A step after ITER
with a hybrid blanket ?

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Introduction

- ITER is under construction; what progresses have to be achieved before commercial reactors could produce power and when ?

- This discussion is based on what is learned on ITER about divertors, first walls and blankets.
- Most of the options presented here could also be valid for the stellarator concept.
- ITER is foreseen to produce 500MW for 10 mn with a Q of 10 as its maximum performance. The construction cost of the machine is now foreseen to be between 12 and 15 Billions € and operation would starts around 2020 – 2026 with tritium.
- It is already a very complex machine.
- The time span between JET and ITER is 40 years.

The divertor

- The divertor is one of the most difficult element due to the plasma drect contacts on the divertor plates at a very high power density, even when it is supposed that the elms are completely controlled by ergodic magnetic fields at the plasma edge, produced by helical coils that partly destroy the edge confinement. It is foreseen to change the divertor when required, but this is not a solution for a reactor

- The material of the divertor have to be of high thermal conductibility (copper, tungsten) and have to withstand the high pressure of the coolant in presence of the neutron flux.

- To limit the surface temperature, the divertor wall thickness, is inversely proportional to the heat load but the sputtering and the evaporation are directly proportional to it. The divertor life time may decrease as the heat load square.

- Tungsten must not enter the plasma as its radiation would become a major lost. As a consequence the sputtering must be suppressed : the plasma temperature must be less than 50 that is difficult in the H mode

The first wall 1

- The first wall has similar problems with a much lower heat flux but the thickness of the wall have to remain sufficiently thin, not to absorb too many neutrons, less than 1 cm thick.
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- The temperature of the coolant have to be higher than that of the divertor, at least 300 ° C . The neutron flux is also a factor 2 to 3 time higher.
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- To allow the heat transport, the coolant, if water or gas, would be at high pressure 10 MPa or more.

- With a liquid metal coolant the pressure could be around 1 MPa , but it is an extremely difficult solution due to the presence of strong magnetic fields. Melted salts may have corrosion problems.

The first wall 2

- The first wall and the structure material must resist to high temperature, high stresses and to the neutron damage. It provide a separation between the plasma and the coolant: its vacuum properties are fundamental.
- Low activation materials, as vanadium alloys, ferritic steels with a thickness of a few mm are candidates. They are operating at high stress and high temperature and must be weldable for repair.
- The coolant with low neutron absorption could be :
- gas: helium, hydrogen,
- liquids: water, metals, melted salts

The blanket constraints 1

- The stresses acting on the blanket are due to :
  - the disruptions,
  - the differential thermal expansion
  - the coolant pressure.

- The forces generated by disruptions:

these forces depend on the eddy currents circulating in the blanket. They are limited by the blanket resistance as the disruption has a time constant. Often large forces are induced. To limit disruptions, operating margins are required for the maximum plasma current (q value), the β limit, the elongation, …

- The temperature variation inside the blanket could generate high stresses depending on the geometry.

- For the coolant : two solutions :

  - the high pressure with a passive coolant as water, helium or hydrogen at 10 MPa , but this pressure demands relatively thick tubes.

  - the low pressure one (1 MPa) where the fuel is the coolant: liquid metals or liquid salts

The blanket constraints 2

- The tritium extraction requires a fuel movement toward the outside, a few revolutions per month. It is the same for an hybrid blanket in order to homogenise the fuel.

- The neutron flux and their absorption by the structure material generate atom displacements and impurities that in general decrease the material properties.

- In case of a severe disruption the blanket and its first wall could be damaged and could only be repaired or exchanged by remote handling. Such a capability has to be provided from the original concept.

The first wall and structural materials

The development of structural materials is needed with:

- a low activation : like vanadium alloys, ferritic materials, SiC....
- high stresses at high temperature
- a low impact of atom displacements and of neutron absorption
- a welding and forging capability

The blanket concept has to be simplified as this would increase its reliability, reduce the fabrication cost and possibly increase its lifetime.

Tokamak continuous operation or not

Two solutions : the current drive (CD) for continuous operation, or a pulsed plasma with a long burn.

The current drive

efficiency is limited. On ITER, Q = 5 is foreseen for continuous operation.

The CD power increases with the current needed for the confinement.

This fact limits the Q obtained to values close to 5 .

Pulsed operation :

A high flux in the central solenoid is required; 1 extra m to the ITER central solenoid radius (and also outside), keeping the same plasma cross-section and performances, provides a continuous 4 hours of operation.

The system complexity also increases the cost

- The margin : the machine operation has to be repetitive without incidents. This demands to work inside the operative domain with a good margin and not at the domain limits. This could increase the size of the machine over the minimum one but the investment cost could stay the same as the internal equipment are easier to make and install.

- The availability is a key element. Without at least a 70% availability, nobody will be interested in such a machine even if the investment is low. These are keys for the success of a commercial reactor; at present we are very far from achieving these goals.

- The reliability of a reactor directly impacts on the availability. The machine has to be planned for an easy maintenance from its conception. Most of it has to be remotely made. A low reliability could have a disastrous impact on the availability.

The impact of the fusion power density

- A low fusion power density at the first wall and divertor level produces a large improvement on the margin and the availability but it may increase the machine cost.

- All the elements in contact with the plasma see their life-time increased as least as the inverse of the power density. A lower heat flux permit also thicker materials. The thermal stresses are decreased.

- The current in the plasma is lower with all the consequences on the machine size and stresses.

- The competitiveness with the other energy sources requires a simplification of the machine

Reactor required power gain G

- In a pure fusion reactor G ≈ Q

- We want to limit the amount of re-circulating electricity that significantly increases the cost of the machine; a 20% re-circulating electricity seems a limit not to be overcome. Such a limit imposes G > 50.

- The economy also implies that the electricity cost produced in such a reactor remains competitive with the other sources of energy. This not only implies a limitation of the construction cost but a high reliability and a availability of the power plant.

