西安交通大學
XI' AN JIAOTONG UNIVERSITY

核反应堆热工水力研究室
Nuclear Thermal-hydraulic Lab

5th Joint ICTP-IAEA Workshop

Multiphysics modelling of Gen-IV reactors
Part 1 – OpenFOAM

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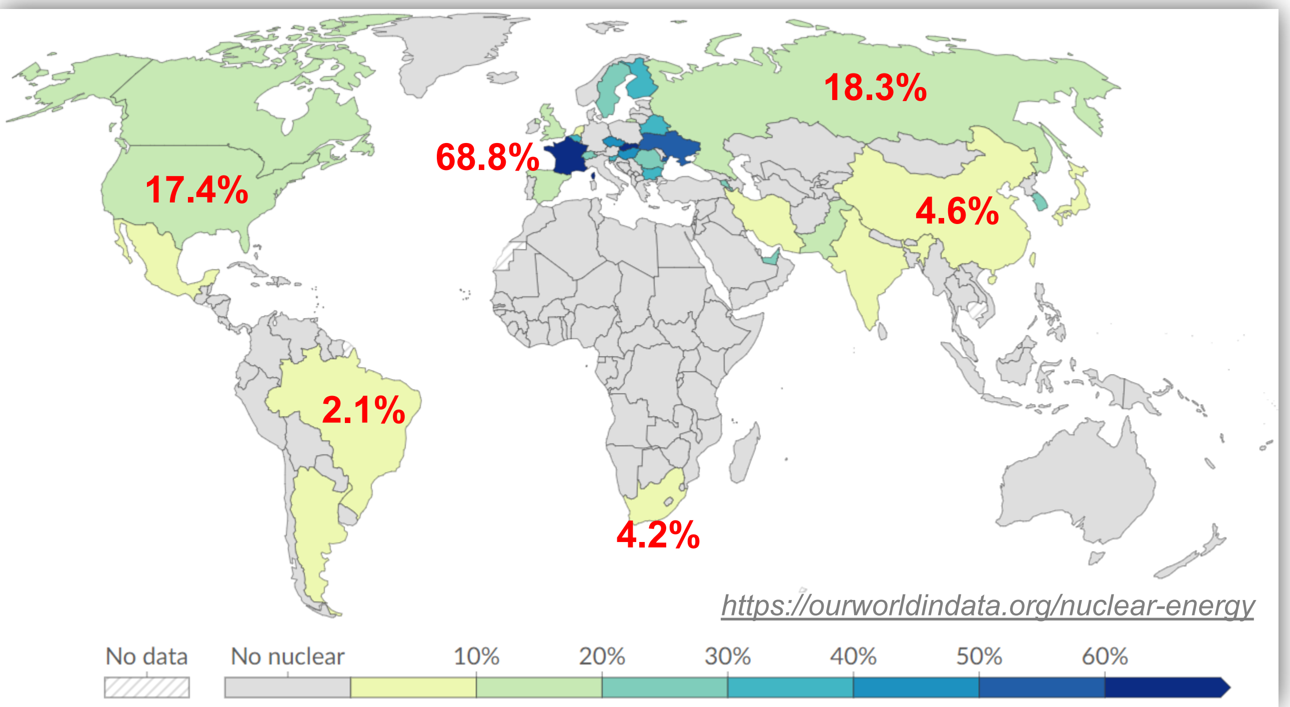
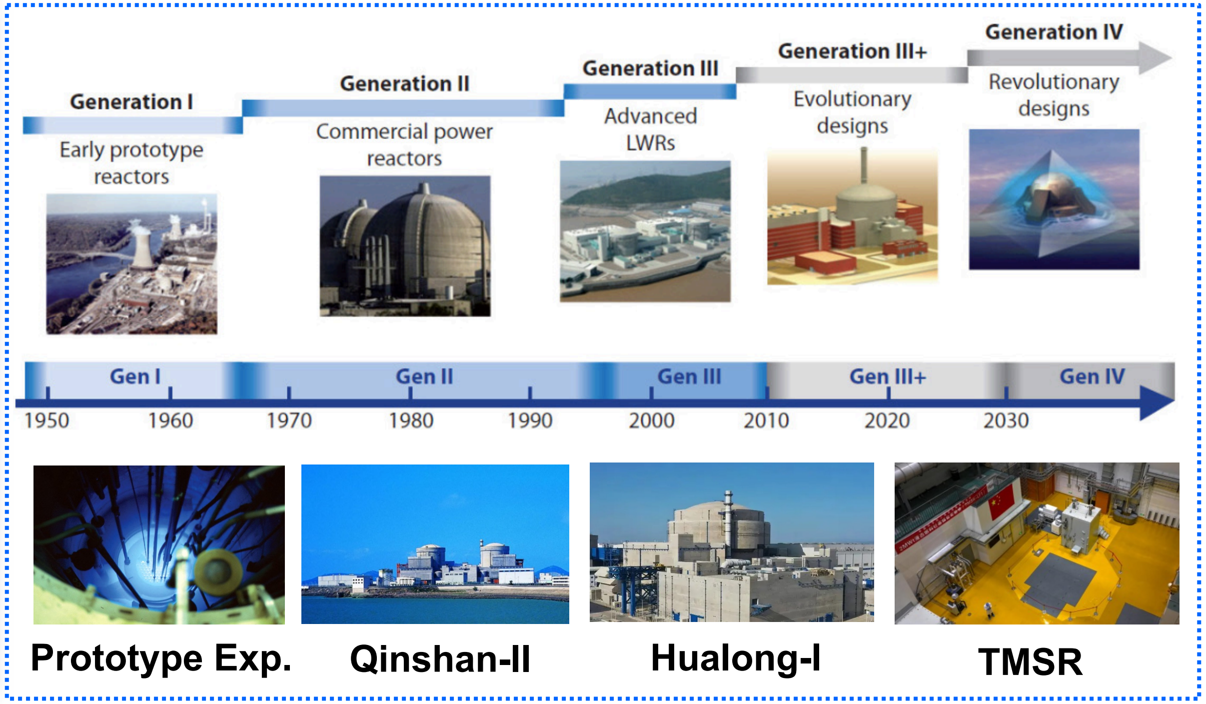
1.1 Development of nuclear energies

