THE EUROPEAN FUSION PROGRAMME

D. PALUMBO - CEC - Brussels

Before introducing the subject of my talk, may I first say ... pleased I am to have been able to accept the kind invitation to address this 'Conference on Industry's Role in the Development of Fusion Power' held under the auspices of the Atomic Industrial Forum.

1. CHARACTER AND VOLUME OF THE FUSION PROGRAMME

The European Fusion Programme, which is coordinated and partially funded by the European Atomic Energy Community (EURATOM) was started in 1959 with an association between Euratom and the French Commissariat à l'Energie Atomique (CEA) and has been gradually extended to all the Institutions of the member States of the European Communities developing a significant activity in the field of fusion. In 1971, the Council of Ministers of the European Communities decided that this programme represents:

> "a long term cooperative project embracing all work carried out in Member States in this field, designed to lead in due course to the joint construction of prototypes with a view to their industrial production and marketing".

More recently, two other European countries, Sweden and Switzerland, non-members of the European Community, joined the European Fusion programme sharing all the obligations including financial contributions and having the same rights as the Institutions of the member States. In 1977, after having accomplished together the detailed design of a very large Tokamak, JET, (Joint European Torus), Euratom on a joint basis. This venture is implemented under the legal status of a Joint Undertaking which gives it a large financial and managerial autonomy. In addition, some activity in the field of fusion technology is carried out at the Euratom Joint Research Centre, mainly in one division of the Ispra Establishment.

The geographical distribution of the programme is shown in Fig. 1. The management structure of the programme is shown in Fig. 2. Each association is managed by a steering committee constituted by a small number of representatives (3 or 4) appointed by the associated Institution and by Euratom.

The JET Joint Undertaking is managed by the JET Council, consisting of two representatives for Euratom and each member or associated country, and by the Director of the Project. It is assisted by an Executive Committee and a Scientific Council.

The overall programme is supervised by the Consultative Committee of the Fusion Programme (CCFP), composed of 3 representatives for each member or associated country. The CCFP advises the Commission on all the technical, managerial, financial and political aspects of the Fusion Programme and in particular on the new investments in the associated Laboratories.

At the beginning of 1981, a Fusion Review Panel chaired by Prof. BECKURTS and composed of eleven prominent European personalities in the field of energy research and development, was constituted to give judgement on the state of fusion research in the world and in Europe in particular, and to advise on the future of the Programme and the Next Step after JET. Its report is expected by the end of June.

According to Euratom Statutes, the Programme is approved for periods which cannot exceed 5 years. In order to avoid gaps or discontinuities, it has been agreed that after the first 3 years a new five-year programme will be implemented overlapping the last 2 years of the previous one. We are now in the sixth period (1979-83) and are preparing the next one (1982-86).

Concerning the financial aspects for the Associations, Euratom contributes 25% against the running costs and 45% against the major investments. For JET, Euratom pays 80% of the total cost ; 10% is supported by the United Kingdom as host country and the remaining 10% is shared between all the associated laboratories, in proportion to their annual budgets. Of course, the activity in the Joint Research Centre is totally supported by Euratom (See Fig. 3). For the immediate future it is proposed that Euratom could support at the 100% level some industrial development useful for the overall programme, e.g. development of HF generators or reactor technology. On the average, the European Fusion Programme is financed at about 50% by Euratom, the remainder being provided by the associated national institutions. The financial volume of the European programme compared with those of USA and Japan is given in Fig. 3.

The Programme has about 1,000 professional staff, of which 150 are Euratom employees. The total personnel including technicians, industrials and clerical etc. exceeds 3,000.

2. CONTENT OF THE PROGRAMME

The content of the programme can be subdivided into :

- the physics and technology of the plasma confinement and
- fusion reactor technology and Next Step.

2.1 Concerning the first part, the European programme is centred on magnetic confinement and in particular on toroidal configurations. We are considering 3 cases (Fig. 4) :

- the Tokamak, where the toroidal magnetic field is essentially determined by external coils and the poloidal field by plasma current (driven by an induced electric field, at least until now);
- the Reversed Field Pinch, where both components of the magnetic field are essentially produced by plasma currents and the toroidal magnetic field is reversed in direction ;
- the Stellarator, where the topology of the magnetic field is determined by external coils.

In the first two cases, the duration of the confinement is limited by the magnetic flux available, (if a different driver for the plasma current cannot be found), while the stellarator could work continuously. The toroidal magnetic confinement can be characterized by 2 quantities :

- first the product $n\tau$: plasma density n by energy confinement time τ (τ defined as the ratio $\frac{E}{W}$ between the thermal energy of the plasma E divided by the rate of energy losses W), - or by the product $nT\tau$ where T is the plasma temperature. Both products can be con-

considered as measuring the quality of the confinement.

