Multi-physics coupling between Serpent and COMSOL

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Contents

- The concept of Small Module Dual Fluid Reactor
- Coupling Methodologies
- Coupling Calculation Examples
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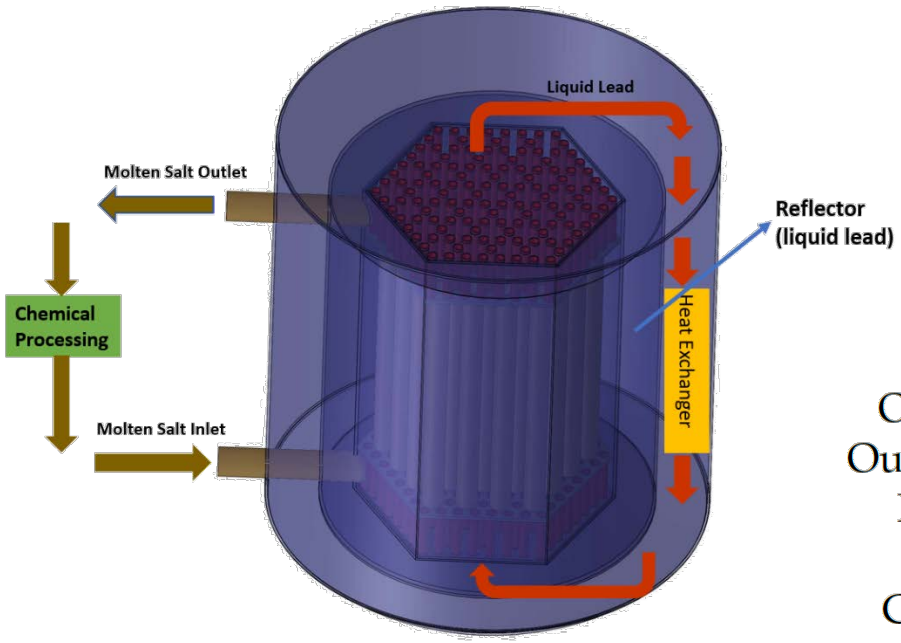
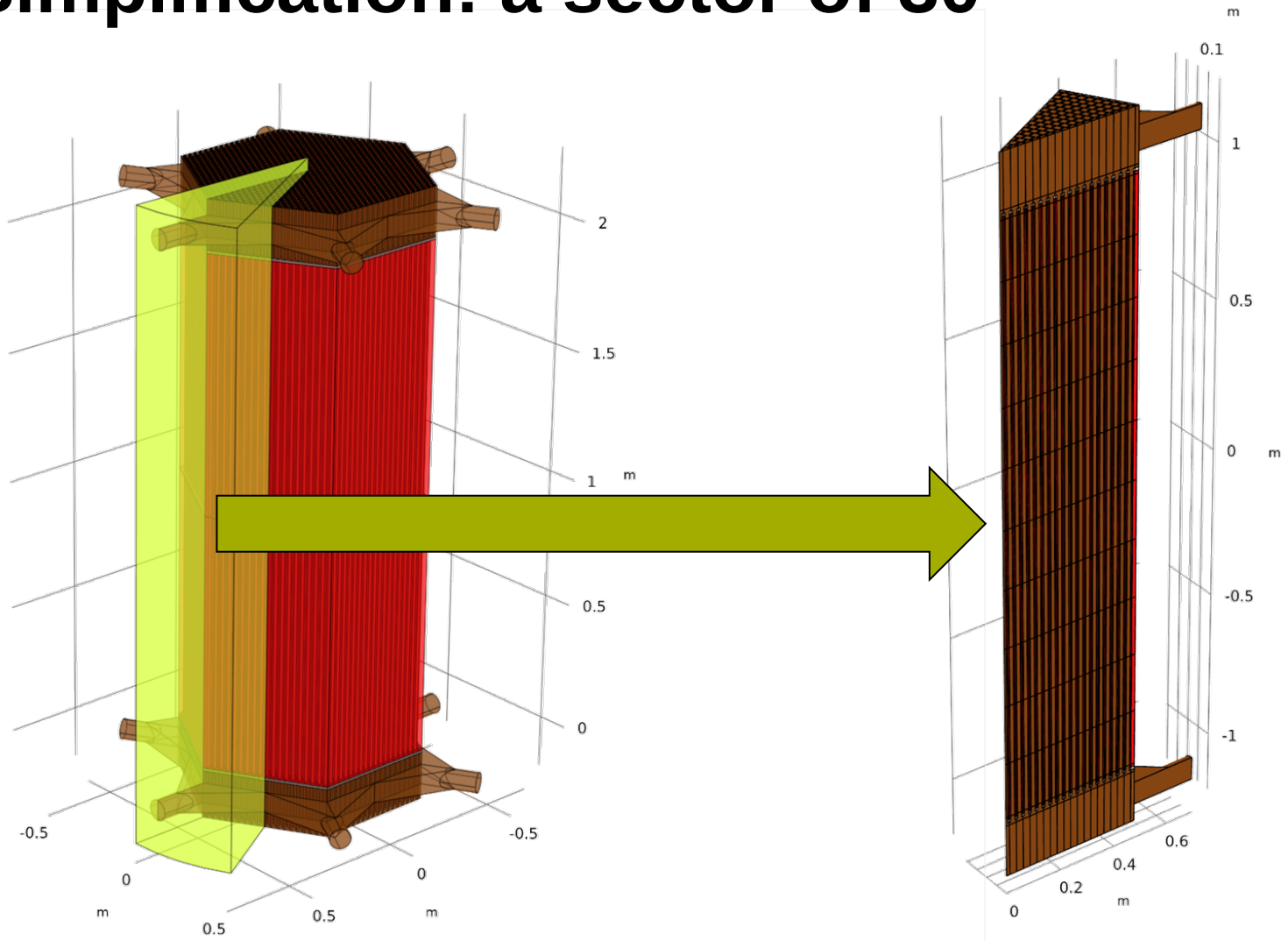
From 3 GW to 0.3 GW
From pipe-type to pool-type

