Finite Elements Modelling of Tritium Permeation

Tritium diffusion and convection in LiPb

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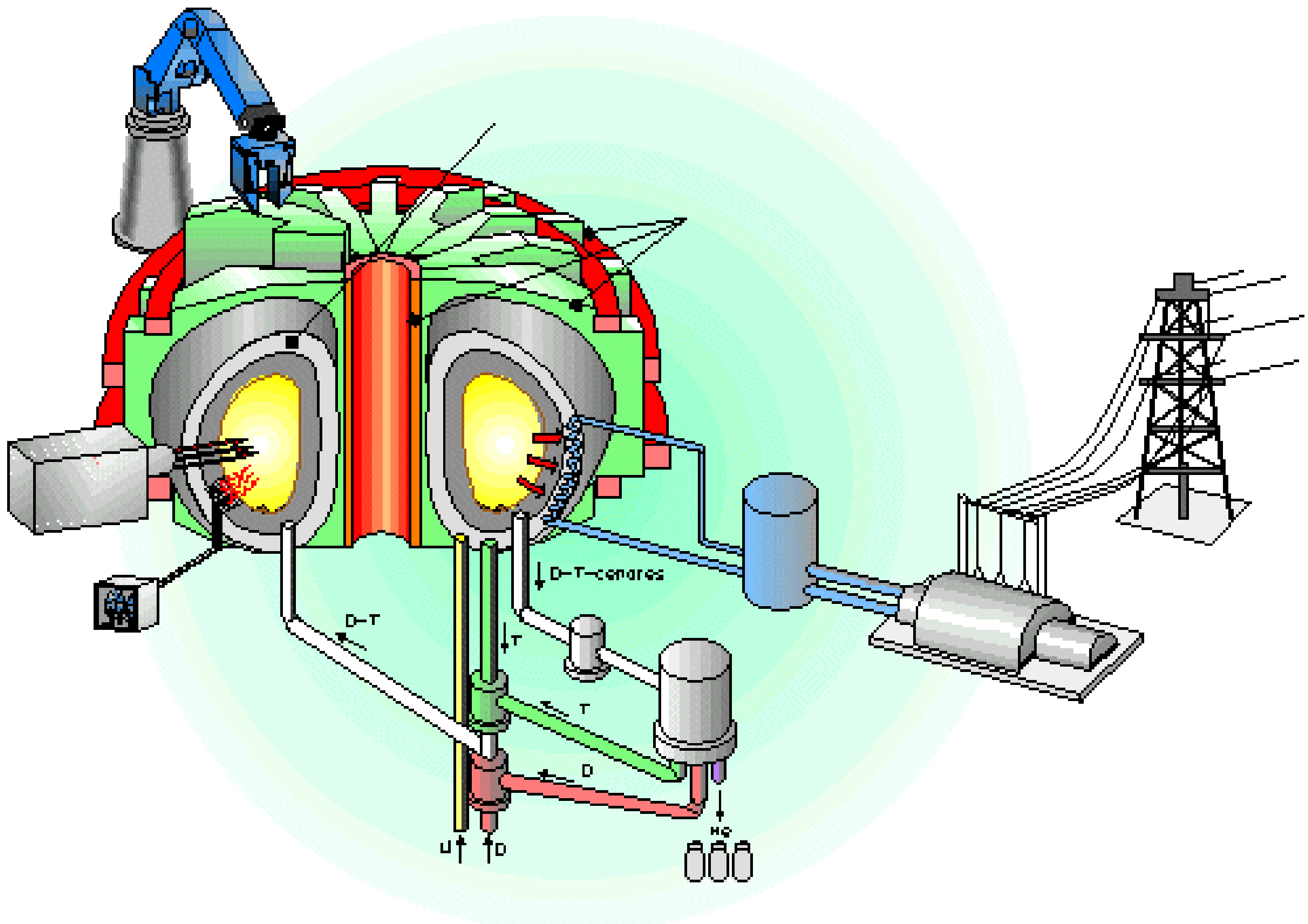
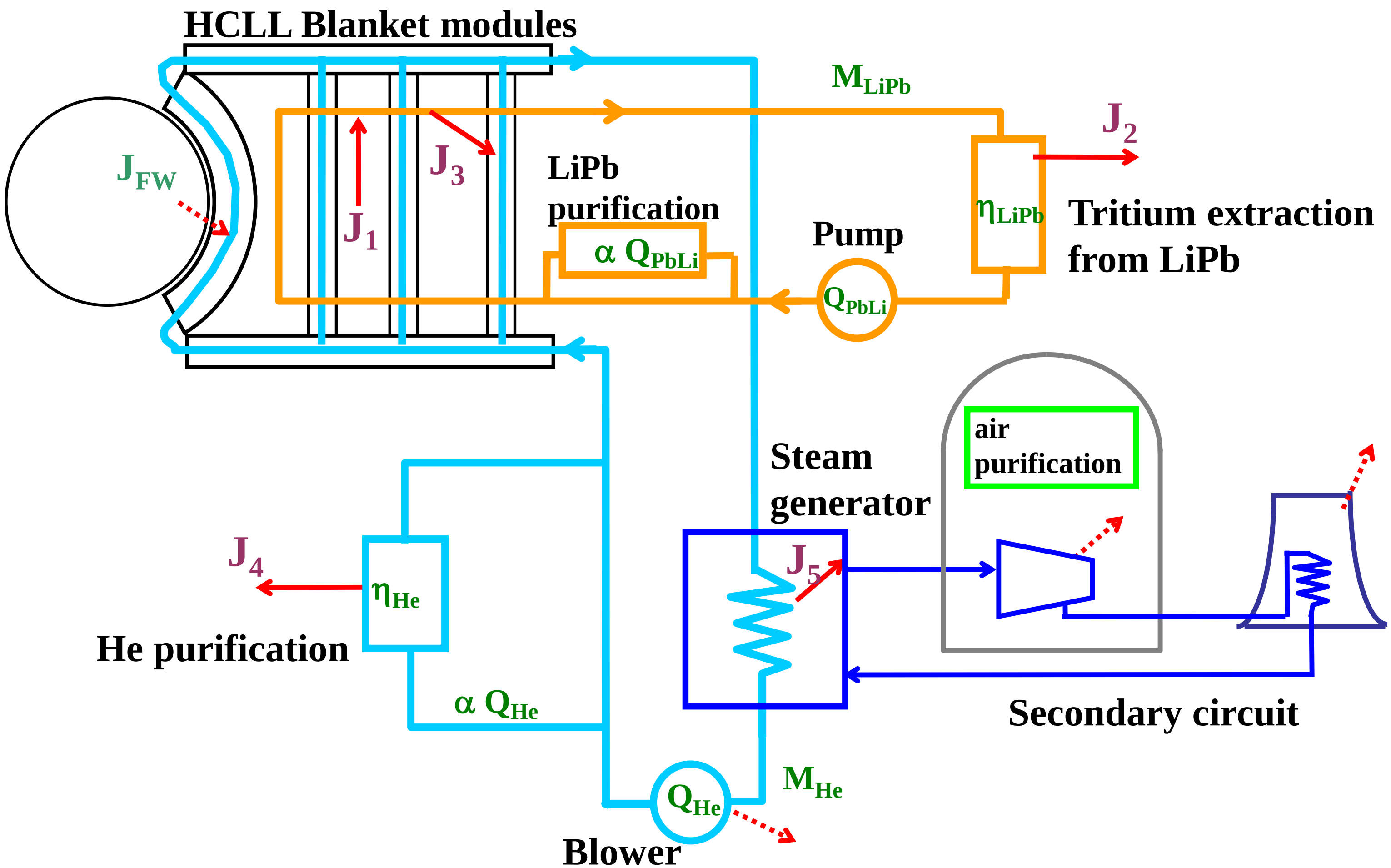
A Fusion Power Reactor



