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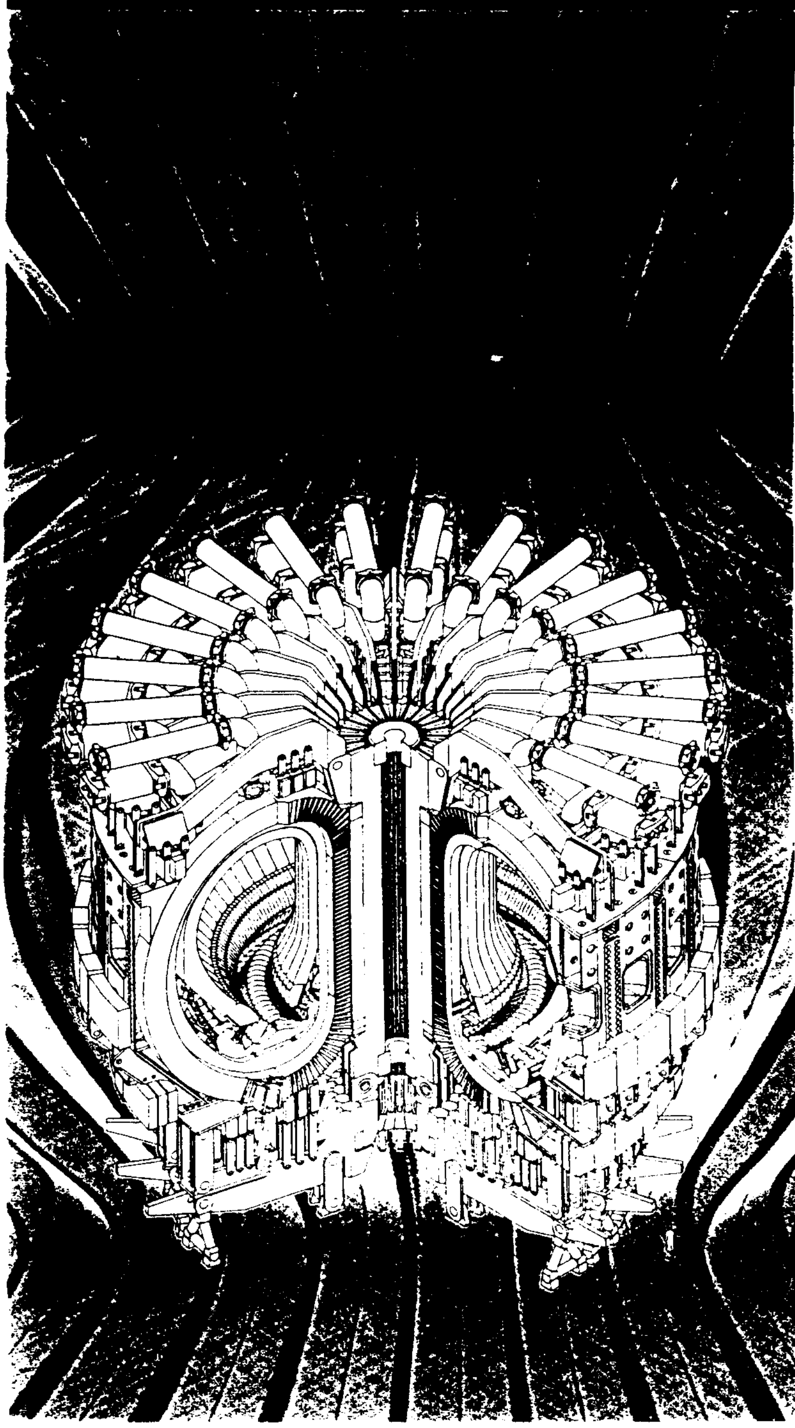

Reflections on fusion future

XII- 109/ 96 May 1996

REFLECTIONS ON FUSION FUTURE

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Summary: This article analyses some of the ITER issues and tries to foresee the main questions to be solved before fusion could become a major energy source. In the present context, a direct path towards a pure fusion reactor does not look as the best way. Hybrid fusion-fission reactors which, from a technical point of view, are less demanding seems attractive as they could span from pure fusion to pure fission. With these considerations in mind, the right next step seems to be a long burn Q=5 Tokamak inside a coordinated world program.