- Nuclear energy has a remarkable application in worldwide. Its percentage of total power is increasing. Particularly, the nuclear energy occupies near 70% power supplement in France.
- China proceeds a step-by-step development of nuclear energy. Gen-III+ reactors are used for main power generation, and the Gen-IV advanced reactors are on-going in research and construction.



Nuclear energy percentage of total power (in 2025)



Roadmap of nuclear power system in China

1.2 Proposal of Gen-IV reactors

- **Gen-IV advanced reactors**

1. *Gas-cooled fast reactor (GFR)*
2. *Lead-cooled fast reactor (LFR)*
3. *Molten salt reactor (MSR)*
4. *Supercritical water reactor (SCWR)*
5. *Sodium-cooled fast reactor (SFR)*
6. *Very high-temperature reactor (VHTR)*

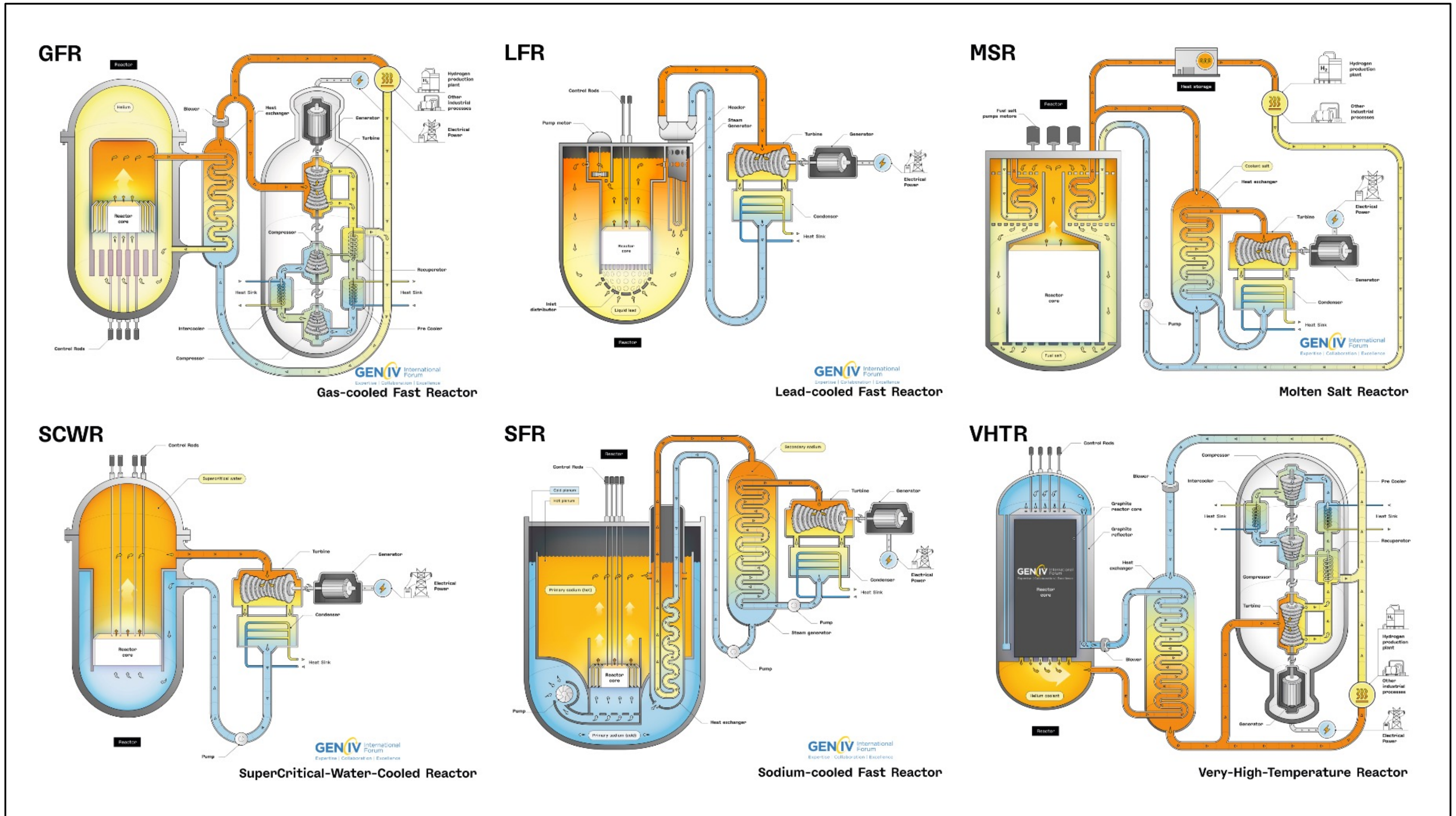
- **Goals**

✓ *Sustainability*

✓ *Economics*

✓ *Safety and reliability*

✓ *Non-proliferation and protection*



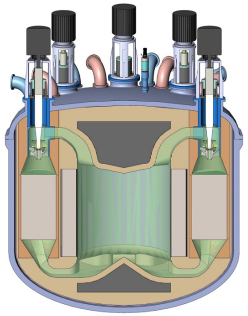
GEN IV International Forum
Expertise | Collaboration | Excellence

