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From JET to the reactor

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Abstract
In the past, JET results have been prominent in defining ITER. Only absolute performances matter in a reactor, and these have to be already optimised, JET can still increase the fusion power and energy produced. The main difficulty toward a reactor is the low performance of the divertor. An hybrid fusion-fission reactor could be an intermediate solution as the fusion power demand is reduced by a factor 10. In this respect, ITER is sufficient to be the core of such an hybrid reactor.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The studies made in the field of fusion are directed towards a reactor, as fusion is considered a clean, cheap and abundant future energy source, but the task is long and difficult, even if we all want to see fusion in operation in as short a time as possible, and we have to keep in mind that the last step will take 25 years or more.

As we enter a new phase in fusion research with the ITER construction now approved, we may be wondering where we are going, how the road is towards a commercial reactor, how many steps have to be financed and what research has to be done.

In this paper I shall give some of my own thoughts on these questions, starting with JET and the reasons for its success.

2. JET

In 1973, a design team was gathered at Culham in the UK to prepare a design for the construction of JET. This team, with the help of the Associations, proposed the JET project in 1975, as defined in the R5 report [1].

I would like to name and thank some of the key members responsible for the JET conception during the design phase: Alan Gibson, Dieter Eckhart, Michel Huguet, David Smart, Enzo Bertolini and also Peter Noll, Tullio Raimondi, Lars Sonnerup, Karl Selin and many others.

[1] Hannes Alfven prize 2006 lecture.

JET is a large step from the previous experiments. The proposal for the JET machine was a major leap forwards when compared with the best parameters achieved at the time, a circular plasma of 1 m^3 volume carrying a 300 kA current. The experimental evidence from the first tokamaks was that the transport in the plasma was anomalous, controlled by instabilities and fluctuations, and could not be the result of coulomb collisions between particles.

It was suggested in the R5 report which defined JET that the plasma current was one of the major parameters determining the confinement. JET was the first tokamak conceived with a D-shaped cross-section, in order to ease the stresses in the toroidal coils and to increase the plasma current. The JET results have proven the soundness of this concept. The impact of the D-shape and a tight aspect ratio on the achievable plasma current and on the stability limit was correctly described in R5 and has been fully justified in the subsequent JET operation, up to 4 MA in H-mode and 7 MA in L-mode.

The JET project was already directed towards the fusion reactor. In the founding R5 document, I recall the JET basic objective that was defined as follows.

In R5 it was also stated as follows.

Therefore the simplest technologies had to be chosen for the coils (copper), the vacuum vessel and, as a rule for all the JET components. The robust construction has allowed machine performance over its initial upper limits and created margins in hand to solve some of the physics limitations encountered during the machine operation.

JET was calculated to withstand 100 000 pulses at full power. As in reality this number of pulses will never be reached, a margin exists in the operating parameters. This margin has later allowed the installation of internal coils to create a divertor, an increase in the magnetic field on axis to 4 T and the achievement of a plasma current of 7 MA. The number of toroidal field coils (32) was chosen in order to have a very low magnetic ripple in the plasma and to be able to use the full vacuum vessel cross-section.

The remote handling capability for maintenance and modifications had to be integrated in the entire design from the beginning. This included all basic operations such as bolting, welding, cutting, positioning and transport of equipment. A remote handling manual describing every elementary operation was created during the design phase and has been regularly updated.

From the D-shape, we could expect ‘ q_{POI} = q_{TOR}, quoting again from R5.

With few exceptions, JET has always operated with a D-shaped cross-section since the R5 predictions were correct. ITER has now also been conceived with a D-shaped cross-section and the same elongation as JET.