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1. INTRODUCTION

THE ENERGY DEMAND

A large increase in the energy production is foreseen in the future due to the demand from countries like China, India. Two sources of energy seem possible to fulfill this demand : fossil fuel and nuclear energy; but fossil fuel burning may be limited by the atmosphere capability to absorb dust, carbon dioxide and other combustion gas; nuclear energy in this respect seems unavoidable. Fission and fusion have to contribute either as separate sources of energy or more realistically as a mixed system which may include hybrid reactors.

FISSION

Fission reactions are easy to produce. A pure fission reactor burns mainly uranium 235 and plutonium 239. The choice of reactions is imposed by the neutron balance and the necessity for the reactor to be critical: this limits the possible fuel cycles. Fission reactors are industrially developed and available, but the questions of the actinide production and the waste level are critical for their future and solutions to burn and reduce the actinide production have to be further developed. The fission reactions produce fission products which are radioactive wastes and which have to be disposed off.

FUSION

Fusion, in this respect, is much cleaner but difficult to achieve, a pure fusion reactor is a much more complex machine, and requires a higher capital investment. The shielding necessary to protect the superconducting coils and the physics conditions required for ignition, impose the minimum size of a pure fusion reactor. The size of an experimental device achieving ignition is large and correspond to the size of a power reactor, in the few gigawatt range; this fundamental fact makes fusion research long and costly.

Today after the tritium experiments in JET [1]and TFTR [2], fusion is at a turning point where the objectives are moving from plasma-physics comprehension to fusion reactor development. For pure fusion, a large technical development has to be made not only to demonstrate ignition, but also to bring the reactor to a point where the availability is high and the economy competitive. This implies a series of experimental reactors to be constructed. A long time is still necessary to bring fusion at an industrial level, at least 50 years as one step takes already 25 years e.g. JET, TFTR.

ECONOMIC AND POLITICAL CONTEXT

In the present situation, energy is available relatively cheaply to the advanced countries and there is no pressure on these countries to pursue an aggressive development on nuclear energy. In addition there is, from the public, a general lack of confidence about nuclear installations. In this context, the budgets for fusion are limited and even tend to decline.

2. FUSION RESEARCH

GENERAL

The fusion program is carried out by the main developed countries: Europe, Japan, USA, Russia. Already JET is done at the European level, and the next step ITER [3] is foreseen at world level to minimize the overall cost and its impact on the national fusion research. It is a major step from present Tokamaks not only by the size but by the power involved and the new technologies to be implemented. In addition the question of a world collaboration limited to a single ITER project versus a full ITER program has to be answered. The precise objective and the different steps to achieve a coherent development towards a fusion reactor have to be reviewed. This might lead to changes in the fusion research programs and in their organizations.

THE ITER PROJECT

OBJECTIVES:

As defined in the ITER EDA agreement [3] between Europe, Japan, Russia, and USA, the overall objectives of ITER is to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes. ITER will demonstrate controlled ignition and extended burn of deuterium-tritium plasmas, with steady state operation as an ultime goal, encompassing technologies essential to a fusion reactor in an integrated system. It will also perform integrated testing of high heat flux and nuclear components.The main concepts and parameters in ITER are the consequence of these agreed objectives. They include the safety and technical margins necessary for this major extrapolation. The discussion which follows is based on the ITER outline design [4].

DESCRIPTION:

ITER is a Tokamak; its toroïdal plasma has a major radius of 8.1 meters and a minor radius of 3 meters with an elongation of 1.6. (table 1.). The toroïdal fields on the axis reaches 5.8 T. The plasma is surrounded by the blanket which includes the first wall and the divertor, in direct view of the plasma. All these elements are inside a vacuum vessel which acts as a shielding for the supraconducting coils. The whole machine is inside a cryostat with a diameter of 40 meters (fig. 1). The additional heating equipment (70 MW) could be located outside the cryostat if neutral injection is chosen. Compared to JET or TFTR, ITER represents a large extrapolation, 15 times the JET plasma volume and more than 100 hundred times the power and pulse duration.

Physics issues:

Confinement

The major ITER objective is to demonstrate long burn ignition. It is a large step in physics: The fusion amplification factor Q is infinite at ignition but the product $nT\tau$, a relevant plasma performance indicator, where n is the plasma density, T the central temperature and τ the energy confinement time, increases by a factor 5 from its value at $Q = 1$. A plasma corresponding to a Q value of 1 was obtained on JET at 4 MA, but in a transient way and in a hot ion regime which does not occur at ignition. As the product $nT\tau$ increases with the plasma current a factor 5 or more increase of the current is required for ignition, e,g, between 20 MA and 30 MA at $q = 3$. The transient condition of present machines must also be extended to a quasi stationary condition. In the ITER outline design, the maximum foreseen plasma current is 24 MA and the predicted confinement is still marginal for ignition.