✓ **Gen-IV Forum (GIF) proposed 6 types advanced nuclear systems in 2002.**

✓ **China participates GIF in 2006.**

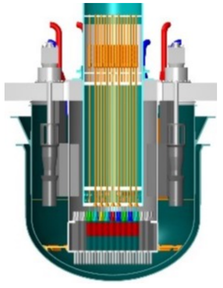
1.3 Status of Gen-IV advanced reactors

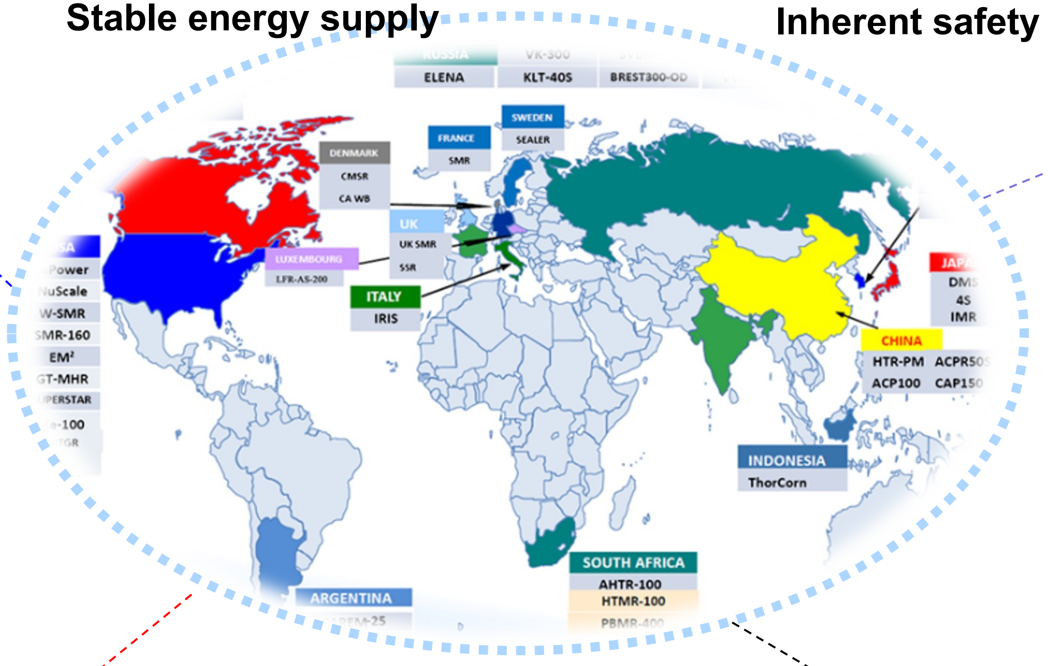
➢ **Wide attention on Gen-IV advanced reactors: SFR, LFR, MSR, GFR, SCWR, and VHTR**



Stable energy supply

Inherent safety



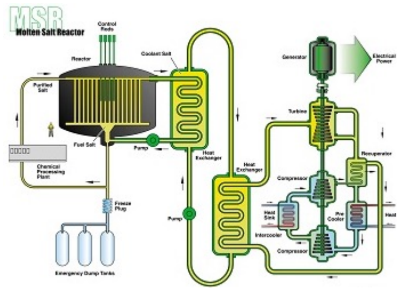


Sodium-cooled fast reactor

- Fast spectrum
- Nuclear waste transmutation

Lead-cooled fast reactor

- High-power density
- Small modularization

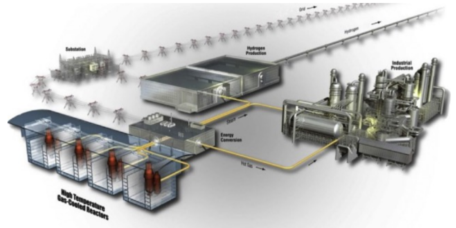


Molten Salt Reactor

- Inherent safety
- Online refueling

Low carbon electricity

High temperature application



Gas-cooled fast reactor & VHTR

- High outlet temperature

1.4 Why we need multiphysics?

1. Inherent physical characteristics

- Gen-IV reactors exhibit the inherent physical coupling characteristics, e.g. Molten Salt Reactor.
- Molten fuel salt flows through the core, **strongly coupling the DNP transport and thermal-hydraulics.**