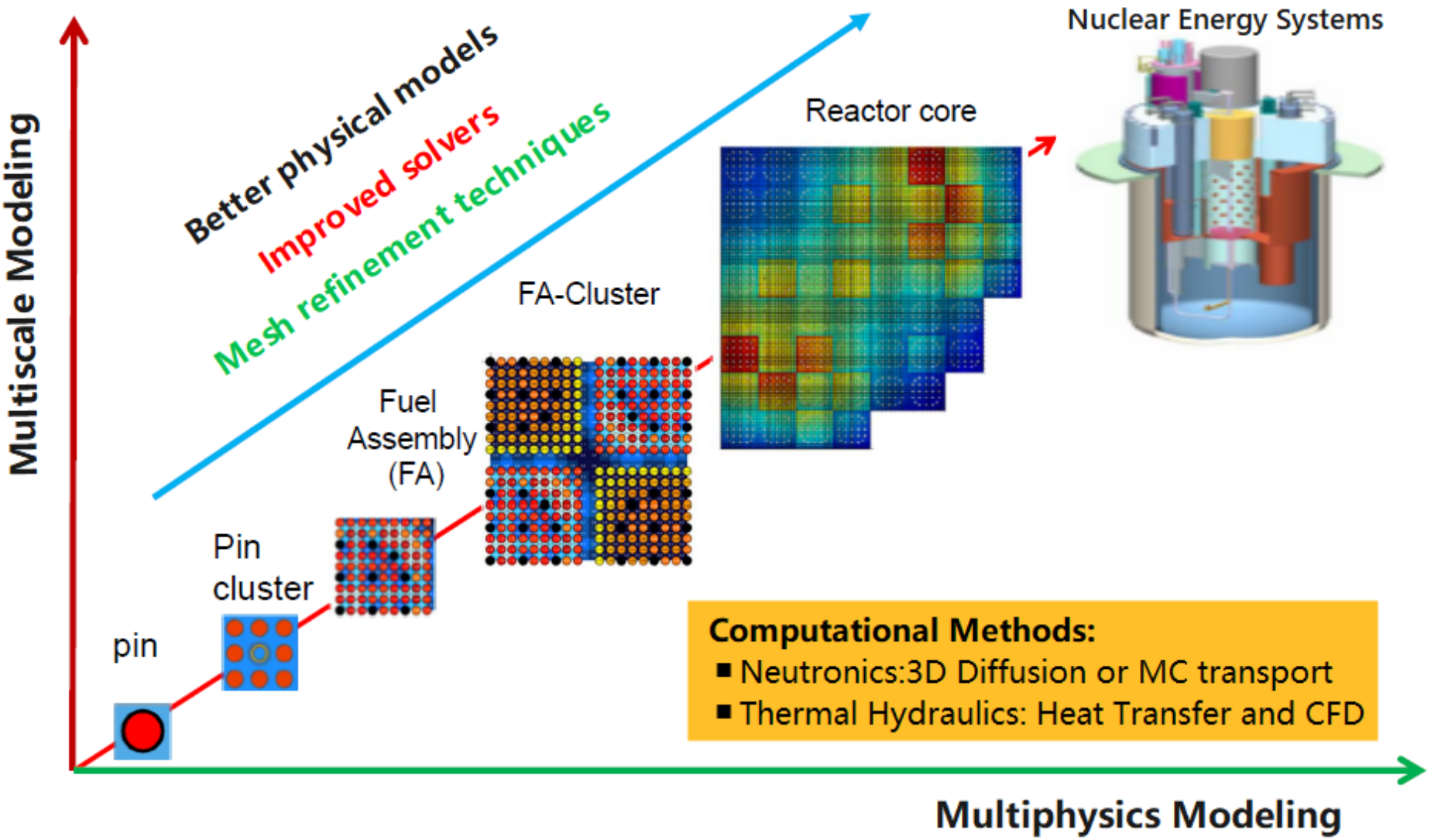


SMDFR Technical Data

Parameters	Values
Core zone D × H (m)	0.95 × 2.0
Distribution zone D × H (m)	0.95 × 0.2
Collection zone D × H (m)	0.95 × 0.2
Height of core (m)	2.4
Outer reflector diameter (m)	1.25
Tank D × H (m)	1.65 × 3.4
Number of fuel tubes	1027
Fuel pin pitch (m)	0.025
Outer/interior fuel tube diameter (m)	0.008/0.007
Outer/interior coolant tube diameter (m)	0.005/0.004
Mean linear power density (W/cm)	609
Fuel inlet/outlet temperature (K)	1300/1300
Coolant inlet/outlet temperature (K)	973/1250
Fuel inlet/in-core velocity (m/s)	3/0.5225
Coolant inlet/in-core velocity (m/s)	5/1.3488

Simplification: a sector of 30°





Multiscale and Multiphysics Modeling Progress

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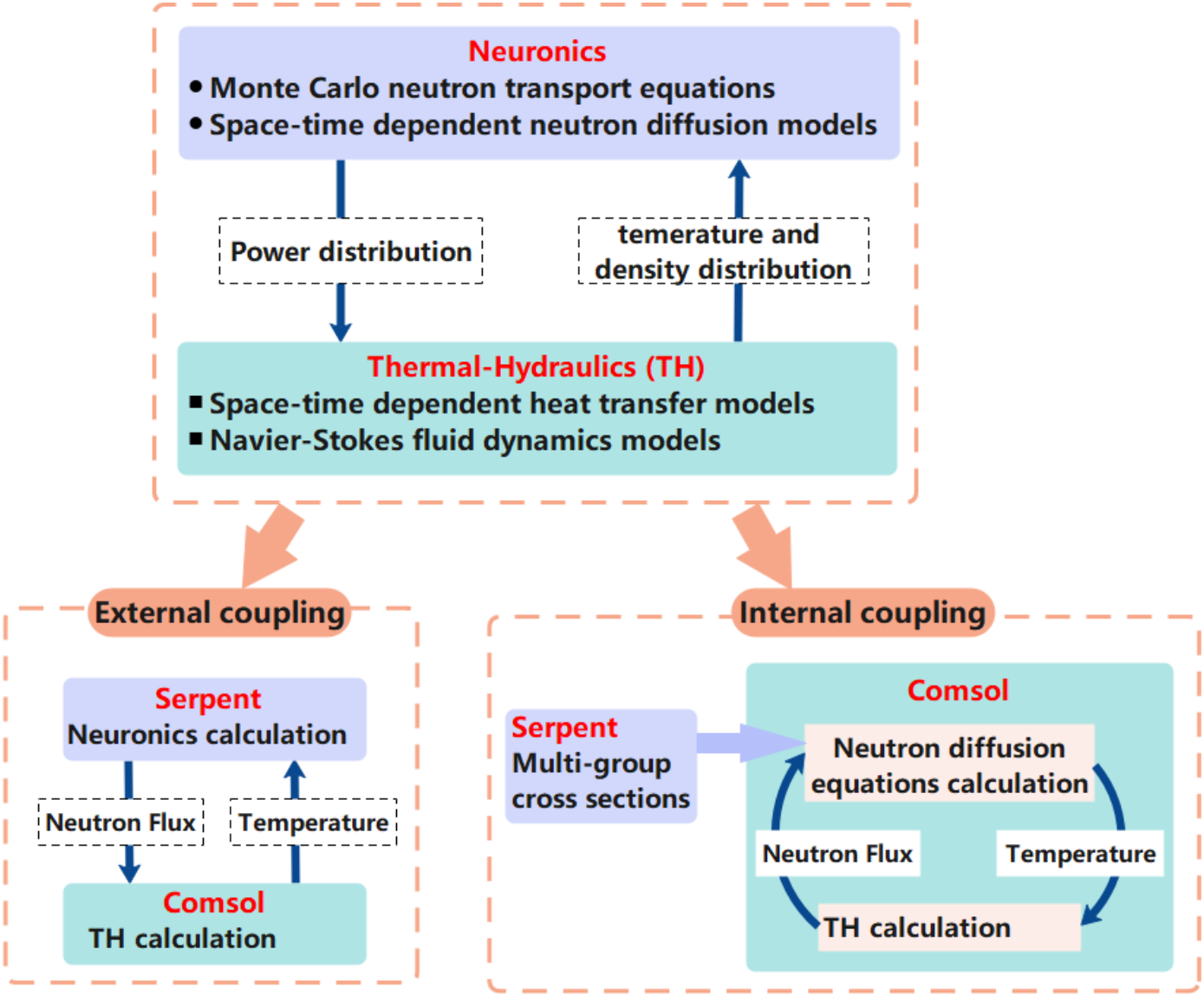