MHD turbulence and instabilities.

Abnormal events, disruptions, vertical displacements, ELMs result from MHD activities. They produce large electromagnetic forces and heat fluxes on the divertor and first wall. The heat pulses which result from these events could melt and evaporate the surface of the material in contact with the plasma inducing a rapid erosion. A sufficient control of these events is required for a reactor.

Impurity control and ash removal.

The divertor has to be conceived to protect the plasma from the impurities created in this region by the plasma contact with the target plates. At the same time, it must be able to exhaust the Helium ashes. The only solution which could be envisaged is to radiate most of the power generated by the α particles through a controlled level of impurities.These divertor and first-wall problems increase with the energy stored in the plasma and the power produced. They involve plasma physics and the thermomechanical and chemical properties of the first wall materials. The life time of these elements will be defined by the MHD abnormal events and by the power that they received (heat and neutrons).

Technology issues :

ITER is a superconducting Tokamak, in complexity close to a reactor, but remains an experimental device. The machine proposed in the outline design would be able to produce one to three GW thermal at ß limit, but will have to operate at maximum performance to ignite, this is true for the plasma as well as for the technical requirements. To study α particules heating and ignition the machine would have to be almost fautless, as the complexity of the superconducting coils and their cryostat, together with the remote handling requirements make any modifications or repair extremely difficult and time consuming when tritium operation has started.

In order to ensure a proper ITER operation and to reduce the risk of failure, all the major components need to be tested before assembly. These test of major individual system will delay the ITER tritium operation by several years (may be 6 years) over the present planning (testing of the magnet, testing the operation of the divertor, the impact of ELMs etc.) but I believe that it is a necessary step for a successful ITER operation. As foreseen now, the coils system will be tested for the first time only after the full assembly of the machine (including the vacuum vessel blanket, divertor, diagnostics, heating system). It is a new technology made at an unprecedented level of magnetic energy, a system which has to operate at its maximum performances if the objective is ignition. A full test of the magnet seems required before the machine is assembled. But this partial assembly is an experiment in itself. In addition, a series of test beds must be started to develop the blanket modules, first walls and divertors which will be installed in ITER.

Reliability and availability will remain poor, even for an experiment, when inside the cryostat planned repairs, accidental interventions and modifications are counted in terms of several month or even years. The time to heat and to cool down the magnets alone takes several months. Without a prior development and test of their life time, the first wall, target plates, protection and sacrificial elements will have to be changed frequently as a result of the abnormal events (erosion, evaporation, stresses). To avoid this situation a continuous high power test bed for the divertor seems unavoidable..

