Comparison of breeder blanket Design

By

Aldo Pizzuto

9th Course on

"TECHNOLOGY OF FUSION TOKAMAK REACTORS" –

Erice, July 26 - August 1, 2004

Outline

- Breeder Blanket functions
- Overview on Candidate breeder, n multiplier materials and Structural materials
- Comparison of EU breeder blankets
    - Thermal mechanical performance
    - Maintenance
    - Safety
    - Waste
- Discussion
- Conclusion

Breeding Blanket Functions

The breeder blanket has to guarantee:

- Tritium production (breeding) and extraction (purging)
- Shielding of the Vacuum Vessel and Toroidal Field Coils

The design has to be featured in order to achieve:

- The easiest possible operation maintenance
- Sufficiently long lifetime
- High safety level and low environmental impact (including waste)
- Reasonable direct cost including operation

Blanket Components

The breeder blanket is made of:

- Breeder (solid or liquid)
- Neutron multiplier (solid or liquid)
- Shielding
- structural material
- Coolant (He, Water, Liquid Metal, Molten Salts)

The combination of the different components should be made on the basis of their compatibility from chemical, thermal and safety standpoints

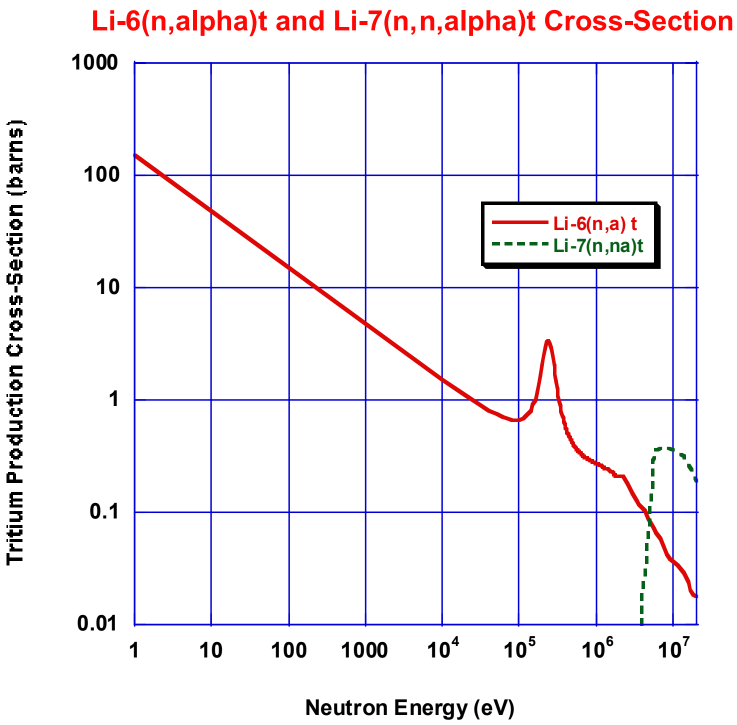
Breeders

The most favorable breeder reaction is :

$$^{6}Li + n \longrightarrow {}^{4}He + T + 4.8\ MeV$$

Another possible reaction is:

$$^{7}Li + n \longrightarrow {}^{4}He + T + n - 2.5\ MeV \text{ (threshold reaction)}$$



Two main breeders materials:

Li ceramics compounds (solid)

Li-Pb eutectic, Molten salts or pure Li (liquid)

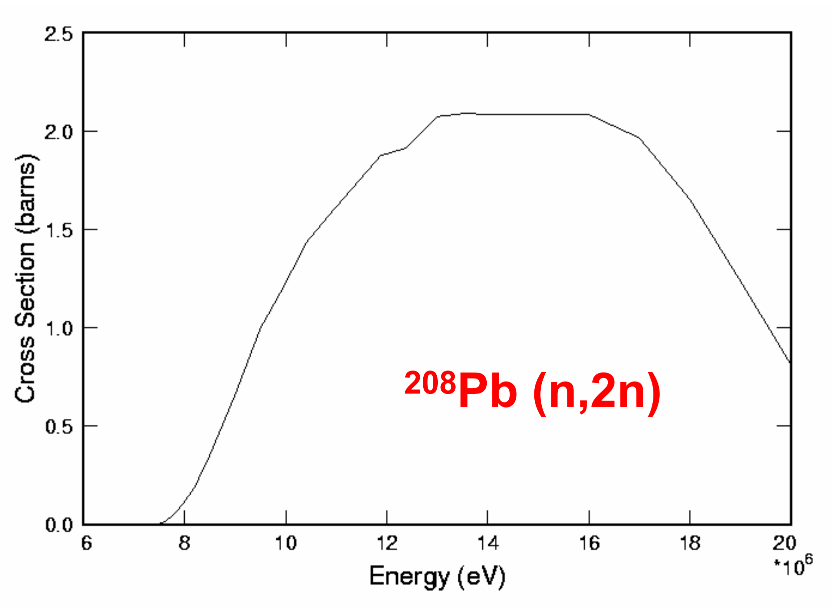
All enriched in ^{6}Li: from 30 to 90%

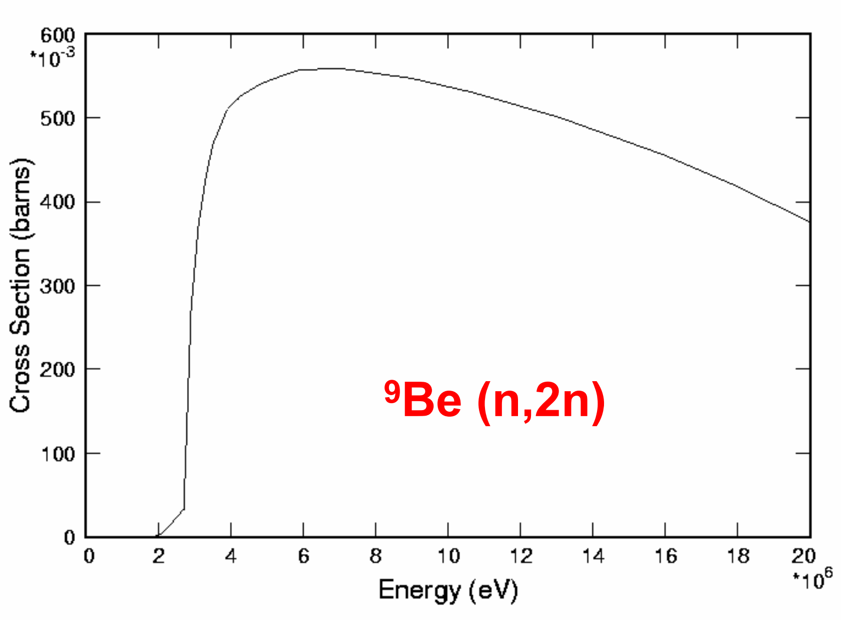
^{6}Li forms the 7.4% of the natural Li

Neutron Multipliers

The neutron multiplier are:

- ^{208}Pb (n,2n) threshold 7.4 MeV
- ^{9}Be (n,2n) threshold 2.5 MeV





Solid Breeder (1)

The main compounds considered are:

Li_4SiO_4, Li_2TiO_3 , Li_2O, (Li_2ZrO_3, $LiAlO_2$)

The selection has to be made on the basis of a trade off between:

- Li content,
- Compatibility with materials of other components
- Thermal-Mechanical behavior under irradiation,
- Reactivity with coolant and structures in case of accident
- Recycling and waste issues

Main advantage: high Li content (higher Tritium Breeding Ratio)