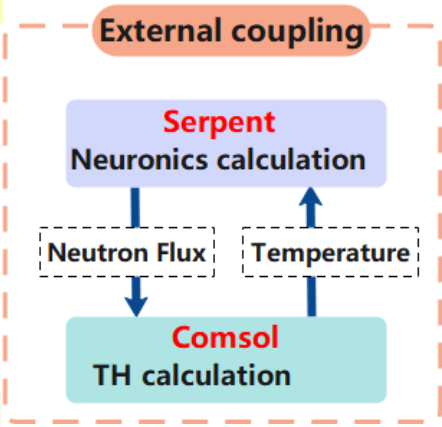
Coupling Methods

- Neutron Fission Process (Serpent Model)
  - Geometric arrangement of fuel pin and assembly arrangement
  - Material composition of fuel, coolant and cladding
  - Continuous-energy cross section (ENDF-VII,JEF22,JEFF311)

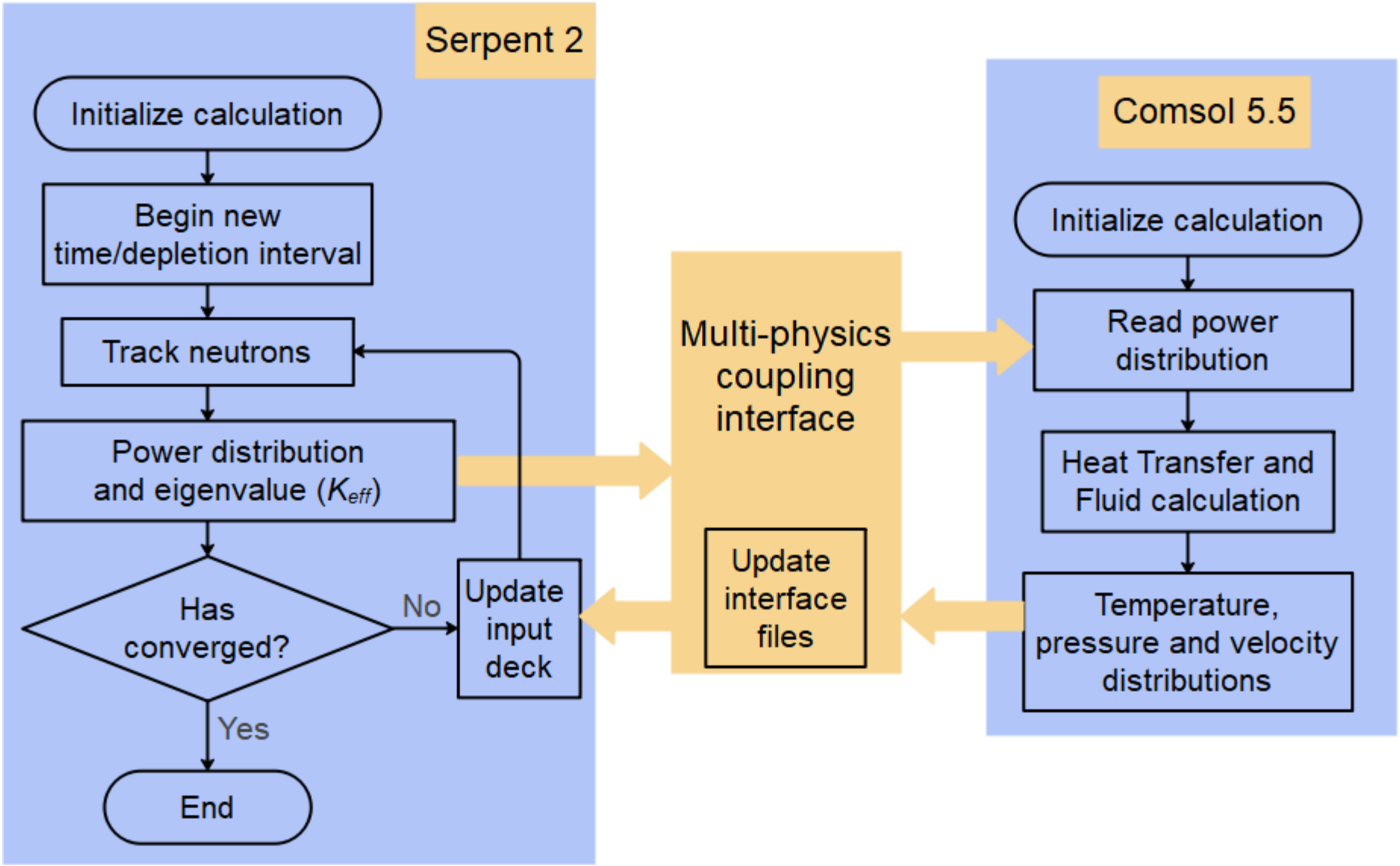
Neutron flux and power distributions

Temperature, pressure and velocity fields

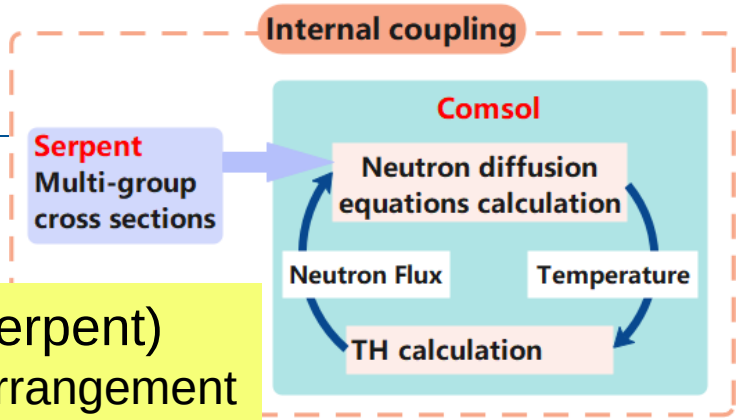
- Heat Transfer and Fluid Processes (COMSOL Model)
  - Geometric arrangement of fuel pin and assembly arrangement
  - Thermophysical properties of fuel, coolant and cladding
  - Inlet and outlet boundary conditions
  - Finite element meshing