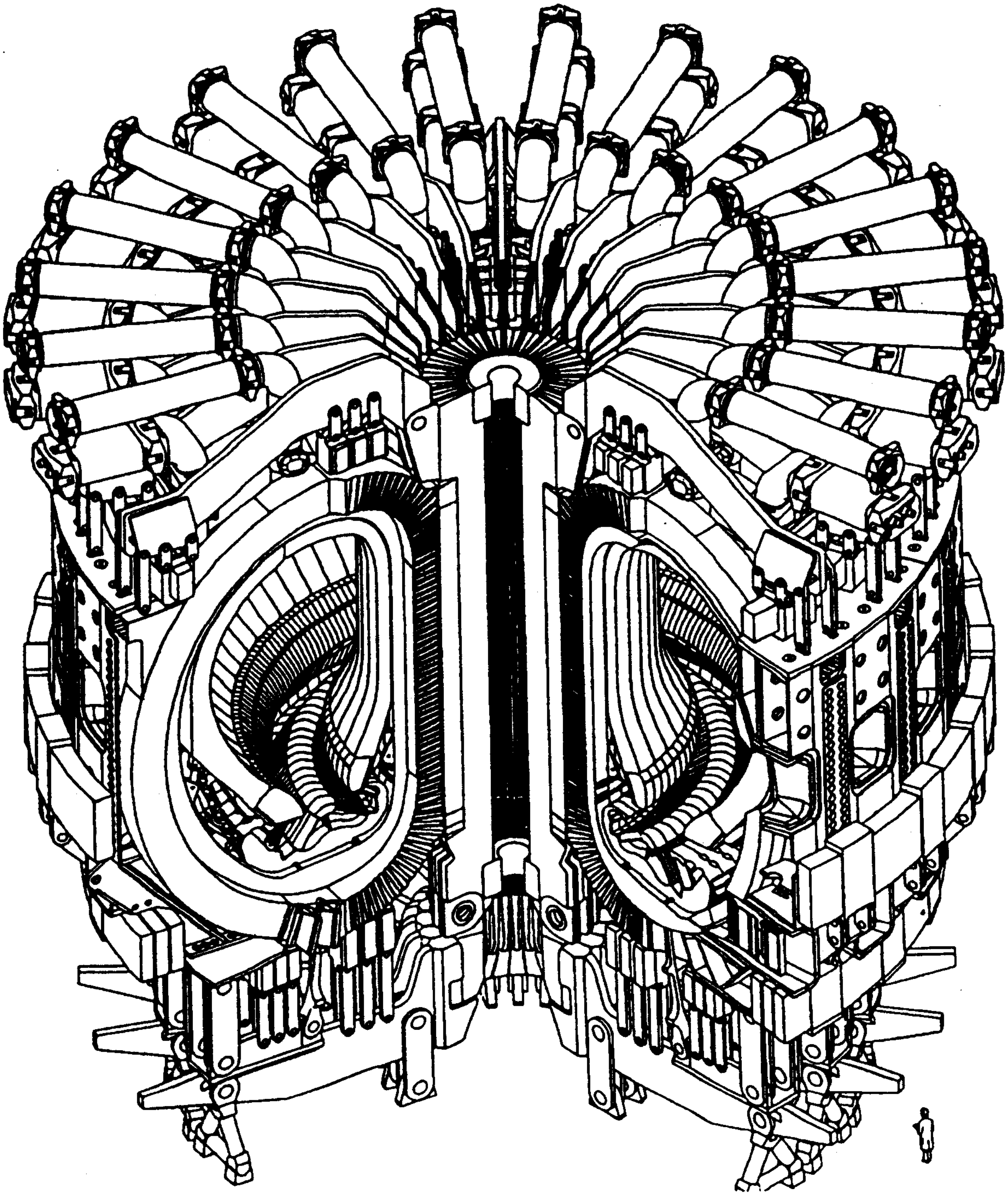

Figure 1: General view of ITER

Operation issues :

Two phases are foreseen each of 10 years. The first one is mainly dedicated to physics studies and the second one to technology. The replacement of the initial blanket which is only a shield seems necessary to provide the Tritium consumed. But this replacement is a major challenge, will take several years and a successfull outcome cannot be guaranteed. In addition the role of the second ITER phase devoted to blanket module testing is debatable as the total fluence expected remains low, < 1 $MW.a/m^2$, and the power density, at which ITER operates, is about a factor 5 lower than in a pure fusion reactor which could compete with the other energy sources.

The cost (probably over 5 billions $) of operating ITER during this second phase, a substantiel fraction of the construction cost, seems to be prohibitive as the data which could be obtained remain far from those required for a pure fusion reactor.

Organization issues :

The ITER Engineering Design Activities, EDA are more international activities than a project oriented organization; where political compromises prevail, responsibilities are diluted and the good will is the main way to progress. Before starting the construction, in order to get a successful project a profound modification of this structure is required, with a completely different mind where the cost and the duration of the project have also to be taken into account. The bare construction cost is around 7 billions $ (95).If the R and D and the ITER Team cost are added, the construction cost might reach 10 billions $. The construction time foreseen is 10 years after a positive decision and a site selection.

REFLECTIONS ON THE ITER OBJECTIVES

ITER demands a large extrapolation from existing machines. As only one experiment of this class will be built there is a requirement for significant technical and scientific margins to be included in the project. But the cost pressure exerted by the 4 Parties push the machine performances down to a value where the probability of achieving all its objectives is doubtful with pratically no margin against potential problems. Ignition is required on ITER to get the power and this corresponds to a well- defined set of machine and plasma parameters. For example, if the magnetic field achieved is 10 % lower, ignition becomes almost impossible.