- An approximate construction cost, with the present conditions, is around 5 billion € for a 5 GW fission power which corresponds to at least a 2,5 cost reduction compared to ITER and a factor 10 increase in the power produced.

When, a fusion reactor ?

- The number of steps toward a commercial fusion reactor :

- At least 2 steps are required, one to demonstrate that the plasma of a fusion reactor could be achieved with a Q close to 50 and a duration of 1 hour or more with a power density on the first wall around **2 MW/m^2**. After this step a prototype of an electricity generating reactor will be needed before a commercial reactor could be built.

- Such a fusion commercial reactor will not be ready before the next century, 40 years have already be spent between JET and ITER (1983 -2022 ?)

- A solution to shorten these delays are the hybrid fusion-fission reactors where a reactor similar in size to ITER would be sufficient. It would require a much lower power density than a pure fusion reactor, around **0.5 MW/m^2** from fusion reactions.

The fusion - fission reactors - 1

Why fusion- fission hybrids ?

- To decrease the demand on fusion by a factor 10 to 30 by a rational use of 14 MeV neutrons in nuclear reactions instead of heating water.

- To be able to use fusion based reactors more rapidly

- Research on hybrid fusion - fission reactors is not new.

Burning plutonium and the other actinides produced by nuclear reactors is, up to now, the main subject of study in this field.

A slightly different view could be taken : it is possible to conceived an hybrid power reactor that, at the same time

- is largely sub-critical·
- consumes U_{238} and or thorium
- burns the actinides produced (mainly Pu)

A large energy amplification M in the blanket

- A single fission reaction produces 200 MeV to be compared to 20 MeV for fusion, a factor 10 less. A balanced hybrid reactor could be defined as **one fission for one fusion reaction** :
M = 10 in such a case :

- The power is mainly generated by fission, but neutrons are dominated by 14 MeV fusion neutrons

Energy gains:

For a reactor, taking into account the thermal and plasma heating efficiencies, a global energy gain G of 50 is required

- as **G = Q*M** , Q being the fusion gain, for example it is possible to have : Q = 5 and M =10 or Q = 2.5 and M = 20

- k_{eff} is in the order of **0.6 - 0.7** far from the critical value 1.

Hybrid consequences for the fusion reactor

- ITER plasmas are largely sufficient with Q=10, Q = 5 is sufficient.

- A lower fusion power, 400 MW **,** gives, with M =10, **4 GWth**

- Compared to pure fusion, there is a low power density at the first wall level and divertor plates which could be thicker

- The erosion decreases and component life time increases by more than a factor 10 ;

- Current drive becomes feasible $Q \leq 5$;

- It is also a way toward pure fusion as Q could increase as we become more confident in plasma control and materials ;

The scheme

The reactor study could be made for a Tokamak reactor similar to ITER with the exception of the blanket :

a main radius of 7 m , a Q = 5 , a fusion power of 400 MW corresponding to 0.3 - 0.4 MW /m2

- with a blanket containing uranium 238 and plutonium 239 in equilibrium (4 to 5 % Pu in the U238) having a global multiplication factor of 10

- heated by 4 neutral injectors, with energy around 500 keV and a power of 80 MW, the global efficiency from the grid being 35 %

- these injectors could also be used to generate the plasma current.

- the power produced by the hybrid reactor is 4 GW . With a 35 % conversion efficiency, the electric production is 1.4 GWe including 230 MWe to power the injectors.

The hybrid blanket

There is a large choice : the first one is **to burn U238** as this domain is well known

- The basic interactions of U238 with 14 MeV neutrons are :

- (fission) - (n , 2n) - (n, 3n) reactions with similar cross sections

- U 238 fission by 14 MeV neutrons produces 4.5 neutrons

- The sum of these reactions gives more than 3 neutrons per incident 14 MeV neutron and an energy gain of 3 .

- The cascade is not finished as the neutrons from n, 2n and n, 3n reactions are still energetic.

- When their energy is decreased, as in fast neutron reactors, there is a plutonium 239 production after a neutron absorption.

- The Pu produced will be in turn burned by fission or will absorb a neutron.

Demands on the blanket

I - A gain in energy > 10 : at least one fission reaction per fusion reaction ;

a low Keff : no control bars needed.

II - An equilibrium between Pu production and consumption and also burning minor actinides if possible.

III - A low Pu inventory.

IV - Tritium regeneration with a factor >1.2

V - If possible, no reprocessing during the reactor life.

A first hybrid blanket concept

This concept was chosen for its simplicity in order to make the neutron computation :

a low pressure system with liquid metal coolant (1 Mpa) :

- a mixture of liquid lithium with uranium :

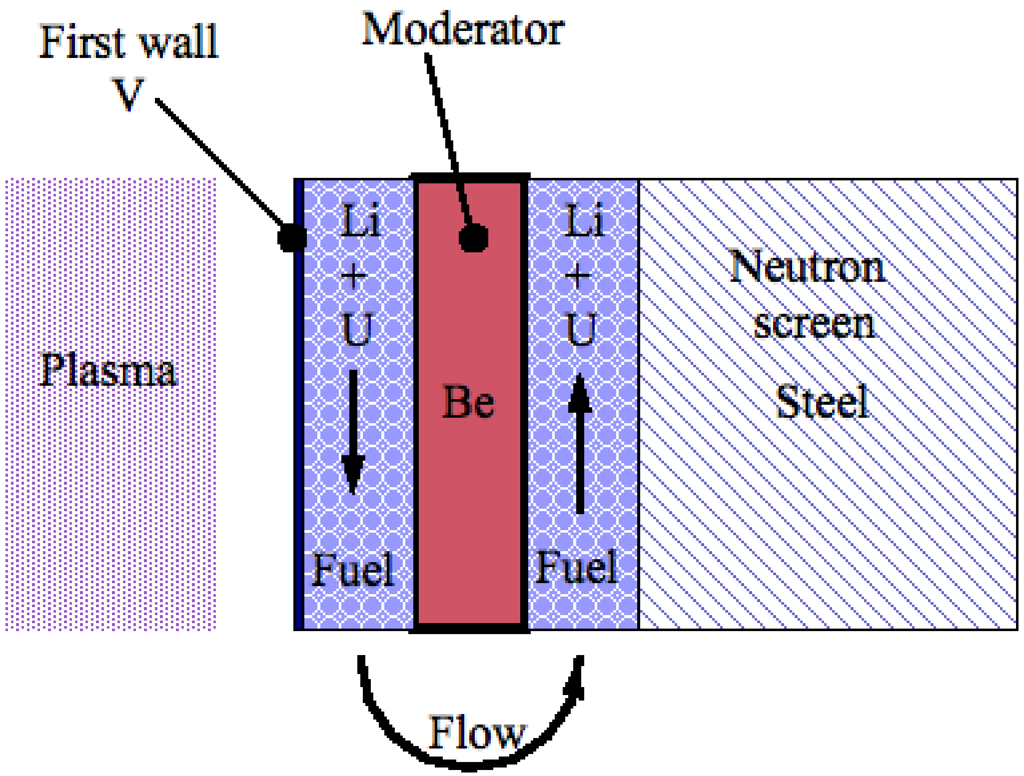
- To have an efficient Pu burning, neutrons must be slowed down, this is done by Be acting as **a moderator**