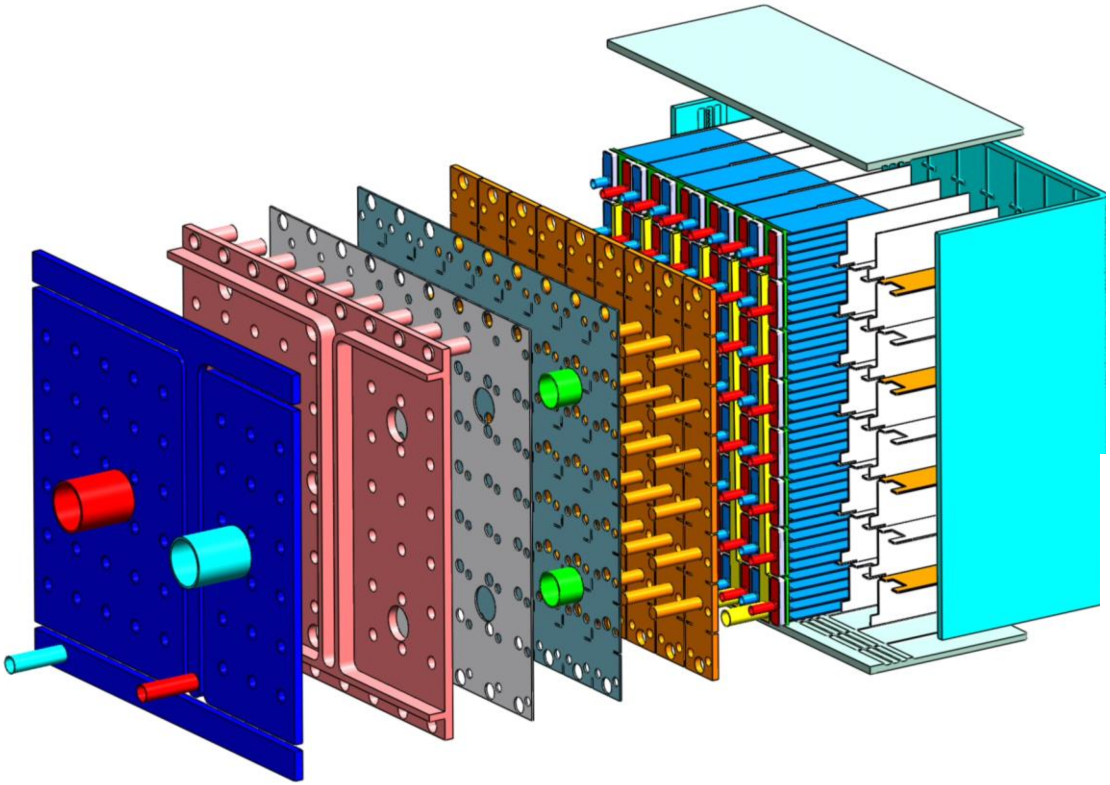
Schematic Fluids Circulation in the PPCS Reactor



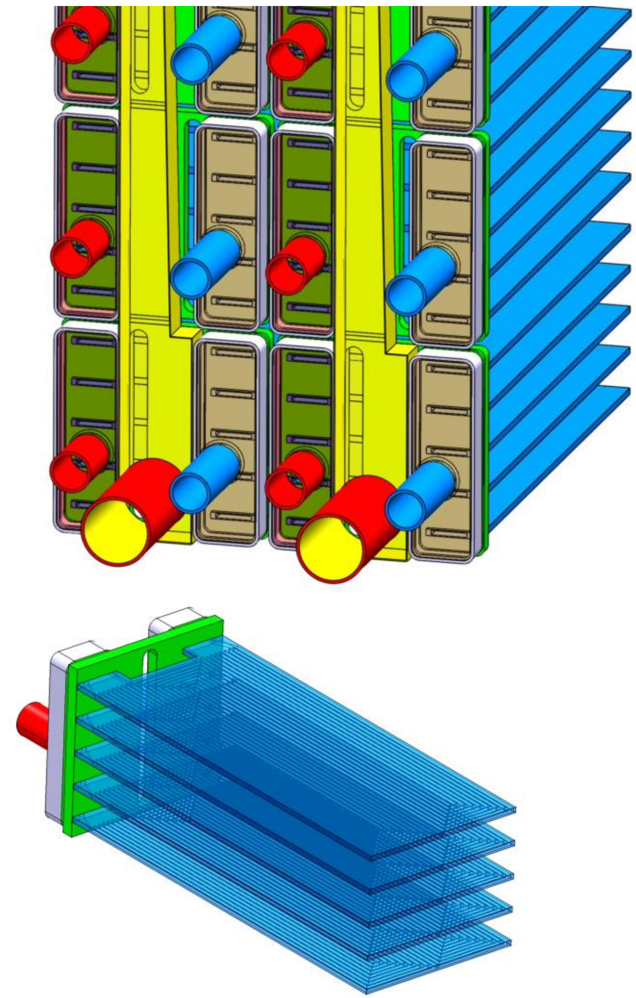
J_1 = 610 g/day (4000 MW fusion power)