External-Coupled Modeling Process



External Coupling Program



- Group constants for 3D diffusion equations (Serpent)
  - Geometric arrangement of fuel pin and assembly arrangement
  - Material composition of fuel, coolant and cladding
  - Continuous-energy cross section (ENDF-VII,JEF22,JEFF311)

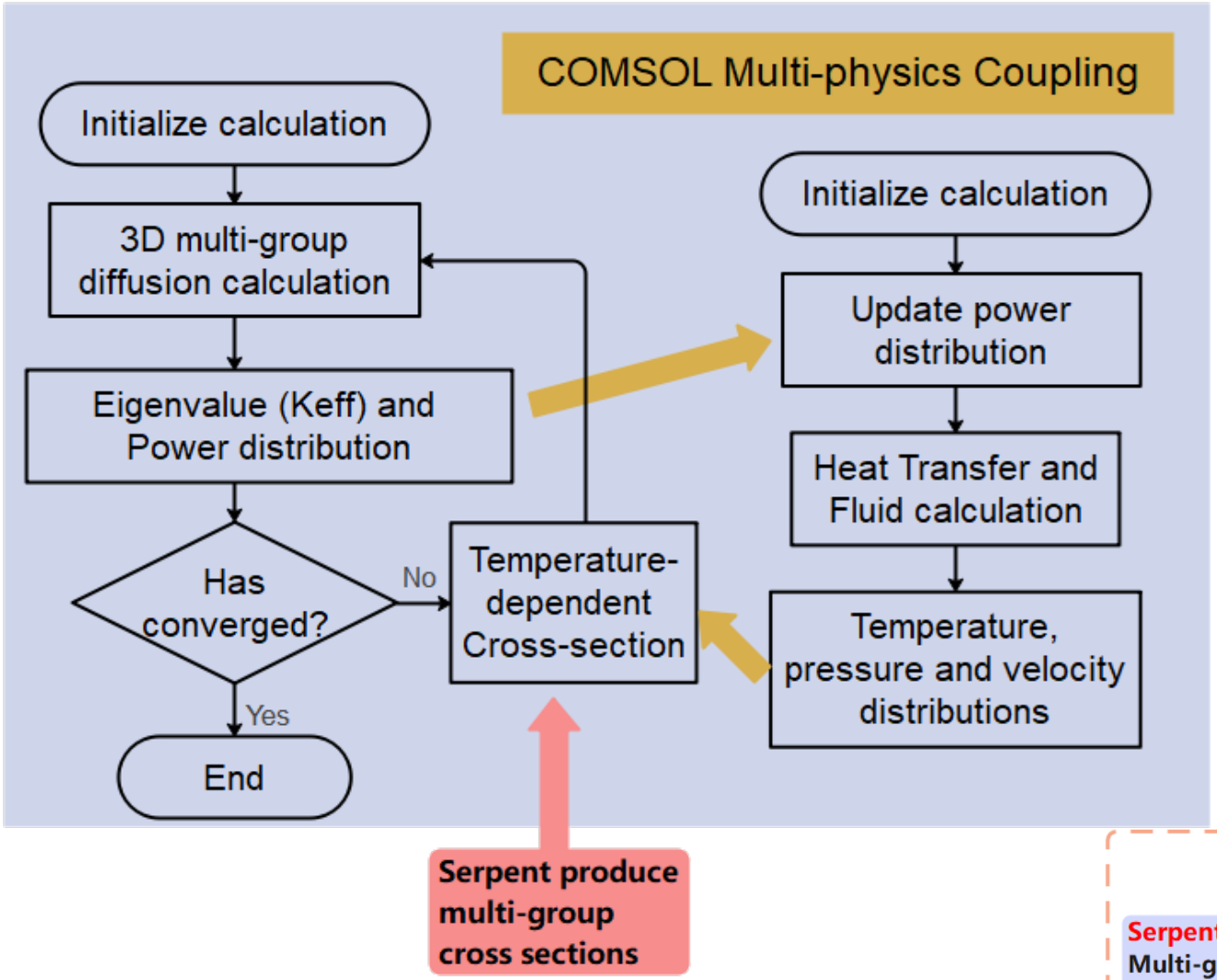
Multi-group cross sections with temperature feedback

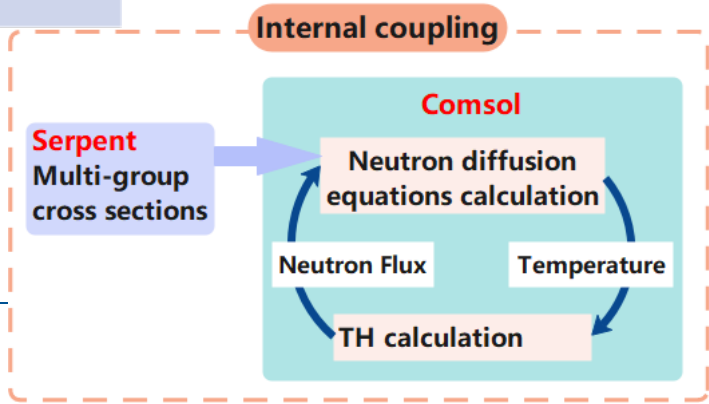
$$\Sigma(T_f,\rho_c,R,H,Z)=\Sigma_0+\left[\frac{\partial\Sigma}{\partial\ln T_f}\right]_{T_{f0}}(\ln T_f-\ln T_{f_0})+\left[\frac{\partial\Sigma}{\partial\rho_c}\right]_{\rho_c}(\rho_c-\rho_{c0})+$$

$$\left[\frac{\partial\Sigma}{\partial R}\right]_{R_0}(R-R_0)+\left[\frac{\partial\Sigma}{\partial H}\right]_{H_0}(H-H_0)+\left[\frac{\partial\Sigma}{\partial Z}\right]_{Z_0}(Z-Z_0)$$

where T_f – fuel temperature, ρ_C – average coolant density, R – average core radius, H – average fuel height and Z – control rod position