Limiting the ITER objectives to those foreseen in the first phase of operation would reduce the complexity and the cost. In order to demonstrate ignition, superconducting magnets are not required even for long burns (1000 sec or more) and could bring a substantial saving of the ITER cost. The impact of the superconducting magnets is large: their cost is already 30% of the capital cost, and the cost of the cryostat, the cryoplant, and the thermal shield have to be added. The requirement on the shield thickness is also reduced allowing the magnetic energy to be decreased. There is little impact on the power supply cost as the cost of the extra power is compensated by the quench protection system cost. In operation, superconducting magnets will also slow down all interventions on the machine which is still an experiment and which will require a series of modifications. Only the second phase of ITER and the proximity of constructing a pure fusion reactor could justify to have a superconducting magnet.

It must also be recognized that ignition is only required for a pure fusion reactor, operating in a pulsed regime, where the total power gain has to be provided by fusion reactions. For the next step, it could be better to demonstrate that the divertor and the first wall of a machine smaller than ITER could withstand a plasma during a long burn (1000 sec) at a power of a few hundreds of MW before embarking on a machine of the ITER complexity and size.

Parameters	ITER	Reactor
Major Radius	8.1m	10.2m
Minor radius	3m	3.3m
Elongation	1.55	1.6
Magnetic field (magnetic field at conductor 13T)	5.7T	7T
Plasma Current	24MA	29MA
Blanket & VV thickness	1.3m	1.4m
Flat top duration	1000s	2.5 hours
Neutron Flux	1 MW/m^2	2.5 MW/m^2
Fluence	1MWa/m^2 (20 years)	25MWa/m^2 (10 years)
Thermal Flux	0.5MW/m^2	0.6 MW/m^2
P_{fus}	1.5GW	4.5 GW
$P_{thermal}$	2GW	6 GW
Capital Cost of fusion reactor	~ $ 7B (95)	~ $ 9B (95)*

Table 1 : Parameters of ITER (outline design) and of a possible fusion reactor.

*based on ITER Outline Design costing

A PURE FUSION REACTOR

A fusion reactor [5] could be based on the concept and studies made for ITER. A slight increase in the major radius could allow a flat top of 3 hours at 29 MA without any current drive. Such a fusion reactor (table 1) would produce an electrical power of 2 Gw with a better ignition margin than ITER and with almost no extrapolation on ITER foreseen plasma performances. On the opposite a major extrapolation has to be made for the blanket and the divertor in order to handle the heat and neutron fluxes at a power per square meter at least 2.5 to 5 times higher and a neutron fluence larger by a factor 10. To achieve a life time greater than 10 years the fluence required at the first wall is over 25 Mwa/m^2. Another crucial question is the availability of the reactor and the control of abnormal events during operations. The solution to these questions mainly depends on the thermo-mechanical properties and neutron resistance of the first wall and divertor materials. The choice of the blanket materials could be Vanadium, liquid Lithium and Beryllium. An aggressive development is required for these first wall and protection materials to obtain and maintain excellent thermo-mechanical properties at high fluence through their whole life in the reactor.

The General requirements for the breeding blanket and first wall are :

- To operate at high temperature (over 400°C) for electricity production
- To withstand a high heat flux (1 MW/m^2) and neutron fluence (25 MWa/m^2 or more)
- To breed tritium with a ratio greater than 1
- To be robust so that replacement is exceptional during the life of the reactor
- To use low activation materials, e.g. Vanadium, Lithium, Beryllium.
- To have a coolant compatible with plasma protections if possible at low pressure (liquid metal)
- To be a light structure to minimize cost and waste management
- To minimize remote repair and eliminate in principle the need for replacement

In order to be regarded as a potential source of energy, fusion reactors must achieve a high reliability and availability, at a cost comparable to the other sources of energy. The first wall and divertor are the most vulnerable elements due to the forces generated and the local deposition of energy during abnormal events such as disruptions, sawteeth, Elms-H.L. transitions, and to the continuous erosion by neutrals and ions. A high reliability and life time generally demands a low power density in opposition to the request of achieving economic competitiveness.

In the case of fusion, 4 times more neutrons are required to liberate one MW than in the case of fission, and the fusion neutron energy is 7 times higher (14 MeV compared to 2 MeV); In a fusion reactor, all the neutrons go through the first wall which has to separate the plasma from the blanket, to survive occasional contacts with the plasma edge, to withstand the coolant pressure and to maintain a high vacuum integrity. The availability of the machine depends strongly on the failure probabilities of the first wall, the blanket and the divertor. If the blanket is not cooled by a liquid metal there will be more than 10.000 cooling tubes which will have a large failure probability, specially if a high pressure coolant is used (helium, water).