Q_{He} = 4000 kg/s (T_{in} = 300°C, T_{out} = 500°C, P= 8.0 MPa

Concept of the HCLL Blanket Modules

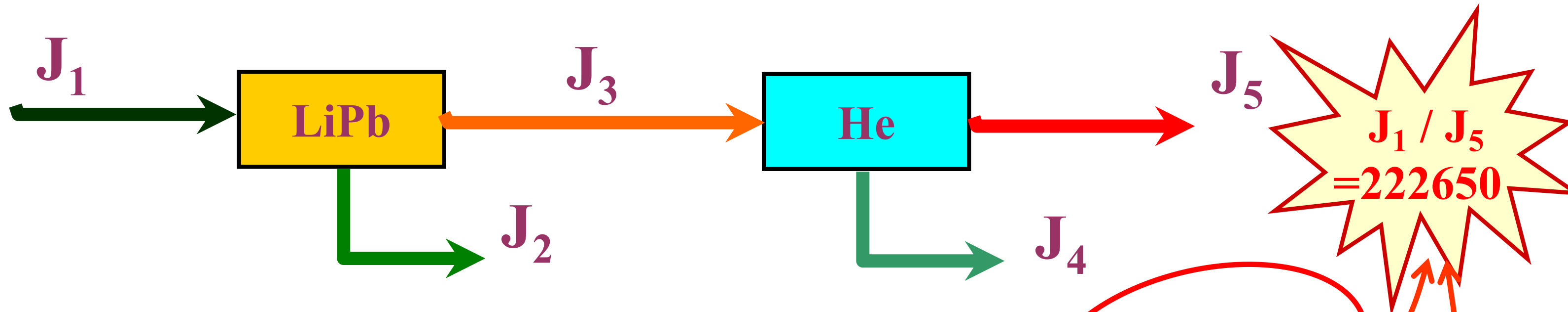


Demo Module



Breeding Unit

Analytical Model – Tritium Mass Balance Equations 1/2



- J_1 : Production rate

$$J_1 = 610\ \mathrm{g/day}$$

- J_2 : Extraction from LiPb

η_{LiPb} : extractor efficiency for LiPb
C_{out} : Tritium output concentration in LiPb (mol m^{-3}),
G_{LiPb} : LiPb flow rate (m^3 s^{-1})

$$J_2 = \eta_{LiPb}\, C_{out}\, G_{LiPb}$$

- J_3 : Permeation towards He coolant

C_{ave} : Tritium average concentration in LiPb (mol m^{-3})
$K_{blanket}$: Blanket permeation factor (m^3 s^{-1})

$$J_3 = C_{ave}\, K_{blanket}$$

- J_4 : Extraction from He coolant

G_{He} : He flow rate to detritiation unit (m^3 s^{-1})

$$J_4 = \eta_{He}\, C_{He}\, G_{He}$$

- J_5 : Release to environment

L_{SG}: Steam Generator leak flow (m^3 s^{-1})
K_{SG}: SG permeation factor (m^3 s^{-1})

$$J_5 = C_{He}\,(K_{SG} + L_{SG})$$

(J_5 max = 1 g/year=27 Ci/day , ITER standard)

Analytical Model – Tritium Mass Balance Equations 2/2

$$\frac{\partial M_{LiPb}}{\partial t} = J_1 - J_2 - J_3 \qquad \frac{\partial M_{He}}{\partial t} = J_3 - J_4 - J_5$$

$$\eta_{LiPb} = 1 - \frac{C_{in}}{C_{out}} \qquad C_{ave} = \frac{C_{in} + C_{out}}{2} \qquad K_{blanket} = \frac{1}{PRF_b} \frac{A}{s} \frac{Ks_{steel} D_{steel}}{Ks_{LiPb}}$$

- A, s : respectively wall surface (m^2) and wall thickness (m).
- Ks_{steel} Ks_{LiPb} : Sievert constants (mol m^{-3} $Pa^{-1/2}$), respectively in Eurofer and in LiPb
- D_{steel} Tritium diffusivity in Eurofer (m^2 s^{-1})
- PRF_b is the Permeation Reduction Factor provided by permeation barrier (if any)

Stationary results (*) :

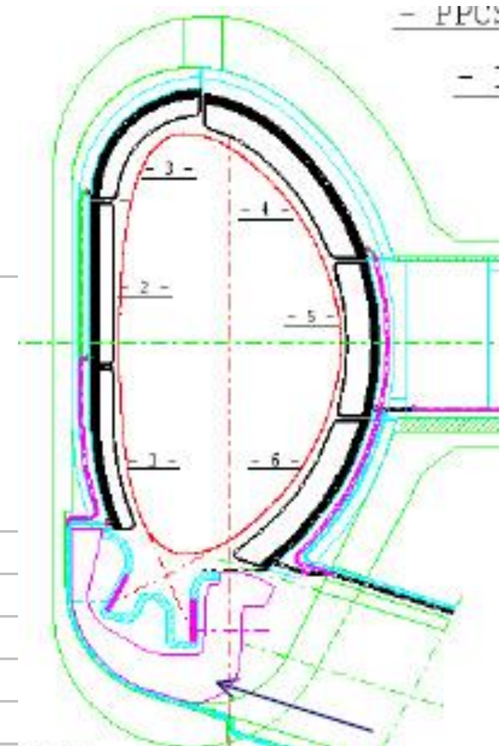
$$J_3 = \frac{J_1}{1 + \frac{2\eta_{LiPb}}{2 - \eta_{LiPb}} \frac{G_{LiPb}}{K_{blanket}}} \qquad J_5 = \frac{J_3}{1 + \eta_{He} \frac{G_{He}}{(K_{SG} + L_{SG})}}$$

$$\left(1 + \frac{2\eta_{LiPb}}{2 - \eta_{LiPb}} \frac{G_{LiPb}}{K_{blanket}}\right)\left(1 + \frac{\eta_{He} G_{He}}{K_{SG} + L_{SG}}\right) \geq \frac{J_1}{J_{5,MAX}}$$

* Thanks to Italo Ricapito (ENEA consultant) who initiated these computations

Computation of $K_{blanket}$ for PPCS

$$K_{blanket} = \frac{1}{PRF_b} \cdot \frac{A}{s}\Psi \cdot \frac{Ks_{steel}\, D_{steel}}{Ks_{LiPb}}$$