For a reactor, the requirements are :

$$n\tau \geqslant 10^{14}\ cm^{-3}.s \text{ and } n\tau T \geqslant 3.10^{15}\ cm^{-3}.s.\ keV.$$

- second, the ratio β between the pressure of the confined plasma and the magnetic pressure. This gives some measure of the quantity of confinement and, for the realization of an economic reactor, it seems that β values of at least 5 to 10% will be necessary.

In general τ increases with the dimensions of the apparatus and is limited by micro-instabilities and impurities, among other factors.

The values of β attainable are limited by equilibrium and stability requirements.

As in the other world programmes (USA, USSR, Japan) the tokamak in Europe constitutes the main line of research. RFP and Stellarator are considered as alternative lines.

2.2 Let me start with these. European activity on the RFP is developed at Culham and Padua and an excellent collaboration exists with Los Alamos. Dr PEASE will report on the work done and planned by the EUR/UK Association at Culham.

In Padua, on the ETA BETA II machine it has been shown that :

- By external field programming various field reversal rates can be obtained, and the confinement properties improve with increasing field reversal.
- In optimum conditions a quiescent plasma is produced, a marked reduction in the level of fluctuation signal being observed.
- Beta values of about 10% and energy confinement times

The Stellarator programme is concentrated at Garching where WENDELSTEIN VII-A (Fig. 5) the largest working Stellarator in the world (R = 2 m, a = 0.11 m, B = 3.4 T, rotational transform, ι = 0.5) is in operation. The recent results obtained with neutral beam heating (300 kW per injector) are :

- almost net current free plasma at high density ($n_o \approx 10^{14}$ cm^{-3})
- no deleterious instabilities
- confinement better than in ohmically heated plasma.

There is a small size experiment having purely poloidal confinement in Stockholm and the SPICA screw pinch at Jutphaas.

2.3 The tokamak activity in Europe has two main purposes :

- the study of Tokamak behaviour and performance (n, T, τ, β, plasma purity, etc.) in order to discover the limits of these performances in view of their optimization.
- Utilization of the Tokamak (which represents by far the easiest way to obtain plasmas of significant density, temperature, lifetime, purity, etc.) in order to develop and test different plasma physics and technology items such as diagnostics, heating techniques, refuelling, etc. A list of the European Tokamaks mainly devoted to the first task is given in Table 1 and for the second task, Table 2.

2.4 It is impossible to give all the detailed results provided by the European Tokamaks. However let me mention a few recent significant results :

- At Frascati, the high field (up to 10 T) Tokamak (Fig. 6) has been utilized in the last few months for the study of as a function of density n, with a high purity plasma. (Fig. 7). At 8 T, the $n\tau$ is 4.10^{13} $cm^{-3}s$; which represents the highest value reached until now.
- In Fontenay, at the beginning of this year, the power capability of the RF-generator for ICRH on TFR has been brought up to 3. MW : the two amplifiers (1.5 MW each) are now supplying two groups of all-metal antenna arrays, (fig. 8), which are separated from the plasma by a Faraday shield. This equipment has already been shown capable of coupling up to 1.5 MW additional power to the plasma, resulting in the record mean value of about 1.W cm^{-3}. Fig. 9/10 shows the corresponding heating of a high density D-plasma ($n_e = 10^{14}$ cm^{-3}, H/D between 5 and 20%.
- In Garching, during the last 15 months, extended analyses on plasma impurity control have been successfully conducted on ASDEX (fig. 11), using poloidal divertors and powerful pumping systems. The very clean plasma thus achieved (reduction of Oxygen by a factor of 10. and of Fe by a factor of 25.) (fig. 12) resulted in very low loop voltages (from 2 to 0.1 Volt) and corresponding exceptional long discharge duration between 3. and 12. seconds according to density.
- Mr PEASE will report on DITE and TOSCA at Culham.

The medium size tokamak TEXTOR (fig. 13), at Jülich is almost completely assembled, operation will start in next October. It is devoted to plasma/wall interaction studies and will be equipped, amongst other mthods, with 3 MW ICR additional heating provided by the Belgian Association. Its construction and operation is the object of an IEA Agreement involving Euratom, Canada, Japan, Turkey, USA, which has already been very useful.

The Neutral Injection development for plasma heating is mainly concentrated in FaR which has produced the Neutral Injectors for TFR and for the ASDEX tokamak in Garching, and Culham which has produced the Neutral Injectors for DITE and for the Stellarator W VII at Garching. Both are developing the N.I. heating for JET.

