Atelier Sûreté-MSFR
Grenoble, France,
24 – 25 Nov. 2014

Couplage neutronique-thermohydraulique et suivi des précurseurs

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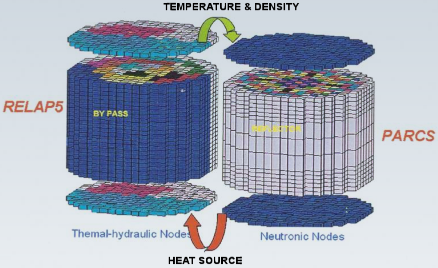
Simulation performed in the framework of a collaboration between POLIMI and LPSC/CNRS within the EVOL Project

Traditional coupled–codes technique

Traditionally, in reactor analysis...

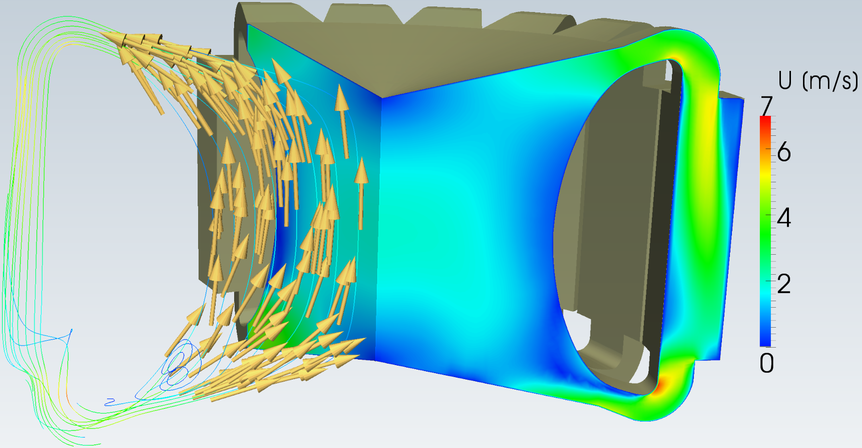


Coupled–codes technique with loosely coupled "single physics" codes

output from one code passed as input to the other, with no sub-iterations

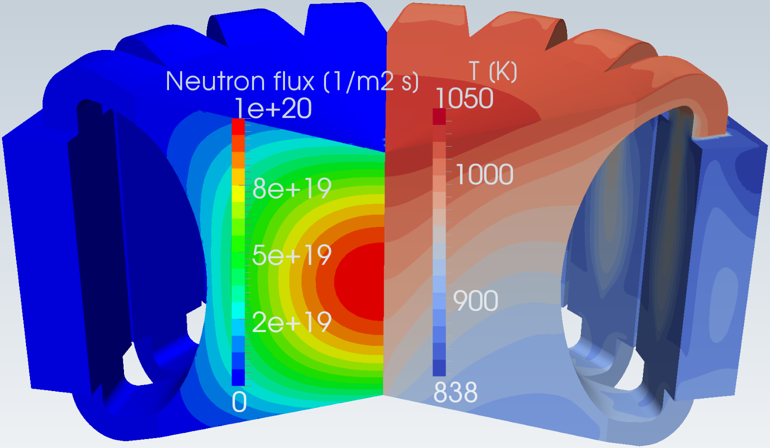
low coupling accuracy, even with high–order time integration in neutron kinetics code and in thermal–hydraulics code

OpenFOAM solver: coupling neutronics and CFD



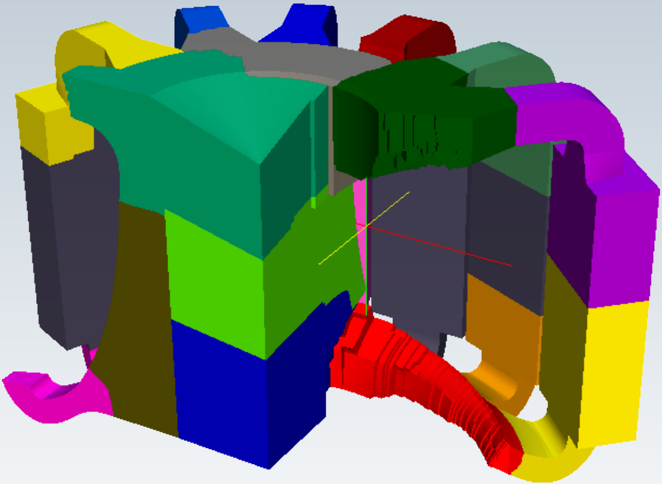
Coupled CFD/neutronics calculation for the MSFR: velocity field

OpenFOAM solver: coupling neutronics and CFD



Coupled CFD/neutronics calculation for the MSFR: ϕ & T

Full-core 3D calculations on realistic geometries



Straightforward parallelization by domain decomposition

Effective delayed neutron fraction

The effective delayed neutron fraction (β_{eff}) is an important reactor kinetics parameter.

