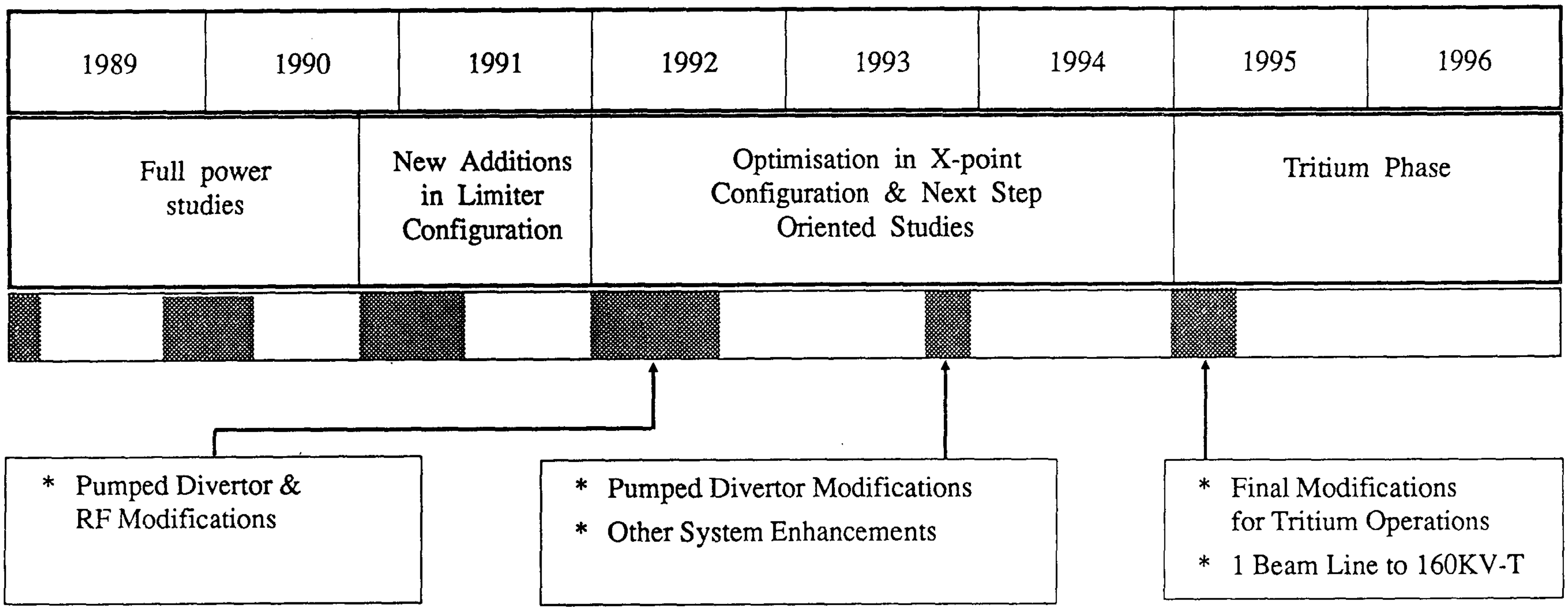

MAJOR FACILITIES PLANNING OF THE EUROPEAN FUSION PROGRAMME
JET
ASDEX UPGRADE
divertor operation
TEXTOR
first wall
operating data
COMPASS
disruption control
SULTAN / TOSKA
superconducting magnets
design data
Tritium Laboratory
tritium handling
NEXT STEP
CDA
EDA
CONSTRUCTION
OPERATION
current drive
Steady state operation
TORE SUPRA
operating data
High field high density operation
FTU
design options
High elongations, beta limits
TCV
Stellarators and Reversed Field Pinches
current free operation
high beta
(ELECTRICITY GENERATED)
DEMONSTRATION POWER REACTOR
DEMO
CDA
EDA
CONSTRUCTION
OPERATION
materials
Materials test Facility
Decommissioning Facility (JET?)
PROTOTYPE COMMERCIAL REACTOR
CDA
EDA
1990
2000
2010
2020
2030

Figure 8

JET PROGRAMME IN THE NEW PHASE



demonstration of the commercial feasibility of fusion reactors sometime in the second quarter of the next century. In order to maintain a sufficient level of political support for the massive, and increasing, spending that is going to be required should the Fusion Programme proceed, decision makers and public opinion must be reasonably confident that the end result of this long quest will in fact be in line with their basic expectations and requirements.

3.2 Importance of Safety and Environmental Issues.

The performance of fusion against what in the second half of the next century will be its most direct competitors for generating base-load electricity (fission reactors - possibly fast breeders - and coal) may in the end be judged on the grounds of environmental and safety advantages, and not just in purely economic terms. We have already discussed in Chapter One the need to explore alternatives to coal in view of the latter's potential contribution to greenhouse warming. Fusion's superiority to fission, which has yet to be fully demonstrated, becomes a critical issue.

It would be particularly important for fusion to qualify in two respects:

(i) it must be clearly shown that the worst possible fusion accident will constitute no major hazard to populations outside the plant perimeter that might result in evacuation;

(ii) radioactive wastes from the operation of a fusion plant should not require isolation from the environment for a geological timespan and therefore should not constitute a burden for future generations.

We believe that these objectives are viable targets with careful design and materials development, but their attainment should not be taken for granted. There is, in our opinion, a parameter of environmental and safety feasibility, the demonstration of which is just as important as that of technological or commercial feasibility. Given the importance public opinion and policy-makers now attach to safety and environmental issues, convincing demonstration of fusion's potential advantages over alternative sources is necessary in order to ensure continuing long term investment on the scale required. Specific attention in this direction cannot be postponed to a much later stage, such as the time of the DEMO or even the prototype commercial reactors.

In addition to the two central points listed above, others issues in the area of safety and environment in which fusion's comparative advantage should be made evident include the following:

(iii) ensuring that operation and maintenance of the plant are quite feasible, with fully acceptable occupational doses to the personnel, and that non-radiological hazards are also negligible;

(iv) ensuring that decommissioning and eventual dismantling of the plant is feasible at acceptable cost and with low radiation exposures;

(v) ensuring that releases to the environment during normal operation (including maintenance and replacement of components) of both radioactive and other noxious materials are well within standards laid down by regulations;

(vi) demonstrating that concern as regards proliferation will be much less than for fission power, and can be dealt with effectively;

(vii) evaluating other lesser impacts on the environment (such as land occupation, water usage, etc.), making sure that they constitute neither a major problem, nor too binding a constraint.

All these points are important and should be properly considered already at an early stage of the Fusion Programme. With adequate solutions, they are, however, unlikely to represent insurmountable obstacles to the diffusion of fusion power. The Board considers that the best way to ensure such solutions is through the establishment of an Environment and Safety Team with the task of monitoring environmental and safety criteria in the European Programme.

Let us now consider specifically each of the seven points we have mentioned:

(i) Consideration of the worst possible accident involves three stages:

(a) the mechanism originating the accident;

(b) the inventory of radioactivity that could be involved;

(c) the mitigation of the evolution of the accident and of its consequences.

Each of the three can in principle be dealt with by appropriate design and choice of materials: the first, (a), by reducing the energy sources that may induce the accident (residual radioactivity; chemical energy of materials used for blanket, first wall protection, coolant etc; heat or electro-magnetic energy that may be liberated, etc.) or by protecting against external events; the second, (b), by reducing tritium inventories, limiting the amount of tritium that is present at any one time in the vacuum chamber, or in any part of the plant that could be involved in an accident; and by an appropriate choice of materials for all the parts of the reactor exposed to neutron irradiation, so as to limit the amount of radioactivity that could be released. Finally, (c), the evolution of the accident and the reduction of its consequences to acceptable levels should be based as far as possible on passive or intrinsic features of the plant, which do not require the active intervention of the operator nor the automatic operation of equipment. The containment building, if based on the same principles, can be a decisive factor in excluding propagation of radioactivity in the environment outside the plant. From these considerations on each of the three points above, it would appear that the only detailed conceptual reactor design developed so far, the late 1970s STARFIRE concept, is outdated from a scientific and technological standpoint and is therefore inadequate to cope with safety and environmental issues as perceived today. The Board thus recommends the launching of a new European reference design for a commercial fusion reactor. Such a design will require periodic updating as research progresses, in particular to incorporate safety and environmental protection features likely to ensure public acceptance and to take into account the requirements of utilities in operating a reactor. In parallel, active involvement in materials research is another prerequisite to answer open questions on the safety of fusion plants. Although appreciative of the work being carried out in this area in the European Programme, the Board believes that the effort must be enhanced and extended in scope.

(ii) 14 MeV neutrons liberated in the deuterium-tritium reaction initiate a variety of nuclear reactions affecting materials used in a fusion plant. The condition that in the parts of the reactor exposed to these neutrons (plasma-facing components, i.e. the first wall and divertor plates, breeding blanket and neutron multiplier, coolant, structures and shield, etc.) no relevant quantities of radioactive nuclides with half-lives longer than, say, in the order of 100 years are produced is indeed very stringent. This is especially challenging since the various materials have to accomplish many different tasks and to respond to exacting requirements, such as endurance under irradiation, neutron balance, compatibility with other materials, heat conduction, low short-time activation, etc.. In the selection of candidate materials, such requirements are often in conflict with each other and with the criterion of no production of waste requiring geological timescale disposal. The development of appropriate materials is likely to be one of the most serious and time-consuming efforts in fusion power development, and should receive recognized priority and attention. Research efforts should therefore focus in directions likely to satisfy heightened public safety and environmental concerns. In other words, the aim should be to concentrate materials research on materials deemed suitable on safety and environmental grounds. This does not seem to be taken fully into account in all the solutions envisaged at present. For instance, lithium 3-aluminate, currently considered a candidate material for ceramic breeders, yields beta- and gamma-emitting ^{26}Al with a half-life as long as 8.10^4 years. Another example is the case of a lead-lithium eutectic in the blanket, which would yield long-living isotopes of lead and polonium.

A 14 MeV neutron source of high intensity for materials testing must be made available soon, possibly even at world level, in order to carry out this materials research. It should be noted, in fact, that the outcome of such materials research is likely to determine the critical path for the DEMO reactor and beyond.

(iii) With regard to the third issue, that of radiation exposure of personnel during normal operations and maintenance, design choices are again determinant. The design must ensure that possible tritium contamination of air and water inside the plant as a result of leakages during routine operations, plus the high activation of main structural components in conjunction with greater demand for maintenance due to radiation-induced fatigue, will not lead to any higher occupational dose rates for personnel. Rates above those currently applicable in fission plants are unlikely to prove acceptable. Advances in robotics and remote maintenance technology, simplified reactor design to facilitate maintenance procedures, and careful selection of materials for key components to maximise endurance thus extending the time before replacement, could significantly lower dose rates. The importance of ensuring the safety of personnel will obviously be a prime design criterion. This is true both for the radiological dangers and for the other hazards that may be present in a fusion plant, deriving from the various vacuum, high pressure cooling, breeding and refuelling systems. Design solutions should be favoured which do not add significantly to operational complexity.

(iv) Decommissioning must be considered as an element in the design strategy of the Fusion Programme. Experience with fission demonstrates that decommissioning raises issues of public concern and cost which must be addressed from the outset. The Board believes that current differential treatment of wastes arising from the various forms of energy production should be rectified, with research undertaken to establish a comparative analysis of radiation levels and toxicities for all wastes generated by different energy sources. For instance, coal ash, which is known to be radioactive and indeed may be more radioactive after a hundred years than most waste from fusion, is currently not covered by radiological protection legislation. By far the greater portion of radioactive waste from fusion is in fact expected to be of short life and of low activity, though concern does arise as to the relative volumes which may be involved. Plant and component design choices, and materials development, will limit the quantities of higher activity wastes produced by fusion, which with appropriate management then should not constitute an insurmountable problem. In the case of JET, given the evolution of attitudes to the acceptability of the different forms of radioactive waste disposal, the Board recommends that decommissioning of potentially tritium-contaminated material should be regarded as part of the Programme, in order for the Community Fusion Programme to acquire experience in a key area of public concern.

(v) There is no indication that, provided sound engineering practices are adhered to, the release of noxious materials from a fusion plant will exceed standards currently in force. Problems may emerge with radioactive emissions, in particular with regard to airborne release of tritium. Safety standards for this will have to be established with a large margin of security, given tritium's reactivity within the biological chain. Continuing research will be needed. Much will depend on the development of tritium-handling technology. Working knowledge has still to be acquired about leakage rates from handling large quantities of tritium and about the tritium-retaining capacity of materials under severe stress from mechanical, thermal and radiation impact. Control of radioactive releases from a fusion reactor will certainly also be assured by a multi-barrier system with a leak-proof, substantially passive, containment building. Reduction of tritium inventories to a minimum must also be seen as a key objective.

(vi) Fusion shares with nuclear fission, if to a lesser extent, some of the problems linked to non-proliferation. The international safeguards system set up to control the flow of fissile material in states signatory to the Nuclear Non-Proliferation Treaty has now been operating with success for many years. Magnetic confinement fusion reactors as envisaged in the European Programme will not generate fissile material during normal operation. Given, however, that the neutron flux of a burning plasma could be used to generate fissile plutonium 239 or uranium 233 from inserted blanket modules composed of uranium 238 or thorium 232, respectively, fusion reactors will have to be subject to international safeguards. In fact, safeguards will be much more easily enforced in fusion, as unusual levels of radiation and the presence of actinides would provide obvious indication of infringement of non-proliferation agreements. Thus, unlike in fission reactors and particularly the associated fuel cycle, where safeguard procedures are inevitably complex and continuous, in fusion plants they could be relatively simple and conducted at long intervals, with no diminution of their credibility. Somewhat more difficult may be control over the relatively large amounts of tritium in a fusion energy system.

(vii) Current programmes must thus be checked as far as possible to ensure that they respect heightened safety and environmental awareness. This is true not only for the peculiar issues raised by fusion, but also for conventional environmental impacts - such as land use, demands on water resources and waste heat generation - which must comply with accepted standards.

Two final considerations remain. Firstly, one should bear in mind that nuclear fusion should be regarded as a nuclear technology, the development of which is facilitated by existing capabilities built up over time in the fission programme, such as a nuclear industry of high standard, radiological protection, licensing authorities and independent experts, as well as an international safeguards system. Nuclear fission technology is itself progressing toward the adoption of enhanced safety criteria based on passive and inherent safety concepts. A realistic scenario for fusion development sees the source replacing fission gradually almost a century after its invention. The introduction of fusion power in the absence of an existing nuclear infrastructure would be much more difficult.

Secondly, over the much longer term, fusion could be based on nuclear reactions that do not involve the use of tritium nor the generation of large amounts of neutrons. While it appears too ambitious at present to realize fusion reactors using fuels other than deuterium-tritium, alternative reactions (for instance, deuterium-deuterium or deuterium-^{3}helium) would not involve tritium breeding, nor generate as many high-energy neutrons as in the currently envisaged deuterium-tritium reaction. In principle, the evolution of fusion as an energy source in the centuries to come, as progress is acquired through the operation of first generation commercial fusion plants, might well lead to solutions that would inherently respond to safety and environmental concerns. This constitutes another motive for supporting fusion as one of the core elements in a long term energy strategy for Europe.