-The fuel (Li-U-Pu) re-circulates in order to **homogenise the fuel** to burn Pu near the moderator, Be .

- - An **equilibrium between plutonium production and consumption could be reached** at a given plutonium-uranium ratio ; over this ratio the plutonium decreases.

- The lithium 6 must regenerate the tritium in competition with Pu burning as lithium 6 absorbs neutrons to produce tritium.

Hybrid blanket scheme



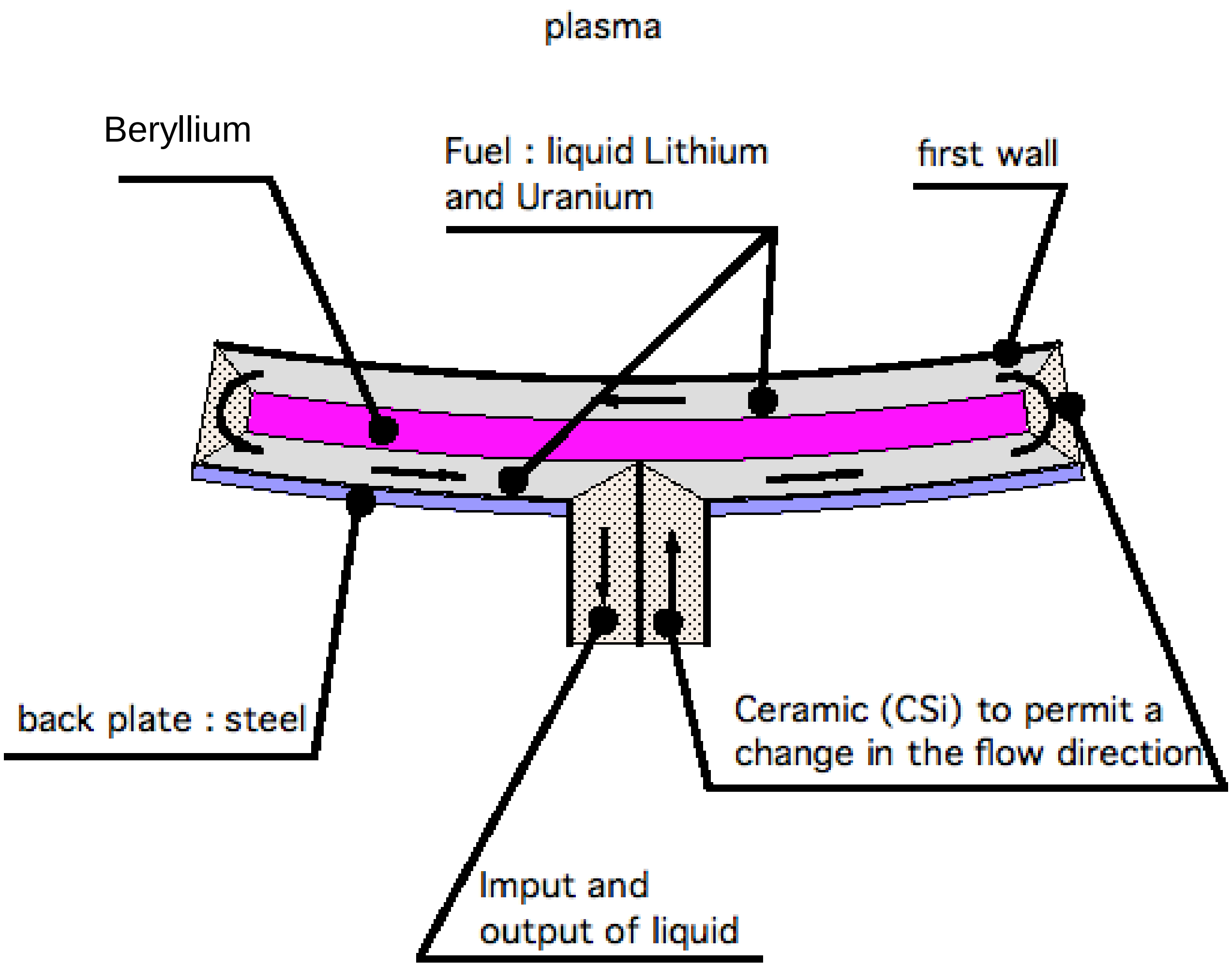
Around Be, neutron energy is smaller

Near the first wall their energy is high

An Hybrid Blanket Module (first concept)

The Hybrid Blanket Module lies in the toroidal direction;

the liquid fuel is also the coolant



Results obtained for the first concept

Computations in cylindrical geometry, R = 8.1 m, were made in Sarov by a Russian team directed by N. V. Zavyalov under contract ISTC 909 and in Saclay par J.P. Deffain

Blanket composition (case 1)

Layer	thick. cm	U+Pu %	Pu 9 (%)	Li %	Li 6 (%)	others
Wall	0.75					V
fuel	15	10	(5)	90	(2)	
Mode.	15					Be
fuel	15	10	(5)	90	(2)	
Screen	44					Be, steel

(values in bracket show the relative fraction, e.g. 5% de Pu9 in U+Pu)

Critics of this first concept

The concept, presented here, was done for neutron computations but presents several weaknesses :

- The coolant is the melted fuel itself and must circulate at a speed of around a few meters per second. That requires an insulating layer deposited on the container to limit the induced current.