Main disadvantages: poor mechanical strength and thermal properties, difficult temperature control and maintenance

Solid Breeder (2)

Solid breeder comparison:

- **Li_4SiO_4 medium lithium content;**
  Low radiation resistance
- **LiO_2 Highest lithium content;**
  Good conductivity but high expansion coefficient;
  Poor behavior under irradiation, precipitate formation
- **Li_2TiO_3 lowest lithium content;**
  good mechanical properties under irradiation
  potentiality for recycling

Liquid Breeder (1)

The main materials considered are:

Pb17Li, Li - Flibe $(LiF)_n \cdot (BeF_2)$, Flinabe (LiF-BeF_2-NaF)

The selection has to be made on the basis of a trade off between:

- Neutron multiplier efficiency
- Compatibility with structural material
- waste issues

Main advantages: both functions in one material; allow higher operating temperature; easier maintenance

Main disadvantages: compatibility; MHD pressure drop; tritium permeation issues (low solubility)

Liquid Breeder (2)

Liquid breeder comparison:

- Li: very attractive (two functions in one)
  safety issue due the high reactivity
- Pb17Li: lowest lithium content
  good compatibility with coolant
- Molten salt: complex chemistry
  low thermal conductivity
  poor data base

Structural Materials (1)

The structural material for fusion devices has to have very good radiation resistance as well as low activation properties.
The high neutron energy, the reactor size and the quite high investment cost make mandatory the minimization of number of blanket replacements.

Material requirements for a Fusion Reactor	
Operating Temperature	**550-700˚C (metallic)** **1000˚C (Composite Ceramic)**
Dose for internals	**~150 dpa**
Max Helium concentration	**~1500 appm** **(~10000 appm for SiC)**

Structural Materials (2)

The structural material considered are:

- **Low Activation Martensitic/Ferritic Steel – MFS (EU, J, US)**
- **Vanadium alloy -V (US, RF)**
- **Composite Silicon Carbide – SiC_f/SiC (EU, J, US)**

Figures of merit to be considered:

- Performance (thermal-mechanical)
- Safety (after-heat)
- Waste disposal issues

Structural Materials (3)

MFS :

- The most of development effort dedicated;
- allows design flexibility;
- operating T not so high (550°C) possible improvements (+100°C) by ODS (Y,Ti)

thermal efficiency achievable around 35%

V :

- would allow the use of pure Li as breeder-multiplier;
- good thermal-mechanical and safety characteristics;
- higher operation temperature than FS (700°C);
- severe chemical compatibility issues (very sensitive to impurities);

thermal efficiency achievable around 45%

Structural Materials (4)

SiC_f/SiC :

- very high operating temperature (1000°C);
- attractive from the safety standpoint (very low afterheat);
- thermal characteristics to be enhanced;
- manufacturing and joining issues;
- Chemical compatibility test in relevant condition gave promising results

thermal efficiency achievable greater than 50%

For all the materials is absolutely mandatory to assess the radiation resistance with fusion spectra neutrons

Thermal stress figure of merit

The thermal stress figure of merit gives the max heat flux allowable.

In steady state:

$$q^* = \sigma \cdot K \cdot (1-\upsilon)/(E \cdot \alpha) \quad \mathbf{[W/m]}$$

Where: σ is the ultimate strength
K is the themal conductivity
υ is the poisson module
E is the Young module
α is the thermal expansion coefficient

The structural material ranking is:

V better than MFS better than SiC/SiC

Even though the comparison is affected by the different operating temperature limit

Blanket Concepts (1)

Solid breeder:

- Breeder separated from n multiplier (Be) and from coolant;
- Helium coolant practically mandatory, above 600°C Be reacts with water producing H (although Japan uses ceramics/Be with water)
- structural material MFS or SiC_f/SiC

Blanket Concepts (2)

Liquid breeder:

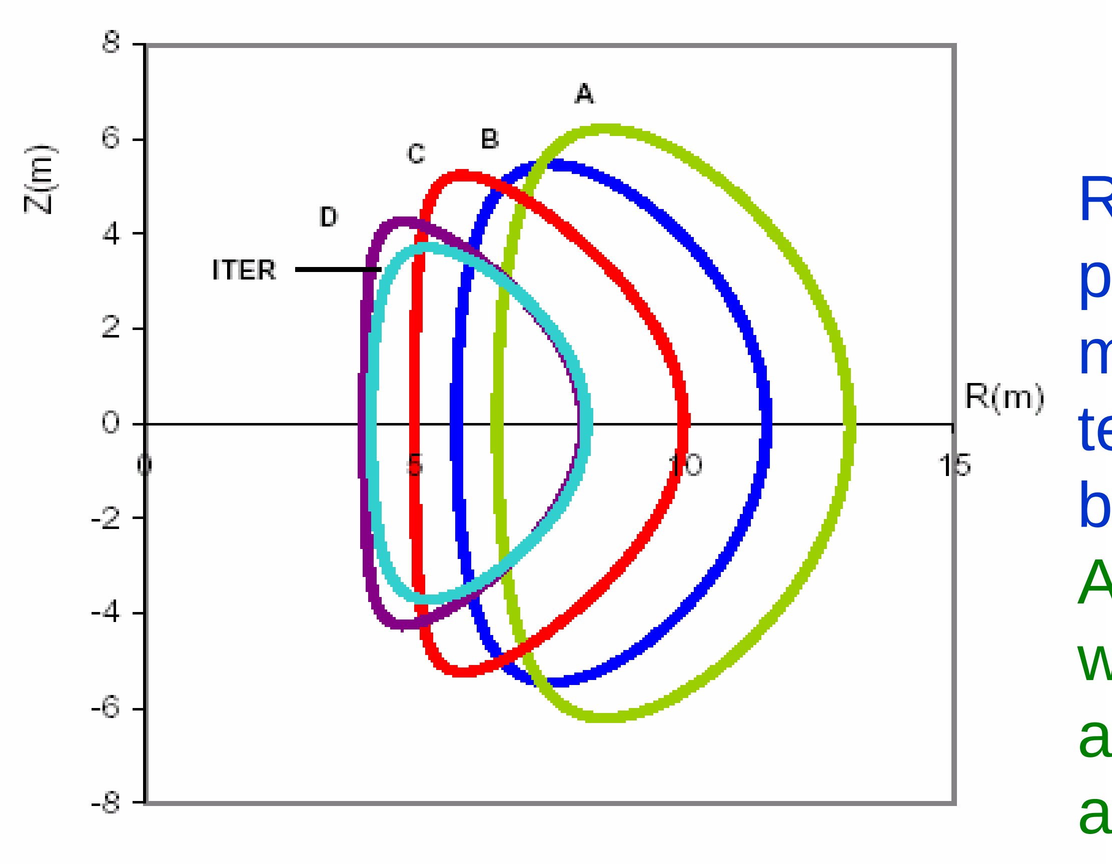
- Breeder incorporates n multiplier
- Helium coolant, water (Pb17Li only) or self cooled
- Structural material V,MFS or SiC$_f$/SiC

EU Concepts

EU focussed its effort in design providing both solid and liquid metal concepts utilising the following materials:

- **MFS and SiCf/SiC as structural material;**
- **Li_4SiO_4 or Li_2TiO_3 as solid breeders;**
- **Be as neutron multiplier for solid breeder option;**
- **Pb-17Li as breeder and n multiplier for liquid metal concept.**