The greatly enhanced importance of safety and environmental issues gives rise to several key conclusions and recommendations.

(i) Demonstration of the safety and environmental feasibility of fusion power must be considered a primary objective of the Fusion Programme, to be pursued in parallel with the demonstration of scientific and technological feasibility. Adequate funding and priority must be devoted to this issue.

(ii) The Board recommends adoption as a safety target that the worst possible fusion accident will constitute no major hazard to populations outside the plant perimeter that might result in evacuation.

(iii) The Board recommends that environmental and safety criteria should govern the evolution of the European Fusion Programme and be monitored by an Environment and Safety Team. Among such criteria, it would list:

- greatest possible utilisation of low activation materials to avoid any need for geological timespan disposal, to reduce residual heat and to simplify maintenance;
- use of environmentally benign neutron multiplier materials;
- reduction of tritium inventories;
- development of materials specifically capable of resisting high neutron fluence so as to minimise component replacement, and hence both the volumes of radioactive wastes generated and the exposure of maintenance personnel;
- development of reliable remote maintenance techniques suitable to the complex geometry of fusion reactors.

In addition, long term development programmes in the fields of technology and system design must take into account environmental and safety prerequisites. In particular, the Board recommends that research efforts in materials or engineering be carried out only on suitable candidates of reactor relevance in terms of safety and environmental requirements.

(iv) The Board recommends the launching of a European reference design for a commercial fusion reactor. This design will require periodic updating as research progresses, in particular to incorporate safety and environmental protection features likely to ensure public acceptance and to take into account the requirements of utilities in operating such a reactor.

(v) Decommissioning must be seen in the future as an integral element in the strategy of the Fusion Programme, starting from the design phase. In the case of JET, given the evolution of attitudes to the acceptability of the different forms of radioactive waste disposal, the Board recommends that decommissioning of potentially tritium-contaminated material should be regarded as part of the Programme, in order for the Community Fusion Programme to acquire experience in a key area of public concern.

(vi) The Board recommends that adequate funds be allocated immediately to ongoing studies of issues of social acceptability in order that the evolution of opinion finds reflection in the orientation of research.

(vii) The problem of the need for a powerful source for high energy neutrons for materials testing should be addressed with the utmost urgency. Such a source should be made an integral part of the ITER programme. The Board understands that - as a first step - an international agreement for the adaptation and use of an existing American facility may be possible, and recommends active consideration of how best to investigate this option.

3.3 Main Directions for Magnetic Confinement in the 1990s in the Context of the Next Step Debate

As already noted, in principle many configurations are possible for the magnetic confinement of plasma required for fusion. Alternative solutions have been explored, both theoretically and experimentally, since the beginning of fusion research. At the end of the 1950s, Soviet researchers at the Kurchatov Institute demonstrated that by inducing the circulation of a strong current within the plasma, a stable configuration could be obtained. When these results were confirmed by a number of other laboratories, this, the "Tokamak", approach gained general acceptance.

There are many arguments in justification. The magnetic configuration in a Tokamak is relatively simple. The same current used to set up the configuration is used to provide ohmic heating of the plasma. The machine is axially symmetric and therefore somewhat easier to design and build than, for instance, a Stellarator. Concentration on the Tokamak concept is undoubtedly one of the reasons for the success of the European Fusion Programme and, in particular, of JET.

The advantages of the Tokamak approach are accompanied by a number of difficulties which have become more apparent with time, difficulties relating to both the physics and the technology often in interdependent ways. Moreover, the original Tokamak concept is intrinsically pulsed, because the current is generated with a transformer. Continuous operation would though seem preferable for commercial operation.

All considered, the advantages of the Tokamak approach still outweigh its disadvantages. Nevertheless the Board accepts that, for a balanced programme, it is a good idea to follow at least two alternative lines, the Stellarator and the Reversed Field Pinch, with a degree of attention. The Stellarator needs no inductive current drive and is intrinsically adapted to continuous operation. The Reversed Field Pinch, on the other hand, should allow for a higher ratio between power density and magnetic field and this configuration does not suffer the limitations of the Tokamak in terms of plasma current versus toroidal field.

It would neither be possible nor advisable to pursue more lines with the same level of commitment. For maximum cost-effectiveness and optimum resource use, effort has to be concentrated on one main line, together with a limited effort on one or two others, essentially as an insurance policy. The reason for this is straightforward. Unlike fission, where a self-sustaining neutron chain reaction can be demonstrated with a relatively small device working at essentially zero power, a self-sustained fusion reaction requires very large machines that are not much different in size and power from full scale commercial reactors in the one gigawatt range. Duplication of effort is unthinkable, and a choice is therefore inescapable. Considering not only the conceptual advantages, but more especially the experience already accumulated in the Tokamak line, there is no doubt that, for the European Programme, the Next Step device should be a Tokamak.

The European strategy for magnetic confinement fusion currently embraces two parallel exercises: a strictly European programme aiming at a commercial reactor by the mid-21st century, presently centred on the NET machine with a range of complementary efforts and some work on alternative lines undertaken by the Associations; and participation in wider international cooperation based on the quadripartite ITER accord for a Next Step device, with subsequent steps (DEMO and the commercial prototype reactor) then left to the individual national programmes. As an ITER agreement becomes more attainable, this two-pronged approach cannot be continued indefinitely.

It is clear that, for Europe, the minimum objective of the Next Step (be it ITER or NET) must be a machine able to reach ignition, and to maintain it for relatively long burn times, as well as able to explore and solve related plasma physics problems in reactor-relevant conditions. In addition, given the anticipated long operational life, the next device must at some stage explore some of the most critical technological problems of fusion. It is obvious, however, that not all technological problems will be tackled, let alone solved, on this machine. For instance, in view of the financial constraints and questions of timing and of availability of adequate scientific and technological data, it would seem unwise for the Next Step machine to be designed to test from the start a full hot breeding blanket at a temperature relevant for commercial generation of electricity.

The present specifications for ITER are more ambitious than those for NET. ITER aims to have a much longer operation time (in the original agreement, between 8,000 and 30,000 hours, compared to the 1,000 to 1,500 hours for NET). With a sizeable tritium requirement, and a conceptual design initiated at a time when international political uncertainties meant that the potential for evolution of the civilian market for tritium worldwide was still unclear, ITER has had to include a blanket for tritium recovery and recycling. As already noted, this blanket is not designed to operate at reactor-relevant temperatures, though some experience in tritium breeding and handling is anticipated. The device is also expected to undertake experiments on current drive. In both machines, some of the presently envisaged solutions (for instance, those for the first wall materials) might not be favoured candidates for a future commercial reactor.

The Board notes that, as in all on-going scientific and technological endeavours, a balance must be sought between timing and improvement. In other words, the problem in many specific areas will be whether to wait extra time so that a more suitable solution becomes available, or to go ahead and adopt whatever option is already to hand, postponing the testing of more advanced alternatives to the following machine. This would seem to be particularly critical in ITER, as compared to NET, given that it places a larger number of still unresolved problems in physics and technology on the critical path.

It is certainly not the task of this Report to give specific indications in such detailed and highly technical questions. Some opinions are, however, in order. It is the Board's view that, in the light of the high capital cost involved in the realization of the Next Step device, a sufficient margin of comfort must be allowed so that the results deriving from research activities over the extended life of JET, as well as in the collateral activities conducted by the Associations and in the fusion R&D programmes in America, Japan and the USSR, can be considered for incorporation in all phases of the engineering design, and even into the first two years of the construction phase. This latter was achieved with JET.

Should the choice fall on ITER, as we shall recommend, the implication is that the first period of activity of the design team should still be devoted to reviewing in depth the specifications of the machine. Two aspects must be borne in mind: the state of the art with regard to technologies specific to the machine, a cost-benefit analysis of the introduction of more advanced features still under development. Consideration of which improved technologies should be adopted by ITER from the start, which might be added later, and which might with benefit be postponed to the following machine, should also be taken into account, particularly with regard to deciding dates by which each of the main design specifications would be frozen.

We have to take into our calculations that ITER must fit with the differing strategies for fusion in the world, and not just with that developed in Europe. Being an international device, ITER will have access to a wider financial base and will draw upon the scientific and technological expertise accumulated in the global fusion community, as well as upon far greater industrial strength than that available to the European Programme alone.

At the moment, exploratory discussions are taking place with regard to quadripartite engineering design activities, but the partners are unable for institutional reasons to make any advance commitments to construction. The fact that no global R&D project has actually been brought to fruition in any major field of advanced technology suggests that Europe would be well advised to prepare itself for the eventuality that the end result of the ITER exercise will only be an advanced engineering design and that construction of the machine may never materialise.

Thus, in spite of its wholehearted commitment to ITER, Europe is still faced with the question of what to do, should the initiative fail to come to term. The European Programme must decide independently what it requires of the Next Step device and make its preferences known to the ITER partners. Besides a realistic assessment of the feasibility of design options, a major determinant in this decision must be awareness of the budgetary constraints under which the European Programme operates, both currently and for the foreseeable future. Europe's fall-back solution will inevitably have to be less costly than ITER. This does not mean, however, that it need not be a scientifically and technologically valid alternative.

Furthermore, it is especially important for the European Programme clearly to define minimal requirements for the Next Step. These may no longer reflect the full range of research options conceived for ITER, nor perhaps even for NET. For both financial and technical reasons, the Board would favour a machine the construction and operation of which could be phased to take maximum advantage of new advances while avoiding dissipation of resources. Such a machine might start out relatively spartan, but would possess from the outset the potential for extension and for upgrading with new systems, as progress in technology and other circumstances permit. A leaner machine able to take the European Programme past the next two milestones - ignition and long burn (with a total operational life of at least one thousand hours) under reactor relevant conditions - might satisfy the European Programme's needs, and still be within its financial means. Indeed, in the Board's view, budgetary constraints and the current state of progress in fusion science and technology together point to the wisdom of a machine that is conceived and designed to be as simple as possible, with complexities, non-critical diagnostics and supplementary systems postponed until such time that their essential nature and validity are better established, and possessing an in-built capability for an upgrade. The Board considers that this stepwise approach makes sound scientific and financial sense for both NET and ITER. European representatives in the ITER negotiations should clearly state Europe's preference for a gradually phased approach to construction and operation of the Next Step device. Should Europe eventually be compelled to go on alone, the Board is convinced that it would be our most valid way forward.

In the context of the vibrant debate on the Next Step inside the European fusion community, the Board received and examined with great interest a proposal by the Director of JET which considers a number of partially overlapping machines, rather than a single device, to divide up risks related to the physics and technological aspects of fusion. Granted the merits of this proposal in decreasing the consequences of risks associated with each component part (the concept of "conservative innovation"), and in allowing a more balanced distribution of effort among partners throughout the Programme, the Board nevertheless considers that the advantages of a more integral test of scientific and technological features of the reactor concept outweight the disadvantages.

The Board believes, for instance, that the Next Step device should be built with superconducting coils, even though this is likely to involve some additional technology development. It is essential that the Next Step machine incorporate a reasonable margin in terms of attainment of the basic objectives of ignition and long burn time. Of the two alternatives that would seem to offer this margin - firstly, a machine of a size currently envisaged in NET/ITER, using superconducting coils and, secondly, a correspondingly enlarged machine using copper magnets (at 13.5 Tesla) - the Board prefers the former. This preference is moreover in line with current design parameters for the ITER and NET devices.

The Board also believes that the arguments that led the ITER conceptual design team to incorporate a non-reactor relevant tritium breeding blanket in the device may now have less validity. In the new climate of international détente and disarmament, it has been postulated that the destruction of nuclear weapons stockpiles now planned will, over time, free sufficient tritium for peaceful use in a global fusion programme, taking into account that nuclear arsenals require a tritium production facility to replace the decayed portion of the tritium isotope. It might therefore be possible for an ITER device without a blanket to operate for a longer burn time than that already anticipated for NET by requiring participants to contribute the tritium needed for an operational lifetime of something in the order of 4,000 hours, or more. The Board is aware that any such proposal will need careful evaluation of the strategic and safety-related implications of the procurement, transfer and storage of the quantity of tritium involved. Nevertheless, it believes that, if feasible, this would represent a possible solution to a major technological problem for the world fusion programme.

While favouring elimination of the tritium-breeding blanket from the Next Step device, the Board nevertheless acknowledges the crucial nature of blanket research for fusion's eventual success. It is clear that considerable effort will be required to obtain adequate breeding ratios from multiplier materials that respect more binding environmental criteria. Current options all possess serious environmental drawbacks. This is another key area demanding long term research in materials.

In the context of the Next Step strategy, and of the future of fusion research, the Board also considered proposals for an intermediate device specifically designed to demonstrate ignition in non-reactor relevant conditions. While it accepts that proof of ignition might have a positive impact, it believes that this would be true only if ignition could be achieved quickly, cheaply and with sufficient margin for assured operation. In the Board's view, despite ingenious engineering solutions, current designs do not satisfy these criteria. It points to the American experience with CIT in support of its preoccupation. The Board listened with interest to presentations regarding IGNITOR. It believes that a machine with an improved design might have some utility in filling the gap in the study of plasma close to, or at, ignition conditions between the end of JET operations and the start of a Next Step device in the first decade of the next century. In the process, it might also smooth out the curve of utilisation of human resources in the fusion effort. But the Board feels that, given the current scarce possibilities of ignition, the projected short burn time and non-reactor relevant conditions for the burning plasma, together with the estimated high cost of the device, it must concur with the conclusions of the Ad-hoc Group for the Phase I examination of the proposal and thus is unable to support construction of IGNITOR as examined within the European Programme.

Despite perplexities concerning intermediate solutions, the Board does believe that there is much to be said in favour of a move away from a single ITER device toward an articulated ITER programme and recommends that this possibility be actively explored during negotiations. Although it may seem that broadening strategic horizons at this early stage could introduce further complications, the reverse is probably true. If one considers quadripartite cooperation as a new frame for a longer range programme of fusion activities, the problem of siting for the ITER device itself appears less sensitive. Costs and returns to each partner for fusion machines and experiments could in fact be better balanced over time.

There are of course other tasks that could be phased progressively in the ambit of international cooperation before a demonstration reactor which is currently viewed as being some thirty years away. As noted earlier in this Report, the first, and perhaps most urgent, is the high energy neutron source essential to an advanced materials development programme. Although itself much less expensive (a new source is estimated at something like one fifth of the cost of an ITER device), the associated materials programme is going to be large and critical for fusion power. The Board has been given to understand that an international agreement for the adaptation and use of an existing US facility may be possible and believes that this could be discussed in parallel with the negotiations on ITER.

Another possibility, although far less certain, would be the construction of a sizeable machine on a line alternative to the Tokamak concept. Should currently planned experiments on Stellarator machines yield sufficiently promising results, for example, this line might become an attractive contender for future commercial devices. At a certain stage, therefore, it might become advisable to build a larger machine, conceivably within the international programme of cooperation.