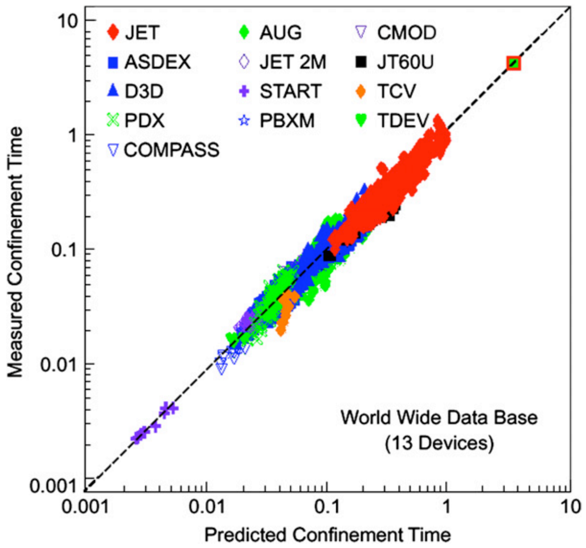

Figure 1. Energy confinement scaling reduced to three dimensionless parameters: □ , □ and □N. Only similar plasma could be compared; this constraint imposes plasmas with D-shaped cross-sections. This diagram shows the importance of JET results in defining ITER (shown by the red square); the experimental data covers almost three orders of magnitude.

From the very beginning, JET engaged itself in studies of transport expressed in terms of non-dimensional parameters, as any underlying physics law is a relation between such non-dimensional parameters, see figure 1.

Beryllium has been one of the materials successfully tested for the first wall plates in contact with the plasma (see section 4). Beryllium was also periodically evaporated on the inconel walls of the vacuum vessel. JET is the only machine able to carry out these tests which are required before this technology could be transferred to ITER.

Additional heating was also announced in R5 as a basic element for JET. '*1*
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3; 1 was foreseen. This was a gigantic step from TFR which, at that time, was equipped with 100 kW of neutral beam injection.

JET was conceived from the beginning as a nuclear machine for tritium operation and was designed to produce a large number of 14 MeV neutrons. This required a full remote handling capability and 3 m thick surrounding concrete walls to absorb the DT neutrons. The nuclear experience gained on JET has proved to be of utmost importance for ITER and the reactor.

The performance and the quality of JET were demonstrated by the first ever DT pulse for controlled fusion in 1991, one megawatt for one second, and the record fusion power of 16 MW in 1997.

Without JET, ITER would not exist today.

In a reactor, only the energy produced by fusion reactions matters and this depends on the absolute performance of the machine, not on a record for some of the non-dimensional parameters.

With advanced tokamak modes of operation which require increased complexity, we must also gain in absolute performance which depends on the volume use, the plasma current and density. The control of the current density imposes energy recirculation, has an impact on the cost and tends to decrease the plasma volume and plasma current. The real gain of such H-modes has to be proven in tritium operation. Only JET could do this prior to ITER.

JET could still increase its absolute performance by almost a factor 2, mainly by adding some neutral injection power and perhaps by taking some advantage of advanced scenarios; it is the only machine in the world able to operate with tritium and it has to do so.

The limitation on neutron production under EFDA, well under its original approved design, is a serious brake on JET exploitation.

The role of JET is also to train physicists to be ready to work on ITER, with the key aim of increasing its absolute performances in DT. JET and ITER will be judged on the power and the energy produced in DT experiments.

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Until the end of 1999, the JET project was a joint undertaking directed by the JET council and the JET director. The JET project was a legal entity. Two annual budgets, one for payments and one for placing contracts, were voted each year. These budgets included the salaries of the JET team. The financial management, the placing, following and payment of contracts were the responsibility of the JET undertaking. The team organization was based on a hierarchy of responsible officers who followed each component from its definition to its construction and operation. The project evolution was publicly discussed each week among the JET team and the necessary decisions were taken. Any equipment not absolutely necessary for the programme was rejected.

This organization and the quality of the JET team had allowed JET to be built in time and stipulated cost and to take the lead in its field.

JET is now under the EFDA organization where the responsibilities are distributed among JET and the associated laboratories but at the cost of a certain loss of efficiency.

3. ITER

A step after JET was clearly mandatory to develop fusion further. That step is the ITER project with plasma heating by □particles for 400 s being the main objective.

JET and ITER have the same shape of plasma cross-section, see table 1. ITER is a larger superconducting version of JET that must achieve a □ of 10 when the □particles are responsible for 2 □3 of the plasma heating; at this □ value the fusion power reaches 500 MW. The ITER objective again underlines the fact that only absolute performance is important to demonstrate advances in fusion research. The □ of 10 for ITER assumes that everything is working at its nominal maximum performance, without large margins built in for technology and physics.