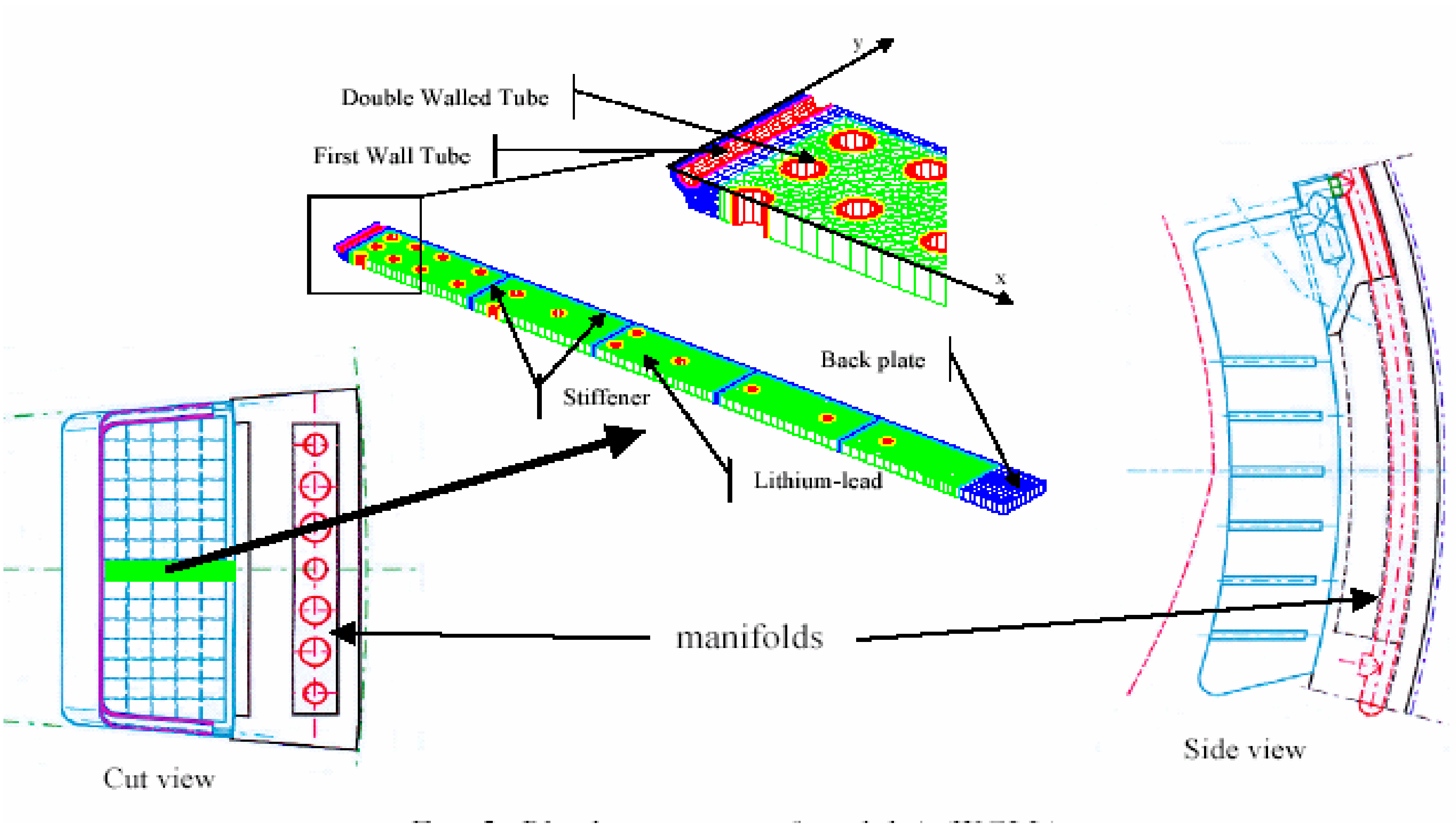
EU Reactor Size



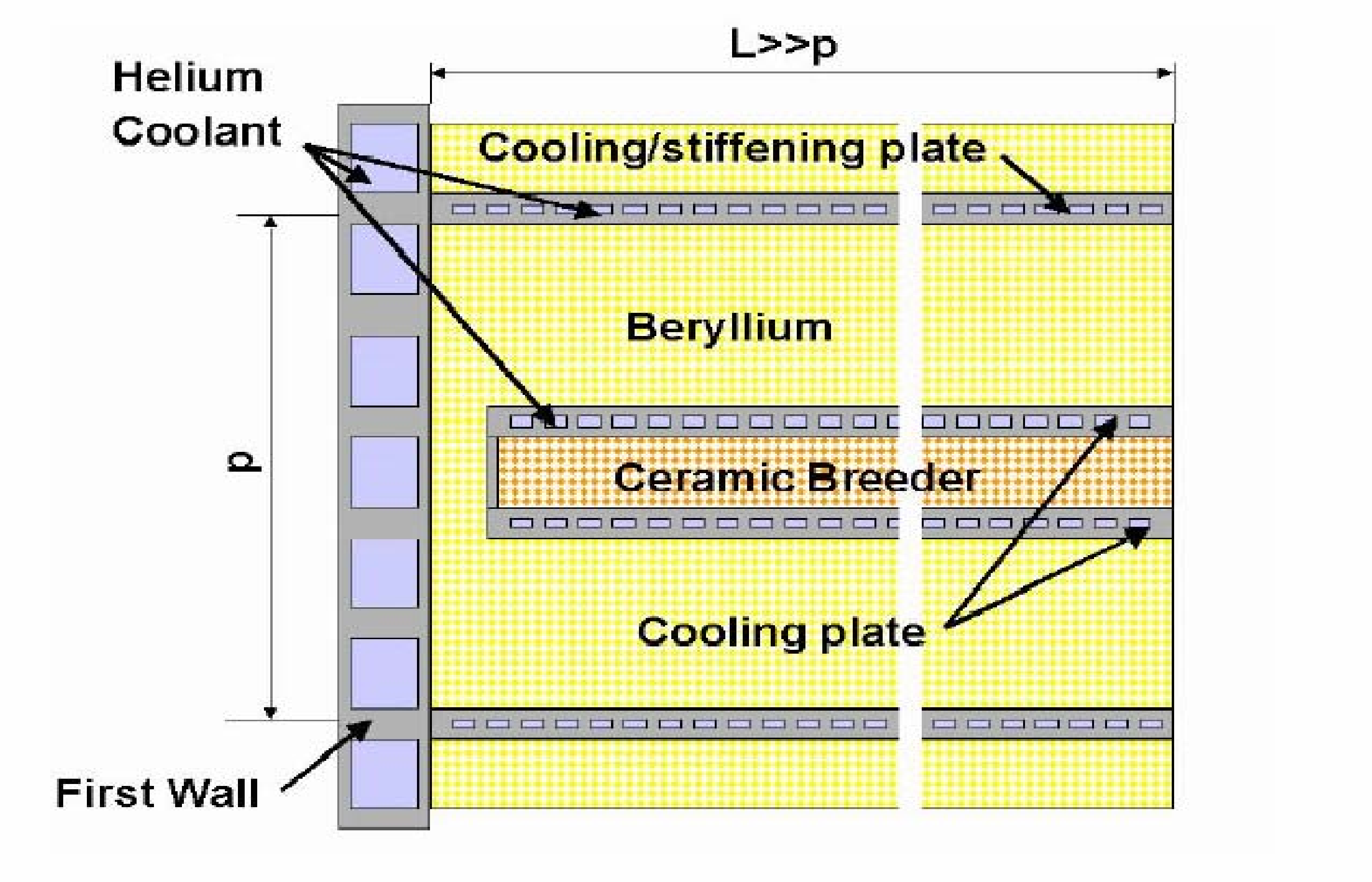
Reactor size depends on plasma power exhaust mechanism and divertor technology rather than blanket technology