A complete change of the first wall requires at least two years, and therefore cannot be done more than once in the life of the reactor: the first wall and the blanket must survive at least 10 years of full operation without a fault.

In the magnets and their cooling system, the reliability of the liquid helium pipes, conductors and connections inside the cryostat must also be extremely high. The time required to repair by remote handling any component inside the cryostat, to heat and cool down the magnets, has a serious impact on the machine availability.

In view of the high technical content of the reactor the estimated capital cost of such a device is found high compared to the other sources of energy if the power density on the first wall and on the divertor is not pushed outside realistic limits. The cost is linked to the mean power density: in the machine only the first 15 cm of the blanket produce heat; the blanket thickness is about 1.4 m to shield the superconductors (including the clearances). Assuming that the neutron power to the superconducting magnet is limited to 10 KW for 4 GW of neutrons, the number of absorption lengths is at least 13 as the slot and the opening in the blanket have to be taken into account. A similar thickness is needed for the magnets. All these elements are high technology. Due to these facts, in comparison to a fission reactor, the capital cost will always be higher by a significant factor. In addition the availability of the fusion reactor will tend to be lower.

In order to control the plasma, to develop the new technologies, to obtain the reliability at competitive cost several steps will still be needed after ITER. To establish a coherent development program towards a commercial reactor is a priority and this must not be concealed behind a single project like ITER.

3. HYBRID REACTORS

***INTRODUCTION* :**

Hybrid fusion reactor have been studied for a long time by teams which where relatively small in countries like Russia, USA, Japan, [6] [7] [8] but these studies have not been generally encouraged by the fusion and fission communities. Hybrid reactors are smaller than pure fusion reactors as they don't have to operate at ignition. Their blanket includes some fission fuel. This only requires a modest change in the blanket and permits a full spectrum from pure fission to pure fusion

In a pure fusion reactor, the 14 MeV neutrons are slown down to produce heat and not used at their full potential. The hybrid solutions will try to use the 14 MeV neutrons as energetic neutrons able to produced extra neutrons; a multiplication factor greater than 2 could be achieved. The best multipliers in this respect seem to be beryllium and uranium 238.

These extra neutrons could be used : a) to increase the power produced in the blanket by induced fission, b) to burn actinides and plutonium, c) to use other fission cycles (thorium, uranium 238). By replacing beryllium by uranium 238 as a multiplier, fast fission occurs and the energy produced could be multiplied by 4 to 10 depending on the criticality of the blanket (0 to 0.5).

POWER BALANCE :

In a hybrid reactor the energy multiplication factor F could be considered as a product :

$F = Q_f \, . \, M$, where M is the multiplication factor in the blanket and Q_f is the gain of the fusion system.

The gain in a fusion device could be expressed by the following formula:

$$Q_f = (5 + b)/(nT\tau_{ign}/nT\tau - 1) + b$$

where $b = P_{bp}/P_{losses}$ and P_{bp} is the power generated by plasma-beam interactions; b could be close to 0.5

To produce energy in a realistic way F must be greater than 25 , when assuming a thermal efficiency of conversion ~1/3 and a beam efficiency production ~ 1/2; for F = 25 , 25 % of the electricity is recirculated for plasma heating

- In a pure fusion reactor $M \sim 1.3$. $Q_f > 25$ imposes $nT\tau / nT\tau_{ign} \geq$ 0.8 value already close to ignition as the product $nT\tau$ is proportional to the square of the plasma current multiplied by the aspect ratio : $(I \, . \, R/a)^2$. If M=5, Q_f must be ~5 . At such a Q, a Tokamak requires only a current of 15 MA compared to 25 MA at ignition but with an increased aspect ratio as the small plasma radius a decreases faster than the major radius R .
- Such an hybrid reactor, at a Q of 5, has therefore a smaller size and cost. At the same time the demands on the first wall and divertor are reduced : the power density on the first wall and the forces arising from a disruption decrease.The specific cost of a MW produced could be reduced by a factor 5 for a given fusion machine, and, or the availability of the reactor could be increased by lowering the fusion power per m^2 . A direct burning of plutonium could also be done. The utilization of other cycles as the thorium cycle could be attractive.