This Report has already noted that it would anyway be beneficial if the present collaboration and exchange of information on all fusion-related activities could gradually evolve into a coordinated international programme avoiding unnecessary duplication of work, though leaving room for healthy scientific competition at the world level. The experience accumulated by the European Associations in many years of profitable coordination could provide a good model for this kind of collaboration.

The Board engaged in considerable discussion with regard to the Next Step. It also received positive comments on the possibilities of successful international cooperation in ad-hoc meetings with the Soviet, American and Japanese representatives in ITER. Taking all these views into account, the Board's recommendation is that, recognizing the greater organisational complexity of any international collaboration, preference should be accorded to the ITER approach given the prospect of shared investment and access to world technology, ideally in the context of a broad quadripartite ITER programme for fusion research. The ITER enterprise would be an example of international cooperation on an unprecedented scale and this in itself is a significant objective. The clearly pre-competitive stage of fusion power at this time makes possible worldwide cooperation that could also include industry. Moreover, a wider international approach, if initiated earlier than demonstration of scientific feasibility, could generate a climate of cooperation favourable to a truly united world effort, unlike the experience of the fission programmes of the 1950s.

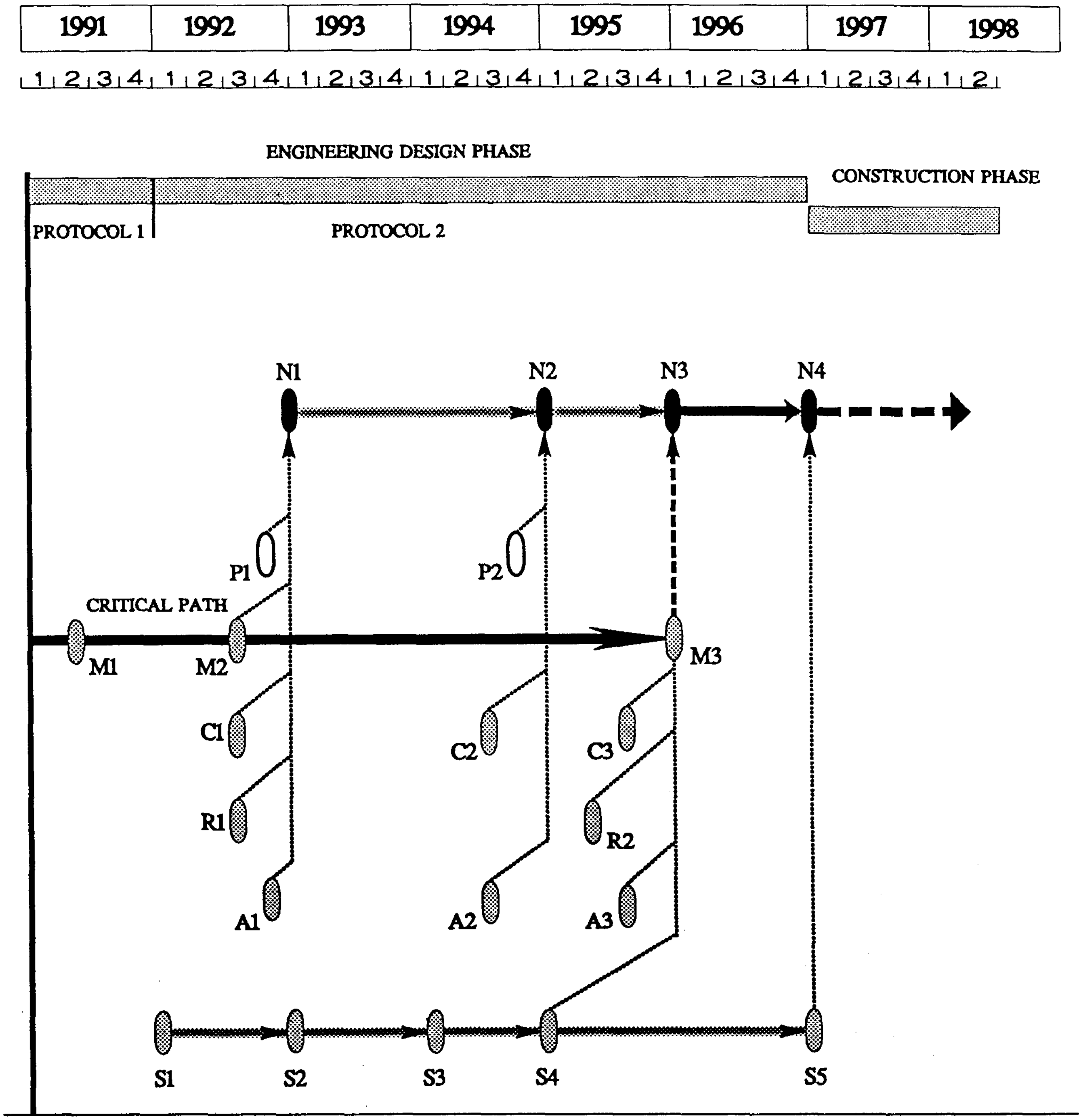
The Board also believes that, with ITER, not only could the high costs of the Next Step in fusion development be shared among four partners - Europe (plus Canada), Japan, the USA and the USSR - but that, if the inevitable organisational complexities inherent in the quadripartite accord can be kept to a minimum, the technical contribution of the whole world fusion community would facilitate achievement of the goals of a wide-ranging programme. Moreover, should one of the partners eventually decide to withdraw, there would still be the potential for the others to continue the project.

Figure 9 gives the European view on a possible Next Step time schedule. The moment seems favourable for a positive decision concerning the process design and the engineering of the ITER machine. The opportunity should not be lost. Difficulties of a non-technical nature must not, however, be underrated. The decision in principle to proceed with the ITER cooperative programme is only the first step. Outstanding problems remain.

Europe's current position of pre-eminence in large Tokamak machines, acquired especially in the JET Programme, means that in terms of know-how Europe may well be contributing significantly more to the project than its partners. To this should be added the long experience of international cooperation already acquired by the European Programme. The Board believes that these two arguments should enable Europe's role in ITER negotiations to be decisive, especially as regards siting issues and definition of the device's design parameters. Selection of a

Figure 9

THE EUROPEAN VIEW ON A POSSIBLE NEXT STEP TIME SCHEDULE



PROJECT MILESTONES

- N1 Outline design finalised
- N2 Design/Layout of the Tokamak device defined
- N3 Design/Layout of whole plant, and construction proposal submitted
- N4 Construction approved
- P1 Bulk plasma physics assessment made
- P2 Edge plasma physics assessment made
- M1 Conductor tested
- M2 Magnet winding and manufacturing tested
- M3 Model coil tested
- C1 Plasma facing component configuration defined
- C2 Plasma facing component options tested
- C3 Plasma facing component prototypes tested
- R1 Remote handling of plasma facing components defined
- R2 Remote handling of plasma facing components tested
- A1 Auxiliaries: options selected
- A2 Auxiliaries: design specification and layout defined
- A3 Auxiliaries: systems/processes tested
- S1 Site requirements defined
- S2 Proposals made for Site
- S3 Sites, environmental impact and licensing procedures assessed
- S4 Site selected and licensing application made
- S5 Formal construction license granted

candidate site will also permit European licensing authorities to prepare themselves for the project. Judging from past experience, all siting negotiations are likely to prove time-consuming. The Board recommends that, as a first step, every effort be made to host the ITER engineering design activities in Europe and that EURATOM formally present a European candidate site for EDA as soon as possible. Procedures should also begin to identify suitable sites for eventual construction of the device.

Cooperation is itself complicated, as each of the four partners understandably intends to use participation in ITER as a means to acquire for its domestic fusion programme and industry not only full knowledge of the science, but also as wide a mastery as possible of the relevant technologies. Problems could also arise from the different attitudes of the partners with regard to procedures for assigning contracts, industrial involvement, quality assurance, cost evaluation, pricing, etc.. The Board moreover feels that there will be need for substantial related preparatory R&D well into the first stages of construction to avoid leaving unresolved issues on the machine's critical path. To the Board's mind, this aspect of Next Step planning has been somewhat underestimated in the European Programme. Thus, for example, there will be a need for full maintainability using remote handling for a reactor operating with tritium, and development of this might require full scale mock-ups in order to ensure safe and reliable operation. The situation with regard to the coils, discussed elsewhere in this Report, represents another example. The Board therefore strongly urges ITER participants to reach rapid agreement on task- and cost-sharing for this research, fearing that otherwise current Next Step timetables may be difficult to maintain.

The Board also recognizes that the European Programme has a definite priority in more research into steady state, and perhaps also a high current device flanking JET to provide more essential input for the Next Step. The Board thus considers parallel contributions to the main effort of value, particularly should funding become more plentiful.

Overall, the Board perceives a need to set a formal benchmark for a basic decision on the future of the long term Fusion Programme. It believes that such a benchmark must be set before any decision is taken as to whether go forward to construction of a Next Step device - a decision which, from then on, will lead to a considerable boost in the level of funding in Europe. Evaluation will also be facilitated by:

- the results from the extended operation of JET;
- a more realistic assessment of the likelihood of success of an international ITER Agreement for construction of a Next Step device;
- initial fall out from increased efforts in R&D on fusion-related technologies, in particular with regard to all-important safety and environmental aspects.

The Board therefore recommends appointment of a further Evaluation Board to report to the Commission not later than 1995, that is before a firm decision has to be taken to commit the amount of funds needed for the construction of a Next Step device. Such a Board should undertake a rigorous independent assessment of the prospects of fusion in the light of available evidence of real progress achieved toward the Programme's ultimate goal. The Board wishes to advise the European fusion community that, while prospects and results may by then be so encouraging as to justify pressing ahead, either independently or in the ambit of a convincing international agreement, one possible outcome of such an evaluation would be to redirect the whole European Programme should the 1995 Report not favour immediately proceeding with construction of the Next Step device. Without prejudice to a possible increase in the fusion effort should conditions warrant, the Board wishes to make it clear that, in its view, the present scale of fusion spending cannot be considered an automatically assured expenditure floor unless there is clear evidence of progress toward the Programme's ultimate goal.

In the context of Europe's forthcoming choice between a European strategy for the Next Step, through NET, and confirmation of European participation in the ITER initiative, the Board makes the following recommendations.

(i) The Board recommends that, for Europe, the minimum objective of the Next Step (be it ITER or NET) must be a machine able to reach ignition, and to sustain it for long burn times, as well as able to explore and solve related plasma physics and plasma technology problems in reactor-relevant conditions.

(ii) Whilst recognizing the greater organisational complexity in any international collaboration, the Board recommends the quadripartite approach of ITER given the prospect of shared investment and access to world technology.

(iii) The Board supports the broadening of the ITER device to embrace an articulated ITER programme. In such a programme, the main functions in fusion reactor development would be shared among the partners in worldwide cooperation. Apart from the principal Next Step project, these should include a large high energy neutron source for materials testing and a major investigation into the potential of alternative lines. The establishment of such an ITER programme might also prepare the ground for an extended worldwide co-operation after the ITER project. The Board therefore recommends that this possibility be actively explored during negotiations.

(iv) Even accepting that any decision to go ahead with ITER construction cannot realistically be expected much before 1996-1997, the Board believes that quadripartite negotiations for successive phases after engineering design, together with complementary preparatory R&D activities and test programmes for components, should commence as soon as possible.

(v) The Board recommends that EURATOM formally present a European candidate site for ITER engineering design activities as soon as possible to the ITER partners and begin procedures to identify suitable sites for eventual construction of the device.

(vi) The Board recommends that moves be made towards a convergence of the NET and ITER designs in the belief that European preferences in concept and design, as represented by NET, are scientifically and technologically the sounder, as well as financially the more attractive.

(vii) The Board recommends a stepwise approach in realization of the ITER device, with later upgrading intrinsic to the design. The Board thus recommends that final agreement on the operating time of the machine should be reached after careful evaluation of the option of generating tritium with a breeding blanket, as compared to the option of external procurement, which the Board would prefer if feasible. Non-inductive current drive should be regarded as an important objective of the research programme of the machine, but be postponed to a subsequent stage of operation.

(iix) While recommending a full commitment to the ITER initiative, the Board is convinced that, at this stage, Europe should retain a fall-back capability in case ITER cooperation beyond the design phase proves impossible. The Board envisages this fall-back solution as a staged version of a final converged Next Step, conceived so as to be able to be built using the resources available in the European Programme alone.

3.4 Non-Magnetic Confinement Approaches to Fusion

3.4.1 Inertial Confinement Fusion

The only alternative approach to magnetically confined fusion could, in the long run, be offered by inertial confinement fusion (ICF).

The basic principle of ICF is to compress a small droplet of deuterium-tritium fuel to very high density (1000 to 10,000 times the liquid density) and to induce at the centre (by ablation at the surface) a temperature sufficiently high to ignite fusion. Provided the nuclear combustion occurs in a time shorter than the hydrodynamic explosion, sufficient energy might be produced to give an overall positive energy balance. For this purpose, small pellets of D-T are irradiated by high energy lasers or particle beams. This leads to fast evaporation of the outer layers, resulting in an inward compression wave.

In theory, ICF offers several advantages. It uses no magnetic field coils, simple geometry for the reactor vessel and separation of driver and reactor vessel. These advantages must be set against a number of drawbacks. First, a high performance driver is needed (of extremely good beam quality, high efficiency and high repetition rate). Second, complex target technology has to be mastered while, third, an elaborate system is required to protect the reaction chamber from the explosions. For this, liquid metal curtains are being considered. Such curtains might, however, lead to high radiation levels. In addition, conceptual design studies have shown that an ICF device will essentially not be smaller than a magnetic confinement reactor (radius about 10m), and the complex and extended driver system then adds to the overall dimensions. High capital investment, one of the drawbacks of fusion with magnetic confinement, will also be needed for ICF.

Two approaches are currently being studied worldwide:

(i) direct drive, in which interaction between the drive beam and the fuel is used for the compression;

(ii) indirect drive, in which the primary beam is converted in an outer shell of the pellet into X-rays, which then produce the compression.

Powerful laser pulses or pulses of charged particles, either light or heavy ions, can be used as the driving beam. Some progress has been achieved over recent years, but scientists are still far from breakeven or ignition.

Vigorous programmes on laser driven ICF are conducted in both the United States and Japan. A weaker effort is carried out in the USSR. The world's largest installations are the NOVA laser facility at Livermore (USA) and the GEKKO facility in Osaka (Japan). The US effort in ICF is currently about half the size of the programme in magnetically confined fusion, but ICF activities are very closely related to weapons development. Construction of a Laboratory Microfusion Facility (LMF) is under consideration in the US, but a decision is unlikely to be taken before 1994. A number of medium and smaller laser facilities are in operation in various countries in Europe, for example, PHOEBUS at Limeil, France, VULCAN at Chilton, UK, ASTERIX V at Garching, Germany, and ABC at the ENEA laboratories at Frascati, Italy.