- Neutron transport

$$\frac{1}{V_g}\frac{\partial \psi_g}{\partial t} + \boldsymbol{\Omega}\cdot\nabla\psi_g = F_{P,g} + F_{D,g} + S_g \underbrace{-\frac{1}{V_g}\nabla\cdot\left(\mathbf{U}\psi_g\right)}_{V_g \gg |\mathbf{U}|,\ \approx 0}$$

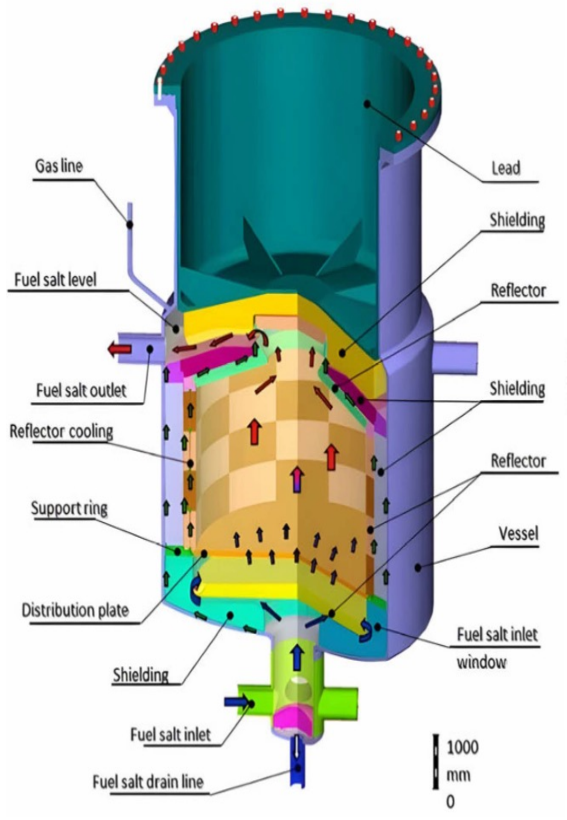
- DNP transport

$$\frac{\partial C_i}{\partial t} = \beta_i \sum_{g'=1}^{G}\left[\nu\Sigma_{f,g'}\sum_{m=1}^{M}\psi_{g'}\right] - \lambda_i C_i - \nabla\cdot\left(\mathbf{U}C_i\right)$$

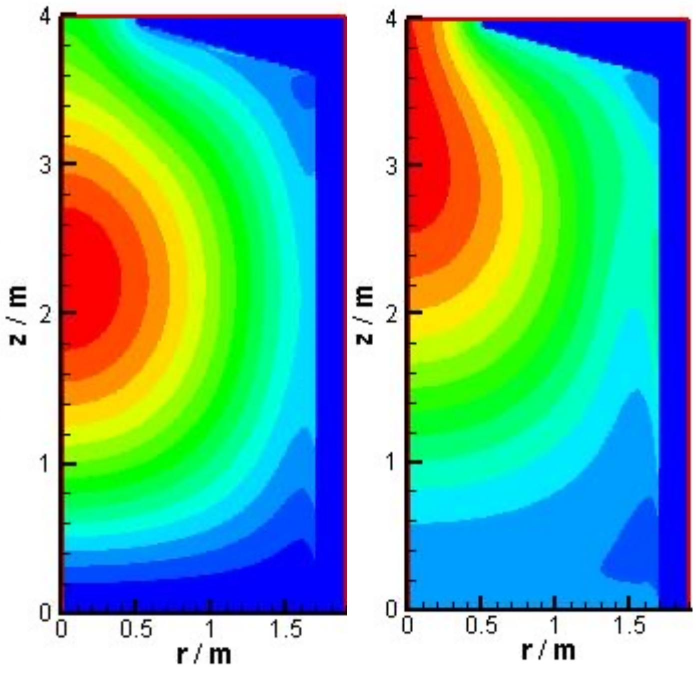
- Thermal-hydraulics

$$\frac{\partial \rho\Phi}{\partial t} + \nabla\cdot\left(\rho\mathbf{U}\Phi\right) = \nabla\cdot\left(\Gamma\nabla\Phi\right) + S$$