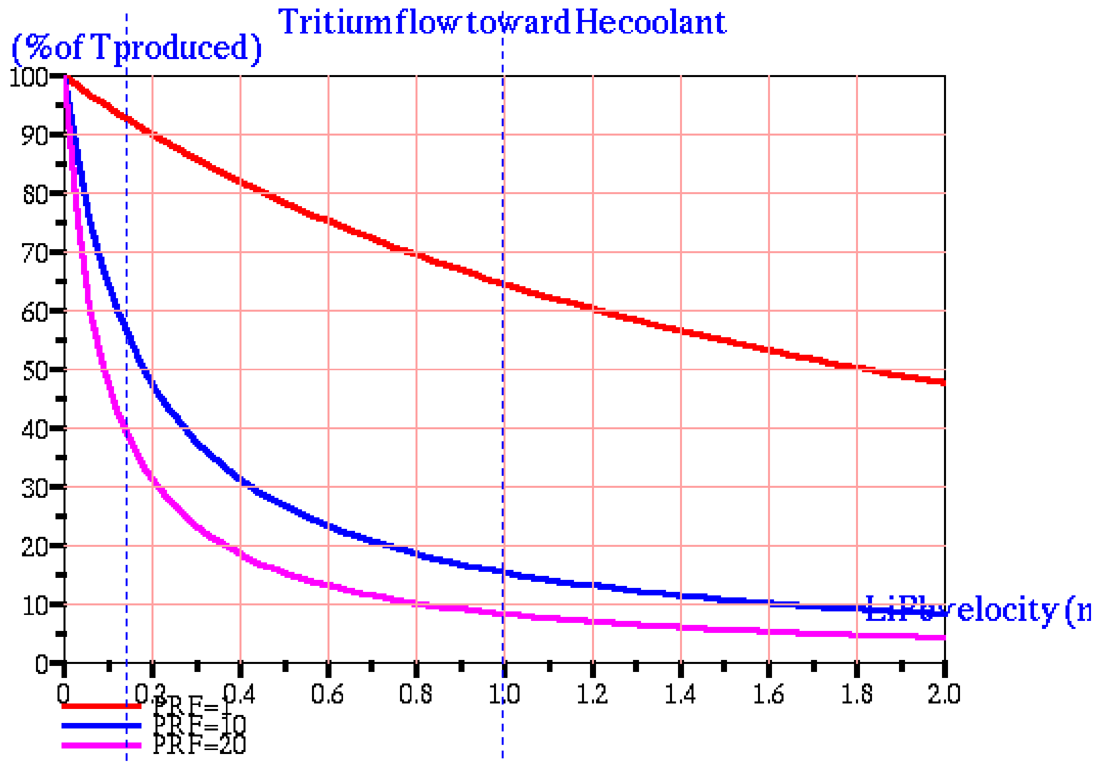
Module type	number of modules	number of BU per module	total CP facing surface per mod. type (m2)	total SP facing surface per mod. type (m2)	A/s * psi for CP (m)	A/s * psi for SP (m)	
1	18	140	1814	806	2,38E+06	3,52E+05	
2	18	140	1814	806	2,38E+06	3,52E+05	
3	27	72	1400	622	1,83E+06	2,71E+05	
4	36	168	7403	3290	9,70E+06	1,43E+06	
5	45	140	7711	3427	1,01E+07	1,49E+06	
6	36	154	6786	3016	8,89E+06	1,31E+06	
total	180	24876	26928	11968	3,53E+07	5,22E+06	4,05E+07

For T_{ave}=480 °C $K_{steel}\, D_{steel}/K_{Lipb} = 2.7\ 10^{-8}\ m^2\ s^{-1}$

$K_{blanket} = 1.09\ /PRF\ m^3\ s^{-1}$

Tritium flow towards He coolant (J_3)

- $K_{blanket}$ = 1.09 / PRF_b $m^3\ s^{-1}$ (T_{ave} = 480 °C, 180 modules)
- η_{LiPb} = 0.8 (reasonable efficiency for packed column extractor)
- G_{LiPb} limitation due to LiPb velocity (MHD pressure drops and corrosion)



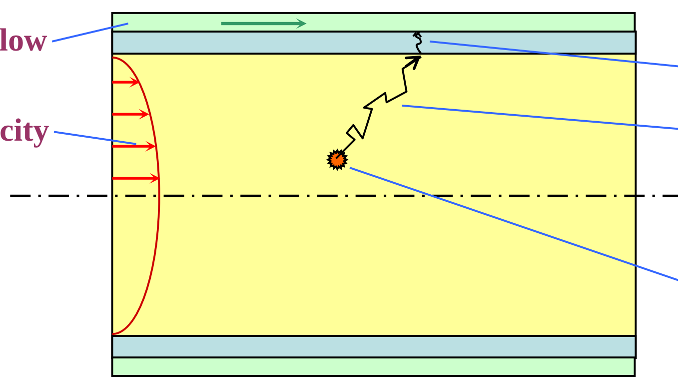
$$J_3 = \frac{J_1}{1 + \frac{2\eta_{LiPb}}{2-\eta_{LiPb}} \frac{G_{LiPb}}{K_{blanket}}}$$