The contribution of delayed neutrons is of primary importance for the safe control of any nuclear reactor.

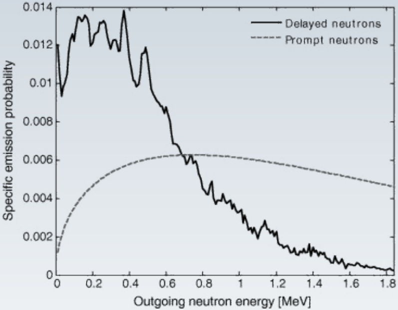
Effective delayed neutron fraction

Why β_{eff} is different from β_{zero}?
Prompt and delayed neutrons have different importance:

Effective delayed neutron fraction

Why β_{eff} is different from β_{zero}?
Prompt and delayed neutrons have different importance:

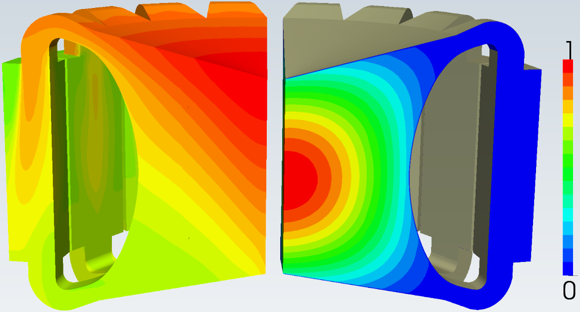
Energy effects



Effective delayed neutron fraction

Why β_{eff} is different from β_{zero}?
Prompt and delayed neutrons have different importance:

Spatial effects



Spatial distribution of the delayed (left) and prompt (right) neutron sources at nominal flow rate (arbitrary unit). OpenFOAM - 3D optimized MSFR geometry at nominal flow rate.

Effective delayed neutron fraction

Why β_{eff} is different from β_{zero}?
Prompt and delayed neutrons have different importance:

Often, β_{eff} in circulating-fuel conditions is calculated by correcting static β_{eff}, with the fraction of precursors decaying inside the core.

This might give inaccurate results due to inhomogeneous spatial neutron importance inside the core.

Calculation of β_{eff} in the MSFR

Analytical approach.

Deterministic approach.

Monte Carlo approach.

Calculation of β_{eff} in the MSFR

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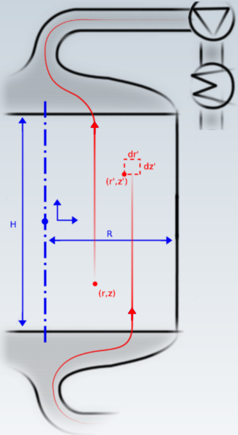
Simulation tools – Analytical approach

Integrating the delayed neutron source weighted with a simple importance shape function...



$$cf_{circ} \equiv \frac{\beta^{c}_{eff}}{\beta^{s}_{eff}} = \frac{\int_{core} D^{c}(\mathbf{r}') \cdot I^{c}(\mathbf{r}')\, dv'}{\int_{core} D^{s}(\mathbf{r}') \cdot I^{s}(\mathbf{r}')\, dv'} \tag{1}$$

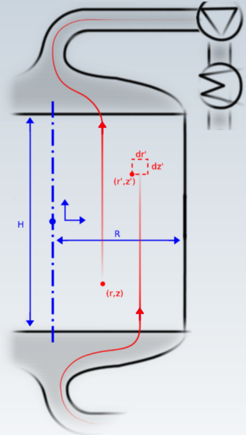
$$D(\mathbf{r}') = \int_{core} K(\mathbf{r}', \mathbf{r})\, S(\mathbf{r})\, dv \tag{2}$$

$$cf_{circ} = \frac{\iint_{core\ core} \left[K^{c}(\mathbf{r}', \mathbf{r})\, S^{c}(\mathbf{r})\, dv\right] I^{c}(\mathbf{r}')\, dv'}{\int_{core} S^{s}(\mathbf{r}') \cdot I^{s}(\mathbf{r}')\, dv'} \tag{3}$$

$$K^{\lambda\,\mathbf{T}}(r'z' \leftarrow rz) = p_{1}^{\lambda\,\mathbf{T}}(r'z' \leftarrow rz) + p_{2}^{\lambda\,\mathbf{T}}(r'z' \leftarrow rz) \tag{4}$$