The general aspect of a hybrid blanket is not so different from the one of a pure fusion reactor, except for the power density and forces on the first-wall and the divertor. The coolant could be liquid lithium carrying 1 mm balls of uranium 238 and operating at low pressure (10 bars). Other solutions for the multiplier and the coolant are also possible, beryllium and liquid lithium, or oxides and helium or water as coolant . But in this latter cases, the pressure has to be high, between 100 and 300 bars.

COMPARISON WITH PURE FUSION

Advantages

Hybrid reactors are only sligthly more complex than a pure fusion reactor, but the main advantages are :

- a gain of a factor 2 to 10 in power could be achieved for a given capital investment
- a decrease of the size (weight, advanced components) by a factor of at least 2
- a much higher availability as a lower thermal load (factor 2 to 3) allows a thicker first wall with lower stress and fatigue and as the energy per m^2 delivered to the first wall, in abnormal events, is a factor 3 lower.The neutron flux per m^2 is also lowered by a factor 2 to 5 and the neutron fluence is reduced by the same ratio.

All these elements increase the life of the first wall by a factor 3 to 10 and will allow, with a good probability, to keep the same first wall for the full life of the reactor. In the same way the solution of the divertor is much simpler and more in line with what is technically possible. The impact of a hybrid blanket on a fusion machine is quite small. There is no increase in the blanket thickness as it is controlled by the 14 MeV neutrons. The general concept of the blanket is also very similar.

The hybrid route gives the possibility to develop the fusion system toward a pure fusion reactor through an industrial way in smaller and less risky steps with a series of reactors used to produce energy or to supplement fission in decreasing the level of actinides produced.

Disadvantages

• Like a fission reactor there is a production of fission products as wastes; there is also a production of a certain level (1%) of plutonium; when over this percentage, the plutonium is directly burned in the hybrid reactor.

• An increased confinement of the radioactive material may be required in such a reactor. A reprocessing of the fuel at the end of its life will be done, but the total reprocessing required could be 1/10 of what is done for a fission reactor.

COMPARISON WITH PURE FISSION

Advantages

- Compared to a fission reactor, the hybrid blanket is a passive system : there are no control bars as such. The hybrid reactor is a two-step amplifier: the power output is directly a function of the heating power injected into the plasma.
- For a fission point of view, the blanket is far from being critical ($k_{eff} =$ 0 to 0.8).
- Uranium 238 could be burned directly, as a fuel, without passing through an external plutonium cycle.
- An hybrid blanket could burn some of the actinides produced by fission reactors.
- No loading, unloading or reprocessing of the fuel during the lifetime of the reactor could easily be achieved.
- Other cycle like the thorium cycle could be implemented.

Disadvantages

- The complexity and the geometry of such a system is similar to a fusion reactor;

There is also a tritium production which in turn is burned in the hybrid reactor but this production is at a much lower level than for a pure fusion reactor as the fusion power is only 1/10 to1/5 of the total power produced.

- The possibity of proliferation is intermediate between a fission reactor and a pure fusion reactor.

COMPARISON WITH THE ENERGY AMPLIFIER (C. Rubbia) [9]

The basic idea proposed by C. Rubbia and others, is also to use an external neutron source to enlarge the possibilities of fission.

The starting neutrons are produced by spallation and have an energy around 25 MeV. Their production doesn't involve any gain from the accelerator as it is in a fusion device. The consequence is that the "blanket" must be relatively close to criticality ($k_{\alpha} = 0.95$) to get a multiplication factor M around 40 ($F = c\ M$) where c is less than one to take into account the more difficult production of Gev beams. As a consequence, the fission part of this system is close to a fission reactor.

The problem of the window between the GeV accelerator and the fission part (the blanket) is similar to the problem of the first wall in a fusion reactor : there are thermo-mechanical problems, neutrons and high energy particles induce degradation, and the requirement of maintaining a high pressure barrier. For these elements, remote handling maintenance is required. But since there is no magnetic field, the use of liquid metals as coolant is easier than in a fusion reactor.

The acceleration systems which is external still need developments to achieved the availability and the efficiency required.

4. A POSSIBLE ALTERNATIVE PROGRAM

As fusion research now centers on reactor development, the position of fusion among the other energy sources needs to be assessed. It is appropriate to integrate fusion in the overall nuclear energy system and to look for a broad range of solutions including hybrid reactors.