10 recycling/day
0.063 m³ s⁻¹

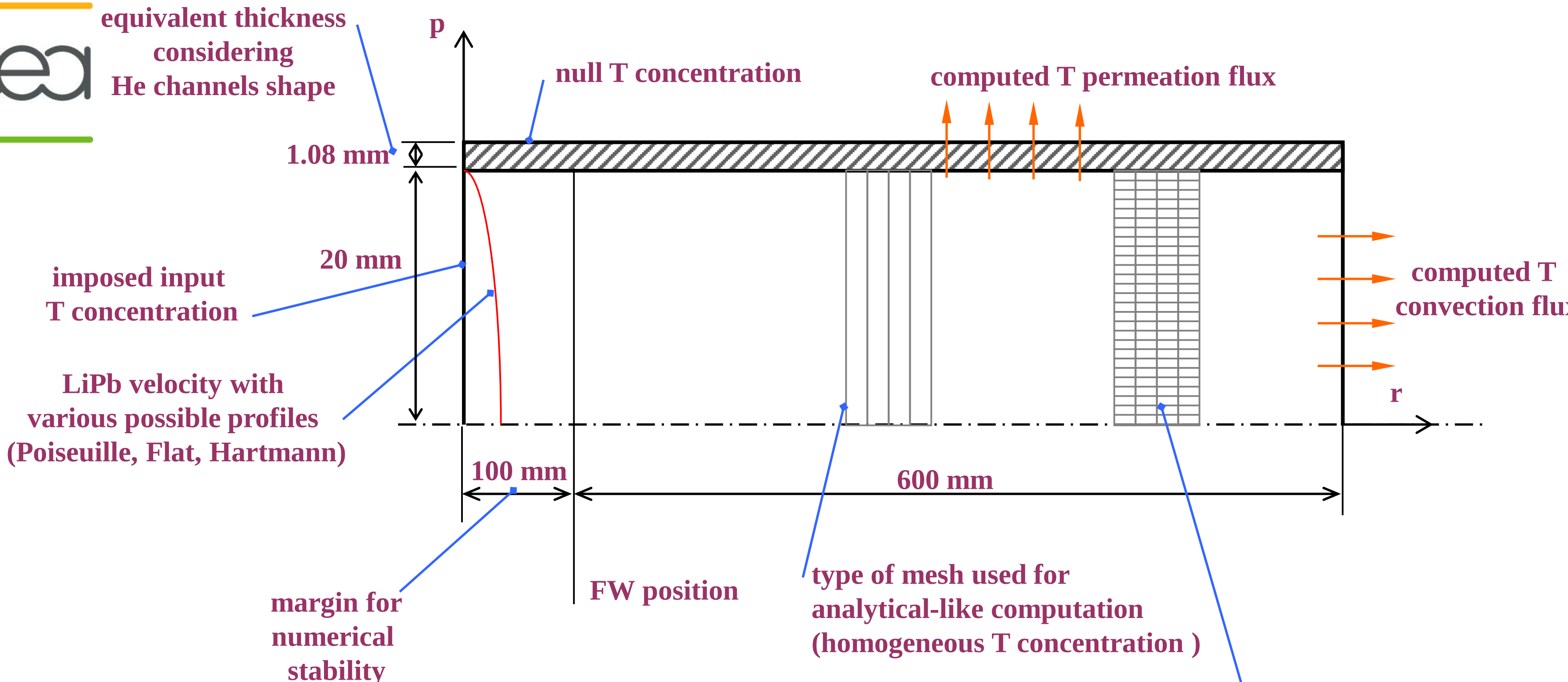
72 recycling/day
0.454 m³ s⁻¹

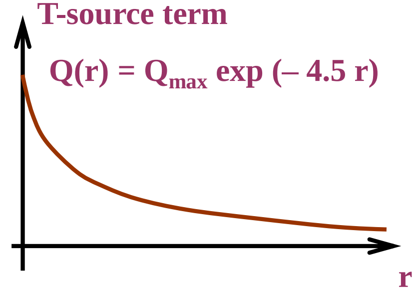
Justification of the FEM Study

- **Previous analytical computations made the assumption that all the produced tritium is immediately available for permeation through the Eurofer walls.**
- **Actually, T has to travel through the LiPb bulk before reaching the walls.**
- **Considering that:**
  - T diffusivity in LiPb is about 10 times smaller than in Eurofer.
  - LiPb layer thickness is 40 times larger than Cooling Plates wall thickness in present Breeding Unit design.
- **Ignoring these facts might lead to very pessimistic results (nearly all the produced T escapes into the He coolant, if no permeation barriers are used).**



CAST3M Model of the BU used for the study





type of mesh used for T diffusion computation (stratified T concentration)

$$\frac{\partial c}{\partial t} + V \cdot \nabla c - D\,\nabla^2 c = S$$

Cast3M results – homogeneous T concentration

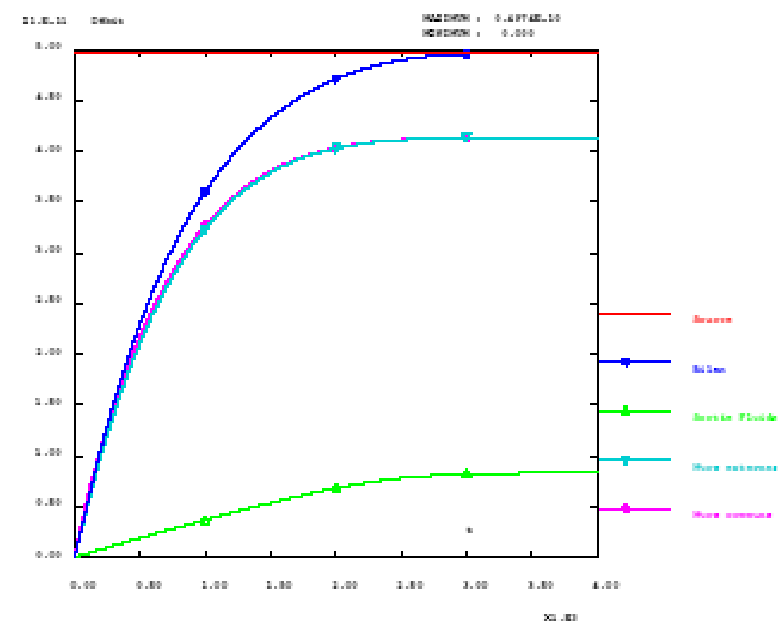
v = 0.25 mm/s
18 recycling/day

83.2 % of permeation

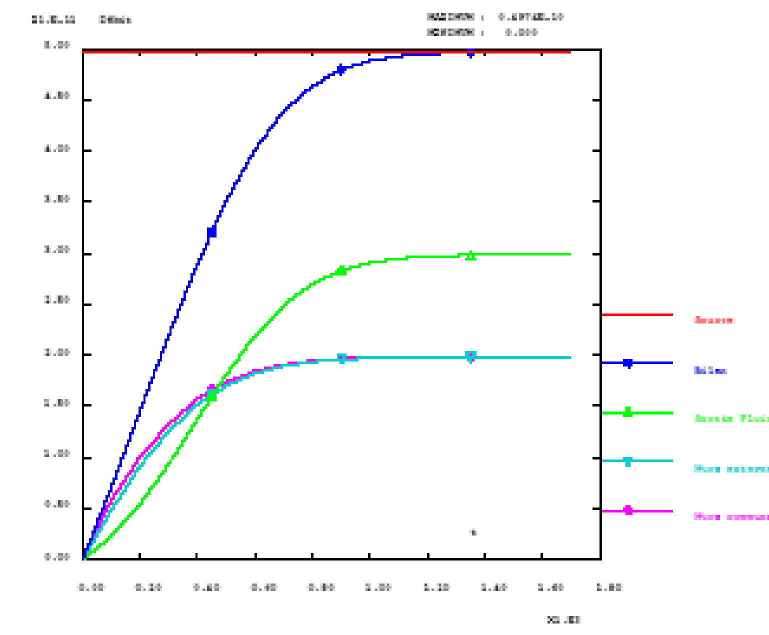
Maximum T concentration
does not reached the outlet