Simulation tools – Analytical approach

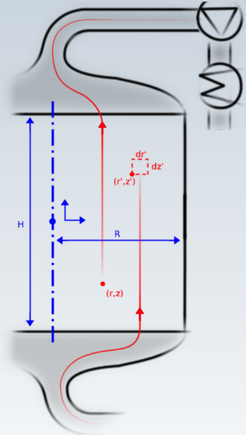
Integrating the delayed neutron source weighted with a simple importance shape function...



$$S(\mathbf{r}) \simeq I(\mathbf{r}) \simeq cos\left(\frac{\pi\, z}{H_e}\right) J_0\left(\frac{2.405\, r}{R_e}\right)$$

- One group diffusion in reflected cylinder
- Zero radial velocity and uniform axial velocity
- Complete mixing in Pump/HEX
- No turbulent or laminar precursors diffusion

Integrating the delayed neutron source weighted with a simple importance shape function...



$$p_1^{\lambda T}(r'z' \leftarrow rz) = \delta(r' - r)dr' \cdot e^{-\lambda T \gamma \frac{z'-z}{H_a}} \cdot \lambda T \gamma \frac{dz'}{H_a} \tag{5}$$

$$p_2^{\lambda T}(r'z' \leftarrow rz) = \frac{2\pi r' dr'}{\pi R_a^2} \cdot \frac{1}{e^{\lambda T} - 1} \cdot e^{-\lambda T \gamma \frac{z'-z}{H_a}} \left(1 - e^{-\lambda T \gamma \frac{dz'}{H_a}}\right) \tag{6}$$

$$K^{\lambda T}(r'z' \leftarrow rz) = p_1^{\lambda T}(r'z' \leftarrow rz) + p_2^{\lambda T}(r'z' \leftarrow rz) =$$
$$= e^{-\lambda T \gamma \frac{z'-z}{H_a}} \cdot \lambda T \gamma \frac{dz'}{H_a} \left[HS(z' - z) \cdot \delta(r' - r)dr' + \frac{1}{e^{\lambda T} - 1} \cdot \frac{2\pi r' dr'}{\pi R_a^2}\right] \tag{7}$$

Calculation of β_{eff} in the MSFR

Analytical approach.

Deterministic approach.

Monte Carlo approach.

Simulation tools – OpenFOAM

Solving the forward and adjoint eigenvalue neutron diffusion problem, with precursors transport...

$$\beta_{eff,i} = \frac{\int \sum_{g=1}^{n} \phi_g^* \chi_{d,g} \lambda_i c_i}{\int \sum_{g=1}^{n} \phi_g^* \chi_{d,g} \sum_{k=1}^{m} \lambda_k c_k + \int \sum_{g=1}^{n} \phi_g^* \chi_{p,g} \sum_{g'=1}^{n} \phi_{g'} \left(\nu \Sigma_f\right)_{g'}}$$

Solving the forward and adjoint eigenvalue neutron diffusion problem, with precursors transport...

Forward problem

$$\nabla D_g \nabla \phi_g - \Sigma_{a,g}\phi_g - \sum_{g' \neq g} \Sigma_{s,gg'}\phi_g + \sum_{g' \neq g} \Sigma_{s,g'g}\phi_{g'} + \\ + (1-\beta_0)\,\chi_{p,g} \sum_{g'=1}^{n} \frac{1}{k_{eff}} (\nu\Sigma_f)_{g'}\,\phi_{g'} + \sum_{i=1}^{m} \chi_{d,g}\lambda_i c_i = 0$$

$$-\nabla(\mathbf{u}c_i) + \nabla \frac{\nu_T}{Sc_T} \nabla c_i - \lambda_i c_i + \beta_{0,i} \sum_{g=1}^{n} \frac{1}{k_{eff}} (\nu\Sigma_f)_g\,\phi_g = 0$$

Solving the forward and adjoint eigenvalue neutron diffusion problem, with precursors transport...