Using the same technology and the same rules to estimate the cost, a slight increase in the machines ITER or MCuQ10, figure 2, costing 20% more, would have been sufficient to get ignition.

Having superconducting coils adds to the complexity and to the cost of the machine; the cryostat will have to be serviced remotely in the space between itself and the tokamak.

Even if there is no doubt that a fusion reactor will have to be superconducting, in my opinion it was premature to do it for ITER, on the program leading machine which is still far from a reactor.

However, the choices have been made, and it is essential for fusion research that ITER be successful.

To achieve this □ of 10, the plasma must operate in the H-mode (high confinement mode). The H-mode appears above a given power threshold in the presence of a divertor. However,

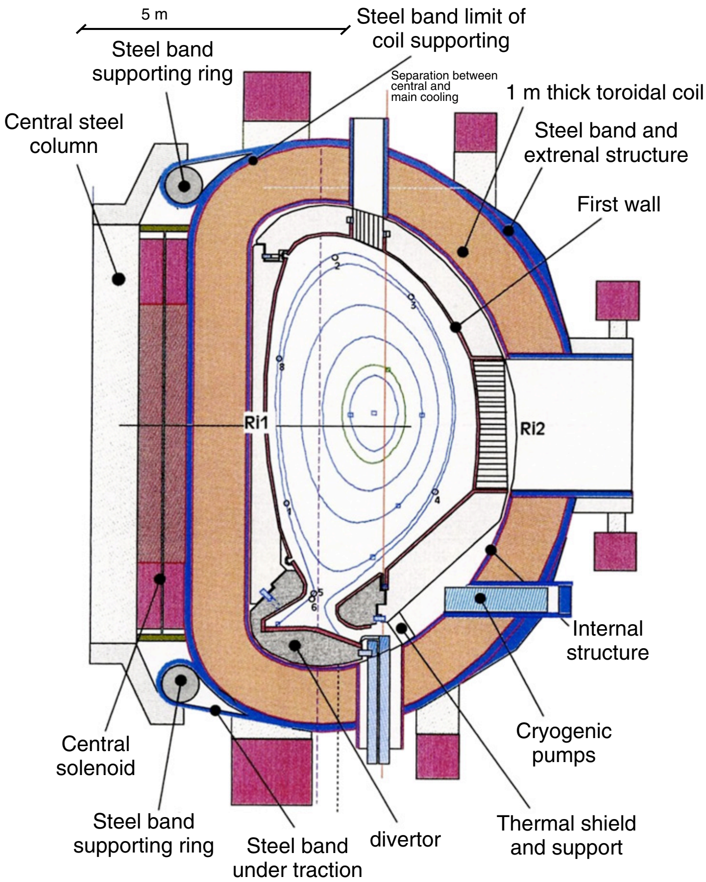

Figure 2. A copper machine with performances similar to ITER: MCuQ10.

it has a specific problem—it is not possible to maintain it for a long time. The edge energy barrier is also a strong barrier for particles. The density and the pressure gradient increase at the barrier location until MHD instabilities appear and destroy the barrier, with a release, in a burst, of the extra stored energy, known as the edge localized mode (ELM). The presence of large ELMs, appearing at low frequency, is not acceptable for ITER or for a reactor, as the power peaks are too high for the divertor. A partly degraded solution, the 'ELMy' H-mode, where the frequency of the ELMs is sufficiently high to limit the energy bursts to a more acceptable value, has been chosen. The ITER performance values are based on this mode of operation, with the hope that the advanced operation mode could ease some of the problems to be encountered.

4. The divertor

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The plasma edge can only be defined through a material contact, where energy is transmitted. If the whole energy produced is radiated, then the plasma boundary is undefined and generally the plasma collapses, e.g. disruptions, MARFEs. A significant part, roughly 20% of the energy heating the plasma, must be evacuated through a material contact at the plasma edge, limiter or divertor to keep an equilibrium stability reserve.

Table 1. JET and ITER main parameters comparison.