- The volume of active fuel is 2 to 3 times that required by the hybrid blanket and stays outside the tokomak.

- It is also difficult to resist to the forces induced in the liquid metal during disruptions.

- The remote handling operations have not been studied.

Blanket constraints

The blanket must take care of and include :

- The cooled first wall
- The fuel movement
- The coolant piping
- The maintenance by remote handling and the access for the R.H. tool

It must resist to :

- The coolant pressure
- The disruption forces
- The thermal gradient stresses

It must be conceive with :

- The neutron efficiency in mind
- The minimisation of structural materials at the front end
- **the safety** as a priority

The concept of the blanket govern the reactor geometry

A solution with gas coolant

•The cooling is made by gas, helium or hydrogen. The coolant outside the fuel is at a pressure around 10 MPa .

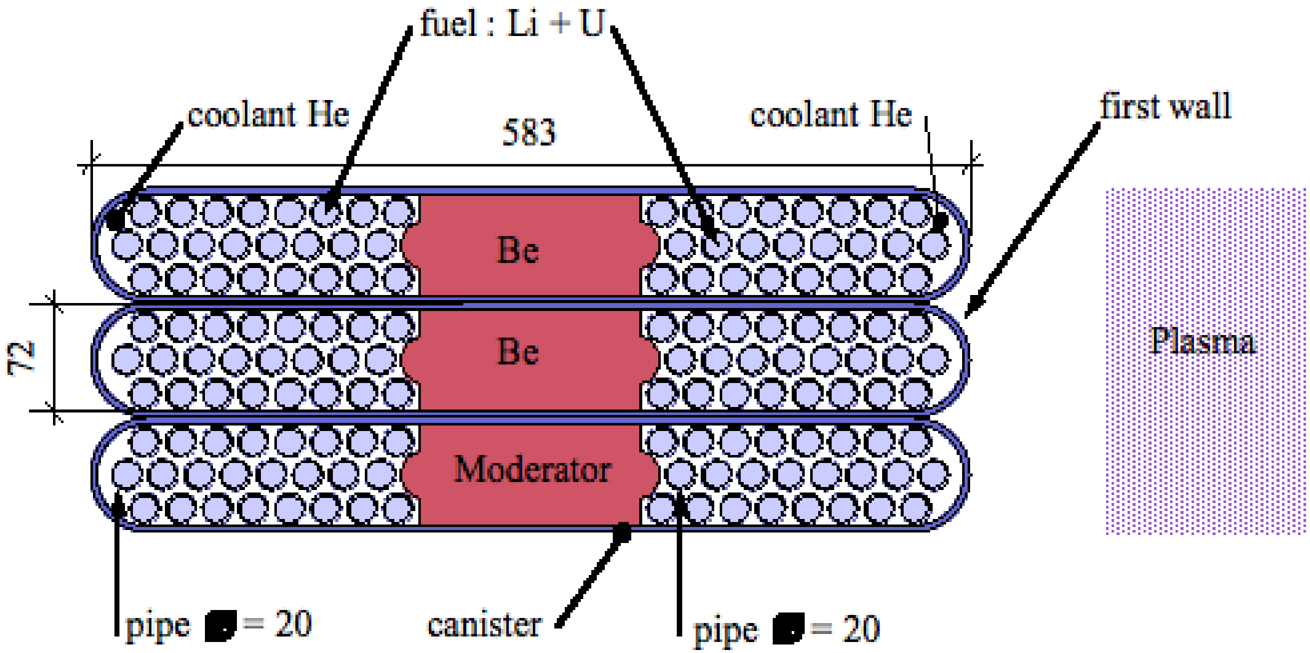
•The fuel as liquid metal circulates in pipes at very low speed : 1 mm /s , but its static pressure is close to the coolant pressure, but it mainly stays inside the blanket. The pipe thickness is ~ 1mm or less.

•The fuel pipes and the gas coolant are inside canisters also providing the first wall. They have a small radius of curvature, 2 to 5 cm in order to limit the thickness of the structure to a few mm, 5 to 10 .

•In order to simplify the cooling inside the reactor, the blanket could be separated into two parts inside the reactor : the power producing elements outside and the tritium generation elements inside.

Cross-section of a possible hybrid blanket module

The helium(or an other gas) flow is
along the pipes. Dimensions in mm



Various cross-section of a hybrid blanket

Total steel : 80cm2 total He : 244 -120 = 124 cm2

Fuel thickness equivalent : 2*8 cm

430 cm2 moderator 105,6 cm2 fuel : 120 cm2 Steel :