The ITER project would not make sense if it is not inbeded into a world program [10] which would have to be implemented in the near future. Such a program must include the research and developement on the different aspect of a reactor. If the cost of such a program is limited to a fraction of present world fusion budget, it will be difficult to build ITER with its present objectives, and ITER could have to be replaced by a smaller machine. In these conditions a world program with several projects, each project being under the responsibility of a major country, with a minority participation from the others, may included a $Q = 5$ long burn Tokamak, a neutron source for material testing and a physics research Tokamak looking at advanced scenario. It has also to include the development of first wall material, the construction of blanket elements suitable for a reactor, a divertor test bed operating in continuous mode at high power density.

AN INTERMEDIATE STEP FOR FUSION

A $Q = 5$ long burned Tokamak, compared to an ignited ITER, would be an intermediate step. It could be a copper magnet machine of 15 MA ($Q = 5$) producing between 300 to 500 MW of fusion power with an additional heating around 80 MW, a toroïdal field on the axis of 4.5 T with a small radius a=2,4 m , a major radius R = 6,2 m and a pulse duration of 1000 s. Such a Tokamak could be built at a cost of about 2.5 billion ECUS on a shorter time scale than ITER and with a simpler and more effective organization. It would produce the plasma required for a hybrid reactor without extrapolation and would also allow to demonstrate the sturdiness and the reliability of a divertor concept but at reduced power. It would be a major milestone toward a pure fusion reactor. A $Q = 5$ Tokamak is also a much more realistic proposition for a steady state Tokamak with current drive. It could be built by Europe with a minority participation of some of the other parties.

DIVERTOR DEVELOPMENT

The divertor and the first-wall protections are critical for the fusion reactor to achieve a high level of reliability. To study different divertor concepts and to choose the material require a series of test at a realistical level of power during a length of time comparable to the desired life time. The test of some of the different concepts will be made in the present Tokamaks, but only during short pulses (generally less than 20 s). To study the divertor behaviour under very long pulses, the constructions of a new divertor test bed with a continuous plasma at high power density seems required. An intermediate step Tokamak would also test a divertor in a realistic way , but the number of concepts which could be implemented in it, is limited .

FIRST WALL AND BLANKET

The first wall and the blanket play also a vital role in the reactor performances. Materials with high thermo-mechanical properties and with low interactions with the neutrons demand a new development. A series of test-beds have to be constructed to test the properties of blanket elements under high thermal load. Small neutrons source of 14 MeV neutrons will permit to define the linear answer of blanket elements, but a high intensity neutron source is required to test the material properties at high fluence ; In order to achieve significant testing in a reasonable time, the neutron- intensity must be higher than in a fusion reactor. This could only be done in a small volume .

5. CONCLUSIONS

For fusion to be a realistic energy option in the next century, it seems timely to develop an overall world program. This could allow to judge the coherence of each individual step. The different elements of such a program could be managed by each party: The European could built a $Q = 5$ Tokamak , the Japanese their JT60 super upgrade (without tritium but with current drive), the U.S. could look for the possibility of advanced scenarios and, with Russia, provide some of the test-beds.With such an organisation the question of responsibility is clear, and there is even no need for major money transfer between the Parties. The laws exist and the continuity of these projects could be assured. In the same way as the collaboration in Europe did not start with JET but with "the Associations", an "ITER" program more than an ITER machine could provide a framework for the world collaboration.

In this respect Europe, together with the other parties, should develop its views on such a world program and defines its participation. But this will take some time and the following actions have to be started, if fusion has to retain its momentum.

An European intermediate step Tokamak ($Q = 5$) needs to be considered, taking into account the different risks, financial, structural as well as technical risks, associated to ITER,.

Serious studies of hybrid reactors must also confirm the gain which could be obtained in terms of power, and the ability of fusion machines to burn or to decrease the production of actinides in a realistic concept.

Test facilities need also to be studied and their construction started, independently of a specific machine : a continuous plasma generator for divertor testing, loops for blanket studies, small 14 MeV neutron sources for neutronic evaluations of blankets, testing facilities for the development of vanadium alloys... In addition a high power 14 MeV neutron source is also required (in a small volume) to study the behaviour of the first wall material under high neutron fluence.

6. ACKNOWLEDGEMENTS

The author thanks Dr.C.Maisonnier, Director of the European Community Fusion Programme, for frank discussions on the matters of this report and for help in publishing it, even if the personal opinions expressed are often at variance with the consensual views underlying the Community Programme.

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European Commission

Reflections on fusion future

Luxembourg: Office for Official Publications of the European Communities

1996 — 14 pp. — 21 x 29.7 cm

ISBN 92-827-0371-1