	Maximum values achieved on JET separately	ITER Design values
R and a	3 m 1.25 m	6.2 m 2 m
Elongation	1.8	1.7
Plasma volume	100 m^3	840 m^3
Magnetic field on axis	4 T	5.3 T
Plasma current in D- shaped plasma	7 MA	15 MA
Plateau current	60 s (1 MA)	400 s
Modes of operation	L, H and ELMy	ELMy
Plasma contact	Carbon and beryllium limiters—pumped divertor	Pumped divertor
Neutral injection to the plasma	22 MW	33–50 MW
Coupled ICRH	22 MW	20–40 MW
Coupled LHCD	7.3 MW	20–40 MW
ECRH	0	20–40 MW
Current drive	3 MA (LH)	5 MA (external))
Central density	2 10^{20} m ^{3}	10^{20} m ^{3}
Electron temperature	20 keV	21 keV
Ion temperature	40 keV	18 keV
□ value in DT plasma	0.6 (0.9 net)	10
Fusion power	16 MW	500 MW
Fusion energy	22 MJ in 4 s	□120 GJ

The ELMy H-mode is obtained with frequent ELMs when the discharge is not too far from the H-mode threshold. The H-mode threshold scaling suggests that the three basic non-dimensional plasma parameters are not sufficient to express it; another parameter is required like one linked to an atomic process such as radiation or ionization.

In other words, the H-mode would be the natural confinement mode in the absence of a neutral flux of particles coming from the walls. The L-mode could be regarded as an extreme mode in which the ELMs are continuous and create edge turbulence.

An important clue concerning the H-mode mechanism is that, on JET, it was possible to obtain H-mode even when the X-point of the separatrix was inside the divertor plates, transforming the divertor configuration into a limiter one. This seems to suggest that what is important is not the typical geometry of the divertor but the fact that the neutrals returning to the plasma have a large path between adjacent magnetic surfaces so that they can be ionized on the outermost surfaces.

We may take advantage of these facts, installing a limiter in the vicinity of the X-point rather than a standard divertor, illustrated in figure 3.

The advantages in a given machine are the following.

– Better plasma performance, a larger plasma volume, a factor 1.3 in the case shown in figure 3, an increase in the plasma current by a factor 1.2, an increase in the plasma pressure by a factor 1.1 and a higher fusion power by a factor 1.5.
– A simpler technical solution with a larger wetted area.
– Greater possibility for sweeping or moving the contact area, increasing the life of the contact plates.

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The power density on the divertor plates is very high, as the thickness of the scrape off layer is only of the order of a few times the ion Larmor radius, generally less than 1 cm, and the wetted

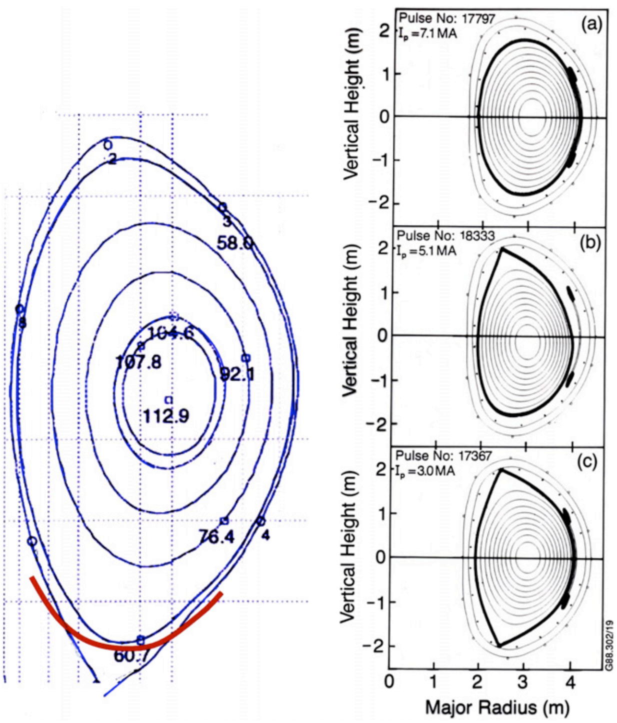

Figure 3. Plasma cross-section. The cross-sections on the right were produced on JET with the X-point just at the limit of the plasma wall. In these conditions, H-modes have been obtained. On the right, the plasma cross-section shows the approximate position of an X-point limiter in red; this plasma cross-section corresponds to an ITER cross-section shape, in fact the plasma shown in figure 2.