2.5 The most important part of our Fusion Programme is the construction of JET (fig. 14) which will be the largest Tokamak in the world. The buildings (fig. 15) are almost finished ; many components of the machine, the toroidal field coils (fig. 16), parts of the vessel (fig. 17), the motor-generator sets are already available. Concerning the JET heating, recently it has been decided to provide 10 MW by neutral injection and 15 MW by ICRH. We hope JET will be in operation in the first half of 1983. The full performance (3.4 T ; 25 MW heating, DT plasma) could be reached by 1988, under these conditions JET could approach, or hopefully even reach, ignition.

2.6 Fig. 18 shows the overall world effort in the field of Tokamaks (existing and planned machines).
Fig. 19 shows the evolution of the different levels of performance reached in Tokamaks. The open circle represents the European contribution and the European targets ; in fact the

JET targets. One can expect, therefore, that plasma physics, in particular with the help of the new generation of machines (TFTR, JT 60, JET) will shortly demonstrate that the physical requirements for fusion can be attained. So the main problem and perhaps the main obstacle on the way to the practical realization of fusion is fusion reactor technology.

2.7 The reactor technology programme in Europe is less advanced than the physics programme. This is due to several reasons including limitation in financial resources and to the lack, until recently, of a clear objective as a focus for technology work. Nevertheless we are active in some fields.

Concerning superconductivity, through an Agreement in the frame of the IEA collaboration, Euratom, (through the Karlsruhe Laboratory, under contract with Garching) and Switzerland (which separately decided to participate in this Agreement before joining the Community programme) will provide one coil (fig. 20) each, for the Oak Ridge Large Coil Task. Two of the six coils will thus come from Europe. In both cases the superconducting material will be NbTi.
The French Association has developed and successfully tested a NbTi coil, cooled by superfluid He at 1.8°K, allowing a maximum field of 9 Tesla, as a basis for the construction of the superconducting tokamak TORE SUPRA.
In addition, in view of the development of advanced A15 superconductors, we have already started the 12 Tesla test facility SULTAN at the Swiss Institute for Nuclear Research (SIN), as a joint project between the Swiss, the Italian and the Dutch

European industry is playing an essential role in all these developments and constructions.

Some modest activity is in progress on tritium handling and remote handling, mainly for JET, and some studies on tritium breeding and more generally on blanket problems are being carried out.

As far as material studies are concerned, a low level R & D activity has been started in several laboratories consisting mainly in radiation damage, fatigue and combined effects studies.

Radiation damage is currently simulated by charged particle irradiation of samples in accelerators. At Ispra the construction of a cyclotron based facility is proceeding. (Fig. 21)
This will be used for the production of displacement damage and of helium in fusion technology materials, principally steels, thereby simulating the neutron irradiation conditions near the first wall and in the blanket.
A more realistic and systematic study would require 14 MeV neutron sources of sufficient intensity. Such sources do not exist now and are very expensive.
An Implementing Agreement on radiation damage in fusion materials, concluded last year in the frame of the IEA between the US, Canada and the EC, provides both for the participation of European personnel in the construction of the Fusion Materials Irradiation Test (FMIT) facility in Hanford and for a broad joint radiation damage programme, including joint experiments and the establishment of a common pool of data. Considering

the importance of the first part of this agreement, the possible cancellation of the FMIT of course causes us some concern.

2.8 In order to prepare the further development of the programme, and to provide the necessary focus for the fusion technology development, at the beginning of 1979 we decided to set up a Next European Torus (NET) group, with the aim of proceeding gradually to the definition and possible design of the Post-JET device. This practically coincided with the start of INTOR and therefore the NET group has so far mainly provided support and input information to INTOR. This has been achieved with the help of most of the associated laboratories and in particular of the fusion technology division of the JRC, Ispra. Our intention is to steadily strengthen the NET activity and we are waiting for advice on this matter from our Fusion Review Panel.

If this advice is encouraging, the design of NET will become, together with the completion of JET, one of the objectives of the next five year programme (1982-86) now in preparation. Obviously the future of NET might depend on the evolution of INTOR or similar cooperative ventures. NET is conceived now as a large Tokamak which should :

- operate with D-T ;
- aim at a long-pulse burn and possible ignition of the plasma ;
- demonstrate on a reactor scale the "intrinsic" technologies, i.e. tritium, superconducting magnets, and remote handling ;
- provide for engineering testing of the breeding blanket and for studies of the first wall, of

structural alloys and other important reactor technologies.

During the period of design, at least the "intrinsic technology" items listed above should be fully developed in parallel.

3. INTERNATIONAL COLLABORATION

The importance of the role played by international cooperation is particularly characteristic of fusion R & D.