All the blanket technology would in principle be applicable to all the concepts

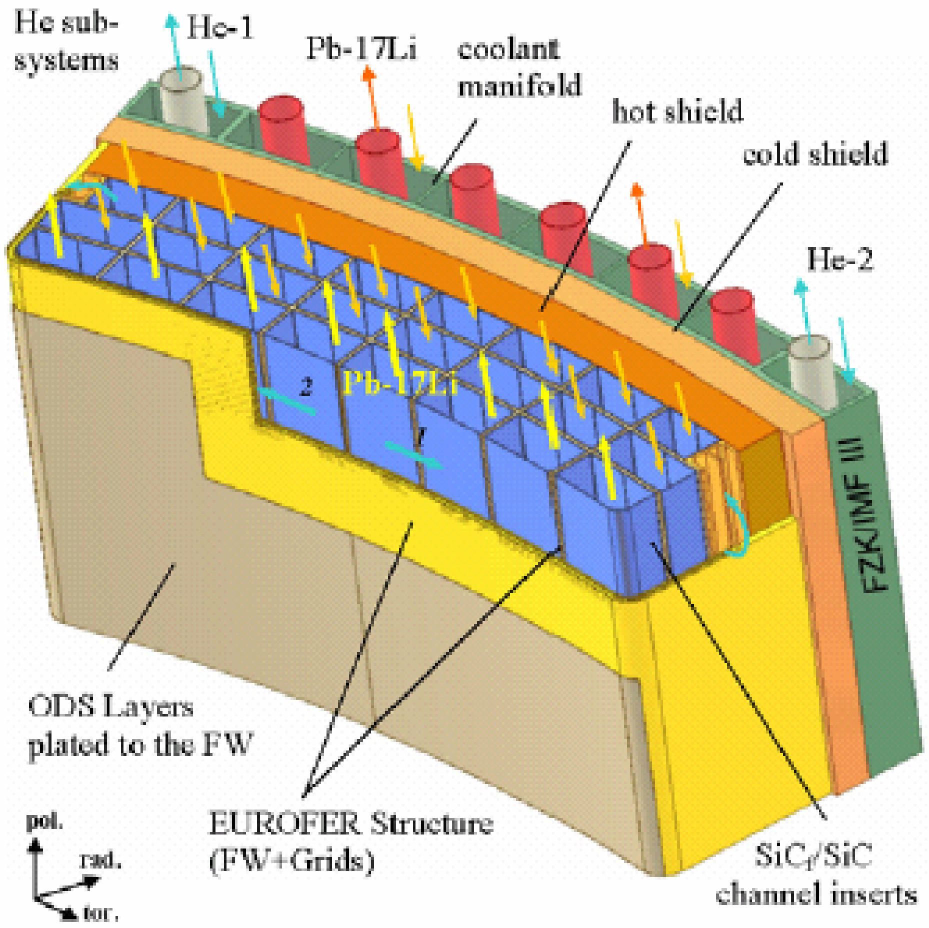
Liquid metal water cooled concept



Solid breeder concept



Liquid metal dual coolant concept

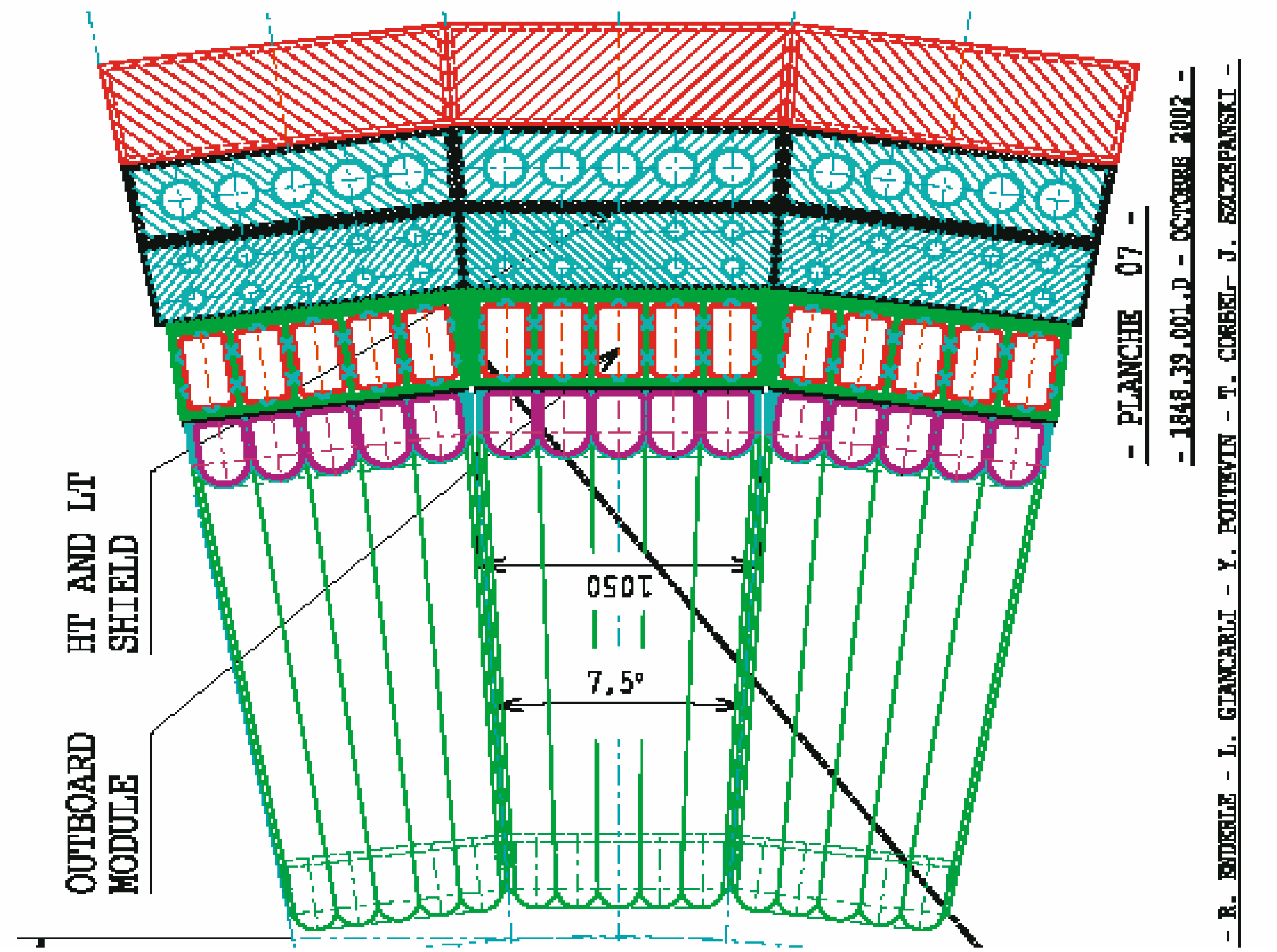


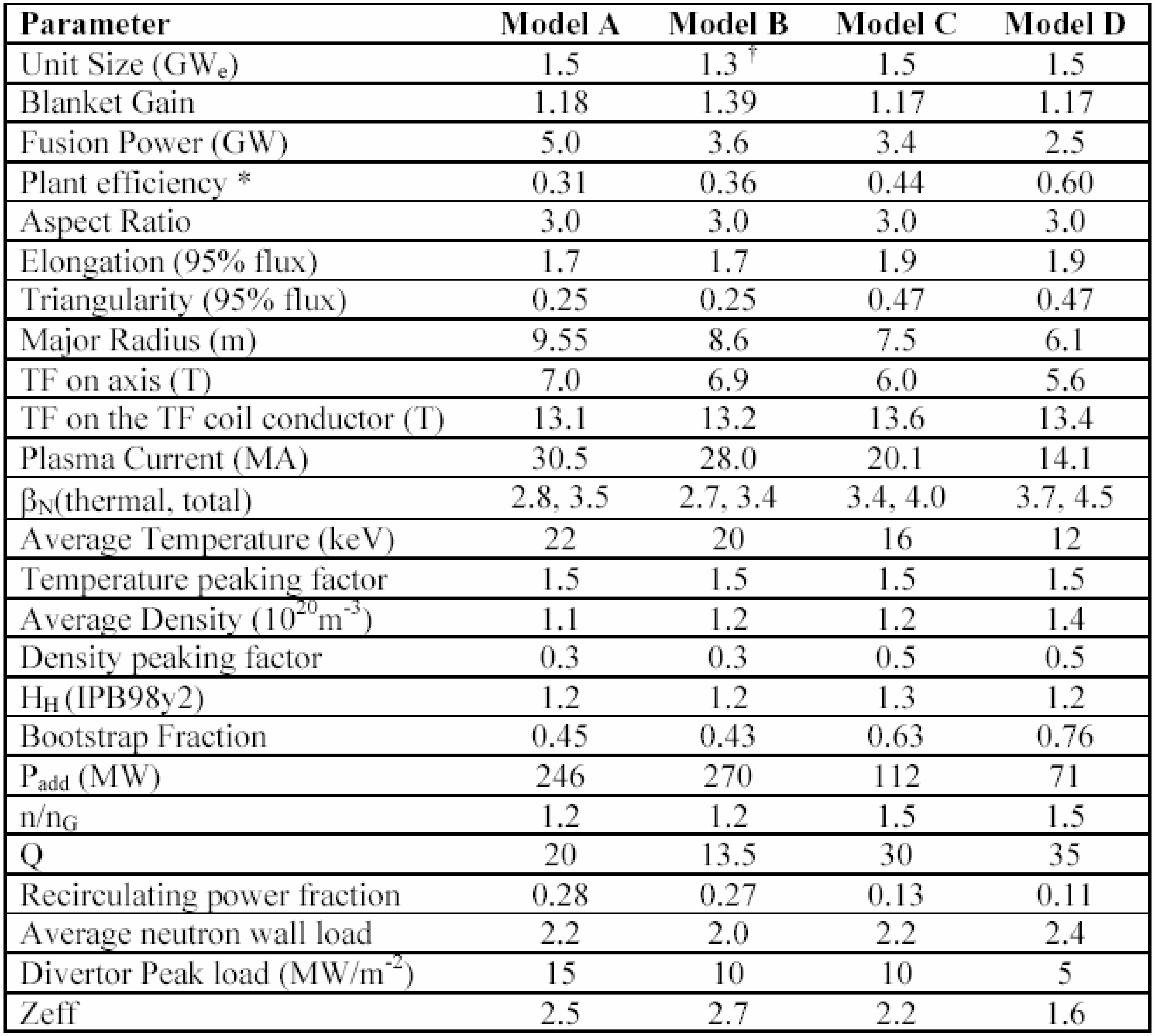
Main features:

- helium-cooled RAFM steel structures (EUROFER)
- ODS plated FW to use the high-temperature strength of ODS
- self-cooled breeding zone with Pb17Li as breeder and coolant
- SiC_f/SiC flow channel inserts as electrical (MHD) and thermal insulators leading to high exit temperature and high thermal efficiency

Dual Coolants	T_{Inlet} (°C)	T_{Outlet} (°C)	ΔT (K)
Helium (8 MPa)			
Overall blanket	300	480	180
FW	300	450	150
Grids	450	480	30
Pb-17Li	480	700	220

Self cooled


OUTBOARD MODULE
HT AND LT SHIELD
1050
7,5°
- PLANCHE 07 -
- 1848.39.001.D - OCTOBRE 2002 -
- R. ENDERLE - L. GIANCARLI - Y. POITEVIN - T. CORBEL - J. SZCZEPANSKI -



Parameter	**Model A**	**Model B**	**Model C**	**Model D**
Unit Size (GW_e)	1.5	1.3 †	1.5	1.5
Blanket Gain	1.18	1.39	1.17	1.17
Fusion Power (GW)	5.0	3.6	3.4	2.5
Plant efficiency *	0.31	0.36	0.44	0.60
Aspect Ratio	3.0	3.0	3.0	3.0
Elongation (95% flux)	1.7	1.7	1.9	1.9
Triangularity (95% flux)	0.25	0.25	0.47	0.47
Major Radius (m)	9.55	8.6	7.5	6.1
TF on axis (T)	7.0	6.9	6.0	5.6
TF on the TF coil conductor (T)	13.1	13.2	13.6	13.4
Plasma Current (MA)	30.5	28.0	20.1	14.1
β_N(thermal, total)	2.8, 3.5	2.7, 3.4	3.4, 4.0	3.7, 4.5
Average Temperature (keV)	22	20	16	12
Temperature peaking factor	1.5	1.5	1.5	1.5