area width is less than 10 cm. On ITER, the total wetted surface is less than 4 m^{2}. At ▫ 10 the plasma heating power is 150 MW and the power falling onto the divertor plates is 30 MW when 80% is radiated, giving a mean surface power density of 8 MW m ^{2}. This is the upper limit of what could be achieved for divertor plates with high conductivity materials, such as copper and CFCs. Even so, the peak density will be higher due to fluctuations in space and time and it would be difficult to avoid surface melting and evaporation.

One possibility of protecting the target plates from the high heat flux is the concept of a neutral 'gas target' or 'gas cushion' in front of the target plates. The direct heat flux is removed through a combination of radiation losses from electrons and charge exchange losses from ions. For the atomic processes to be effective for hydrogen, the electron temperature must drop to a few electron volts. A more realistic concept was that of a 'radiative divertor' in which the energy is mainly dissipated by radiative processes involving a controlled impurity inside the divertor.

These concepts require a high particle density in the divertor and increase the total power which is radiated, easing the requirements on the design of the ITER divertor plates. On the other hand, the very high transient power loads associated with ELMs still pose a problem since they burn through the protective gas.

Tokamak operating scenarios must avoid large ELMs, even at the cost of a partial loss of confinement. Key questions are the compatibility of a high density divertor with an ELMy H-mode and/or an advanced tokamak mode and the effect of the neutral flux on the plasma behaviour.

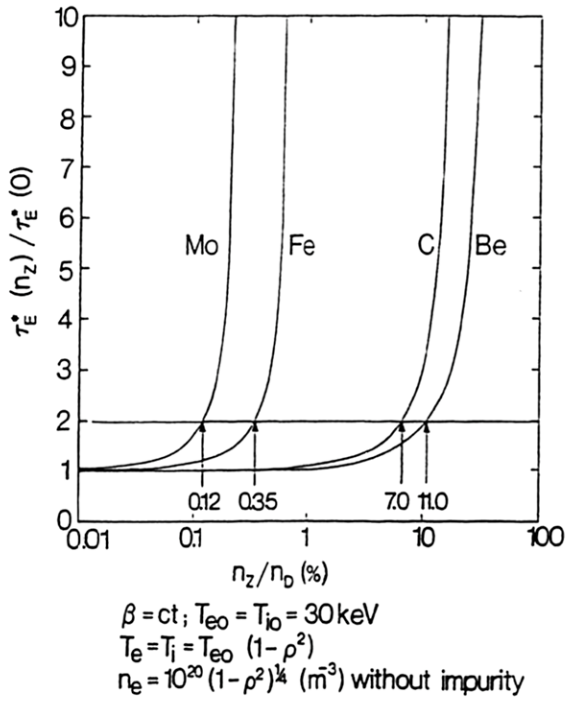

Figure 4. Enhancement factor of the energy confinement time required to reach ignition versus the impurity concentration. For medium and high Z impurity such as molybdenum and iron, the enhancement compensates the radiation losses. For low Z material such as carbon and beryllium, dilution is the dominant factor.

The materials in contact with the plasma are also subject to erosion by sputtering induced by ion impact when the ion energy is over a threshold, which depends on the material chosen. The sputtered material will deposit on the adjacent surfaces, at the same time burying some deuterium and tritium. This last phenomenon is especially important with carbon, when one hydrogen atom is associated with one carbon atom, increasing the tritium inventory in the machine.

Part of the sputtered material will find its way to the plasma as impurities. Even if the plasma can tolerate a relatively large percentage of low Z impurities, up to 5%, it is very sensitive to the presence of high Z impurities, tolerating less than 0.1%.