v = 1.0 mm/s
72 recycling/day

39.9 % of permeation



v = 0.25 mm/s

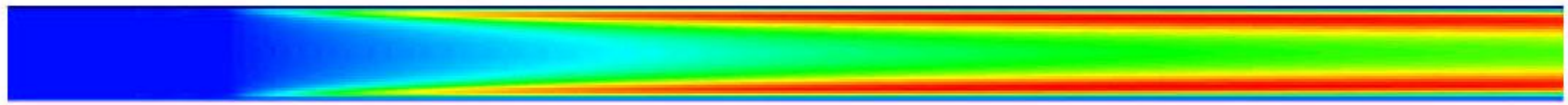


v = 1.0 mm/s

Diffusion with Poiseuille velocity profile

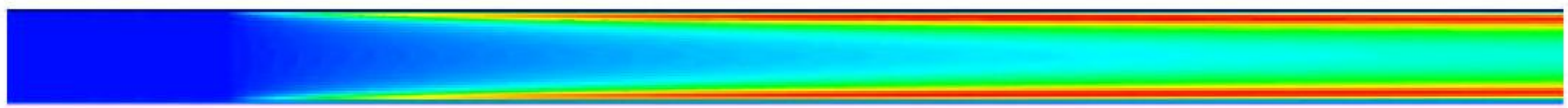
v = 0.25 mm/s
18 recycling/day

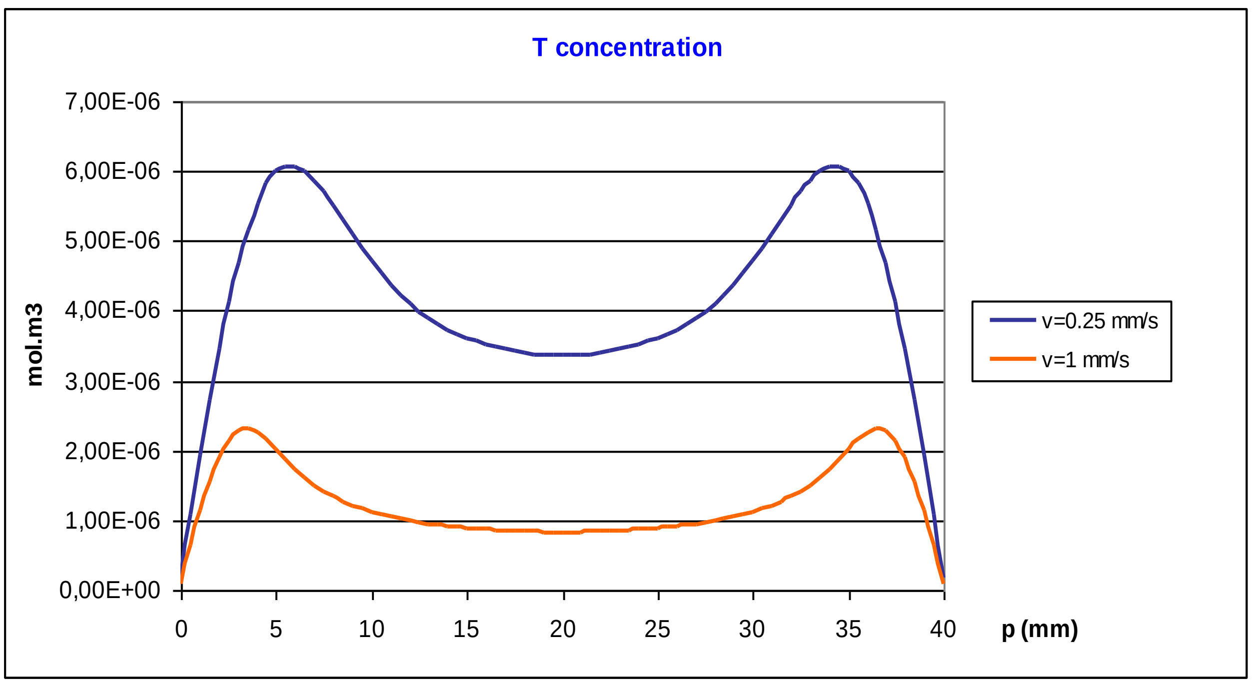
15.4 % of permeation



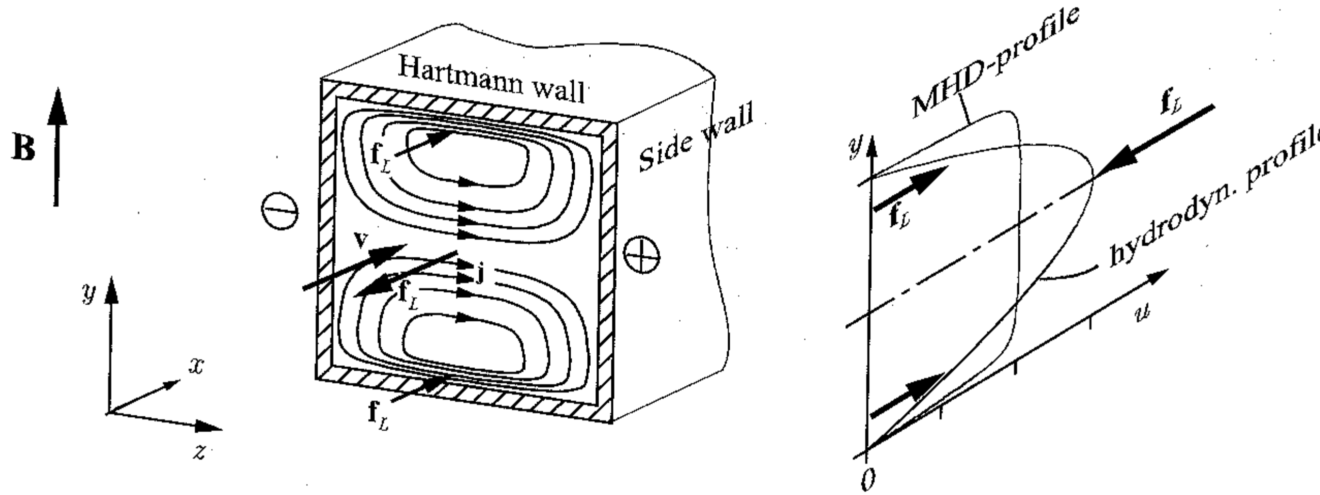
v = 1.0 mm/s
72 recycling/day

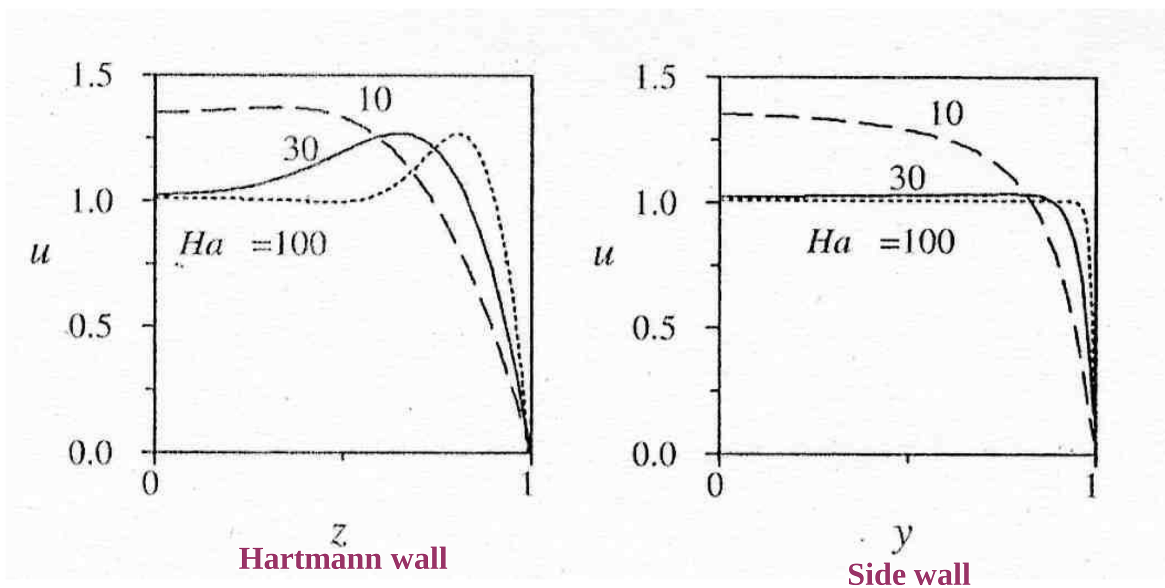
9.4 % of permeation





Some velocity profiles induced by MHD





from Magnetofluiddynamics in Channels and Containers, U. Müller, L. Bühler, Springer