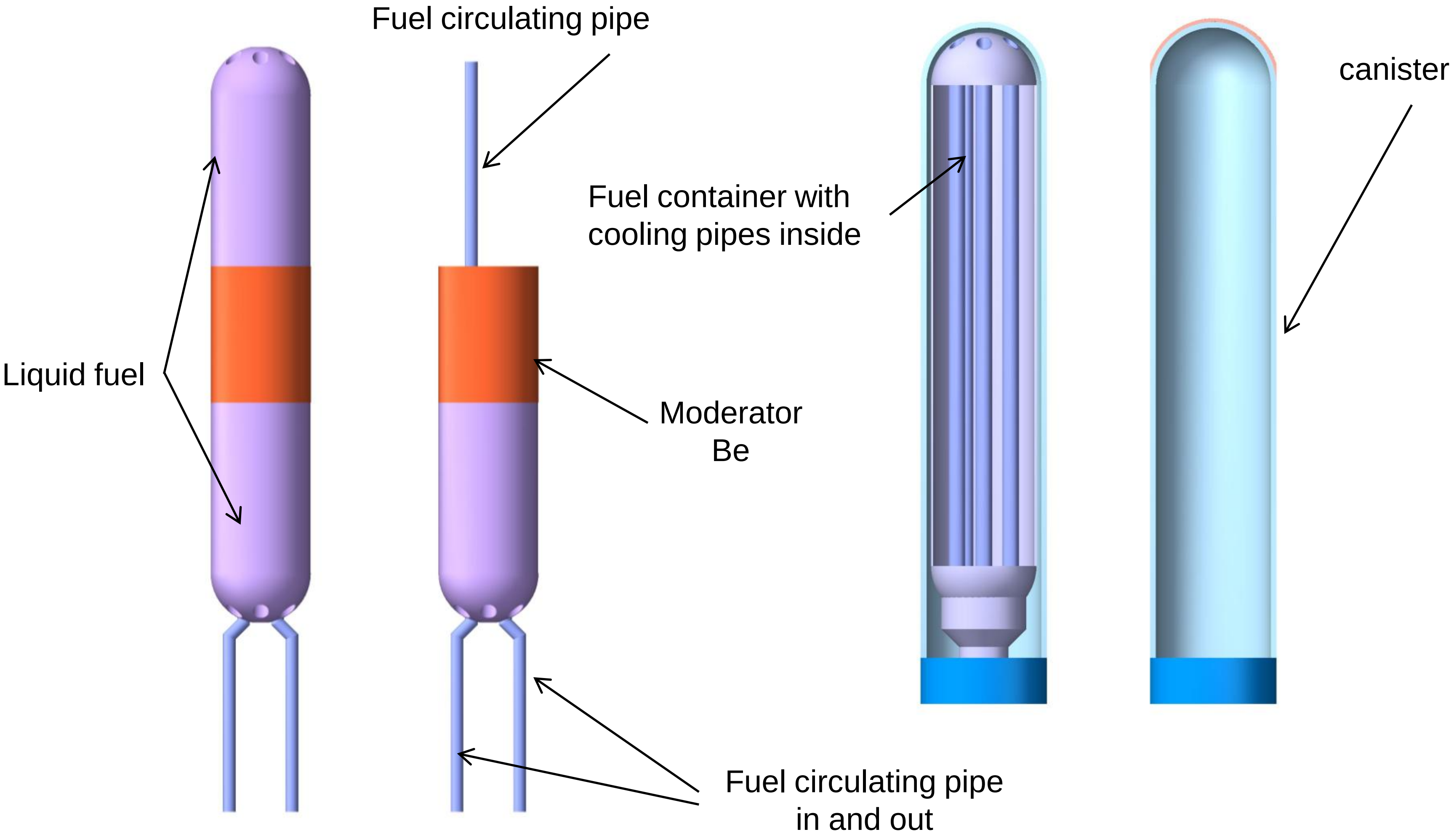
canister 50 cm2 tube 0,628 cm2 s total tube : 30 cm2

A blanket with high pressure coolant water - 10 MPa

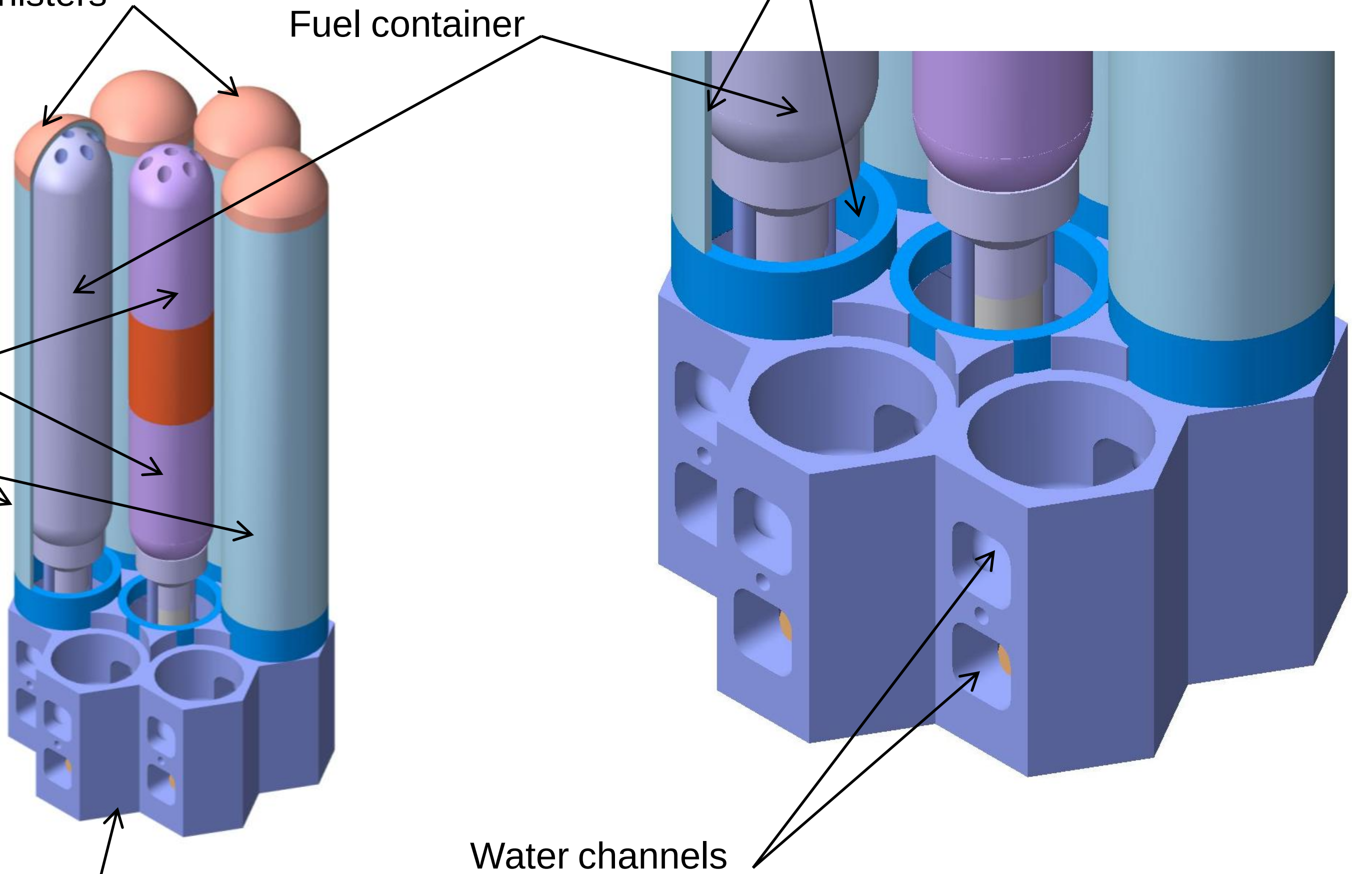
- The blanket is made of tubular elements welded on a thick plate supporting the disruption forces and distributing the high pressure water.
- The tubular element are composed of a steel or vanadium alloy canister which hold the high pressure water (5 mm thick). The canister contains the liquid fuel, a melted metal or salt which includes the uranium 238 and the actinides formed included in a thin container.
- The top of the canister forms the first wall and is covered with beryllium. It is directly cooled by the water.
- The fuel is liquid. It slowly circulates to homogenise its composition. Internal cooling pipes evacuate the heat and insures the return of the water.
- A moderator is inserted in the middle of the container.
- Due to the small extension of each element the disruption forces are limited.
- The remote handling operations are done from the back of the support plates; it allows to cut and weld the canister without disconnecting the container.
- Space is required at the back of the blanket to install the main pipes and to be able to perform the maintenance.
- This arrangement could also be used for gas or vapour.