Some important milestones have been achieved with laser facilities in recent years as far as compression or neutron production are concerned. Experiments with proton drive beams (mainly carried out in the US and Japan) have made significant advances, but development has been slower than expected. As a result, the gap between light ion and laser-beam experiments has widened and, at present, this kind of driver does not seem very promising.

Heavy ions as driving beams are of greater interest. Heavy ions have a short stopping range and hence the interaction between beam and target is more efficient. Heavy ion accelerators might achieve relatively high efficiencies - about 25%. Heavy ion driver research is still at a relatively early stage. There is some work at Berkeley in the USA, at Moscow and at GSI, Darmstadt in Germany. At the latter institution, a new accelerator-storage ring facility has recently come into operation. The world ICF community believes that this will provide excellent opportunities to study the outstanding problems.

Major problems still requiring intensive research effort include:

(i) driver requirements

In order to achieve the necessary energy densities, driver pulses must be very powerful and short. Pulse energy must be in the range 2 to 10 MJ with a pulse length of 10 to 20 ns. These pulses must be produced with repetition rates of the order of 10 Hz. To obtain an overall energy gain, the product of target gain and driver efficiency (ratio of energy output to input) must be sufficiently high and efficiencies higher than about 10% for lasers and about 25% for particle accelerators seem to be the minimum. Lasers, and also particle accelerators, have not approached such high efficiencies, though future developments might be promising. Some of the best results achieved so far are:

(a) for Nd-glass lasers, NOVA 125 kJ/1ns 10 beams and GEKKO XII 25 kJ/1ns 12 beams with efficiencies of less than 1% and repetition rates of about 1/2 hour;

(b)for Kr-gas lasers, AURORA 5 kJ/5 ns, efficiency of a few percentage points, light ion beam drivers (pulsed diodes), PBFA II (Sandia) 2 MJ/ 20 ns, reasonable efficiencies but there are problems with beam focusing and transport energy spread and repetition rate, heavy ion drivers (induction Linacs or RF Linacs with storage ring) and GSI 500 J/50 ns Iodine (I^{+20}, 300 MeV/amu).

As these figures indicate, there is still a long way to go before a realistic reactor design can be considered.

(ii) target problems

The Lawson criterion can be written for ICF in the form ρ R > 3g/cm^2, where ρ is the density and R the radius of the compressed pellet at ignition. Since R will be small, very high densities (more than 1000 times the liquid density), must be obtained. In addition, an ignition temperature for the ions of more than 5 keV has to be achieved.

In order to avoid instabilities of the imploding target, illumination with an extreme spherical symmetry is necessary. At present, this seems feasible only with indirectly driven targets. Encouraging results have, apparently, been obtained at Livermore, but information is very scarce because of classification problems. Moreover, the high-Z outer shell of pellets for indirect drive may lead to high radioactive levels, an issue which seems not to have been studied in detail as yet.

Very little is known about target gains (fusion energy output to drive-beam output). Gains of about 100 and more are needed. Model computations show that such gains might be obtained if driver pulses with the required properties can be produced. So far, the best results were obtained by GEKKO, with ρ.R = 0.2 g/cm^2 but at the very low temperature of 0.4 keV. Interesting results have also been obtained at NOVA at somewhat higher temperatures.

In conclusion, comparing achieved results with the values needed for breakeven, or even ignition, it is clear that considerable progress is required before an ICF device can be realized. Many parameters have to be improved by at least one order of magnitude. Heavy ion drivers currently seem to be the most promising line, in particular should new ideas to overcome particle dilution in phase space at injection be brought to fruition. Efficient international collaboration in ICF is, however, seriously impaired by the close relationship to weapons development, and many results remain classified. There are complex issues involved. Still, in view of the rapidly changing global political situation, a new, more open, policy facilitating international cooperation and the exchange of information in the ICF field might emerge for the first time.

Taking into account the information currently available to it, the Board cannot recommend additional allocation of resources over the current low level from the Community Fusion Programme to support ICF research. At this stage, this line of development is not seen in Europe as competitive with magnetic confinement fusion. The ongoing exploratory research programmes should continue to be financed essentially from national resources. The Board believes that, together with results reported from other programmes elsewhere in the world, these will provide adequate information to judge whether ICF has a real future for commercial power application. Progress should be monitored however and, in the event of any breakthrough, the Community's watching brief should be reviewed.

3.4.2 Cold Fusion

In March 1989, claims were published that some kind of nuclear fusion had been obtained in cathodes of palladium (or other transition metals) during electrolysis of heavy water. Neutron emission was then observed in experiments involving an interaction between deuterium gas and titanium. Since these results seemed to hold out hopes for a novel and cheap way for energy production, the announcements aroused considerable interest. Subsequently, some laboratories indeed claimed to be able to reproduce the original results. In the meantime, however, more rigorous experiments have been carried out. As no evidence has yet emerged that nuclear fusion actually takes place in so-called cold fusion experiments, and accepting that some hitherto unknown complex effects may have been found, the Board is of the opinion that this research is of purely scientific interest. There is no indication that it will provide a possible source for energy and the Board therefore recommends that, should Community support be granted for basic research, this should be found from sources other than the Fusion Programme budget.

There has been some research on muon-catalysed fusion for many years. Here a muon provides the binding in the deuterium-tritium molecule. Because of its large mass, the distance between the deuterium and tritium is sufficiently reduced so that fusion can take place at low temperatures. The fusion process occurs in a fraction of a time that is very short even when compared to the muon lifetime of 2 microseconds. Thus, one muon could catalyse many fusion processes. The process is, however, limited by the rate of formation of the molecular system and by the fraction of muons sticking to the alpha particle produced in the fusion reaction. Experiments have shown that up to 150 fusions per muon are possible. For a realistic energy source, several thousand fusions per muon would be required. Emphasis has recently been placed on measuring the sticking factor and the values obtained indicate that the fusion yield may be limited to less than 250 per muon. The current work now going on in the United States, Japan and certain European countries (for example at the Rutherford Appleton Laboratory in the United Kingdom, and at the Paul Scherrer Institute in Switzerland) should be followed closely. In the event of any unexpected breakthrough, a new review of the energy potential should be undertaken.

3.5 The Balance between Physics and Technology

It is undeniable that European research into magnetic confinement fusion has developed essentially as a plasma physics programme. From the outset, the existence of difficult technological problems was fully recognized, but it was decided, and in the view of the Board rightly so, that key questions in physics - confinement and plasma heating - be accorded over-riding priority and that technological problems, no matter how important, must take second place. However understandable in the past, this approach has generated some inconvenience. Recently, there has been some shift in emphasis. This is linked to the start of NET activities. In fact, in line with a recommendation contained in the second Beckurts Report, technology development is primarily targeted on satisfying the requirements of NET itself. Those in charge of the Programme were always well aware of the need to solve more long term technological problems, in particular in materials; the importance of finding such solutions in terms of the environmental and economic aspects of fusion was also perceived. So far, however, in part as a result of limited financial resources, it has not proven possible to undertake sufficient work in this direction. An attempt was made to develop a 14 MeV neutron source in association with the United States fusion programme, but without success.

Despite these handicaps and a perhaps different view of priorities, the portion of total funds dedicated in the Programme to technology (excluding JET) increased in the 1980s from around 10% to 22%. This covers areas such as magnets, blanket, robotics, materials, etc.. Other spending in technology has also occurred under the physics budget, for example in the construction of the superconducting coils and the smaller fusion devices and in building large systems for plasma heating. The Board is nevertheless of the opinion that this effort remains inadequate and that considerably more attention and resources must be devoted to technological aspects, especially where these aim ultimately at ensuring the economic, and above all the environmental, attractiveness of fusion as a commercial power source.

It has to be said that many of the issues relating to technology that were identified earlier in the Programme retain their importance and are still largely open. They are essentially of two kinds. Some, for example those relating to superconducting magnets and robotics, are of wider interest than for just the fusion effort and might be expected to derive benefit from advances achieved in more generic research programmes in technology. Additionally, industrial involvement could also be stimulated as spin-offs emerge. Others, and this is particularly the case of problems linked with the production, handling and containment of tritium and the need for special neutron-resistant materials, are more specific to fusion and thus fall squarely on the Programme itself. These latter also have direct relevance to the environmental acceptability of a future fusion reactor, and on the economics of fusion power. It is the Board's belief that there must not only be a sizeable quantitative increase in funding for technology, but also a change of attitude translating into stronger management of the technology programme.

With regard to the specific question of materials, without a major boost in effort, it will be impossible to foresee the options available for the future construction of a DEMO reactor. The Board is convinced that it is not too early to start tackling issues which are notoriously difficult and likely to require long R&D lead times. As noted elsewhere in this Report, access to a high energy neutron source of sufficient size can no longer be deferred and we reiterate our belief that this device should preferably be constructed in the context of a wider international research agreement.

In addition, as recommended in Chapter 5, the European Programme must assign a bigger, more incisive, role to industry in developing technology for fusion. The latter must no longer be viewed as a mere supplier of components, designed and ordered by the Programme itself. It must be encouraged to participate as a major player in all stages of the design process, as already occurs in other fusion programmes, most markedly in Japan.

The Board notes that the European Fusion Programme will have access to two full scale tritium laboratories, in addition to the JET tritium plant which could remain available even after termination of the proposed JET tritium experiment in 1996 and subsequent decommissioning of the device. Despite the importance to be attached to adequate research in tritium technologies and techniques, and some potential for differentiated research programmes, duplication might point to the need for better coordination, given the many other areas of research still to be tackled.

The Board heard a wide range of opinions concerning the materials for the magnetic coils of the Next Step device, from copper to the superconducting materials, niobium-titanium and niobium-tin. Differences of this kind are inevitable in any advanced technology, but given the vital importance of correct functioning of the coils for the success of the Next Step, and the impact the choice of the material will have on design parameters, a way of resolving the technical arguments must be found as soon as possible. The role and responsibility of the future project director in making certain design choices has to be acknowledged, but one of the first tasks of the management body of the Next Step machine must be to arrive at a technological assessment of the coil options, the capacity and willingness of European industry to commit itself to their construction, the impact on the design in terms of timing and cost, acceptable to the main parties, so as to eliminate a worrying source of disagreement at the technical level.

The very tight schedule upon which NET planning is based raises some disquiet. Even granted the margin of one year built into the schedule, the interlocking and phased demands placed upon science, and especially upon technology, in the run up to the proposed construction date and the fact that a number of imponderables are on the critical path mean that it is difficult to be sure that the timetable can be respected. The lack of back-up solutions to be developed in parallel with the reference choices, for adoption before the construction phase should the latter show themselves infeasible, is a definite weakness.

It is clear, therefore, that the technology programme should be granted a higher priority, together with greater access to both human and financial resources. The valuable work being undertaken in Associations should be further encouraged, with the new emphasis on only financing those solutions identified as environmentally and economically suitable for a commercial reactor programme made explicit. It is possible that the pattern of management in Brussels so far adopted by the Fusion Directorate with regard to technology will have to be reviewed, with the aim of obtaining better organisation of the programme, establishing priorities and orchestrating what is an essential long-term research endeavour.

3.6 The Continuing Role of the Associations.

The link between EURATOM and the Associations provides the European Fusion Programme with its unique and highly positive character as a truly pan-European effort. The Associations have played their part in enabling the European Fusion Programme to assume a vanguard position in this area of research, and more particularly in the physics of fusion. In addition, the Associations have contributed directly to the JET project through the secondment of staff, the development of new heating and diagnostic systems and by carrying out specific investigations at the request of the JET Team. The scientific and technical results obtained by the Associations on smaller devices are recognized as having made an essential contribution to the success of JET.

Of the 1,700-1,800 professional scientists and engineers in the European Fusion Programme, about three quarters are in the Associations. The Associations have been determinant in creating links between all the actors in the European Programme: the other Associations, Brussels, JET, NET, Europe's universities and industry. The Board recommends that these links, especially those with the rest of Europe's scientific community, be further strengthened. The Associations play a significant role in attracting and training young scientists and engineers via liaison with the universities, providing the link between university training and research and large scale international projects, like NET or ITER. Collaboration between Association laboratories and national industries and non-fusion research institutes will become of increasing importance in the future.

In the context of an eventual ITER programme, the role of the European Associations and of their counterparts in the programmes of the other ITER partners would largely be to develop and expand the scientific and technological data base necessary for the successful design and implementation of the major devices. The scientific, managerial and financial expertise acquired by the Associations in long term international scientific collaboration is likely to prove of real benefit for ITER. It represents unique European know-how vis-à-vis the other ITER partners, offering a pattern for resolution of any potential differences that may arise from future task-sharing or resource allocation in the ambit of quadripartite agreement.

Throughout the early 1990s, results from both JET and the Associations will influence the design of the Next Step. As stated elsewhere in this Report, the Board believes that flexibility in design of the Next Step device must be retained as long as possible so as to maximise the transfer of advances achieved in the Association laboratories, JET and other efforts, worldwide. By analogy with experience acquired during the planning and design phases of JET, information gained from the operation of smaller devices can be taken into account in the design of ITER or NET after the start of the detailed engineering phase, even though the basic configuration cannot be changed. It should still, however, be possible to influence important elements, such as the choice of heating, at this stage.

The Board considers that the critical issues referred to earlier in the Report, should continue to be addressed in the early 1990s. These include:

- understanding confinement;
- current drive;
- disruption avoidance;
- power and particle exhaust physics.

With regard to tasks assigned to the Associations in the research programme covering alternative lines, Stellarator research at Garching will continue to use the Wendelstein VII-AS, which has already yielded important results. As noted, a more advanced Stellarator, the Wendelstein VII-X, is now under active study. Contributions to Stellarator research are also anticipated from the TJ-II machine, under construction in Madrid. With regard to Reversed Field Pinch, European activity will centre on the RFX, due to enter operation in Padua at the end of 1991. This device is expected to make an important contribution to RFP research by virtue of its high current (2MA). Additional work on a hybrid Stellarator-RFP, will be carried out using the Swedish Association's EXTRAP-T2 device.

In the Board's review of activities carried out in the Associations, some overlapping of research objectives and duplication of facilities has been noted. A certain amount of duplication of effort may be regarded as an inevitable corollary of stimulating national efforts in fusion. It can indeed be positive, provided kept within reason. In view of the increased cost of the Fusion Programme as it moves towards the Next Step, the Board would prefer that overlaps and duplications now be kept to the minimum. Collaboration between the Associations, actively encouraged by the Commission, have proved to be extremely useful and should be further extended.

The Board believes that the work of the Associations represents a major success for the European Fusion Programme. It may also be regarded as a good investment, considering the level of contribution from the Community's budget to the cost of the Associations' activities (25% for general expenditure, 45% for fixed investment). The Board believes, however, that the balance between the activities of the Associations will need to change in the context of decisions relating to the Next Step. The current ratio of Community funds to the direct contributions of member states through the Associations may equally require some adjustment in order to ensure greater potential for strategic planning from the centre.