Multi-group cross sections





Internal Coupling Program

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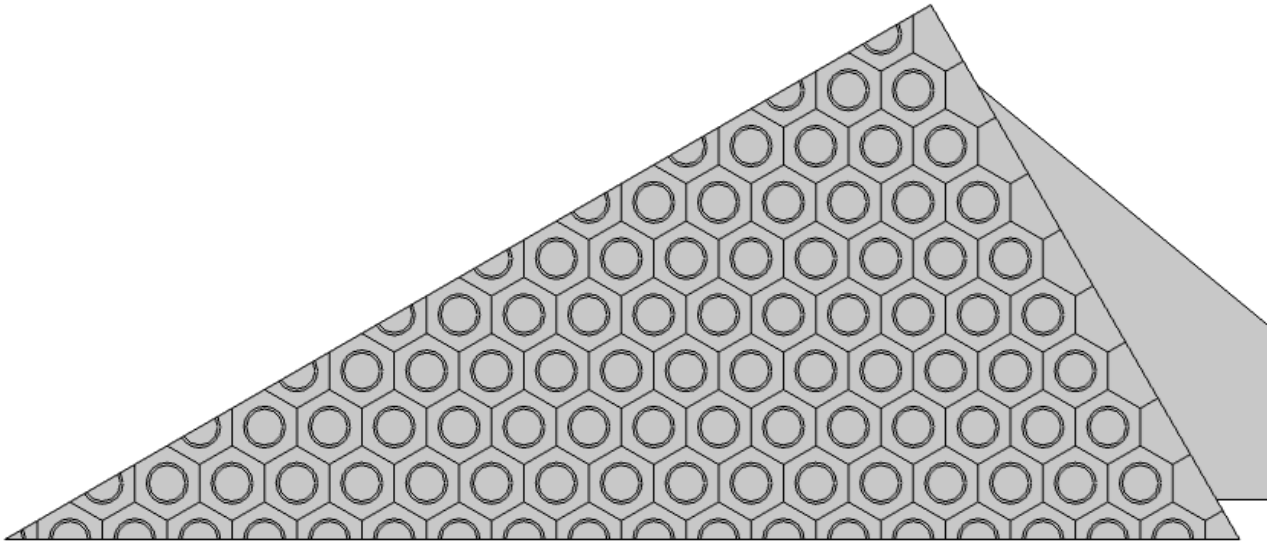
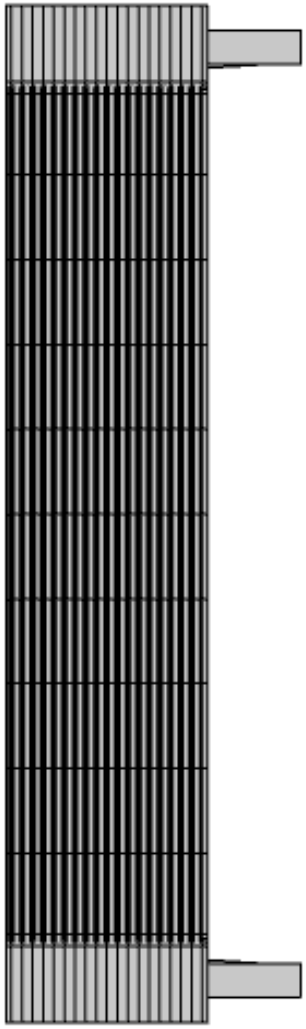
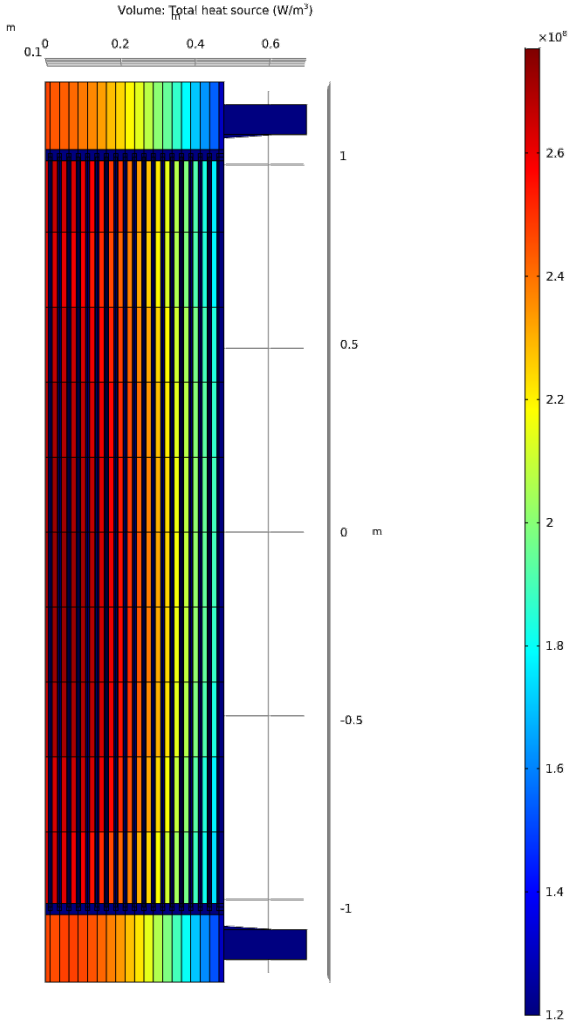
External Coupling: COMSOL nodalization