Average Density ($10^{20} m^{-3}$)	1.1	1.2	1.2	1.4
Density peaking factor	0.3	0.3	0.5	0.5
H_H (IPB98y2)	1.2	1.2	1.3	1.2
Bootstrap Fraction	0.45	0.43	0.63	0.76
P_{add} (MW)	246	270	112	71
n/n_G	1.2	1.2	1.5	1.5
Q	20	13.5	30	35
Recirculating power fraction	0.28	0.27	0.13	0.11
Average neutron wall load	2.2	2.0	2.2	2.4
Divertor Peak load (MW/m^{-2})	15	10	10	5
Zeff	2.5	2.7	2.2	1.6

Temperature Control

Temperature profile control during the lifetime is one of the most important issue in determining the reliability of a reactor.

Concerning this issue it can be observed that:

- **Solid breeder is more demanding due to the swelling and cracking of the pebbles that could modify substantially the effective thermal conductivity**

Performance

- **Solid breeder blanket has a much higher neutron multiplier but higher parasitic effect**
- **Liquid metal blanket has the potentiality to operate at much higher temperature**
- **He cooled blanket has pumping head around 10 times higher**

Model	A	B	C	D
Pf [GW]	**5**	**3.6**	**3.4**	**2.5**
Padd [MW]	**246**	**270**	**112**	**71**
Alfa [MW]	**984**	**729**	**672**	**497**
Q	**20**	**13.5**	**30**	**35**
n mult.	**1.14**	**1.37**	**1.17**	**1.17**
Blanket Gain	**1.18**	**1.39**	**1.17**	**1.17**
TBR	**1.06**	**1.12**	**1.15**	**1.12**
pump head [MW]	**58**	**375**	**35**	**15**

Maintenance and Operation

Maintenance and operation complexity depend on both design features (removal issues) and breeder handling (purge, regeneration)

Design features which impact on remote handling depend on structure material rather than on the breeder type