Design and construction of the Next Step machine will require substantially larger teams than that required for JET. In addition, supporting scientific and technological tasks will undoubtedly be on a larger scale. The Board anticipates that the consequent increased demands made by the central project on the Associations will mean, over time, a probable reduction in the number and variety of nationally-based large and medium size fusion devices. The Associations' capacity for exploration of confinement-concept improvement, for the development of diagnostics, heating systems, etc. and their role in training will remain important. Existing Tokamaks and Tokamaks about to come into operation should be fully exploited to address critical issues associated with the main line. But in the

Board's view, any proposed new devices should be subjected to in-depth examination similar in scale and scope to that undergone by IGNITOR in 1989/1990.

For the Fusion Programme to take maximum advantage of the Associations and of their contacts with universities, research institutes and industry, it must encourage increasing concentration on the long term technology objectives of the Programme. As noted elsewhere in the Report, the present fusion technology programme operates primarily on the basis of a variety of small short term tasks. The structure is adequate for addressing short term needs as represented by the NET and ITER team requirements. The European technology effort can, however, conceptually be divided into two parts: specific technology targeted for the Next Step and broader long term and generic technologies relevant for fusion. The Board believes that this distinction should be allowed for in the future planning of resources. The present structure is inappropriate for the equally essential long term developments in areas such as materials, safety and environmental issues and the operating requirements of the utilities. These concerns must be addressed in a project-oriented fashion which will encourage participation by the most imaginative scientists and engineers. Strong leadership will be required to ensure an enhanced and focused effort on these long term technology questions. In order to overcome this situation, the Board recommends the establishment of a Long Term Technology Team, with the responsibility of drawing up and directing a planned programme of activity involving the Associations in a coordinated way. The higher profile thus provided to long term technology issues within the overall Fusion Programme should accelerate progress in these areas. The Board also suggests that in the materials area the Associations further increase their collaboration with non-fusion materials laboratories. The long term development of suitable materials will require a broader range of multidisciplinary skills, which may well extend the Associations' current capabilities.

While therefore recognizing that the Associations have been the backbone of the European Programme and the reservoir of skills, the Board believes that, as the next phase of the Programme is likely to develop in the direction of greater internationalisation and new demands will be placed upon it, the relationship between the Associations and Brussels will need to be reviewed. While the Board agrees that the present arrangements can be left essentially intact for the next five years, it recommends that the mandate of the Evaluation Board proposed in Recommendation 36 should include assessment of the role of the Associations. To expedite this, it recommends that the Associations be called upon to present their views on the relationship between themselves and the central effort directed from Brussels to that Evaluation Board, and that the Fusion Directorate commission a detailed report analysing the Associations' contribution in terms of expertise, staff and financial resources, as well as related management and coordination issues, for submission to the new board.

CHAPTER FOUR

INTERRELATED ISSUES OF MANPOWER, MANAGEMENT AND FINANCE

4.1 Manpower and Personnel

The Fusion Review Panel of 1981 drew attention to the fact that the average age of staff working in fusion was about 45, with the age distribution particularly concentrated around this average. Today, the outlook has much improved. The average has fallen to about 42 years and the age distribution now has two peaks, in the early 30s age group and a second, smaller, peak around 50, with about 15% close to sixty and retirement. The population of those working in fusion is no longer steadily ageing and there is an encouraging regular influx of young scientists and engineers. Accumulated experience and expertise is thus no longer in danger of being dissipated through natural wastage and the reluctance of gifted young scientists to choose a career in fusion.

An estimate can be made of future manpower requirements, though clearly these critically depend on Next Step choices. One first assumption would be that, unless construction of new machines is launched, the number of professionals employed in the Associations is likely to remain constant, or even to decline. The management of the Fusion Programme may need to be enhanced, should the present Report's recommendations be accepted.

A decision to go ahead with NET would require the current NET Team of 70 professionals to be increased during detailed design to about 200: 150 of these on site, the rest in the Associations and industry. During construction, perhaps 300 professionals would be required on site. JET could provide some of these additional staff, more especially during the construction phase. The remainder will have to be sought in the Associations and in industry.

With ITER, on-site staff requirements during the engineering design activities (EDA) are likely to be greater, perhaps in the order of 180 professionals. The European personnel could be taken in the main from the NET Team. An additional 130 from the Associations and industry would work off-site. Calculations of manpower needs for the ITER construction phase are so site- and design-dependent that the Board does not feel able to commit itself to any numbers. Certainly, one advantage of international cooperation derives from the contribution in skill and expertise from the other partners and this might mean a reduction in the size of the European contingent.

The Board feels that any overlapping of individual responsibilities between NET and ITER should be avoided, especially after the first two years of EDA. Political and, indeed, psychological arguments militate in favour of maintaining the two teams distinct, though this may create some tension as effort is progressively concentrated on just one option.

The experience of JET suggests that, for either ITER or NET, salary levels be harmonised from the outset, with due allowance made for expatriate employment. In order to ensure access to the best skills, the salary and pensions position of engineers brought in from industry may call for special treatment. Within these limits, the Board believes that the project director should be accorded full responsibility for staff policy.

The position of the JET Team remains problematic. Should JET operations be extended into 1996, as recommended, then many members of the Team will remain employed at Culham well into the phase of Next Step EDA. The Board does not foresee actual construction of a Next Step device before end-1997 at the earliest, and thus even those members of the JET Team moving over to the Next Step will face a gap in their employment. Moreover, it cannot be anticipated that the totality of the JET Team will be taken on by either ITER or NET, and some shedding of specialized staff is therefore seen as inevitable. While the break-up of a valuable team is unfortunate, this issue should be kept in perspective in the context of a multi-million ECU programme stretching over decades.

4.2 Management

So far, the European Fusion Programme has had the character of a research activity, even if one with a very clearly defined scope. The management structure, with direction of the Fusion Programme from DG XII in Brussels, has proven adequate and efficient. There have been many real achievements, even if, as noted elsewhere in this Report, some structural weaknesses can be discerned, most obviously in the area of technology.

With the advent of the Next Step, be it either NET or ITER, a change in the character of the Community's fusion effort is clearly due, as it will develop in directions far outside the scope and dimensions normally associated with a scientific research programme. The Board therefore considers that the time may be approaching when the Commission should start to reflect on the opportuneness of introducing modifications in the organisational structure and management methods of the Fusion Programme, in order to achieve a more focused management that will enable Europe to prepare itself for new frontiers of endeavour. In the Board's view, major tasks will have to be tackled in the near future and these suggest the wisdom of changes sooner rather than later. The Board thus recommends that the Commission begin a consultative process involving the competent bodies in the member states, as well as the Associations and other interested parties, to consider ways forward.

In the light of this recommendation, it is clear to the Board, for instance, that, if the Programme continues as planned, the body in Brussels entrusted by the Commission with responsibility for the next, even more challenging, stage of the Fusion Programme must be endowed with adequate status, independence, technical capacity and continuity to ensure success. Flexibility in manpower management will be essential, as will authority to negotiate and coordinate industrial, Association and mixed industry-Association consortia. The Fusion Programme management must also have access over time to sufficient funding to affront its tasks, both on the European and, quite possibly, on the global level. We must bear in mind, in addition, that should the first choice for the Next Step fall upon ITER, as the Board recommends, then the organisational implications for the Commission will be considerable. Given that much about ITER has still to be defined and decisions will not be taken in a purely European context, but be the object of negotiation among the four partners, it is not easy to make a detailed assessment of management needs. Nevertheless, the Board thinks it may be wise to consider in due course establishment of a specific new body to focus fusion management in a strategic frame as provided for in the EURATOM Treaty.

It does not fall to this Board to suggest where such a body might best be placed in the Commission's organisational chart, though we note that direction of the Joint Research Centre is within the brief of DG XII. We are, however, able to sketch some of its responsibilities:

(i) a project-oriented approach to development of a commercial fusion reactor, taking into full consideration the technological, economic, environmental and safety implications of the research effort;

(ii) management of JET up until termination, following closely highly successful established practices, together with eventual participation in the decommissioning of potentially tritium-contaminated material, should the extension and introduction of tritium be agreed;

(iii) management and coordination of the physics programme conducted in the Associations and Community laboratories;

(iv) organisation, management and coordination of a new, radically expanded, technology programme;

(v) establishment of closer, more organic, links with European industry in order to increase the latter's direct involvement in the Fusion Programme;

(vi) interaction between the Fusion Programme and other research activities funded by the Community or in which the Community participates;

(vii) acting as the European partner and international point of reference for the Next Step, on the supposition that this is ITER, for managerial, scientific and technical matters;

(iix) management of the greater financial resources required for an anticipated expanded effort in fusion as the Next Step progresses toward the construction phase.

As already stated, the transition between the current tried and tested structure and that hypothesised here is not necessarily urgent. Still, in view of the complexity of any institutional change within the Community, the Board recommends that the Commission start to consider a different, more distinct, framework in which to conduct the new phase of fusion research which will open with the Next Step. There are also problems which, in our view, could best be tackled in a new structure. These relate above all to the extension of JET with use of tritium, a Commission role in the subsequent decommissioning of the device, and issues arising from the second phase of ITER.

4.2.1 Organisational and Management Issues and ITER

The extent of responsibilities under point (vii), above, would vary considerably according to whether ITER progresses in the way currently envisaged, as an equal quadripartite collaboration for construction of a single ITER device, or whether it evolves as the Board hopes into an ITER programme, comprising several complementary devices constructed in the four cooperating regions in close sequence, and thus partially overlapping in time, as outlined in Section 3.3. of this Report.

In the first case, that of the ITER device, the management structure of ITER will presumably consist of a Board of Directors, assisted by committees and, in the beginning, project groups, then construction groups as work progresses. In this case, the excellent results of JET, and the satisfactory manner in which it has been managed, might be taken as a guide for an eventual ITER structure, though the Board accepts that initially this may prove less readily acceptable to the other three ITER partners than it was to those in EURATOM. In the ITER device solution, a European body managing fusion would:

- provide the European representatives in the central councils of ITER;
- propose the European candidates for the team;
- provide the European members of the team, and cover part of their remuneration;
- furnish the European quota of funding;
- act as the host organisation, should the device be built in Europe;
- provide house support to ITER in the design and construction phases;
- coordinate and encourage the participation of European industry.

In the second case, that of an ITER programme, one of the devices, hopefully the most important, would be built in Europe, others elsewhere. For each machine, there would presumably be a system granting a majority shareholding to the host partner, with prime responsibility also in direction and management. The other three partners would then contribute an amount agreed in negotiation. The ITER programme would be governed by a central Council, invested with complete responsibility for ensuring active participation by all the partners and sharing of results.

More specifically, with regard to a machine sited in Europe, mutatis-mutandis, a similar structure to JET (a joint undertaking under the EURATOM Treaty) might be envisaged.

4.2.2 Organisational and Management Issues and NET

The timing set out in the "Notes on NET Planning", received by the Board and dated April 4th 1990, reassumes the three phase strategy. Realistically, this comprises:

- Next Step: the construction phase of which could start perhaps in late 1997 and is estimated to last eight years;

- Demonstration Reactor: construction could start sometime around 2015 and last about eight years;
- Prototype Commercial Reactor: construction could be launched before the mid century, followed by an undefined period of commercial operation in association with utilities.

Under such a strategy, fusion power stations could be expected to make a gradually increasing contribution to European electricity supply as penetration into the energy system increases, but this will not be sizeable until the second half of the next century.

For its Conceptual Design Activity (CDA), NET has been organised as a joint project between the Commission and the Associations. NET is thus not a legal entity. Its existence rests upon a contract (the so-called NET Agreement) between the Commission and the Associates, the effectiveness of which relies largely on the goodwill of the Associations in providing the necessary support. The NET Team is relatively small (70 professionals) and has no permanent staff, staff being either temporarily assigned from the Associations or hired on limited term contracts from industry. Contracts in the frame of the NET Agreement are placed by the Commission. Supervision is ensured by the Fusion Technology Steering Committee, a sub-committee of the CCFP.

As already noted above, with construction, inevitable changes will take place in the programme organisation and management. NET will presumably have to become a legal entity. This could take the form, for example, of a joint undertaking, following the generally positive experience of JET. Under a supervisory body, the NET Director would then be able to manage his own budget and directly place contracts to industry and to the Associations. The Board believes that during both construction and operation NET would need a strong centralized management and its own staff. Yet it should also, like JET, remain fully integrated in the European Fusion Programme and maintain links with the Associations.

Between conceptual design and construction, a six to eight year period of EDA is foreseen. During this phase, the NET organisation could develop in several ways, as EDA progresses. Three distinct phases, each lasting two to two and a half years are anticipated. In the first phase of EDA, during which the objectives of NET and its conceptual design will be assessed and gradually frozen, CDA structures could continue. This might be particularly appropriate if, as the Board believes possible, the definitive NET/ITER choice was still unresolved. By the third phase of EDA, with its emphasis on site-specific work, prototype development and the application for a construction licence, however, both the legal basis of the project and its permanent management structures will have to have been established. Transition to a formal structure should take place sometime during the intermediate phase of EDA (i.e. once the Engineering Design proper is under way).

The Board believes that, in the event of proceeding with NET, management and advisory structures of the Fusion Programme, based on the Fusion Programme Directorate in Brussels, the CCFP, the FTSC, the Association Steering Committees and the JET Council, would require some modification, if not necessarily fundamental change. Substantial strengthening of overall management and co-ordination of the various aspects of the Programme, of the contributions required of the Associations and specifically of technology development will, without doubt, become necessary. It is here that the Board proposes that the Council of Ministers might wish to evaluate assigning these greater responsibilities to an eventual new body for fusion management, at some stage after 1995 as the Next Step moves toward construction. Specifically for NET technology, the NET Team must become more responsible for definition of tasks, for monitoring work performed in the Associations and for any redirection of Association activities to avoid duplication and any delays.

Though NET is to be seen primarily as a European solution, the Board is convinced that international collaboration should continue, using bilateral and multilateral agreements.