A basic choice has to be made between low Z and high Z material. The materials in contact with the plasma must have stringent properties: good thermal conductivity, a high melting point, a low vapour pressure at high temperature, good mechanical resistance to fatigue, a low sputtering coefficient and good stability in the presence of the neutron fluence. There exists no ideal material. The choice varies between low Z materials, Be, C and high Z materials, W. However, the low Z materials suffer large erosion, and the sputtering threshold for W is relatively low: 50 eV for hydrogen and even lower for materials with higher Z, see figure 4. The choice of W demands a high pressure in the divertor.

In view of these difficulties, it is planned to frequently replace the divertor using remote handling, a difficult operation since the cooling of the divertor plates has to be extremely strong and efficient.

For a given material, the erosion is proportional to the energy flux. Keeping the same stresses, the same temperature variation, the divertor plate thickness varies with the inverse of the energy flux, but the erosion is proportional. The lifetime of the divertor plates therefore tends to vary with the square of the inverse of the energy flux.

For sustained operation at high power, there is still no satisfactory solution for the divertor even for ITER. In my view, the divertor is the most critical component on the way to the reactor. Test beds for divertors, continuously operating at high power, have to be developed, but the real test has to take place in reactors themselves.

5. The fusion reactor

Energy production is the fusion reactor's . The energy produced has to be maximized for a given installation. Considering the cost of the investment for a commercial reactor, to re-circulate more than 20% of the electricity produced would have a serious negative impact. Taking into account the efficiency of the conversion from heat to electricity, 1 □3, the efficiency of the auxiliary heating and plasma control, 1 □3, adding the demand on cryogenic pumping and divertor cooling, a □ of 50 is required for the fusion reactor. In certain reactor studies a lower □ is taken but this seems to me linked to a too optimistic estimation of the technical performances.

Such a high □ means that only 10% of the total plasma heating can be provided by the auxiliary heating and control systems. This value looks insufficient to provide an effective control of the current and its profile in the plasma.

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One of the key elements has been already discussed, which results from the divertor operation. The ELMy H-mode with a high ELM frequency is generally the mode of operation foreseen, but the stability of such a mode in it is not fully mastered in combination with a high density divertor. The particle energy reserve could increase the plasma pressure and trigger a disruption if the plasma is too close to the □ limit. On the other hand the ELMy H-mode could switch back to L-mode with resulting confinement degradation.

Another point is the question of the control of the current and its profile, required for continuous plasma operation or for advanced tokamak mode of operation. This requires current drive systems which actually tend to operate better at low density and are not very efficient compared with the associated energy dissipation. The generation and control of the plasma current profile tends to lead to operation with plasmas at a relatively high safety factor □ 4–5. With these modes it is difficult to get □ values much higher than 5, e.g. ITER.

Disruption avoidance is also of major interest for the routine operation of a reactor. All these points militate in favour of reactor operation far enough from the various stability limits and limiting the current profile control to the minimum. Continuous operation seems too difficult for a pure fusion reactor but long (several hours) pulses are possible by designing a reactor in which the major radius is increased to enhance the central solenoid, without changing the plasma cross-section. A 1 m major radius increase with respect to an ITER type machine could bring a several hours long pulse.

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The availability of a fusion reactor is one of the key elements for an energy producer.

For a fission reactor availability is 70 to 80%. In a fusion reactor, the most loaded elements are the divertor and the blanket. It is not conceivable that a remote handling replacement of these elements has to be programmed every 2 years. In addition to the time lost for such an operation, the cost of the exchange would weigh heavily on the cost of electricity. In addition to those stoppages, any unplanned shutdown caused by a component failure must be extremely rare.

For the first wall and blanket concept, let us simply say that the structure has to be as simple as possible. This precludes a high pressure coolant like water or helium and a heat–exchanger inside the blanket subject to thermal fatigue and neutron damage. Even in fission reactors, where the heat-exchangers are outside the reactors, they have been responsible for many failures.

The solution is to use a liquid metal or a fluidzed bed to slow down and absorb the neutrons to generate the tritium and to carry out the heat.

Having a light structure inside the blanket reduces its absorption of neutrons and activation. The fabrication of a structure using low activation materials is also simpler and the cost of changing the blanket is less. But a new problem appears such as the circulation of liquid metal through a magnetic field, requiring insulating material.