The choice between 'Large Module' and 'Banana' concepts have to be made evaluating the impact on the availability and the reliability of the reactor
e.g. maximum number of joints to be made(reliability, welds being the driving factor) and their position (availability)

Maintenance and Operation (2)

Comparing the operation issues related to solid and liquid metal breeder blanket, it could be argued that with liquid metal blanket it is possible to:

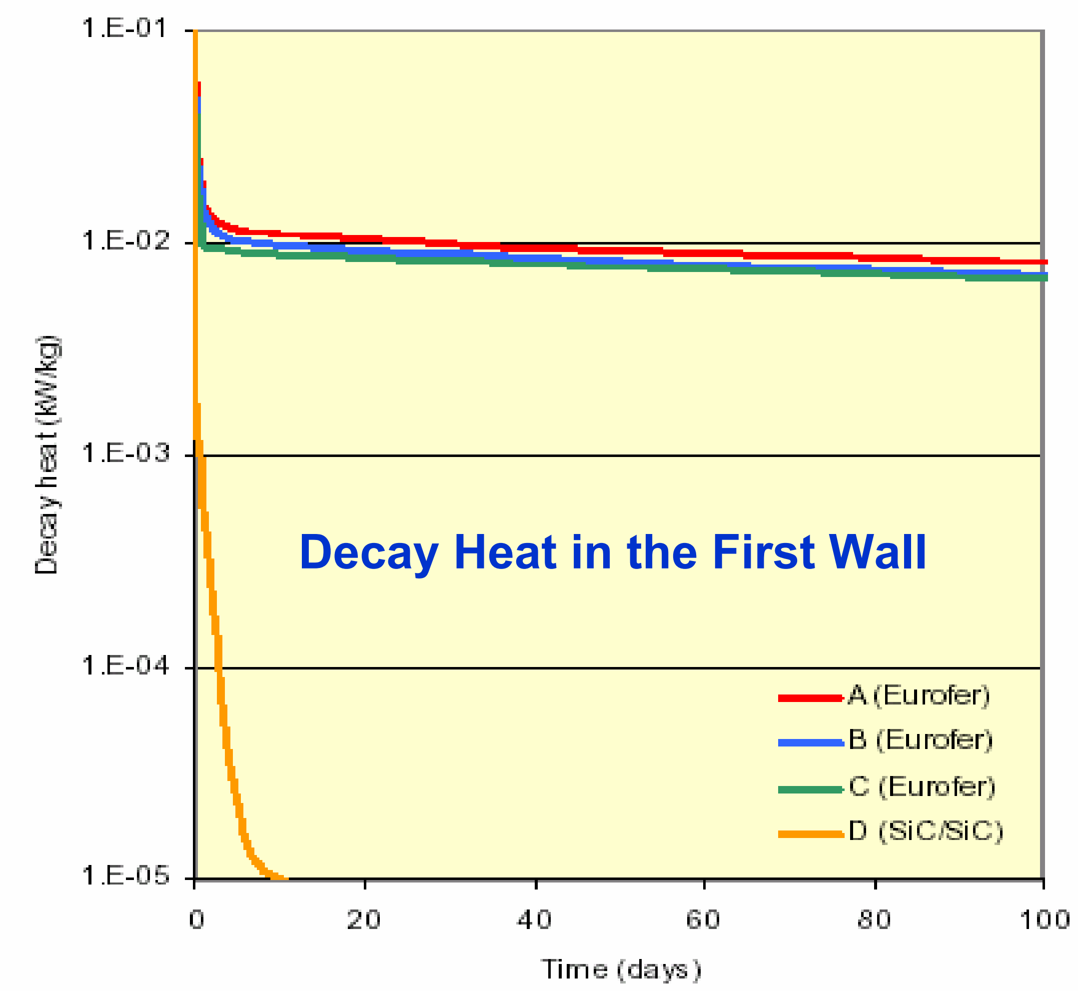
- **purge and regenerate the breeder out of pile without dismantling the blanket modules**
- **have one breeder charge for the entire reactor lifetime**

Safety and Waste Issues

The comparison of the different concepts has to be made on the basis of:

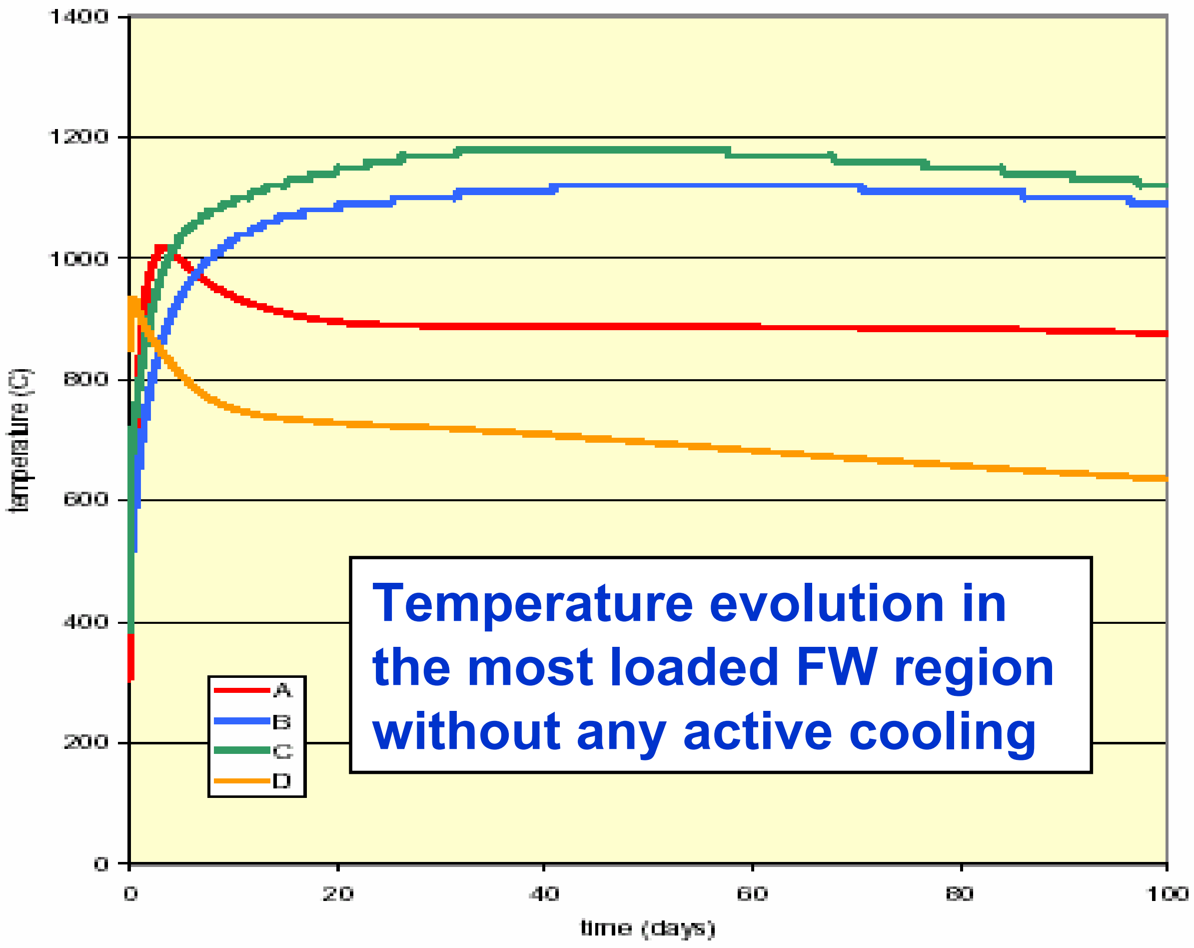
- **the behavior in case of accident**
- **the waste management issues**