4.3 Finance

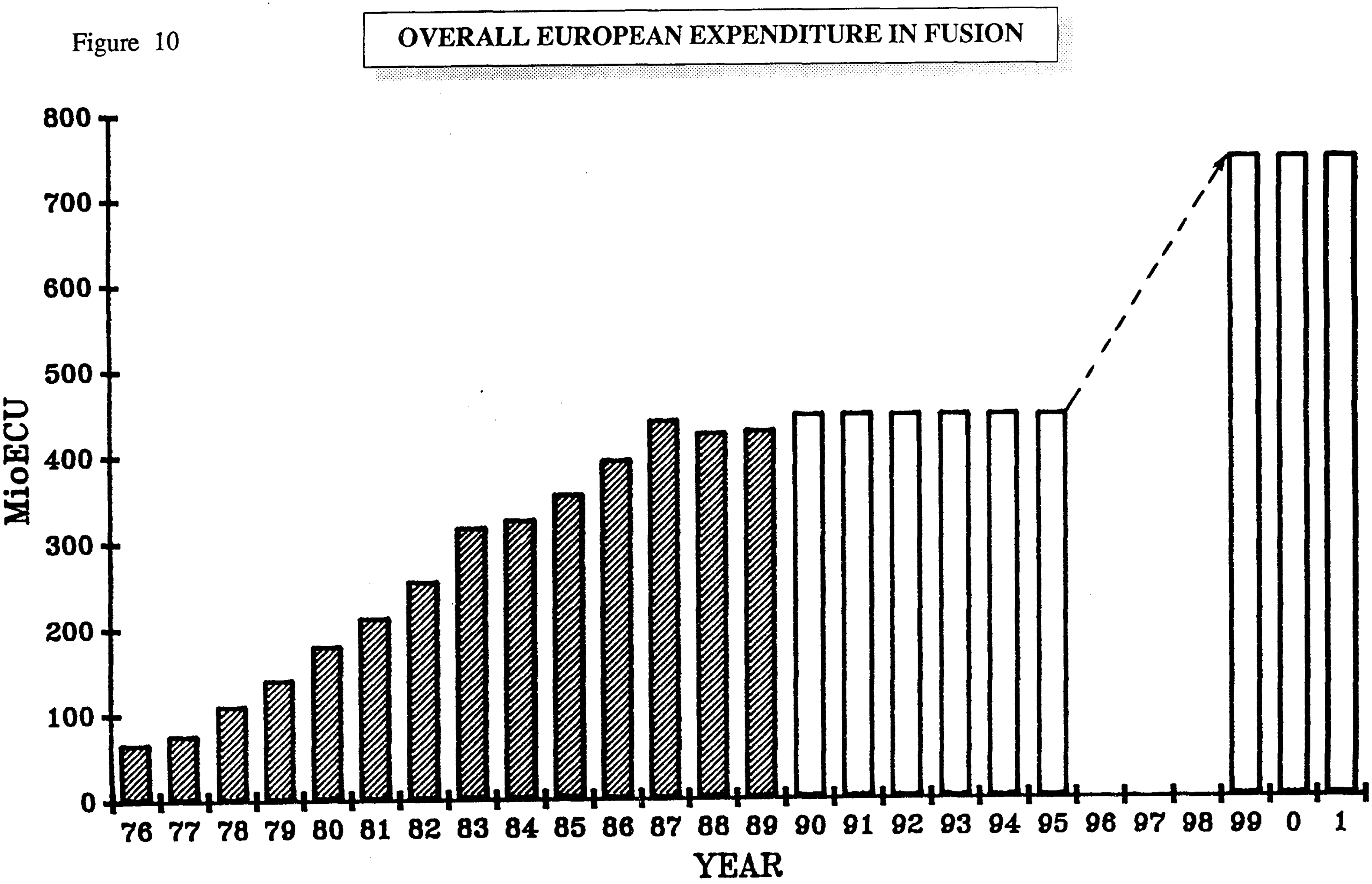
In round terms, total annual spending on fusion research in the frame of the Community Programme has settled at between 400 and 450 MioECU a year since the late 1980s, including expenditure by Sweden and Switzerland (see Figure 10). About one-quarter of this is on the JET project, while the amount spent on NET technology has risen from about 40 to 68 MioECU.

In terms of total expenditure, this level is considered by the Board to be sufficient for the European Fusion Programme as currently envisaged. The Board proposes, in fact, that the changes in emphasis and direction recommended in its Report be financed by re-allocation of present funding, reducing or ending spends in unpromising areas and channelling finance to those assigned new priority. In the presence of financial constraints affecting the overall Community research programme and research priorities in member states, the Board feels that it is unrealistic for the Fusion Programme over the next five years to be planned around a significant increase in funding and recommends this continue at the current 450 MioECU per annum. In fact, Next Step construction is not foreseen until some time in the second half of the 1990s and currently most work is in design activities, related research and testing and the operation of existing facilities. Should other new capital projects be contemplated, the existing financial constraints will demand a reassessment of priorities. The Board is confident that this restriction will not unduly hamper research.

The first half of the 1990s will therefore represent an opportunity for the Programme management to exercise its skill in maximising the use of available resources while redirecting the effort more tightly to its end objective, a commercial reactor for the generation of electricity.

A new level of expenditure decided following the independent assessment of progress and the real prospect of attaining the Programme's ultimate goal will clearly be dependent on whether the Next Step is to be a European venture or, instead, undertaken in a wider international frame. As a purely European Next Step, it is currently estimated that NET would have a capital cost of around

Figure 10


OVERALL EUROPEAN EXPENDITURE IN FUSION
800
700
600
500
400
300
200
100
0
MioECU
76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 0 1
YEAR

3,000 MioECU spread over 8 years. Averaging this out during the construction phase, the overall expenditure of the central programme could settle at 700 - 750 MioECU a year. From accumulated experience with the construction of fission plants, the Board thinks it possible that this estimate might be too low, especially if building delays occur. During the operation phase of NET, which could cost on average about 300 MioECU a year over 12 to 15 years, the overall expenditure of the Programme is expected to fall back to about 600 MioECU a year, until work starts on DEMO.

The Commission estimates that, for the Community to continue to develop fusion as a commercial power source alone, costs in terms of R&D could total about 50 billion ECU for the period 1990 to 2050. Such a sum covers current estimates for the Next Step, DEMO, a prototype power plant and all supporting R&D, including specialized R&D facilities (such as a high energy neutron source for material testing). The Board feels that any costing of complex, capital-intensive, projects over such a long time span is inherently uncertain, and is thus hesitant to commit itself to these figures.

With regard to internationalisation of the fusion effort, the extent to which the above total might be reduced through international collaboration depends on many factors, for example:

- the number of partners, and their willingness to participate in financing;
- whether international collaboration is limited only to pre-competitive research (i.e. to the Next Step), or embraces both the Next Step and DEMO;
- whether, as a partner in one step, Europe would wish to preserve a fully independent capability to go to the subsequent step, if necessary alone;
- whether the host for a particular device would be required to pay a substantial premium.

On the perhaps optimistic assumptions given to the Board that there will be four partners as in ITER (the Community plus Sweden, Switzerland and Canada, Japan, the USSR and the USA), that the Next Step, the DEMO plant and all major supporting facilities such as a Materials Testing Facility will be open to full international collaboration and that the scale of the host premium for a device will be kept small enough not to move the overall funding pattern too far from equality, the Fusion Directorate calculates that the 50 billion ECU Europe would have to pay to proceed alone might be reduced by 40%. From its evaluation of the current prospects for international cooperation, the Board feels that, if Europe wishes to retain the capability to construct a purely European prototype power plant, it is unlikely that any savings could be of this order.

The Board recommends that the mandate of the Evaluation Board proposed in Recommendation 36 should include a rigorous assessment of costs and spends for continuation of the European fusion effort, as part of a review of financial allocations prior to the major commitment represented by the construction phase of a Next Step device. By that time, harder data on the wider energy picture - both technical and environmental - should be available to assist in making a realistic evaluation upon which a major strategic decision for the future of fusion can be based. This might lead to an increase in the budget, in view of:

- new positive results affecting the prospects for fusion as an energy source;
- a possible reordering of priorities, following deterioration in the environmental and climatic situation sufficient to justify a shift in the direction of limits to the use of fossil energy sources.

It is also conceivable, however, that a decision in 1995 might go against funding fusion research on the current scale, perhaps deriving from:

- disappointing scientific and technical progress, with results insufficient to warrant the substantial increase in investment needed for construction of a Next Step device;
- uncertainty as to the economic or environmental acceptability of an eventual fusion reactor;
- an appreciation of other priorities with a higher claim to the European Community's limited resources.

CHAPTER FIVE

FUSION AND INDUSTRY

5.1 European Industrial Involvement in the Fusion Effort

Fusion research represents a new problematique. For the first time in history, man must build enormously complex and costly machines in order to experiment their feasibility. The investment in capital and manpower to build a machine to prove the feasibility of nuclear fusion is similar to that which will be required to build an industrial reactor.

Currently, European industry participates in the fusion effort essentially only as a supplier of components and services. This restricted role has been true both for the specialized machines built in the Associations and in the construction of JET. Design work has been the responsibility of project teams of scientists, with industry called upon merely to build components to specification.

Despite this limited involvement, the challenge to industry has been sizeable. Highly specialized development contracts have also transferred to industry some of the knowledge acquired in the advanced scientific research programme. Though perhaps plasma physics has limited relevance to the core businesses of most of the firms involved, some have derived direct technological benefit from participation in the Fusion Programme. This is a point also touched upon in Section 5.3, 'Spin-offs from the Fusion Effort of Wider Benefit to Industry'.

The industrial market generated by the European Fusion Programme since its inception has been small, but it embraces quite a variety of activities. The rapid sequence of construction or upgrading of the many devices in the Associations, together with work for the JET project, has provided perhaps insufficient continuity of orders for the many suppliers, who have competed on the basis of European-wide calls for tender. The European Commission's tendering system has caused difficulties in securing continuous commitment by industry according to some evidence given to the Board. The problem has been magnified by the fact that business applications are so far ahead in time and most of the research is so specific that direct spin-offs tend to be limited.

In discussing the Programme's relations with European Industry, a distinction must be drawn between the attitude of European companies with broad technological skills and others. As a rule, the former tend only to dedicate their best people to a major research effort if they can somehow identify a market linked to their core business. Extension of current knowledge of a key technology used elsewhere in the firm's activities is an important criterion, even in cases where the direct relevance may be limited. This could be true, for example, of gyrotron development and of special materials. Companies which do not possess a broad scientific and technological base tend to enter programmes if offered a contract which guarantees them a financial return adequate to the level of their investment plus a margin for profit. This distinction should be borne in mind by the Fusion Directorate.

Specifically with regard to the role of the Fusion Directorate, there has also been criticism expressed of rigidity and of an inability to adapt contract arrangements originally conceived for smaller scale, short term, research work to the long lead times, complex inter-relationships and size of effort demanded by fusion. It has been stressed to the Board that a way must be found to ensure continuity in project allocation. The Board agrees that in the contractual arrangements required for fusion research the contractor/customer relationship must inevitably differ from that found elsewhere, and that open competition among all European firms who wish to tender for a fixed price contract may conflict with industry's need for continuity. Changes are required particularly as further concentration of effort on the Next Step (ITER or NET) and beyond will result in fewer specialized devices in the Associations.

Clearly, the role of industry must be better defined. There are some reservations among scientists involved in the Programme as to the relative importance to be attached to industrial involvement at this stage. There are those who hold that industry must continue to play the limited role of sub-contractor for many years to come, except in specific cases. So long as fusion research remains essentially science-driven, the argument goes, the market orientation of industry will be unable to provide sufficient stability in any partnership. This stability, in terms of integrity of design and project teams, must be found within the Programme itself, and especially in the Associations and national laboratories. A guarantee of higher rates of return to tempt industrial involvement will translate, it is asserted, into an added cost that will inevitably further inflate the Programme budget.

The Board has examined this position, but is convinced that it must insist on the need for a bigger role for industry in the European Fusion Programme, especially in view of the need to inject industrial expertise into realization of the Next Step. There are several arguments that could be adduced in support. Firstly, it is time that the enormous reserves of skill and imagination possessed by European industry were brought into what is the Community's biggest research programme at an early stage of project definition. This is likely to improve current procedures for the production of prototypes, sub-assemblies and components. Early involvement of industry may also mean easier identification of potential spin-offs. A key to facilitate know-how acquisition by industry is its active participation in the engineering design phase from the outset. The construction phase is, in fact, more a matter of industrial organisation.

Second, up to now the Programme has been essentially driven by plasma physics and its catchment area for recruitment and public support is small. Fusion is an exciting endeavour that could change the way of life of every generation to come. A partnership between fusion scientists and technologists and their peers in industry will provide a window for the former into mainstream R&D, and an opportunity for the latter to become acquainted with a truly leading-edge area of research in which Europe occupies a global position of excellence.

Third, European industry must establish a position from which it will be able to compete in the eventual market for commercial fusion reactors. This requires continuous build up of technical know-how within industry. The engineering design and construction of the Next Step will offer an unprecedented opportunity - technical, financial, organisational - for this kind of knowledge acquisition.

Nevertheless, it remains unlikely that greater industrial involvement will mean direct investment by the private sector in fusion for the foreseeable future. Fusion is still at the phase that is most risky from both the technical and the financial points of view, and is still making massive demands on both science and technology. Funding such a sustained effort over the timescale required is clearly a strategic choice to be taken at the level of government. The most that can be expected of the private sector is a willingness to get involved on terms which recognize the special characteristics of fusion research. Still, it is wrong to imagine that the fusion market is unique. The defence market bears striking similarities in that it too is science and technology driven, with very long lead times, only one end customer in the public sector, very high costs, and frequently requires one-off prototypes, only one of the many of which may go to series production. Companies in the defence sector have evolved with their preferred customer, the State, contractual arrangements and working relationships which do not reflect simple free market practices. European defence suppliers have been guaranteed orders, ensured R&D contracts, offered special terms and tax breaks, assisted in the creation and exploitation of export markets, and so on. These practices have been seen as the only way to ensure continuation of long term strategically important research projects, and indeed the physical survival of selected key manufacturers. Europe thus has much experience in financing defence R&D which could be drawn upon in any move to a new procedure for Fusion Programme contracts.

It is important for the long term success of the fusion effort that all the critical technologies be available in Europe. It is the industrial and technological potential that must be assured and this has to be paid for. In fusion, magnets and specialized radio frequency, neutral beam and other heating sources are on the critical path and it is essential for European industry to acquire experience in their manufacture and testing. While other applications may then follow, development of these technologies demands a long term commitment which should be supported without reference to current contracts or to specific bids for tender. The Board in fact believes that it should be possible to decouple Community research contracts and the demands of the Associations. In addition, it considers that too great a concentration in the Programme on the exigencies of NET has hampered emergence of a portfolio management view of the contributions of the Associations and national laboratories and reduced the programme mix. An overview which better orchestrates what should be demanded of the Associations in return for Community funding is likely to lead to tightened management control and greater effectiveness.

The Board moreover believes that in this still pre-commercial phase there are identifiable areas in which the lead times for technology development are such that the Community should initiate pre-financing of selected suppliers to ensure their ability to develop the required components, sub-sets and sub-assemblies at the time these become critical. 100% funded research agreements, lasting between a minimum of five and a maximum of ten years should be considered as a way of ensuring European access to key technologies.

The Board proposes that a watching brief be assigned to a technology procurement function, independent of an eventual Programme Director of Technology and of the NET/ITER teams, the responsibility of which should be to make sure that Europe possesses the capability to generate certain technologies to meet anticipated demand. This function would interact with industry and with the Programme's scientists, but would rely on its independent assessment of Europe's needs in making financial decisions. An intimate knowledge of the industrial base of Europe would be essential. In the Board's view, determined Community commitment to European industry is necessary so that it is able to respond to the technical and organisational challenge implicit in the internationalisation of fusion.

As it is, the Board notes that there has been no real attempt at drawing a market profile for fusion as a product. In the Board's view, as stated elsewhere in this Report, fusion can offer two prime market advantages: safety and environmental acceptability. In order to maximise these advantages, the Board recommends that adequate funds be allocated immediately to ongoing studies of issues of social acceptability in order that the evolution of opinion finds reflection in the orientation of research. Long lead times especially for materials and technology development mean that these studies should not be postponed beyond the conceptual design phase of the Next Step. The likely input will also prove valuable for decision makers in industry and government.