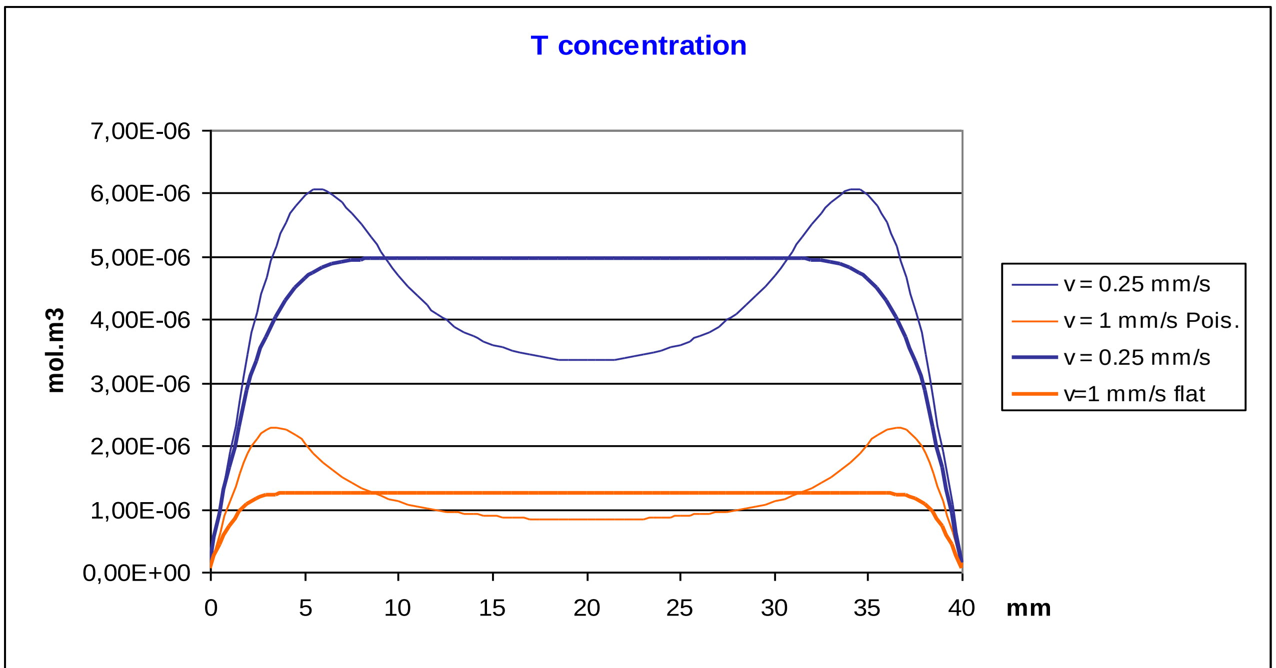
Diffusion with flat velocity profile

v = 0.25 mm/s
18 recycling/day

10.3 % of permeation

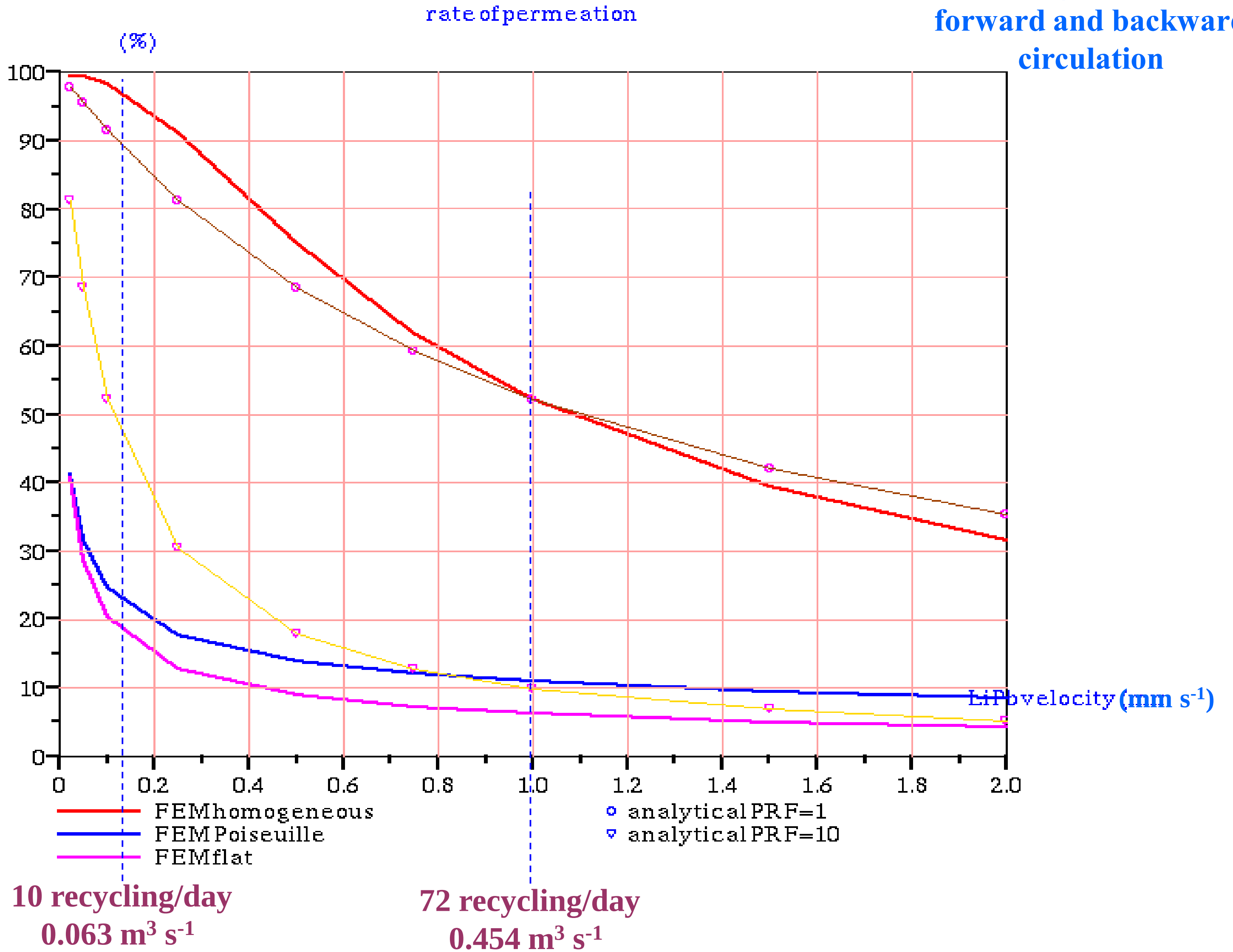
v = 1.0 mm/s
72 recycling/day

5.0 % of permeation

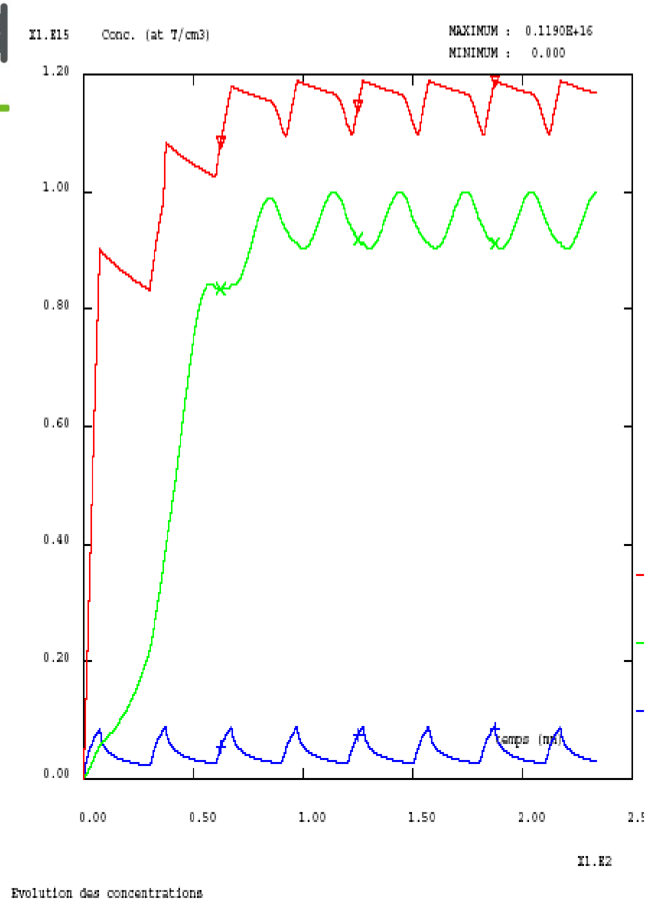


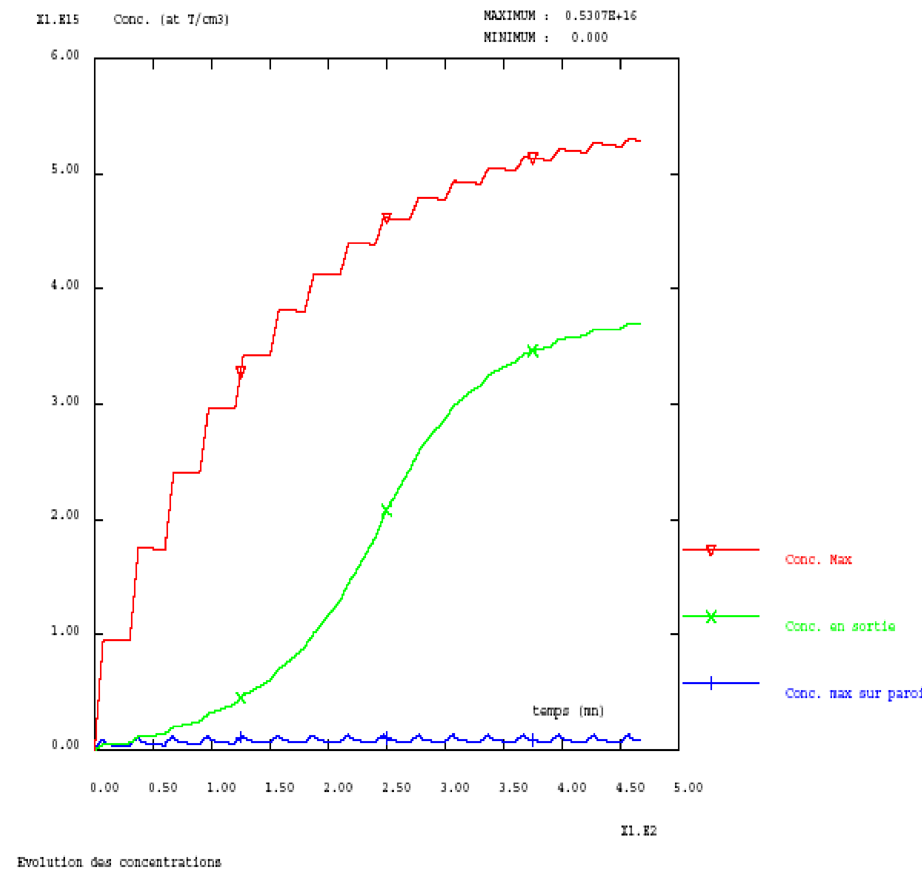
Permeation vs. LiPb Velocity for various cases

η= 1.0
forward and backward circulation



Application of ITER duty factor (400 s / 1800 s)





v = 0.2 mm/s

v = 0.04 mm/s

Conclusions

- Taking into account T diffusion in the LiPb bulk drastically reduces the permeation rate as previously analytically computed.
- Further works are to be completed to assess the LiPb flow (thermal convection with MHD, duct expansion/contraction, possible stagnation areas)
- Further refinement can be introduced in the model (temperature chart for diffusivity, input T concentration, Stiffening Plates, 3D)
- However, higher confidence in these results can only come from experimentation
- Cast3M allows to fit TBM experiments in ITER in order to find Power Reactor equivalent working points