Adjoint problem

$$\nabla D_g \nabla \phi_g^* - \Sigma_{a,g}\phi_g^* + \sum_{g' \neq g} \Sigma_{s,gg'}\phi_g^* - \sum_{g' \neq g} \Sigma_{s,g'g}\phi_{g'}^* +$$

$$+(1-\beta_0)\frac{1}{k_{eff}}(\nu\Sigma_f)_g \cdot \sum_{g'=1}^{n} \chi_{p,g'}\phi_{g'}^* + \frac{1}{k_{eff}}(\nu\Sigma_f)_g \cdot \sum_{i=1}^{m} \beta_{0,i} c_i^* = 0$$

$$-\nabla(\text{-}\mathbf{u}c_i^*) + \nabla \frac{\nu_T}{Sc_T} \nabla c_i^* - \lambda_i c_i^* + \lambda_i \sum_{g=1}^{n} \chi_{d,g}\phi_g^* = 0$$

Calculation of β_{eff} in the MSFR

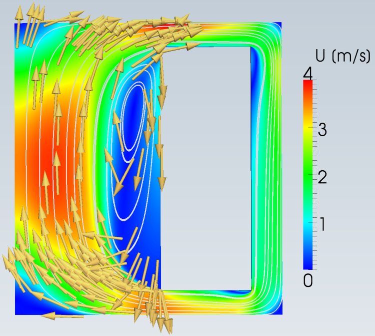
Analytical approach.

Deterministic approach.

Monte Carlo approach.

Simulation tools – SERPENT

Transporting DNP inside the Monte Carlo simulation...



When the emission of a delayed neutron is sampled:

- Sample the neutron emission time according to the decay constant
- Transport the precursor until the decay position (Dormand-Prince algorithm)
- Sample the neutron energy

c_i	a_{ij}						
0							
1/5	1/5						
3/10	3/40	9/40					
4/5	44/45	-56/15	32/9				
8/9	19372/6561	-25360/2187	64448/6561	-212/729			
1	9017/3168	-355/33	46732/5247	49/176	-5103/18656		
1	35/384	0	500/1113	125/192	-2187/6784	11/84	
b_i	35/384	0	500/1113	125/192	-2187/6784	11/84	0
b_i^*	5179/57600	0	7571/16695	393/640	-92097/339200	187/2100	1/40

Simulation tools – SERPENT

Calculating the effective delayed neutron fraction...

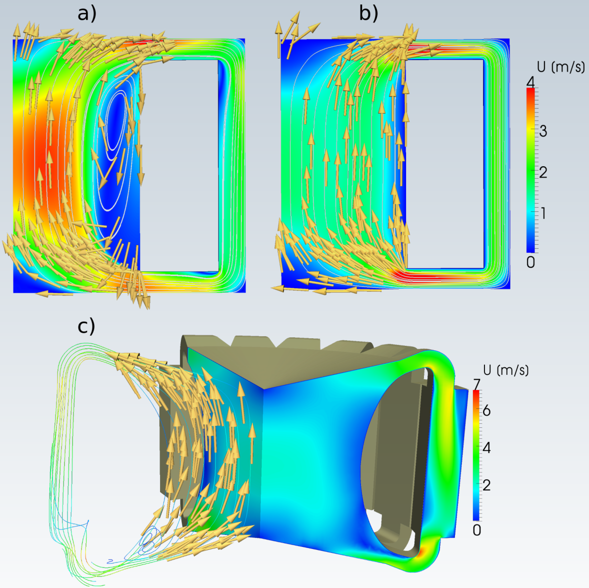
Prompt method is inefficient for β_{eff} and useless for the single $\beta_{eff,i}$ fractions.

Approximate methods (e.g., van der Mark and Meulekamp) are not suitable due to the presence of high spatial importance effects.

Iterated Fission Probability is adopted for adjoint calculations.