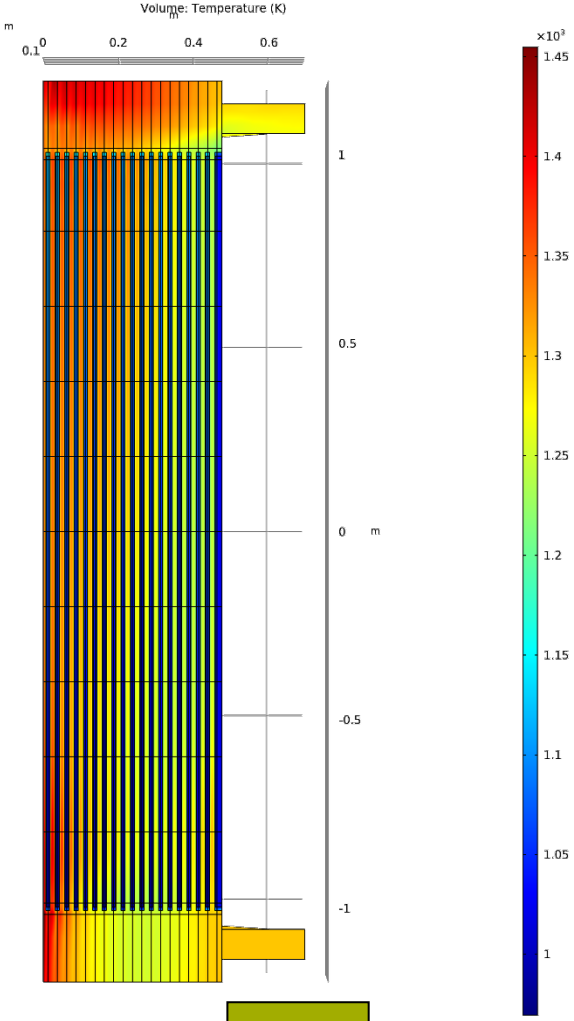




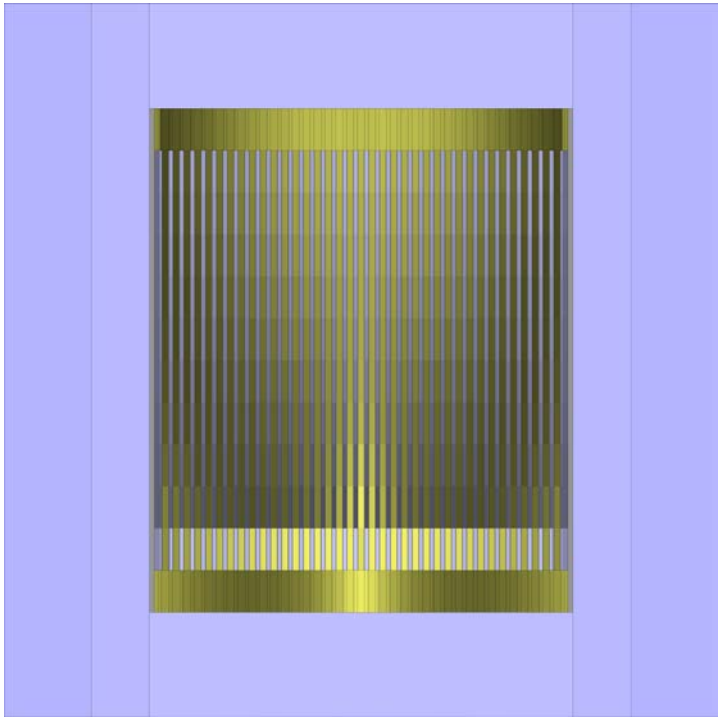
Power distribution from Serpent is applied to the COMSOL model as volumetric heat source

External Coupling: COMSOL

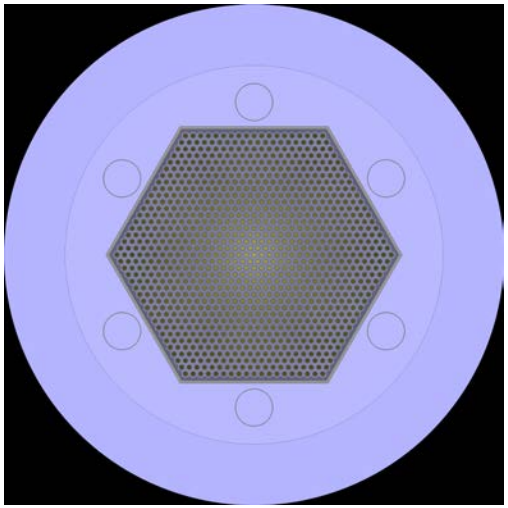




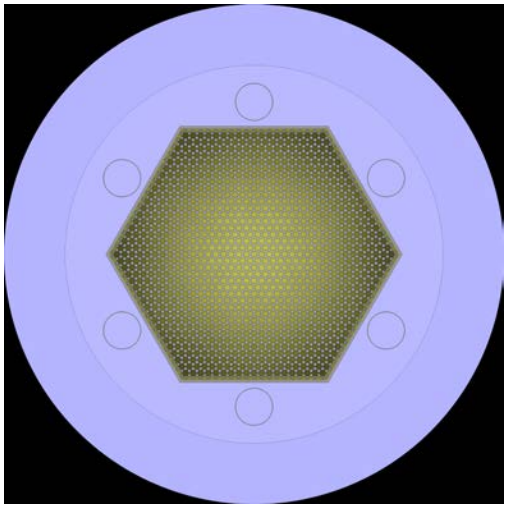
AS of Core Zones



CS of Core Zones



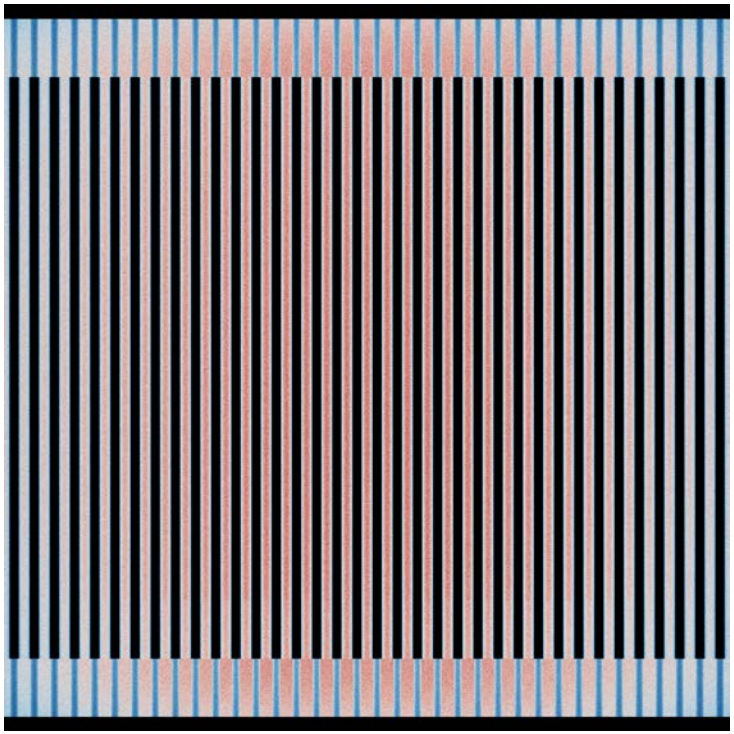
CS of Dis/Coll Zones



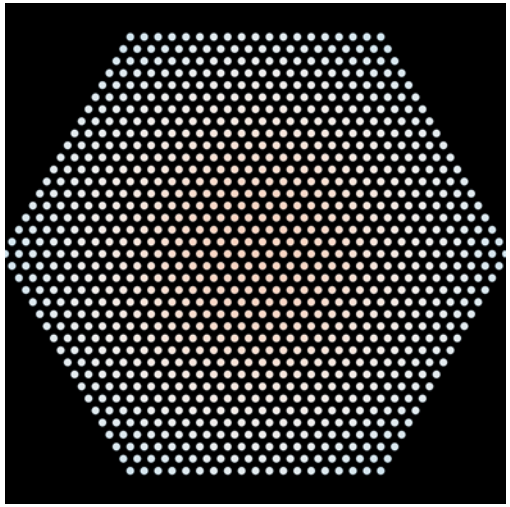
T and rho distributions from COMSOL are given to the Serpent model

External Coupling: Serpent Input Deck (Temperature)

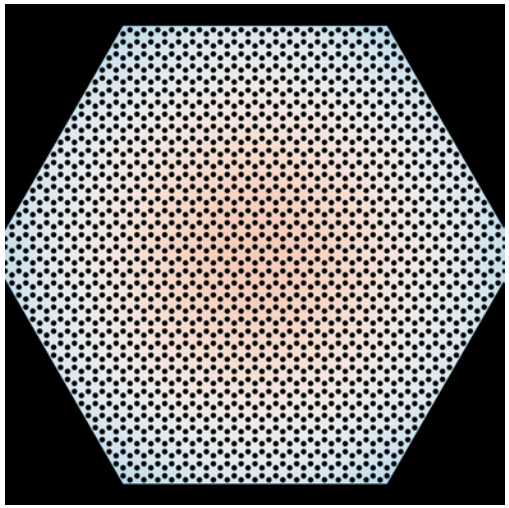
AS of Core Zones



CS of Core Zones



CS of Dis/Coll Zones



T and rho distributions from COMSOL are given to the Serpent model

External Coupling: Serpent Power Distribution

Simulation: Internal Coupling

Neutron Transportation directly solved by PDEs and coupled with the CFD and Heat Transfer Module in COMSOL