Moreover, in any international approach to fusion, moreover, Europe will have to change its attitude to industrial involvement in order to ensure that its nuclear fusion effort is eventually commercially successful. Whatever the philosophy of the European Programme, we can be assured that, should the Next Step be ITER, American and Japanese industry will be directly involved in design and construction choices.

The Board has come to the conclusion that if the Community structure will not allow financing of industrial involvement in fusion to develop as outlined above, then questions will sooner or later emerge as to whether the Commission is the body to host this programme, or whether a different European structure would not better serve Europe's needs. As it is, the Fusion Programme is approaching the point where big project management has greater relevance, and this is an area in which European industry has considerable experience. When a project assumes the size of the Next Step, it can be refined by experts but no longer managed by them. This is the time to introduce these skills into the Programme, during the negotiation period leading up to commencement of the Next Step.

It is likely that management issues will dominate the realization of the Next Step, be it NET or ITER. In the Board's view, there will be need for concertation between the Commission, European industrialists, the Associations and other interested parties, and within the Commission itself, to establish modalities for the creation and management of pan-European consortia operating at the cutting edge of technology, several decades away from commercial exploitation of nuclear fusion. The aim must be to place European industry on a level playing field with that in other parts of the world. Management of such long term consortia in R&D and then in construction represents uncharted territory for both the Commission and for European industry. Consortia will not emerge naturally: companies will have to be approached, persuaded, encouraged. Forms will have to be developed which permit long term consortia to undertake fabrication and construction with sufficient flexibility to permit the rapid write-off of capital and hiring and firing of labour as the project demands. Consortia will also have to be created for systems design, ensuring reliability assessment, quality control and maintainability requirements. Carrying through the Next Step will demand a project manager possessing the ability to organise these new style consortia and, at the same time, negotiate guarantees of on-going financial commitment. From its experience, the Board believes that this task cannot be entrusted to a committee. Like the exercise of the procurement function proposed above, it requires an individual with strong institutional backing at the highest level.

5.2 Final Customers - the Requirements of the Utilities

It is not an easy task to assess, fifty or more years ahead, what the requirements of the utilities will be when fusion becomes a commercial energy source. Informal discussions with the European electricity generating industry have, however, given an indication of some possible trends.

It is likely that the large unit size of fusion plants (one or more GW) will not represent a major obstacle. By then, in fact, utilities will be confronted with the need for huge investments, for replacement of old plant and perhaps expansion of capacity. Plants of this size may be common by then, especially as international grid integration is expected to be effective even beyond the present limits of the European Community. The utilities will probably operate by the middle of the next century in an economic and regulatory climate quite different from that of today, in particular as a result of concern for protection of the environment and climate. This shift in attitude should, in principle, be favourable to non-fossil fuel sources, including nuclear fusion. Utilities will have to be sure not only that the economics of fusion competes with that of other energy sources, but that fusion plants will comply with all regulatory requirements, at the time of construction and throughout their useful life.

In many countries, utilities have developed understandable sensitivity to the dangers of overrunning schedules while building nuclear plants. Delays are a major cause of cost increases and are, in turn, often due to the uncertain timing and outcome of licensing procedures. It is therefore very important that problems connected with safety and with public acceptance of fusion be resolved from the start, preferably by virtue of design choices, and that the licensing procedure be as straightforward and predictable as possible.

Operation and maintenance are obvious concerns of the utilities. Fusion devices are rather complex machines. Intrinsic complexity should not, however, entrain excessive complication in operation and maintenance. Currently, utilities would appear to favour continuous operation of a reactor over pulsed operation, even though from a technical point of view pulsed operation with long pulses and a duty cycle close to 1 would be similar, to all practical effect, to steady state. Another operational requirement is likely to be that off-duty times be kept short, unfrequent and, as far as possible, programmable. The unforeseen shut-down of a generating unit of such large capacity could create problems even for a medium-sized grid.

Maintenance of fusion plants will involve in most cases reliance on remote operations by advanced robots and systems. Although remote maintenance is becoming more and more common in scientific environments, it is still far from the level of sophistication that will eventually be required, as routine procedure, in utilities. While progress can be expected in robotics, every effort will also have to be made to simplify the design of fusion plants, to enhance the durability of components and to make such robotized intervention less complex and, wherever possible, standardized. As already noted, utilities will require that occupational doses for personnel be maintained below accepted limits (which, up until now, have been decreasing with time), both for normal operations and for ordinary and extraordinary maintenance. Non-radiological hazards must also be shown to be negligible. In addition, decommissioning and dismantling of plants will have to be feasible at acceptable cost and with as low as possible exposure of workers to radiation hazards. End users and licensing authorities will also want the volumes of radioactive wastes demanding engineered storage before disposal to be kept to a minimum.

5.3 Spin-offs from the Fusion Effort of Wider Benefit to Industry

Although nuclear fusion is at an early stage of development, the Board was impressed by the results of the analysis carried out in September 1988 by the Commission. This analysis, which included interviews with fifty-six European companies, revealed appreciation of the spin-offs from these contracts.

Several specific examples of spin-off benefits are cited. one class concerns products originally developed for the Fusion Programme that have subsequently found markets in other applications. Examples here include radio frequency generators, high voltage power supplies, plant control software, low leak valves, remote handling devices, etc.. A second class of benefits derives from the extension and broadening of company know-how in various advanced technologies, such as vacuum technology, RF technology, precision engineering, control technologies, magnet construction, cryogenics, remote handling, fibre optics, advanced materials, etc. as a result of participation in the European Fusion Programme. Another positive role played by fusion contracts has been that of advancing application of quality control, demanded by the extremely stringent specifications of fusion devices. This is now made possible through use of new test facilities and more sophisticated control programmes for the testing of equipment and components under exceptionally severe conditions.

Industries and individual firms have also declared they have benefitted from involvement in the Fusion Programme in areas ranging from organisational and managerial improvements to marketing and exports, from closer links with research institutions to opportunities for international cooperation and staff training.

CONDENSED SUMMARY AND RECOMMENDATIONS

- Fusion is a viable energy option for Europe:
  * virtually inexhaustible source for base load electricity supply
  * potential environmental and safety advantages over all current alternatives
- European science occupies a vanguard position:
  * progress has been achieved in plasma physics improving confidence in the scientific feasibility of fusion energy
  * technical complexity delays achievement of ultimate programme objective
- Generation of electricity in a commercial prototype plant is expected only around 2040:
  * three stage strategy (Next Step, DEMO reactor, prototype) each requiring approximately fifteen years
  * technology, including materials development, does not permit acceleration of time scale
- European strategic choices in physics have been confirmed by success, though the technology programme demands greater attention, thus:
  * retain emphasis on magnetic confinement fusion
  * continue research into alternative lines
  * maintain watching brief on inertial confinement fusion
  * accentuate the long term technology effort under a Long Term Technology Team
- Europe should prepare for the Next Step:
  * minimum objectives are ignition, long burn times, solution of plasma physics and plasma technology issues in reactor relevant conditions
  * convergence of the current parallel designs of the Next European Torus (NET) and the International Thermonuclear Experimental Reactor (ITER)
- The potential for worldwide collaboration to achieve the Next Step must be fully exploited:
  * support for the quadripartite ITER initiative to share investment and knowledge
  * expansion of the ITER agreement to an ITER programme covering alternative lines and technology development, including a source for high energy neutrons
  * a stepwise approach to the realisation of the device
  * European leadership is justified by current excellence in the science of fusion
  * formal presentation of a candidate European site for EDA
  * identification and preparation of a European site for construction
- Urgent decisions must be taken within the European Fusion Programme:
  * prolongation of JET until 1996, with a tritium phase
  * resolution of the controversy surrounding decommissioning of JET after tritium

* preparation of a fall back capability for a purely European Next Step, in the event that ITER fails to materialise
* designation of a specific candidate site for ITER EDA

- Fusion's potential environmental and safety advantages require a strong long term development effort:
  * establishment of strict safety design targets
  * acceptance of environmental and safety criteria as governing the evolution of the European Programme
  * monitoring of compliance with these criteria by an Environment and Safety Team
  * emphasis on low activation materials to facilitate disposal of radioactive wastes and reduce levels of exposure for personnel

- It is now imperative to assign a bigger role to industry:
  * establish modalities to foster formation of and support to pan-European consortia
  * pre-financing of selected suppliers to ensure development of critical components, subsets and subassemblies
  * assurance of sufficient continuity in industrial commitment

- The Associations must prepare for a change of role in the context of an evolving Fusion Programme:
  * increased effort in environmental and safety issues and in technology
  * coordination of their input to the Next Step
  * stronger links to the rest of the European scientific community, especially to the universities

- The managerial structure of the European Programme must be strengthened as fusion prepares to enter a new phase:
  * stronger direction of the Long Term Technology and the Environment and Safety Programmes
  * consideration of the establishment of a specific new body under the EURATOM Treaty

- No substantial increase above the current level of funding is required over the next five years
  * a spend of about 450 MioECU per annum
  * new capital projects should undergo rigorous examination as to cost and timing and to their impact on priorities

- A further Evaluation Board should be called to report by no later than 1995:
  * critical assessment of progress in science and technology and of the prospects for continued international collaboration
  * justification of any major stepping up of financial allocations.

ACRONYMS, NAMES AND ABBREVIATIONS

ALCATOR	Tokamak for high density, high magnetic field operation at MIT, Boston, USA
ASDEX	Axisymmetric Divertor Experiment. Tokamak with closed divertor at Garching, Germany (EURATOM-IPP Association)
ASDEX-Upgrade	Tokamak with open divertor succeeding ASDEX at Garching, Germany (EURATOM-IPP Association)
ATF	Advanced Toroidal Facility, a large Stellarator at Oak Ridge, USA
ASTERIX V	Iodine laser at MPQ Garching, Germany
AURORA	Kr-gas laser at Los Alamos, USA
CCFP	Consultative Committee for the Fusion Programme (advisory body to the Commission)
CDA	Conceptual Design Activities
CEA	Commissariat à l'Energie Atomique, France
CIEMAT	Centro de Investigaciones Energéticas Medioambientales y Tecnológicas, Spain
CIT	Compact Ignition Tokamak, a project aiming at studying a self heated plasma, USA
COMPASS	Compact Assembly, a Tokamak for studies of plasma stability, at Culham, UK (EURATOM-UKAEA Association)
CPRF	Confinement Physics Research Facility, a Reversed Field Pinch under construction, Los Alamos National Laboratory, USA
CRPP	Centre de Recherches en Physique des Plasmas, Ecole Polytechnique Fédérale de Lausanne, Switzerland
D	Deuterium, isotope of hydrogen
D-D	Deuterium-deuterium: fuel consisting of pure deuterium, which, in comparison with D-T, releases smaller neutron flux, but which requires a much higher fusion product (see glossary) to reach ignition
D-He3 (or D-^{3}He)	Deuterium-^{3}Helium: fuel for fusion with low release of neutrons, but which requires much higher fusion product than D-T to reach ignition. ^{3}Helium is an isotope of helium which is not available in appreciable quantities on the earth
D-T	Deuterium-tritium: the fuel which requires the lowest fusion product to reach ignition, but which has the highest release of neutrons

DEMO	Demonstration Reactor (first device in the European fusion strategy to produce electrical power)
DG XII	Directorate-General XII (Science, Research and Development) of the Commission of the European Communities, Brussels
DIII-D	Doublet III, Tokamak at General Atomics for elongated plasmas, San Diego, USA
EB	Etat Belge, Belgium
ECCD	Electron-Cyclotron Current Drive. See current drive
ECRH	Electron-Cyclotron Resonance Heating. See wave heating
ECU	European Currency Unit
EDA	Engineering Design Activities
ENEA	Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energie Alternative, Italy
ETL	Electrotechnical Laboratory, Sakura-mura, Japan
ETR	Engineering Test Reactor, device in US fusion strategy
EURATOM	European Atomic Energy Community
EXTRAP	External Ring Trap. Configuration similar to RFP, with additional (multipole) stabilising fields
EXTRAP-T2	See OHTE
FER	Fusion Engineering Reactor, the proposed Japanese next step device
FOM	Stichting voor Fundamenteel Onderzoek der Materie, The Netherlands
FTSC	Fusion Technology Steering Committee, Subcommittee of the CCFP
FTU	Frascati Tokamak Upgrade, a high density, high current Tokamak at Frascati, Italy (EURATOM-ENEA Association)
GAMMA-10	Tandem Mirror device at Tsukuba University, Sakura-mura, Japan
GDP	Gross Domestic Product
GEKKO	Largest Japanese laser facility, at Osaka University, Japan
GSI	Gesellschaft für Schwerionenforschung, Darmstadt, Germany
H-mode	Also H-regime. High Confinement regime, up to twice the confinement time than in L-mode
H-transition	Transition into the H-regime
HELIOTRON E	Large Stellarator at Kyoto University, Japan
HTO	Tritiated water

IAEA	International Atomic Energy Agency (of the United Nations), Vienna, Austria
ICF	Inertial Confinement Fusion, using frozen D-T target pellets imploded by either laser or particle beams
ICRH	Ion Cyclotron Resonance Heating by launching waves into the plasma in the range of the ion cyclotron frequency (radio frequency)
IEA	International Energy Agency (of the OECD), Paris, France
IGNITOR	Ignition Torus, a project for a compact Tokamak with the goal to achieve ignition for a short period, proposed by the EURATOM-ENEA Association
INTOR	International Tokamak Reactor, design effort for a next step preceding the present ITER cooperation
IPP	Max-Planck-Institut für Plasmaphysik, Garching, Germany
ISTTOK	Instituto Superior Técnico Tokamak, for study of non-inductive current drive, at Lisbon, Portugal
ITER	International Thermonuclear Experimental Reactor (the Next Step as a quadripartite collaboration between EURATOM, Japan, the USSR and the USA, under the auspices of the IAEA). See Next Step
JAEC	Japan Atomic Energy Commission, Tokyo, Japan
JAERI	Japan Atomic Energy Research Institute. Headquarters in Tokyo, Japan
JET	Joint European Torus. The largest Tokamak in the Community, and in the world, at Abingdon, UK (JET Joint Undertaking)
JFT-2M	Tokamak Experiment, Tokai-mura, Japan
JRC	Joint Research Centre, Ispra, Italy
JT-60	Japan Tokamak, Naka-machi. The largest Japanese Tokamak
keV	Kilo-electronvolt. Unit to measure temperature and energy in a plasma (1 keV corresponds roughly to eleven million degree centigrade)
KFA	Forschungszentrum Jülich GmbH, Germany
KfK	Kernforschungszentrum Karlsruhe, Germany
Kr	Krypton, a noble gas. Used as medium for high power gas laser systems
LCT	Large Coil Task, international project for test of superconducting coils for the toroidal magnetic fields of Tokamaks (1977-1988)