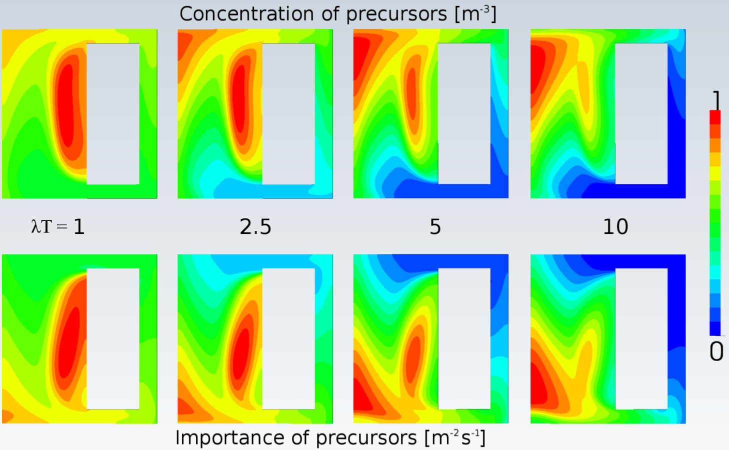
IFP methods have been implemented in Serpent-2 (available to users since version 2.1.13) and are presented in:

Case studies



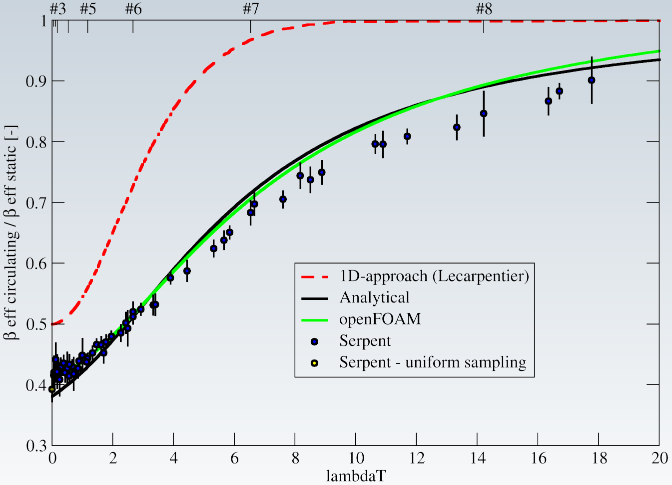
Results

Precursors concentration and importance, as function of the dimensionless parameter λT (k-epsilon case study)



Results

$\beta^c_{eff}/\beta^s_{eff}$ correction factor as function of λT (uniform velocity)



[*] Lecarpentier, D., 2001. Le concept AMSTER, aspects physiques et sûreté. Ph.D. thesis

Results

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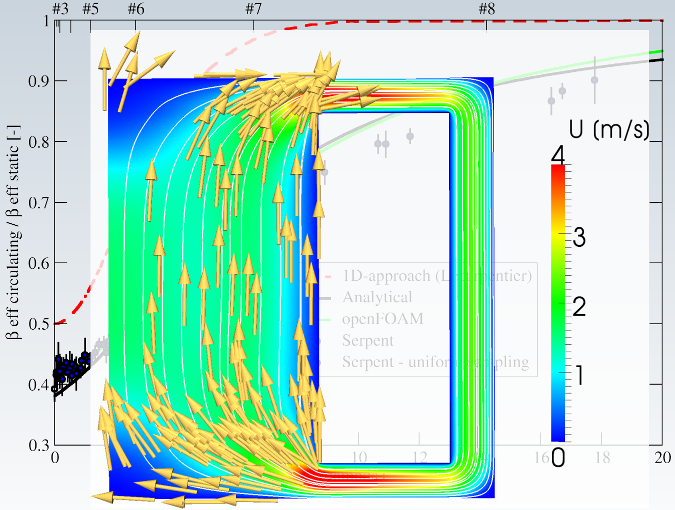
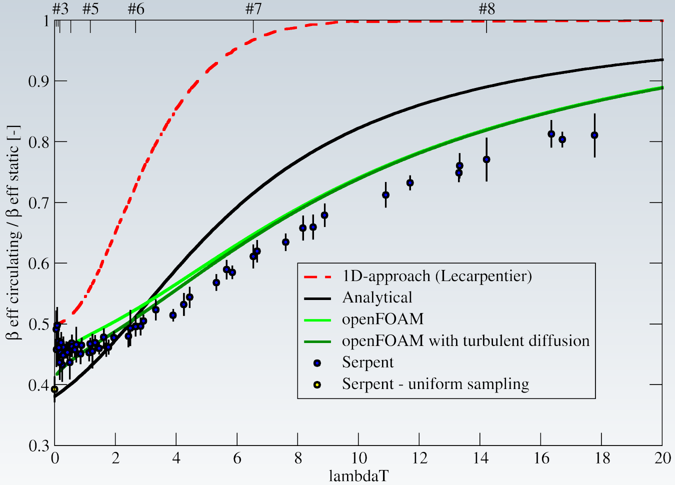