Diffusion Equations:

$$\frac{1}{v_g}\frac{\partial \phi_g}{\partial t} = \nabla \cdot D_g \nabla \phi_g - \Sigma_{a,g}\,\phi_g - \sum_{g' \neq g} \Sigma_{s,gg'}\,\phi_g + \sum_{g' \neq g} \Sigma_{s,g'g}\,\phi_{g'}$$

$$+(1-\beta)\chi_{p,g} \sum_{g'=1}^{4} (\upsilon \Sigma_f)\,\phi_{g'} + \sum_{i=1}^{6} \chi_{d,g}\,\lambda_i C_i$$

$$\frac{\partial C_i}{\partial t} = \nabla \cdot D_C \nabla C_i + \nabla(U \cdot C_i) + \beta_i \sum_{g'=1}^{4} (\upsilon \Sigma_f)\,\phi_{g'} - \lambda_i C_i$$

Convection of Precursors

N-S Fluid Equations:

$$\rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla \cdot [-p\mathbf{I} + \mathbf{K}] + \mathbf{F}$$

$$\nabla \cdot (\rho \mathbf{u}) = 0$$

Heat Transfer Equations:

$$\rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q$$

$$\mathbf{q} = -k \nabla T$$

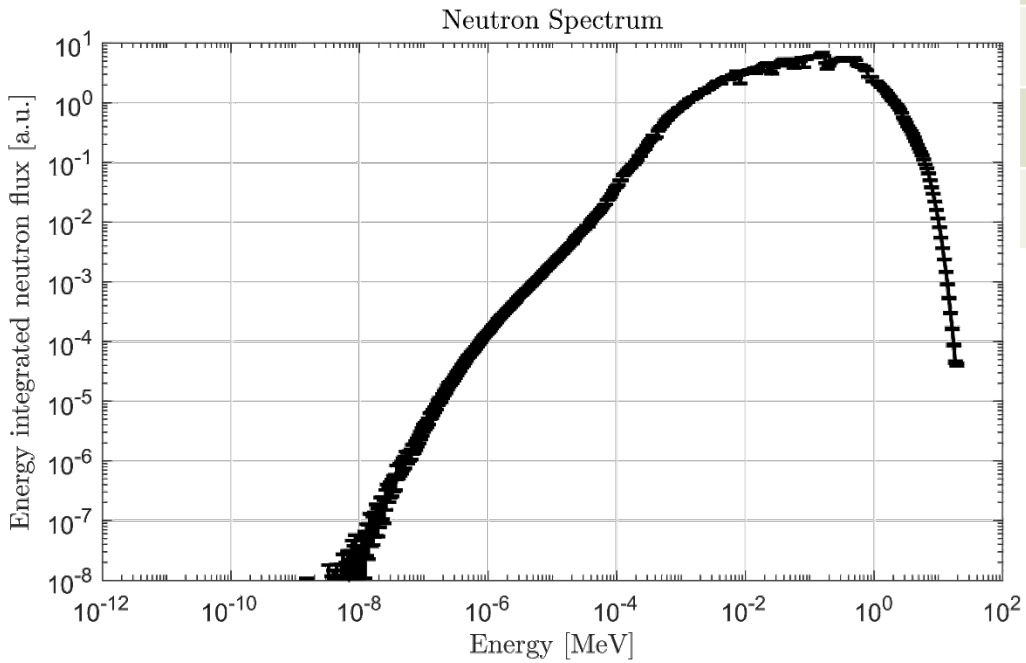
Simulation: Internal Coupling

Serpent

KEFF = 1.03444

1 Group

KEFF = 1.0394



4 Groups

Group	Lower Energy
1	820 keV
2	110 keV
3	15 keV
4	0

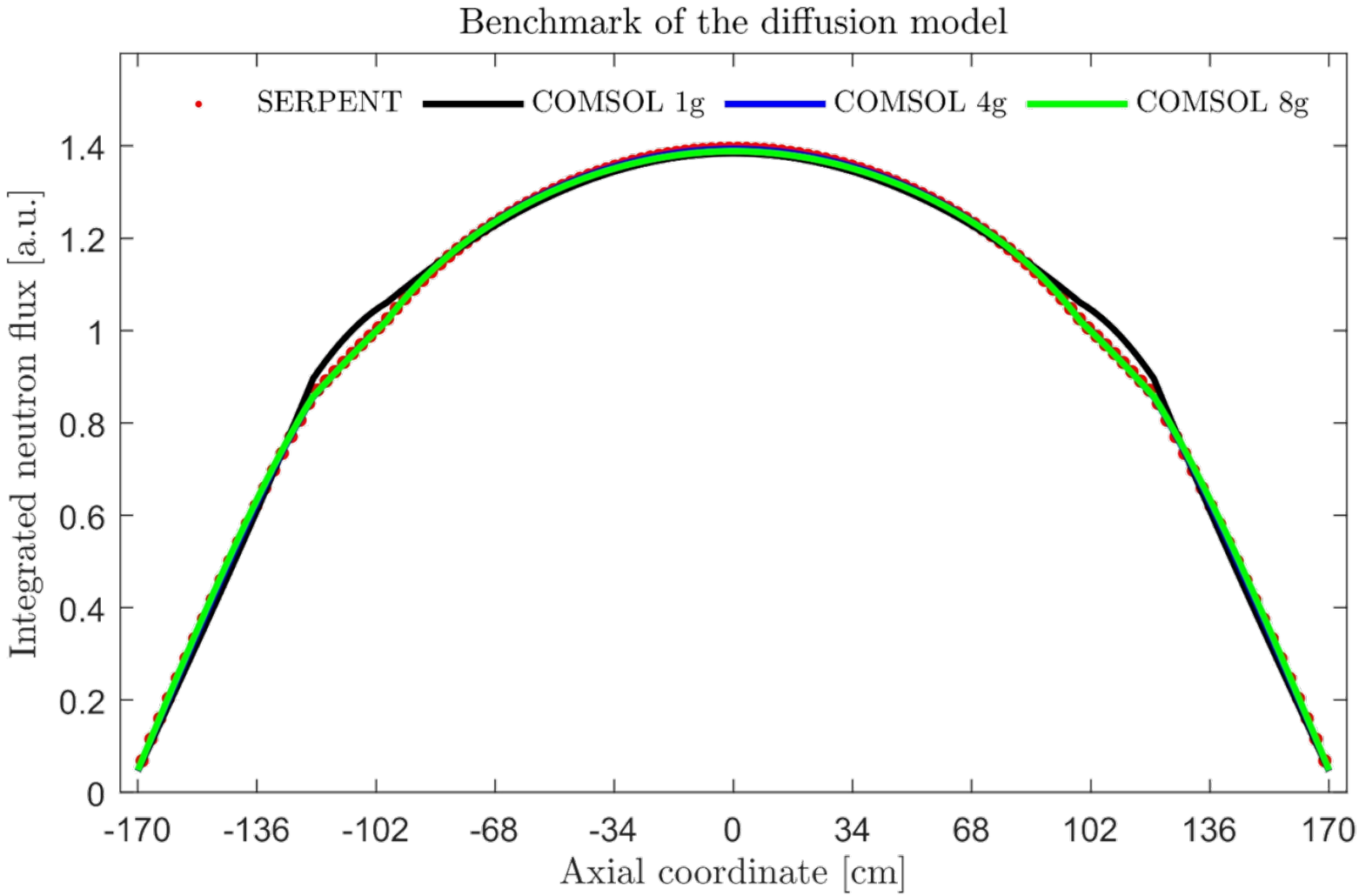
KEFF = 1.0350

8 Groups

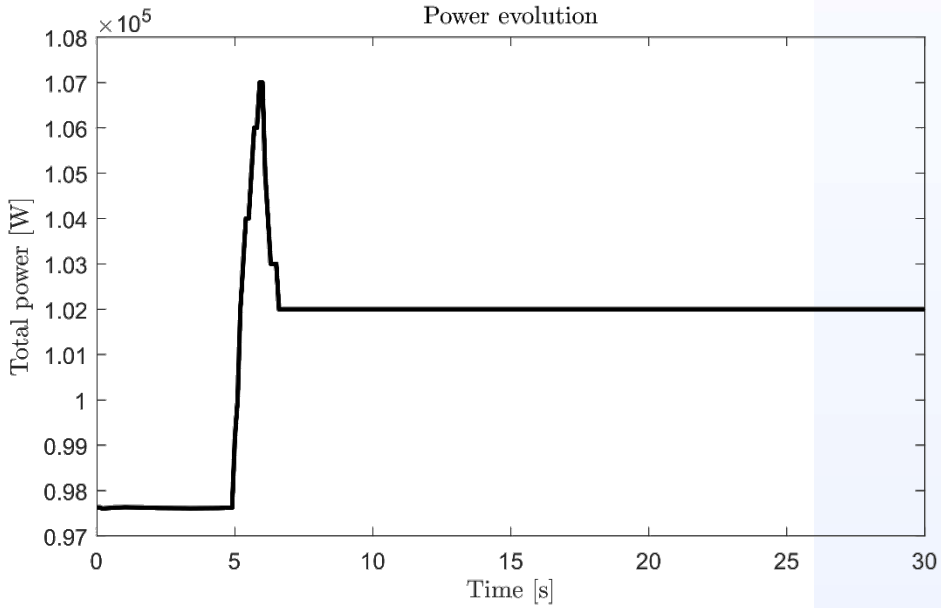
Group	Lower Energy
1	2.2 MeV
2	820 keV
3	300 keV
4	110 keV
5	40 keV
6	15 keV
7	750 eV
8	0

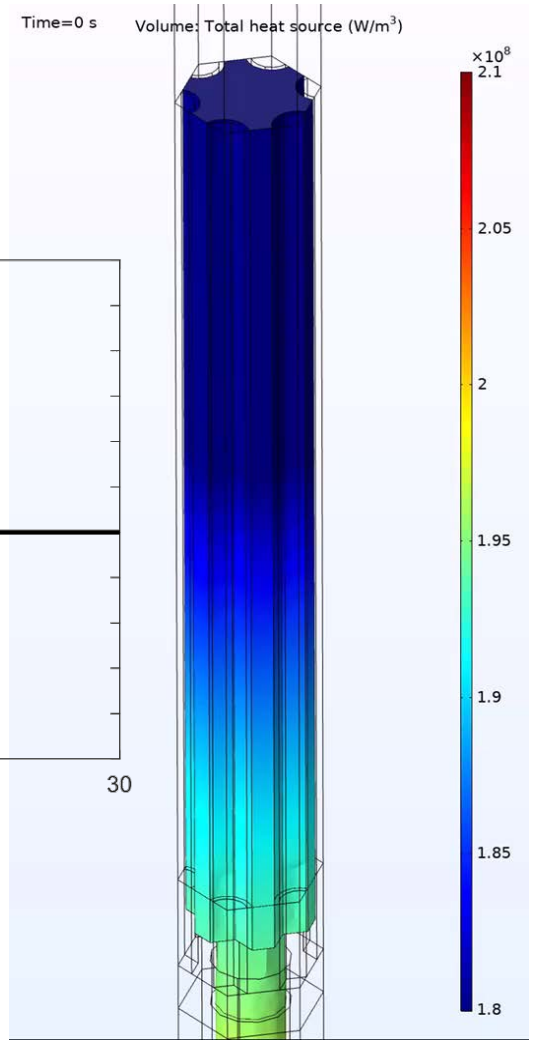
KEFF = 1.0362

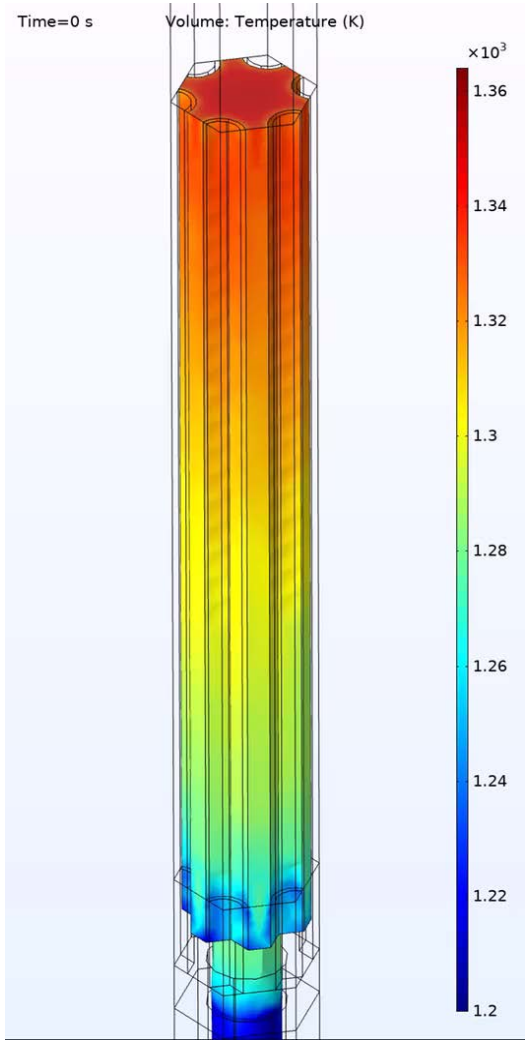
Simulation: Internal Coupling



Simulation: Internal Coupling, 100 pcm







Power

Temperature

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Challenge and Outlook

- Convergence: meshing, solver maturity
- Computational Resources

- Multiscale and Multiphysics Modeling (with ATHLET)
- Uncertainty and Sensitivity Analysis