Specific Decay Heat



The decay heat is in any case fairly low. SiC/SiC however can give a impressive advantage

Temperature behaviour in case of accident



Temperature evolution in the most loaded FW region without any active cooling

The max T remain always below the melting value

Dose in case of bounding accident

The dose released in case of the bounding accident, even making the most conservative assumptions, ranges

from 1.2 mSv to 18.1 mSv in one week

due mainly to dust and activated corrosion product

The corresponding evacuation dose prescribed by regulator authorities is 50 mSv

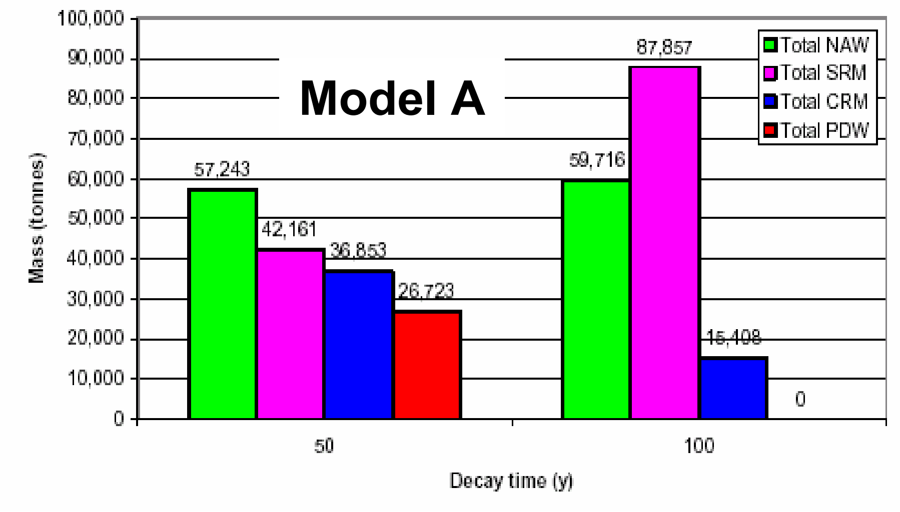
Waste Recycling Limits

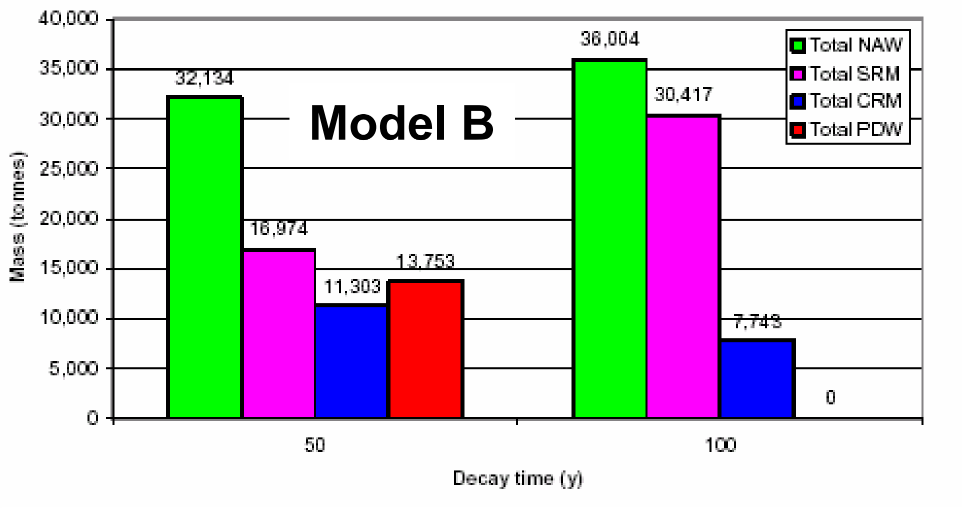
So far the EU waste strategy is based on the full recycling approach

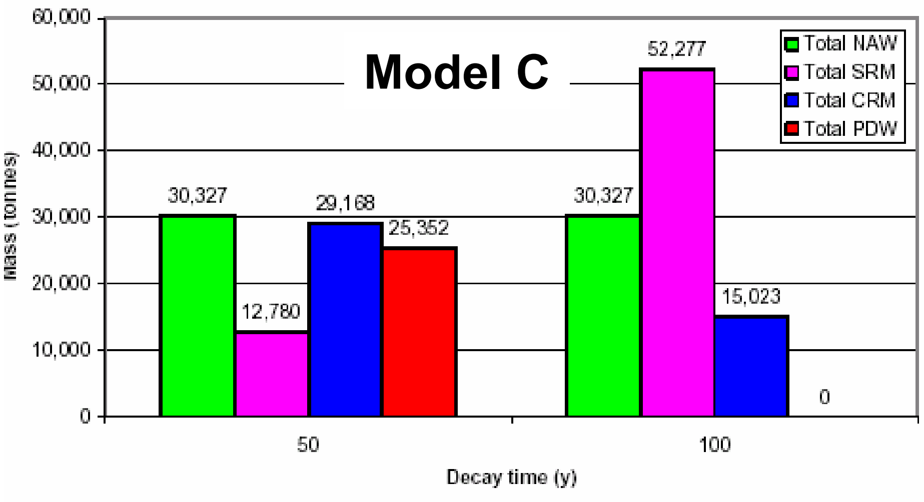
Activated material classifications for recycling	Contact Dose [mSv/h]	Decay Heat [W/m3]
CRM = Complex Recycle Material* (Recyclable with complex RH procedures)	2 - 20	1 - 10
SRM = Simple Recycle Material (Recyclable with simple RH procedures); (HOR = Hand-On Recycling for D <10μSv/h)	< 2	< 1

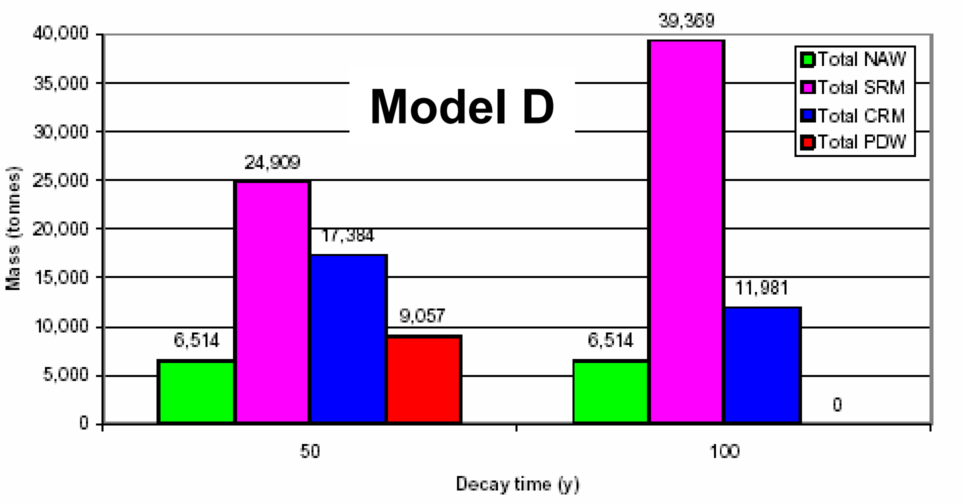
*Complex recycling viability has still to be assessed