To summarize, the availability of a fusion reactor is the first key to success; every system has to be simplified as far as possible, and the fusion reactor must operate away from the stability and operational limits.

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ITER costs at least 6 G$ for a 500 MW thermal power without any electricity generating plant. Today a fission reactor costs 1 G$ for a 4 GW thermal power, a factor 50 between the two. Of course ITER is an experiment, and a unique one, and fusion has the advantage of operation cleanliness, but a factor of the order of 10 still has to be gained on the reactor performance. This again underlines the importance of volume use to produce a maximum power in a given machine and to achieve low energy recirculation to limit the extra cost on the investments. To gain the factor of 10, a higher fusion power will be required than ITER and this will again increase the power density on the divertor plates.

Several steps from ITER to a commercial fusion reactor are necessary to develop the required availability, the divertor plates, the erosion and co-deposition, the blankets and at the same time to reduce its costs. The basic question is how to finance such a development?

6. Hybrid fusion–fission reactors

Let us have a look at the 14 MeV neutrons produced by the DT reaction. In a pure fusion reactor, these are slowed down in the blanket where their energy is transferred. On the other hand, these neutrons have unique properties: they could induce fission reactions in most actinides, including uranium 238 and thorium.

Hybrid fusion–fission reactors take advantage of this property: 14 MeV neutrons induce fission reactions in U 238 located in the blanket. With one fission reaction for one fusion reaction, the energy gain in the blanket is 10, but the neutron flux is controlled by the fusion reactions.

Starting with a gain of 5 (□ 5) for the fusion core we get a global gain of 50 for the hybrid reactor, sufficient to produce electricity. Such a reactor operates very far from a critical condition (□eff 0 □).

Plutonium 239 and minor actinides are also produced in this process, but several of these actinides could also be burned in the same reactor. We then obtain an equilibrium for the

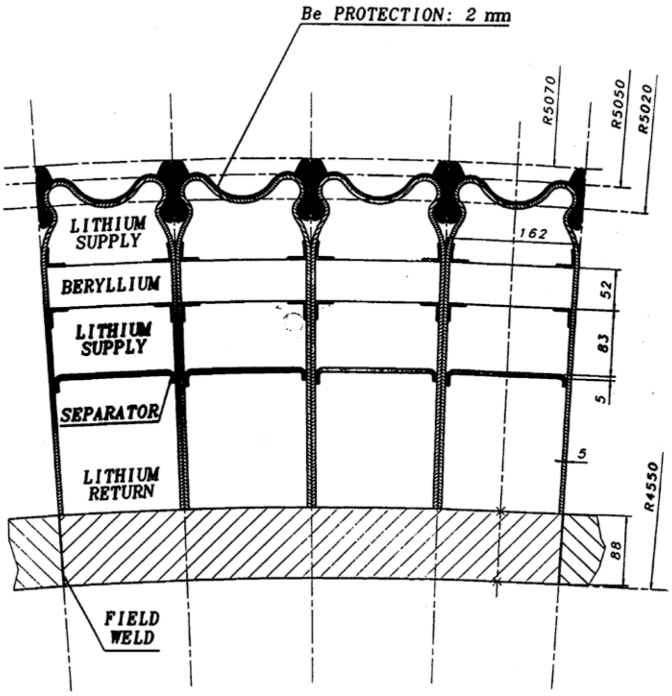

Figure 5. Cross-section of a blanket module. The structure is made of vanadium with the exception of the back-plate. The blanket is filled with liquid lithium and beryllium blocks.

actinide concentrations. This kind of study was performed at Sarov [2] in Russia within the ISTC framework.

A simple blanket model was chosen. This model is derived from the study of an ITER blanket, a low pressure system with liquid metal (figure 5). The blanket consists of a light structure in vanadium filled with liquid lithium. Beryllium blocks are used to multiply the incident neutrons. In the hybrid blanket, the lithium is loaded with small uranium balls that stay in suspension as a result of magnetic viscosity (figure 6). The dimensions are slightly changed. The three layers lithium + uranium—beryllium—lithium + uranium, are each 15 cm thick. In the hybrid blanket, the role of beryllium is to moderate the neutrons in order to ease the burning of the plutonium which is formed in the uranium balls.