The high pressure coolant basic element

canister typical dimension : Φ = 11 cm h = 60 to 80 cm



Part of a high pressure coolant blanket



Be first wall welded on the canisters

Fuel container

Water

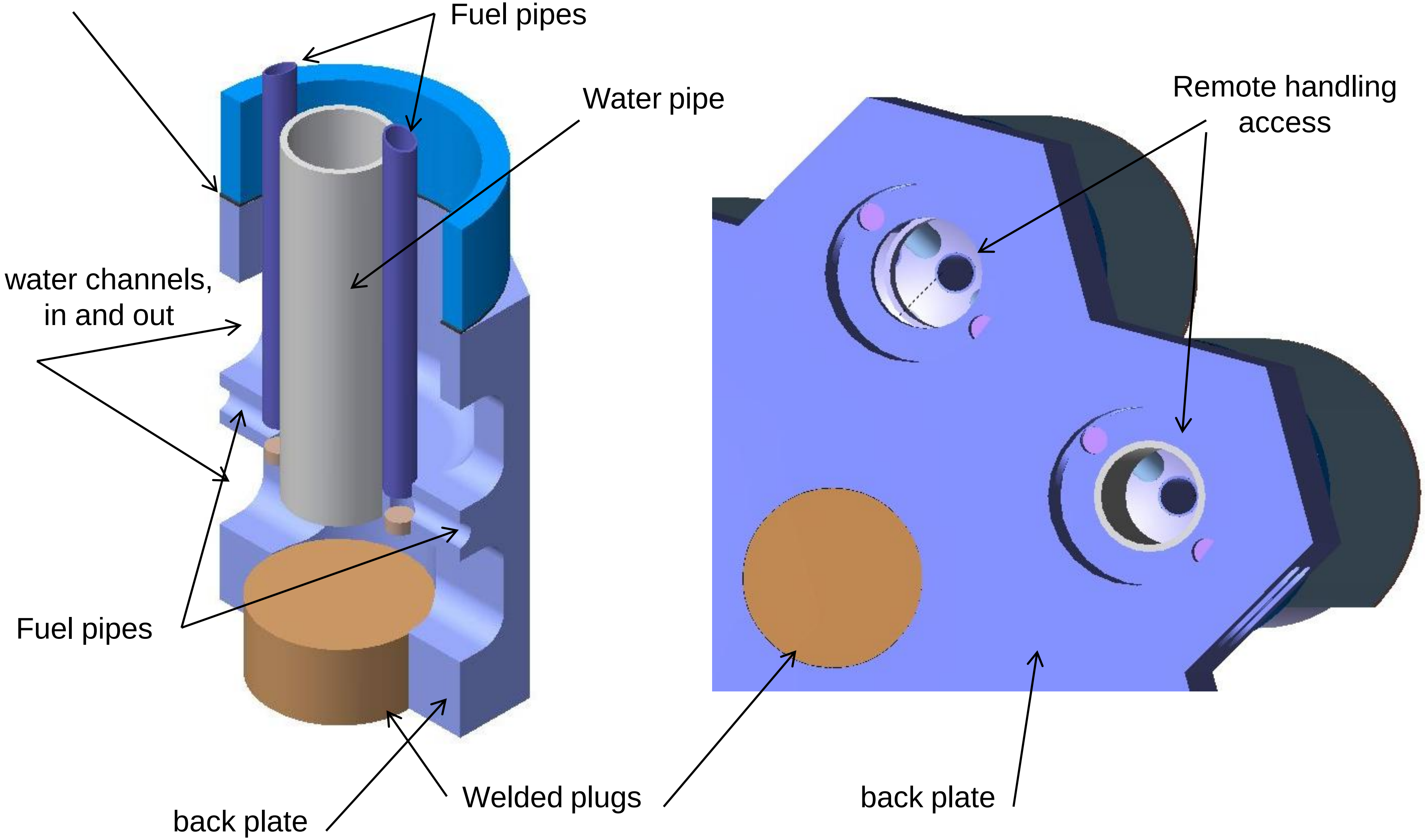
Liquid fuel

canister

back plate

Water channels

Blanket access for remote handling in the back plate



Weld to the canister

Fuel pipes

Water pipe

water channels,
in and out

Fuel pipes

back plate

Welded plugs

Remote handling
access

back plate

Advantages of these solutions, from a fusion point of view

- The neutron flux is a factor 5 lower at the first wall level than in the case of a pure fusion machine of the same power.