$\beta^c_{eff}/\beta^s_{eff}$ correction factor as function of λT (k-epsilon)



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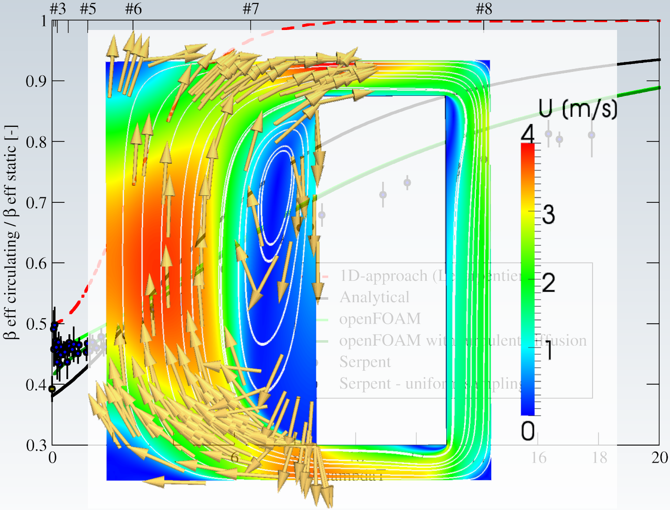
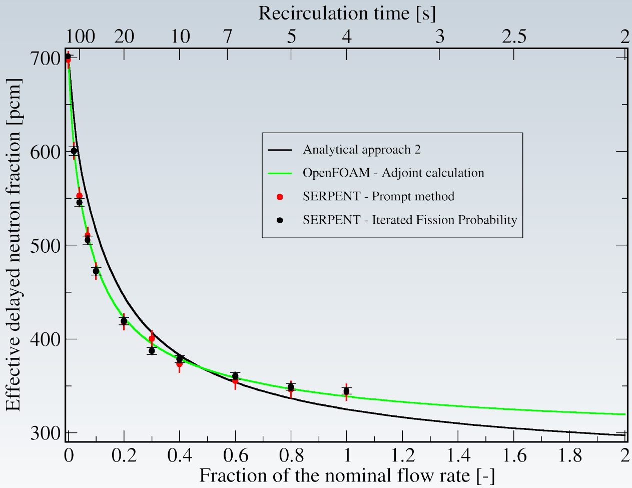
$\beta^c_{eff}/\beta^s_{eff}$ correction factor as function of λT (k-epsilon)

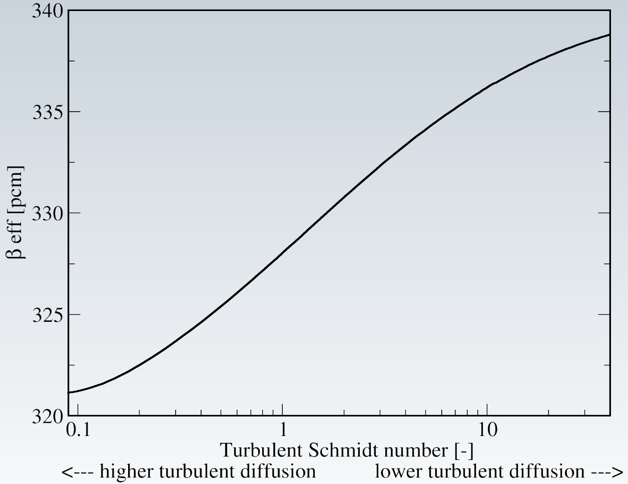


Results

β_{eff} as function of the flow-rate (U^{235}-started, k-epsilon)

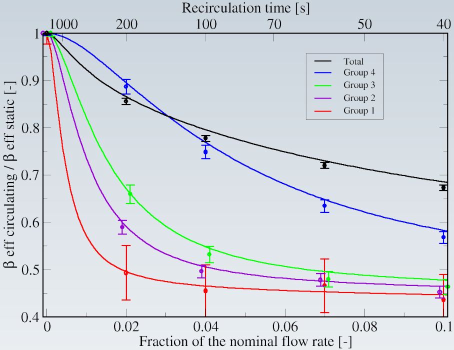


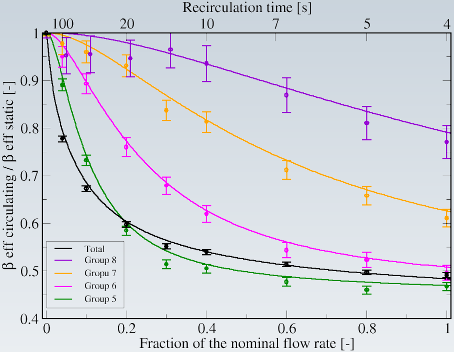
Effect of turbulent diffusion (U^{235}-started, k-epsilon)