LHD	Large Helical Device. Large Stellarator project in Japan
LHH	Plasma heating by radio frequency waves at the lower hybrid resonance frequency in the plasma
LLNL	Lawrence Livermore National Laboratory, Livermore, USA
LMF	Laboratory Microfusion Facility, laboratory under consideration for construction in the USA
L-mode	also: L-regime. Low Confinement regime, with degradation of confinement for additionally heated plasmas, originally found in limiter Tokamaks
MBS	Mombusho. Ministry for Education, Science and Culture, Japan
MCF	Magnetic Confinement Fusion
MeV	Megaelectronvolt, unit for nuclear energies. Energy which an electron acquires passing a voltage difference of 1 million volts
MHD	Magneto-hydro-dynamics, theoretical description of a plasma as magnetized fluid. Successfully used to describe the gross behaviour of fusion plasmas
MIT	Massachusetts Institute of Technology, Boston, USA
MPQ	Max-Planck-Institut für Quantenoptik, Garching, Germany
MST	Madison Symmetric Torus, a large Reversed Field Pinch at the University of Wisconsin, USA
MTX	Microwave Tokamak experiment, LLNL, USA
NBI	Neutral Beam Injection
Nd	Neodymium, a rare earth metal. Used as medium (addition to glass) for high power glass laser systems
NET	Next European Torus
NEXT STEP	Either NET or ITER. An experimental reactor with an ignited and long burning plasma
NFR	Naturvetenskapliga Forskningsrädet, Sweden
NIFS	National Institute for Fusion Science, Nagoya-shi, Japan
NOVA	Largest US laser facility, LLNL, USA
NRIM	National Research Institute for Metals, Sakura-mura, Japan
ns	Nanosecond (10^{-9}s)
OHTE	A Reversed Field Pinch at General Atomics, San Diego, USA, now transferred to Stockholm (EURATOM-NFR Association) and to be rebuilt as EXTRAP-T2

ORNL	Oak Ridge National Laboratory, USA
OTR	Next step fusion device of the USSR, originally planned as fusion-fission hybrid system
PFBA II	Light ion beam facility at Albuquerque, USA
PbLi	Lithium-lead alloy considered for use as blanket material
PBX	Princeton Beta Experiment, a Tokamak for strongly shaped plasmas, PPPL, USA
PC	Programme Committee, Subcommittee of the CCFP for physics and plasma engineering
PDX	Princeton Divertor Experiment, a former Tokamak at PPPL, USA
PHOEBUS	Nd-glass laser at Limeil, France
PLT	Princeton Large Tokamak, a former Tokamak at PPPL, USA
PPPL	Princeton Plasma Physics Laboratory, New Jersey, USA
PSI	Paul-Scherrer-Institut, Villigen, Switzerland
Q	Ratio of fusion power to total heating power (self heating included).
RF	Radio Frequency
RFP	Reversed Field Pinch. See glossary
RFX	Reversed Field Pinch Experiment. The largest RFP in the Community, and in the world, under construction at Padua, Italy (EURATOM-ENEA Association)
RISØ	Forskningscenter Risø Denmark
RTP	Rijnhuizen Tokamak Petula, for study of transport in a plasma, at Nieuwegein (Rijnhuizen), the Netherlands (EURATOM-FOM Association)
STA	Science and Technology Agency, Japan
STARFIRE	Commercial Tokamak Power Plant Study (Ch. C. Baker et. al.: ANL/FPP80-1, Argonne National Laboratory, 1980)
SULTAN	Superconductor Test Facility, Villigen, Switzerland (EURATOM-SUISSE Association)
T	Tritium, isotope of hydrogen
T-10	Large Tokamak, Kurchatov Institute, USSR
T-15	Large superconducting Tokamak, Kurchatov Institute, USSR
TBR	Tritium Breeding Ratio

TCV	'Tokamak à Configuration Variable', for study of elongated and specially shaped plasmas, at Lausanne, Switzerland (EURATOM-SUISSE Association)
TEXT	Texas Experimental Tokamak, a medium-sized Tokamak, at Austin, USA
TEXTOR	Torus Experiment for Technology Oriented Research. Tokamak at Jülich, Germany (EURATOM-KFA Association)
TFTR	Tokamak Fusion Test Reactor. The largest US Tokamak, at PPPL Princeton, USA
TJ-II	A Stellarator to be built at Madrid, Spain (EURATOM-CIEMAT Association)
toe	(metric) tonne oil equivalent
TOKAMAK	Russian acronym for 'toroidal magnetic chamber'. Toroidal magnetic confinement concept with high plasma current. See glossary
TORE-SUPRA	Tokamak with superconducting toroidal field coils, at Cadarache, France (EURATOM-CEA Association)
TRIAM-1M	Superconducting Tokamak, Fukuoka, Japan
TSP	Compact high-field Tokamak, Kurchatov Troitsk site, USSR
UKAEA	United Kingdom Atomic Energy Authority
VULCAN	Nd-glass laser at Chilton, UK
WENDELSTEIN VII-AS	Advanced Stellarator, with modular (non-interlocked) coils, at Garching, Germany (EURATOM-IPP Association)
WENDELSTEIN VII-X	Large Advanced Stellarator, optimised for the reactor relevant plasma parameters in pre-design at Garching, Germany (EURATOM-IPP Association)
WT-3	Tokamak for radio frequency heating and current drive, Kyoto, Japan
X-point	Cusp point on the cross-sectional plasma boundary found in the topology of a divertor
Z	Atomic charge. Atoms of elements with low Z (e.g. hydrogen, helium, beryllium, boron, carbon) can radiate much less electromagnetic radiation than high-Z materials (like e.g. tungsten)

GLOSSARY

adiabatic compression	a method to heat the plasma by compression
alpha particle (^{4}He)	nucleus of the helium atom composed of two protons and two neutrons, is one of the two products of the D-T fusion reaction (the other one is a neutron). The alpha particles being electrically charged, can be trapped by magnetic fields and therefore can release their energy to the plasma as opposed to the neutrons which escape from the plasma and release the energy to the blanket
alternative lines	development lines in magnetic confinement pursued in parallel to the Tokamak concept within the European Fusion Programme
Associations	institutions, active in fusion research, in the Member States of the European Community and in Sweden and Switzerland are linked by Contracts of Association to EURATOM
beta	ratio of outward pressure exerted by the plasma to the magnetic pressure necessary to confine the plasma. Since fusion power density increases with the square of plasma pressure, a high beta is favourable
blanket	a structure containing lithium or lithium compounds surrounding the plasma core of a fusion reactor. Its functions are to breed tritium via lithium-neutron reactions and to collect most of the fusion energy to be eventually converted into electricity
breakeven	intermediate milestone in fusion development at which the fusion power generated in the plasma equals the heating power which is added to the plasma to sustain its temperature
breeding ratio	the number of tritium atoms produced in the blanket of a fusion reactor for each tritium atom burned in the fusion plasma
compact tori	class of closed magnetic configurations where no material elements (coils, conductors or walls) need to link through the bore of the plasma torus. Thus the reactor vessel could be spherical or cylindrical

confinement parameter	the product of plasma density and (energy) confinement time. To a given plasma temperature corresponds a minimum value of this parameter which ensures a positive energy balance in the reactor (see also fusion product and also Lawson criterion)
confinement time	in a fusion plasma both particles and energy are not perfectly confined. The energy confinement time is a measure of how fast a plasma cools down if there were no heating. Particle confinement time is the time during which the particles, on average, stay confined. The energy confinement time can be shorter than the particle confinement time
current drive	in a Tokamak, plasma current is driven inductively, i.e. the ring-shaped plasma acts as a secondary winding of a transformer whose primary coil is at the central column of the device. The plasma current cannot be driven by transformer action for very long pulses or in steady state. Hence 'non-inductive' current drive methods are applied either by injecting particles with directed momentum into the plasma or by accelerating electrons by electromagnetic waves so that they carry the current
cyclotron frequency	natural frequencies of gyration of either electrons or ions in a magnetic field. Energy or momentum can be transferred to plasma particles by electromagnetic waves in the region of these or other resonance frequencies. Thereby the plasma can be heated or the electric current within the plasma can be sustained non-inductively
deuterium	natural, stable isotope of hydrogen; the nucleus consists of one proton and one neutron. In heavy water, normal hydrogen is replaced by deuterium. Seawater contains 34 g deuterium per m^3
diagnostics	special equipment to measure physical quantities e.g. plasma density or temperature
degradation	when additional heating, such as neutral beams or waves, is applied to the plasma, the energy confinement time decreases with increasing heating power. See L-mode, H-mode
disruption	sudden, very fast loss of confinement of the plasma in a Tokamak and other current carrying devices leading to a release of large energy to the wall and insurgence of strong electromechanical forces on the device

divertor	a system which removes heat and particles from the plasma by proper shaping of the plasma boundary with magnetic fields
driver	in inertial confinement fusion, the laser or particle beam system that is used to compress the target pellet
Field Reversed Configuration	a compact torus where the plasma is strongly elongated. The plasma is contained in a cylindrical vessel inside a straight solenoid for the confining magnetic field which has no toroidal components. Not to be confused with Reversed Field Pinch
first wall	the first material boundary that surrounds the plasma
fusion product	the triple product of density, confinement time and temperature used to give a measure of plasma performance
gyrotron	tubes for generating high power, high frequency electromagnetic waves which are used to heat the plasma. See wave heating
hydrogen	the lightest element; the nucleus consists of only one proton, the atomic shell of one electron
ignition	at ignition, self heating from the alpha particles is sufficient to compensate for all energy losses from the plasma. External sources of heating power in principle are no longer necessary: the fusion reaction becomes self-sustaining
impurities	in the plasma, particles of elements different from deuterium and tritium dilute the fuel and hence reduce the fusion reaction rate. Also, the radiation by impurities provides an additional loss to the thermal plasma energy and cools the plasma
inertial confinement	intense beams of laser light or particles (light or heavy ion beams) are used to compress very rapidly and heat tiny target pellets of fusion fuel to initiate fusion burn in the centre. Sufficient fusion reactions must occur before the fuel expands under its own pressure, thereby reducing drastically the frequency of reactions. Since only the inertia of the pellet's own mass limits the timescale of expansion and hence provides the timespan for fusion reactions to occur, the name inertial confinement is used
integral burntime	the total time a fusion device will operate with d-t fuel producing substantial fusion power

Lawson criterion	the value of the confinement parameter (at the required temperature) which must be exceeded in a fusion reactor to reach positive energy balance
limiter	material component on the plasma boundary which removes heat and particles and limits the plasma size
low-activation materials	materials that, under neutron irradiation, do not generate intensely radioactive, long-lived radioactive isotopes
lower hybrid	a resonance frequency of the plasma which is used for wave current drive or heating
magnetic confinement	restraint of plasma within the reactor core volume by the action of magnetic fields
mirror	a linear magnetic confinement concept (a magnetic bottle) with a uniform magnetic fields in a central region and with strong field at both ends which reflect escaping particles (mirror effect). Some variants exist to increase the magnetic field in all directions from the centre or to improve the closure of the bottle necks (tandem mirror)
muon	a short lived elementary particle which can be used to substitute an electron in a deuterium-tritium molecule. It is much heavier than the electron and therefore the size of the molecule and hence the distance between the nuclei is reduced. This makes fusion of the two nuclei much more likely to occur
negative ion beam	to produce neutral beams, ions are accelerated and then neutralized before entering the plasma. Since it becomes difficult to neutralize the usually positively charged ions at the high energy required for injection into a fusion reactor plasma, negative ions (having one electron more than the neutral atom) will be used as they are easier to neutralize at these energies
neutral beams	since charged particles cannot easily penetrate the magnetic confinement fields of the plasma, high energy beams of neutral atoms are injected into the plasma for fuelling, heating and current drive. In the plasma, the atoms of the beam become ionized and are then confined

neutron multiplier	The fusion of deuterium and tritium consumes, per reaction, one tritium nucleus and produces one neutron. Since in a real blanket not every neutron reacts with lithium to produce a new tritium atom, in a closed fuel cycle a neutron multiplying element is needed in the blanket to make the reactor self-sufficient in tritium supply
ohmic heating	the resistive heating resulting from a current through the plasma. Corresponds to the heating of a wire by a current flowing through it
pellet	in inertial confinement concepts, the fuel is contained in tiny spheres, called pellets, which are compressed by laser- or particle beams. In magnetic fusion concepts a means of fuelling the plasma is with cryogenically frozen pellets of hydrogen, deuterium, tritium, etc. which are injected after acceleration up to several kilometers per second
Phase I, II examination	the procedure to examine a proposal for an action or a device. The European Fusion Programme foresees a Phase I examination for the scientific and programmatic issues and a Phase II examination for the technical and financial aspects
plasma	state of matter above a few thousand degrees where all atoms are broken into their constituents, ions and electrons. Any plasma interacts strongly with electric and magnetic fields
preferential support	a project can be supported by Euratom preferentially i.e. with a higher percentage, if it has been awarded priority status
priority status	a project can receive priority status after Phase I and II examination if it is of direct interest for the Fusion Programme as a whole, satisfies advanced specifications, is available to all associated laboratories
radio frequency heating	see wave heating (here with waves in the radiofrequency range)
Reversed Field Pinch	configuration similar to the Tokamak but capable of carrying a current several times higher. Requires for stabilization a conducting shell close to the plasma
scientific feasibility	the successful demonstration of high gain or ignited fusion in an experimental device that lends itself to development into a net power producing system. In the past, less stringent definitions have been used

self heating	nuclear reactions provide heating to the plasma (alpha particle heating). If this heating dominates external heating, the plasma is called self heated
steady state	a fusion reactor preferentially should operate in steady state, i.e. with continuous plasma burning and hence constant power production
Stellarator	closed configuration having the shape of a three-dimensionally distorted ring in which the plasma is mainly confined by action of a magnetic field produced by non-planar coils wrapped around the plasma. Does not need a transformer and has therefore good prospects for steady state operation. Stellarators can be built with modular magnetic coils
technological feasibility	beyond scientific feasibility the demonstration of the engineering and technological capability to design and build a fusion reactor
Tesla	unit to measure magnetic field strength (more exactly the magnetic induction) 1 T = 1 Vs/m^2 = 10,000 gauss
toroidal field	the component of a magnetic field directed along the major circumference of a torus
Tokamak	configuration with the shape of a torus. The plasma is confined mainly via magnetic fields produced by plasma currents and by toroidal coils judiciously placed around the torus, determining the shape. The plasma is stabilized by a strong toroidal magnetic field
torus	a ring. The topology of closed configurations like the Tokamak, the Stellarator and the Reversed Field Pinch is toroidal i.e. that of a ring
tritium	radioactive isotope of hydrogen with a halflife of 12.3 years. The nucleus consists of one proton and two neutrons. Due to its rapid decay, tritium, formed by cosmic radiation and by terestrial nuclear reactions, is practically absent in nature and therefore, to be available as fuel, it must be obtained either from fission reactors or from breeding in the blanket of a fusion reactor
tritium inventory	the amount of tritium contained in a fusion reactor or one of its parts
wave heating	heating of a plasma by launching powerful electromagnetic waves via antennas or waveguides into the plasma at frequencies at which they can be absorbed by the plasma