Waste production after 50 and 100 years



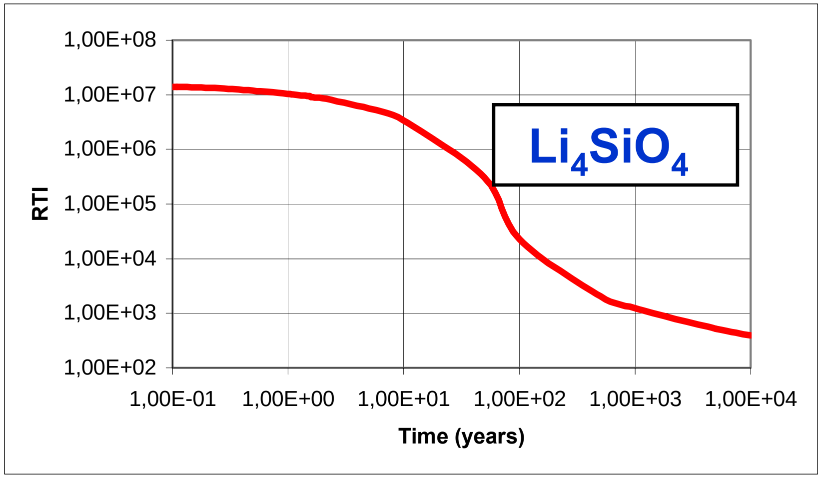


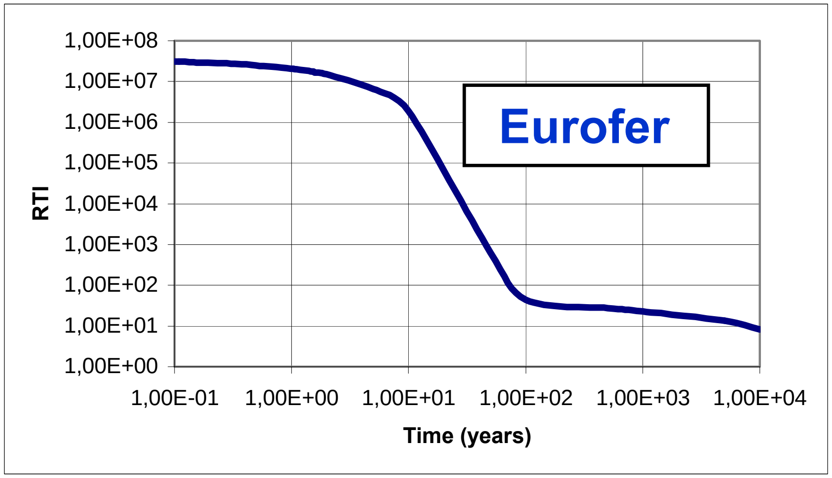


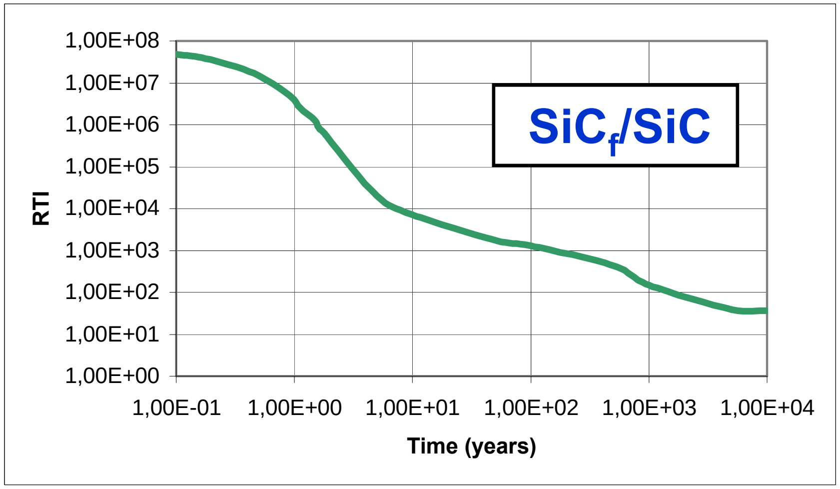


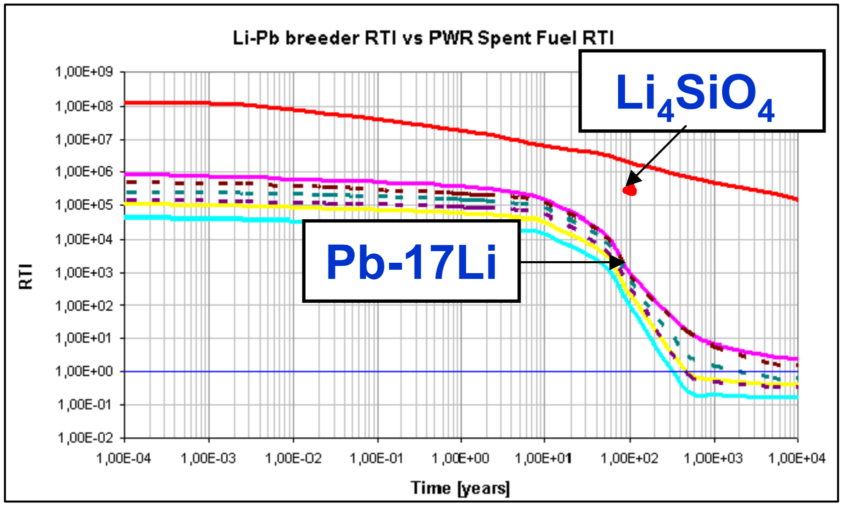
Radio-toxicity Index after shutdown

RTI= Radio Toxicity Index related to U ore dose ($2.71*10^{-2}$Sv/kg)









Blanket Comparison (1)

Regardless to the route to be followed for the reactor development, fusion in the early stage:

- **cannot be economically competitive**

BUT

- **must be attractive from the performance standpoint**

Blanket Comparison (2)

To be attractive a fusion reactor should:

- **be as small as possible but the size is determined by plasma power handling constraints**
- **Have the highest possible thermal efficiency**

  i.e. operate at the maximum possible temperature to alleviate the burden due to the high re-circulating power and show potentiality for other possible utilization like hydrogen production

Blanket Comparison (3)

Furthermore we have to understand if it would be worthy to build DEMO/FOAK utilizing technologies which differ substantially from those desirable for the first of a kind reactor.

A blanket for DEMO with low performance has:

- **Lower technological risk**

but also

- **Lower attractiveness for investors which eventually look, very likely, more to direct rather than externalities cost**

Conclusions (1)

All the EU concepts satisfy the requirements for achieving a safe and environmentally compatible energy source:

no waste requiring deep underground burial after 100 year provided RTI of 1000 be acceptable.

Among the four concepts two (Model A&B) require R&D activity well in line with the reactor program but have limited performance

Model D is so far globally the most attractive but has still unresolved issues that require a longer term R&D activity

Conclusions (2)

- Model C utilize almost all the technology of Model A&B plus ODS insert in the FW and SiCf/SiC inserts in the breeder zone.

  It could also be considered as a candidate for DEMO because:
  - SiCf/SiC inserts do not require very high thermal conductivity and have not severe constraints in terms of porosity, so, the material grade available so far don’t require major R&D
  - Even though ODS will be not available in time for DEMO the reduction in performance is very limited
  - The development of suitable heat exchangers can take advantage from the activity performed for HTGR

  And, certainly, it could shorten the route towards FOKR