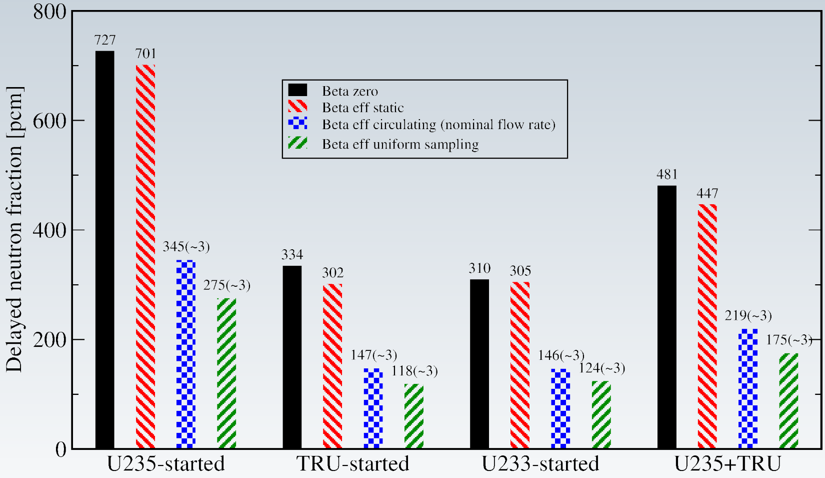
Results

β_{eff} as function of the flow-rate (U^{235}-started, k-epsilon)