Let me quote some examples coming from different areas of fusion work :

- in 1969 a team of British physicists from Culham moved to the Kurchatov Institute in Moscow with their diagnostic equipment and confirmed the very encouraging measurements made on one of the first tokamaks. This has strongly influenced the rapid diffusion and the further development of these devices.
- in the fusion technology area, the already mentioned superconducting coil assembly in Oak Ridge will be made up of 3 coils from the US, 2 coils from Europe and one from Japan.
- further, I can quote the European Programme, though strictly speaking it must be considered a Community rather than an International cooperation. In our case, by the cooperation between the associated laboratories on the fields of common interest ; by separation and distribution, where possible, of the tasks among different laboratories ; by the common construction of a large object, JET, we have certainly reached results, unattainable by the separate efforts available in the member States.

Now we are facing larger problems, especially in the field of Fusion Technology and in the requirements of the Next Step Machine.

I think it is in the interest of all of us to face these larger problems by equally large attempts at cooperation, if possible world wide.

The increasing involvement of the IAEA and of the IEA in fusion R & D is a proof of the importance of international cooperation in this field.

Such a strong international cooperation is more than just a helpful contribution ; it will be a necessary ingredient for success. As long as it is a matter of exchanges of ideas between physicists, cooperation is rather easy. It might become more difficult when other interests start playing a role. This is one of the reasons why it is urgent to establish soon the appropriate framework for cooperation.

One can distinguish three areas of work :

- Tokamak physics, and related plasma technology where the programmes are overlapping, aiming at the demonstration of scientific feasibility and at the optimisation of these devices. A good example of cooperation in this area is TEXTOR.
- Other problems such as diagnostics, refuelling, and heating, especially in relation to new initiatives could be dealt with in the frame of IEA or bilateral agreements. Let me quote as an example Neutral Injection by Negative Ions, where some activity in Europe already exists and good results have been obtained through joint work at Grenoble, Stockholm and Amsterdam.

- Alternative lines, where the programmes are, in general, already complementary. Here one should recall that although the tokamak line is the most advanced and promising one, there is no absolute guarantee that it will provide an optimum basis for the fusion reactor. Other confinement systems, closed (like the stellarator, compact toroids and the RFP), or open as the mirror machines, might eventually provide a better solution. To bring all the alternative lines to the same level of development reached by the Tokamak is extremely expensive both in manpower and money.
- About a year ago there was an extensive exchange of views between Europe and the USA on alternative line cross participation, and the sharing of tasks between the various programmes appears as an obvious solution. Europe could for instance take the main responsibility for stellarators and the US on mirror machines. The next step in the development of the Reversed Field Pinch line could be undertaken by Europe, with a US participation, and without prejudging who will take the main responsibility for the following step. Such agreements could easily be set up, in the frame of the IEA, or by bilateral agreement.
- The Next Step and the related technology where the problems are the most important and the most difficult ones. This is a field in which the speed of the development is an important factor and is limited by resources, both financial and human. The cost of JET is about half a billion dollars. The Next Step, whatever its level of ambition may be, will cost at least three times more. Even if this amount of money were to be in line with the financial capacities of our countries and with

the interest in the aim, two questions would arise :

1) is there for each of the four large world programmes the political will to undertake such enterprises while maintaining the necessary activity on the remaining problems such as tokamaks physics, alternative lines, long term reactor technology ?

2) if it is possible to undertake simultaneously, or separately, the construction of several next steps in the world, is it wise and useful ?

If at the moment of the almost simultaneous launching of TFTR, JET and JT 60 there had been a worldwide coordinated programme, it is not certain that we would have gone ahead and built these three devices ; perhaps a single one for quicker results or a more ambitious venture might have resulted.

The questions were discussed between the representatives of the large world fusion programmes in October 1977 at the MIT upon the initiative of Prof. ROSE.

It was recognized that the financial, scientific and technological requirements fully justified or even necessitated a joint venture at the world level, which could be undertaken in the frame of the IEA or of the IAEA, depending on the partners. The INTOR venture started a few months after, by a Russian initiative. Whatever the future of INTOR turns out to be, an 'INTOR-like' venture shared between all, or some, of the present partners still appears to me to be the best solution. If this aim proves difficult to achieve several alternative scenarios can be considered.

If each of the programmes builds its own next step simultaneously, it would be desirable that at least some complementarity in the aims and in the design be agreed. If such devices are not to be built simultaneously they should be staggered in their aims and cross participation should be possible.

The problem is important and rather urgent : the forums for these discussions and the structures for the possible implementation of these issues are existing or can be created.

I hope that with some goodwill and imagination a realistic solution can be found.