- There are a lower erosion and heat load of the divertor plates and first wall. Thicker plates could be used and their lifetime could be increased (more than a factor 10).

- A lower Q is required : 5 , that means a lower current and a smaller machine.

- The ITER plasma is sufficient for an hybrid reactor; a hybrid blanket test with the proper parameters, heat load, neutron flux ... could be done on ITER.

- The time to develop the materials is very much reduced as the demand on them is an order of magnitude lower.

- The step number toward a commercial reactor will be reduced.

Inconveniences of the hybrids

Two problems will nevertheless have to be resolved :

– The presence of uranium, plutonium and fission products will produce a strong activity of the fuel. As Pu and fission products are present inside the tokamak, the safety requirements will increase.
This may demand another confinement barrier inside the blanket.
As proposed here with a gas as coolant of the fuel lithium 7- U 238, the fuel could stay inside the reactor when it operates. The same coolant is also used for the first wall.

– Reaching the plutonium equilibrium is slow as this depends of the neutron flux inside the blanket which is kept at a modest level, 0,3 to 0,5 MW/m^2 .
The time required is a few tens of years starting from pure U238.
Nevertheless it is possible to start with some blanket elements which will produce the required plutonium and still have a gain between 2 and 3 at the beginning. It is also possible to start with natural U or U238 enriched with Pu or other actinides.

Conclusions - 1

- A pure fusion commercial reactor will not be not ready before the next century as we are still far with ITER of the parameters needed. The materials require large improvements.

- A solution to shorten these delays is the hybrid fusion-fission reactors where a reactor similar to ITER would be sufficient ; It would require a much lower power density of neutrons, around 0.5 MW/m^2.

- The objectives for the hybrid blanket could be fulfilled in a large domain of parameters.

- A great number of possibilities exist thanks to the 14 MeV neutrons and to the k_{eff} low value that allows nuclear variations without changing the basic reactor behaviour.

Conclusions - 2

- In spite of the added complexity, I think that it is, for fusion, a way that must be followed and could be tested on modules at full-power on ITER.
- The study of a realistic hybrid blanket has to start in the world taking ITER as the fusion core.

Conclusion -3   Work to be done

Blanket

- Optimisation of dimension
- Materials
- Thermal stresses
- Disruption stresses
- Neutron computations
- Define blanket assembly and segments
- Remote handling tools and access
- Fuel composition and properties
- Construction of prototypes
- Thermal and mechanical tests.

Divertor and first wall

- Erosion by the plasma
- Construction of a test bed working in continuous
- Impurity retention, radiation

FIN

The fusion - fission reactors - 2

Each of these different objectives requires an optimized blanket. Both of them could also be combined. Objective (a) has mainly been studied in the States and (b) in Russia, and China who seems to show a strong interest in this line.

Properties of 14 MeV neutrons

- Cross-sections for non elastic reactions of actinide, fission, n,2n and n,3n are around 3 barns :

- with a 1 MW/m^2 14 MeV neutron flux, 240 years are required to burn or transmute an initial load in the case 1 presented.

- 5 MeV are required to extract a neutron in a n2n or n3n reaction.

- a 14 MeV neutron is equivalent to 3.1 4 MeV neutrons

- in producing neutrons, 1 fusion reaction is equivalent to 1 fission reaction

Results obtained in a first phase - 2

Nuclear reactions per 14 MeV neutron

Reactions	domain fast	domain moderated	Total
Fission U 8	0.158	0.029	0.187
Fission Pu 9	0.395	0.276	0.671
Absor.Pu9	0.603	0.437	1.037
Captu.U28	0.596	0.27	0.867
total fission	554	0.305	0.858
Pu produced	0.484	0.021	-0.17
Total tritium			1.837
Energy gain			10.6 (relative to neutron power)

Results obtained in a first phase - 3

Blanket composition (case 2)

Layer	thick.	U+Pu	Pu 9	Li	Li 6	others
	cm	% Pu	(%)	%	(%)	
Wall	0.75					V
fuel	15	51	(2)	49	(0 ?)	
Mode.	15					Be.
fuel	15	51	(5)	49	(0 ?)	
Screen	44					steel

Nuclear reactions per 14 MeV neutron

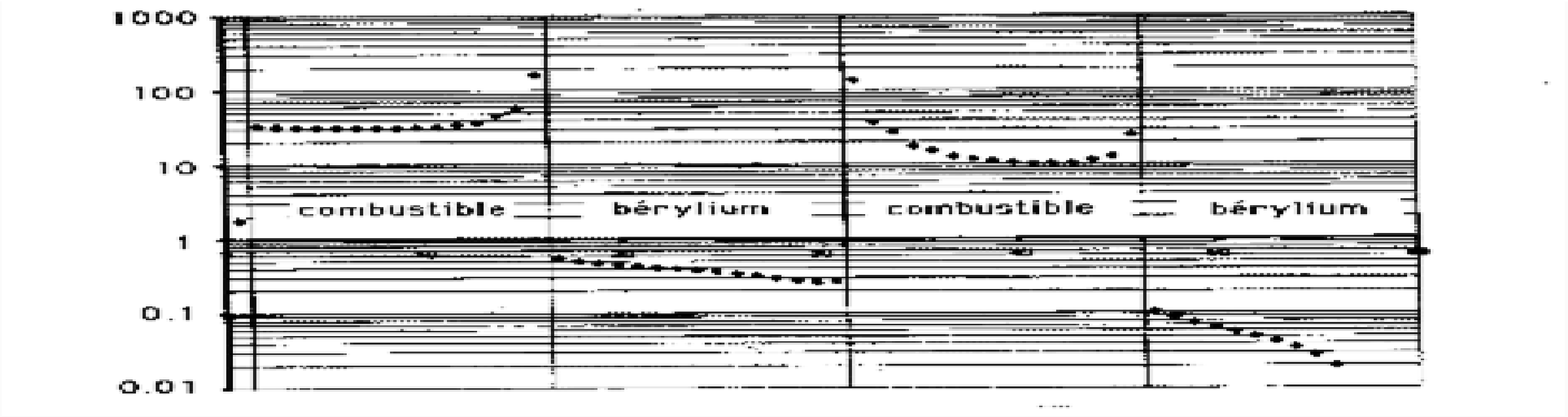
Reactions	domain fast	domain moderated	Total
Fission U 8	1,19	0,44	1,63
Fission Pu 9	2,53	1,79	4,32
Absor.Pu9	3,6	2,6	6,2
Captu.U28	6,46	2,41	8,87
total fission	3,72	2,23	5,96
Pu produced	2,86	-0,19	2,12
Total tritium			1.58
Energy gain			78
Nuclear reactions			