The Li–U fuel circulates around the beryllium blocks at a speed of a few m/s with insulating walls.

The computation of this system was made with 14 MeV incident neutrons. The goal was to calculate the U and Pu concentrations to have (a) an energy gain of 10 and (b) the plutonium at equilibrium (as much plutonium is burned as it is produced).

The study produced a Pu concentration in U 238 of 5% at equilibrium and 10% of U 238 in the fuel (in atoms).

To summarize, in a hybrid reactor, the energy is produced by fission reactions but the neutron population is defined by fusion reactions. The assembly is way undercritical and very tolerant to a modification of any parameter; the blanket is a fusion energy amplifier.

One further advantage is the ability to burn uranium 238 or thorium directly, without needing U235 at the start, and to minimize nuclear waste.

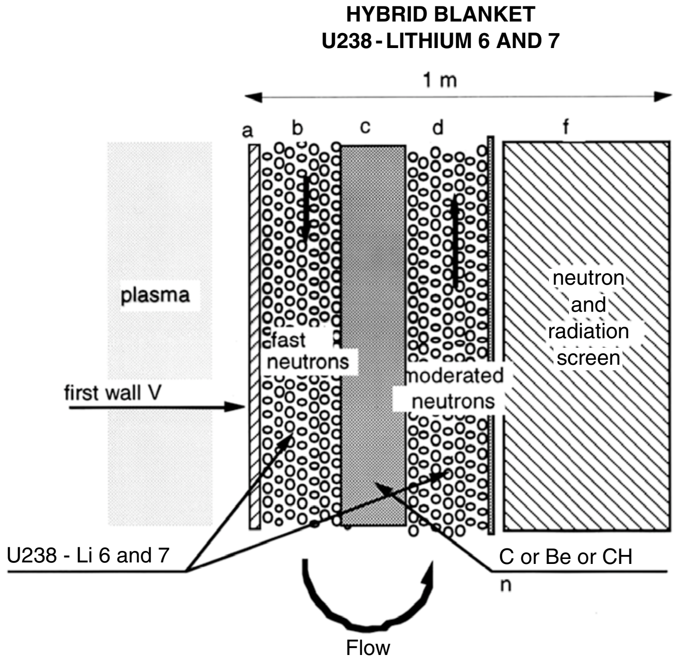

Figure 6. A modified vanadium liquid lithium beryllium blanket (figure 5) for a hybrid fusion–fission reactor. Small beryllium balls have been added to the lithium. Most of the power is produced inside the balls. The uranium balls are transported within the liquid lithium.

The ITER plasma with a fusion gain □ 10 and 400 MW thermal power is almost too powerful for a hybrid reactor core, since it would produce 4 GW total thermal power. With ITER it would be possible to test hybrid blanket elements at full size. Only the operation duration and the integrated neutron flux would remain far from reactor conditions.

The advantages of such a concept are the following.

(i) Compared with a pure fusion reactor:
- the constraints on materials are reduced by a factor from 5–50,
- this solution is quicker to develop than a pure fusion reactor.

(ii) Compared with a fission reactor:
- nuclear energy reserves are increased by at least two orders of magnitude,
- minor actinides are in part burned and the waste reduced,
- the uranium cycle is closed in the system.

This solution allows a harmonious development towards pure fusion. It is possible to increase the gain and the power density of the fusion core as soon as material developments allow it.

7. Conclusions

This paper draws the following conclusions.

- A reactor must operate at a good distance from the operating limits, current, density and pressure.

– An overall simplicity is necessary to achieve a high availability and a competitive cost per MJ.
– The time scale and the number of experimental reactors to be operated prior to a commercial reactor have to be reduced.
– For fusion financing to continue, it is important that fusion should have some use quickly.
– A hybrid fusion–fission reactor is a solution since ITER plasmas are sufficient for it.

References

[1] 1975 ′ - %) EUR-JET-R5(1975) (Brussels: Commission of the European Union)
[2] Zavialov 2004 ( ) . +- # & 909-2, work supported by the European Union