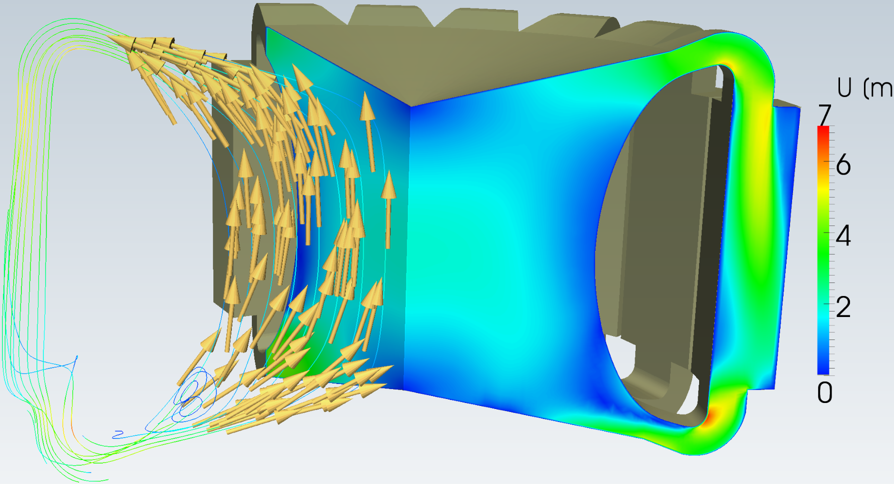




β_{eff} for different fuel composition

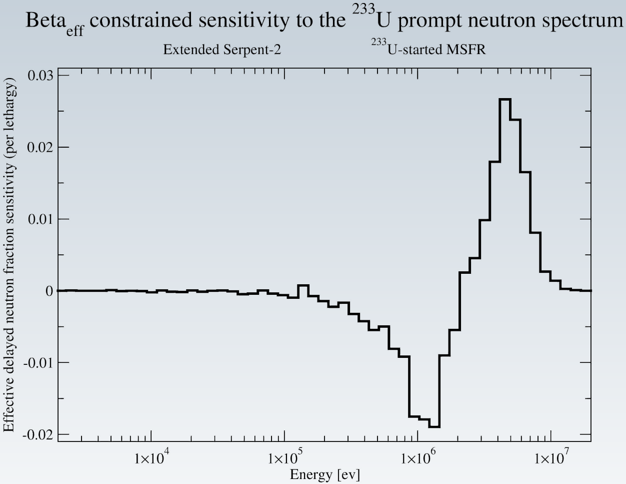


Calculating the "complete" β_{eff} uncertainty in MSRs

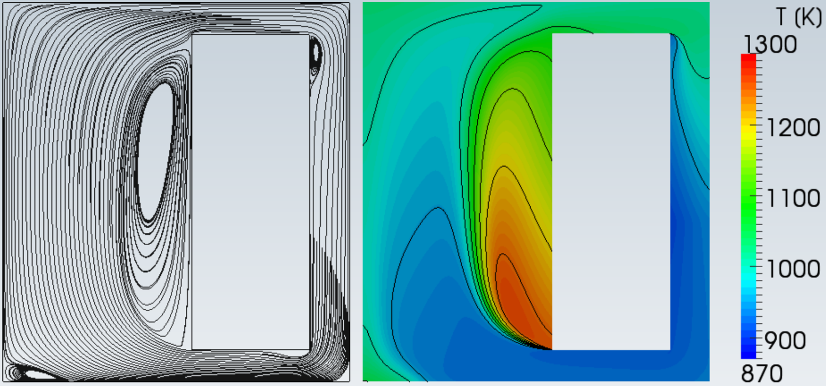


Nuclear data + DNP decay constants + fluid flow

Sensitivity/uncertainty from nuclear data



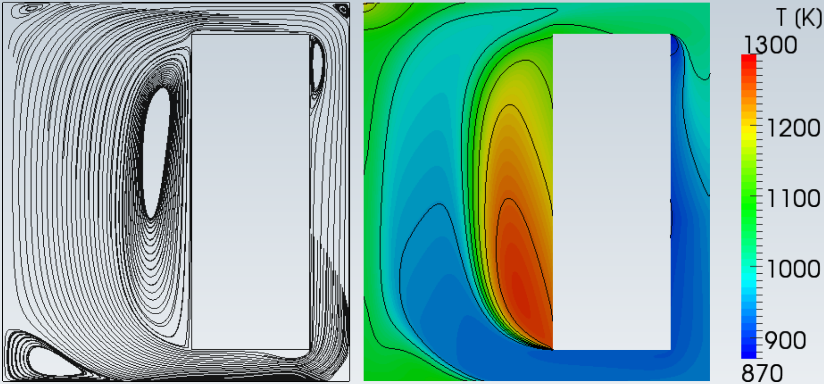
Effect of turbulence modelling on β_{eff}



k-ε model

[13] Losa, Multiphisics modelling of the Molten Salt Fast Reactor. Comparison of three turbulence models, Master thesis, 2013.

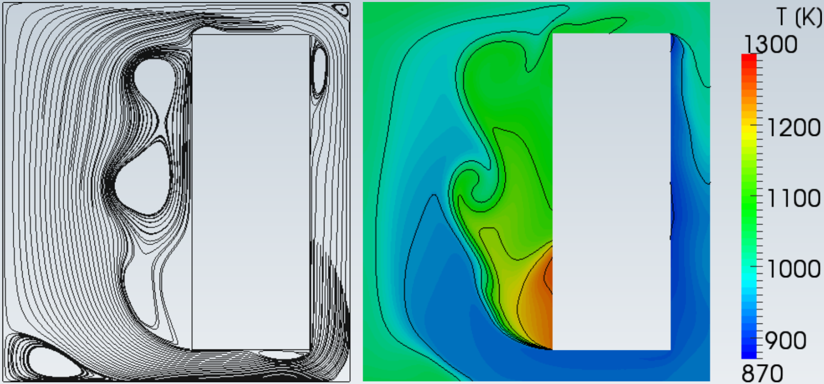
Effect of turbulence modelling on β_{eff}



k-ω model

[13] Losa, Multiphisics modelling of the Molten Salt Fast Reactor. Comparison of three turbulence models, Master thesis, 2013.

Effect of turbulence modelling on β_{eff}



RSM model

[13] Losa, Multiphisics modelling of the Molten Salt Fast Reactor. Comparison of three turbulence models, Master thesis, 2013.

THANK YOU FOR THE ATTENTION

Vue sur l'agglomération Grenobloise depuis le sommet du Moucherotte (Bertrand93)

QUESTIONS? SUGGESTIONS? NEW IDEAS?