A large margin exists and results could be interpolated

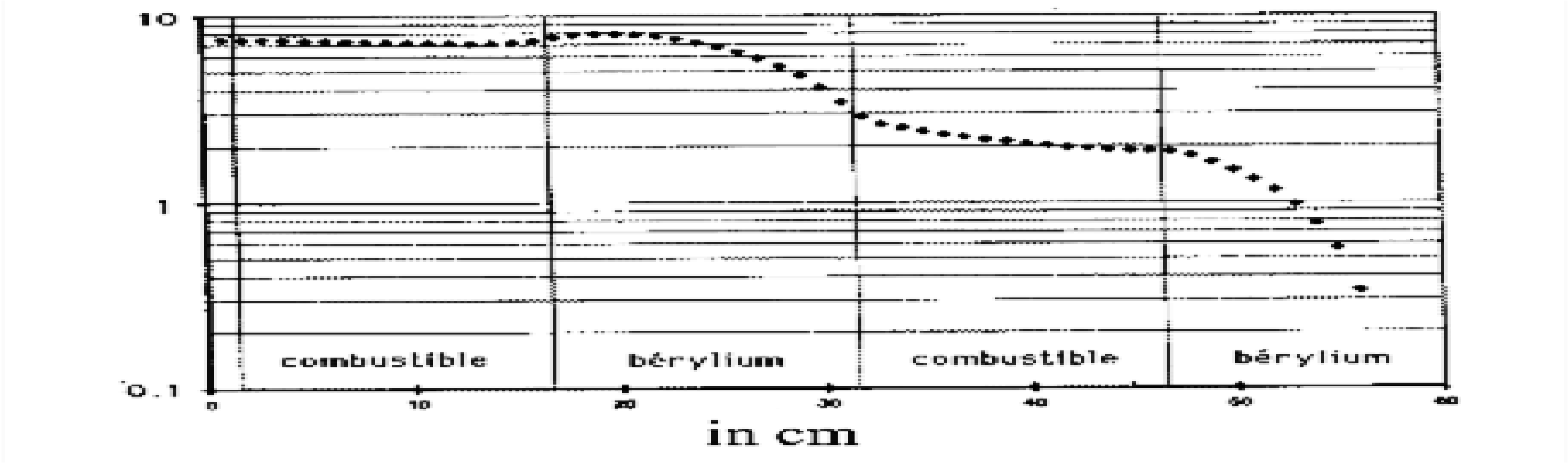
Results - case 1

1MW/m2 corresponds to 1.77*10^{19} n/m^2s for 14 MeV neutrons

Power density radial profiles in MW /m^3



Neutron flux in 10^{18} n/m^2s



More recent computations

Various numerical codes were used and compared at Sarov - VNIIEF using different computation methods :

- Monte Carlo
- Neutron groups 4 to 38
- codes including other actinides Np ....

Recently the blanket evolution over a 3 year period of continuous operation has been followed without significantly degrading the performances, with the exception of the tritium production as the Li6 fraction and 1.5 % U8 have been consumed. A computation for a 3 year continuous operation at 10 MW/m2 neutron flux was also made (80 year operation for ITER) ; various actinides are produced in decreasing proportion :

Pu 240 , Pu 241 , Np 237 ,Pn 238 ...

- several of these actinides seem partly burned

Experimental check of codes

The model tested is a sphere composed of successive concentric layers. They are alternatively of LiH and U 238. The lithium is Li 6 except for the central layer which is constituted of natural lithium. A 14 MeV source is placed at the centre of this sphere. The radius of the assembly is 27 cm and the weight 400 kg.

The experimental results from this model have allowed to validate the different codes used.

Other blankets

- Other moderators, water, carbon, ..
- Other fluids for heat transport, water,vapor, helium, liquid lithium-lead..
- Other fuel cycles: thorium or mix cycle
- Other objectives ; incineration of minor actinides

Comparison between fast fission and hybrids

Advantages : 2 successive amplifications : first, fusion from the additional heating with the gain Q and second, fission with the gain M.

There is no possibility of any power surge.

No control is required to limit the power produced; the output depends of the additional heating power injected in the tokamak. K_{eff} is very low : it is not sensitive to the blanket composition.

A very long period before a fuel re-treatment if any during the reactor life.

The reactor can start with only U_{238} or with natural U without having a Pu stock, in the case of a fast development.

The minor actinides could be recycled and burned.

Disadvantages : the complexity of a hybrid reactor and at the beginning of its usage, its availability in operation.

Comparison with hybrids accelerator - fission

- In this case, the reactor is sub-critical but with a small margin as the gain from fusion doesn't exist ; the blanket gain must be at least 50 .

- The incident neutrons have a very large energy spectrum, but a mean energy around 1 MeV and are less efficient.