Couple



- DNP distribution in MOSART



No couple ❌ Couple ✅

1.4 Why we need multiphysics?

2. Closer to reality, promoting safe operation

- Multiphysics coupling is **a hot research topic**, which is usually listed as a special track in conferences.
- It can help us to figure out a more realistic behavior of reactor, such as **SFR “blossom” effect**.

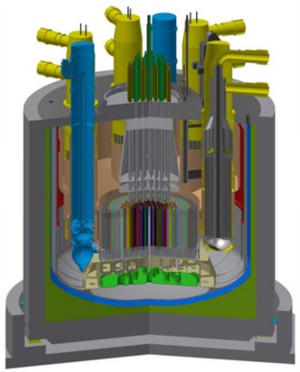
19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-19)
March 6 - 11, 2022 • Brussels, Belgium • The Square

TECHNICAL TRACKS

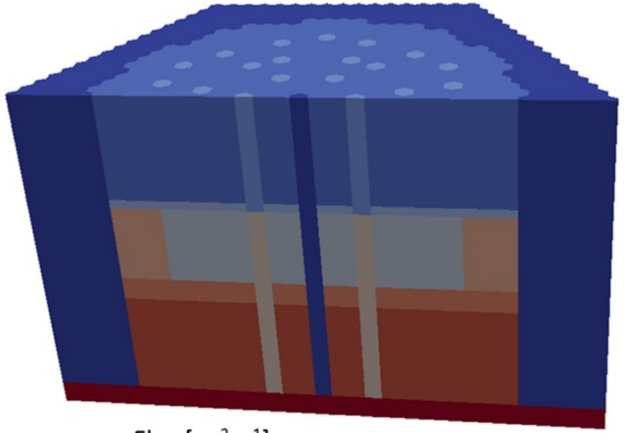
2. COMPUTATIONAL THERMAL HYDRAULICS
- 2a Thermal Hydraulics System Code Analysis
- 2b Computational Fluid Dynamics
- 2c Computational Multi-Fluid Dynamics
- 2d Multi-scale Analysis
- 2e Multi-physics Analysis
- 2f

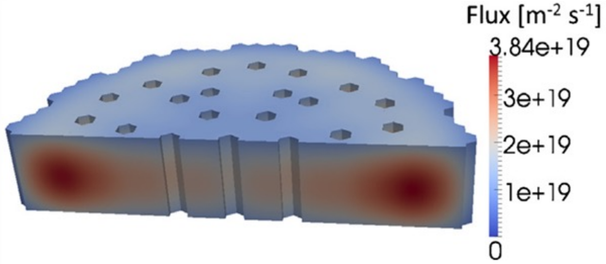
7. ADVANCED REACTORS
- 7a Advanced Reactors General
- 7b Small Modular Reactors
- 7c High-Temperature Gas-Cooled Reactors
- 7d Salt-Cooled High-Temperature Reactors

Proceedings of Advances in Thermal Hydraulics (ATH 2024)



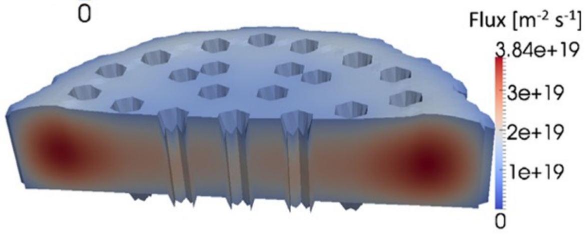
ESFR





Fiorina et al (2015)

SFR “blossom”



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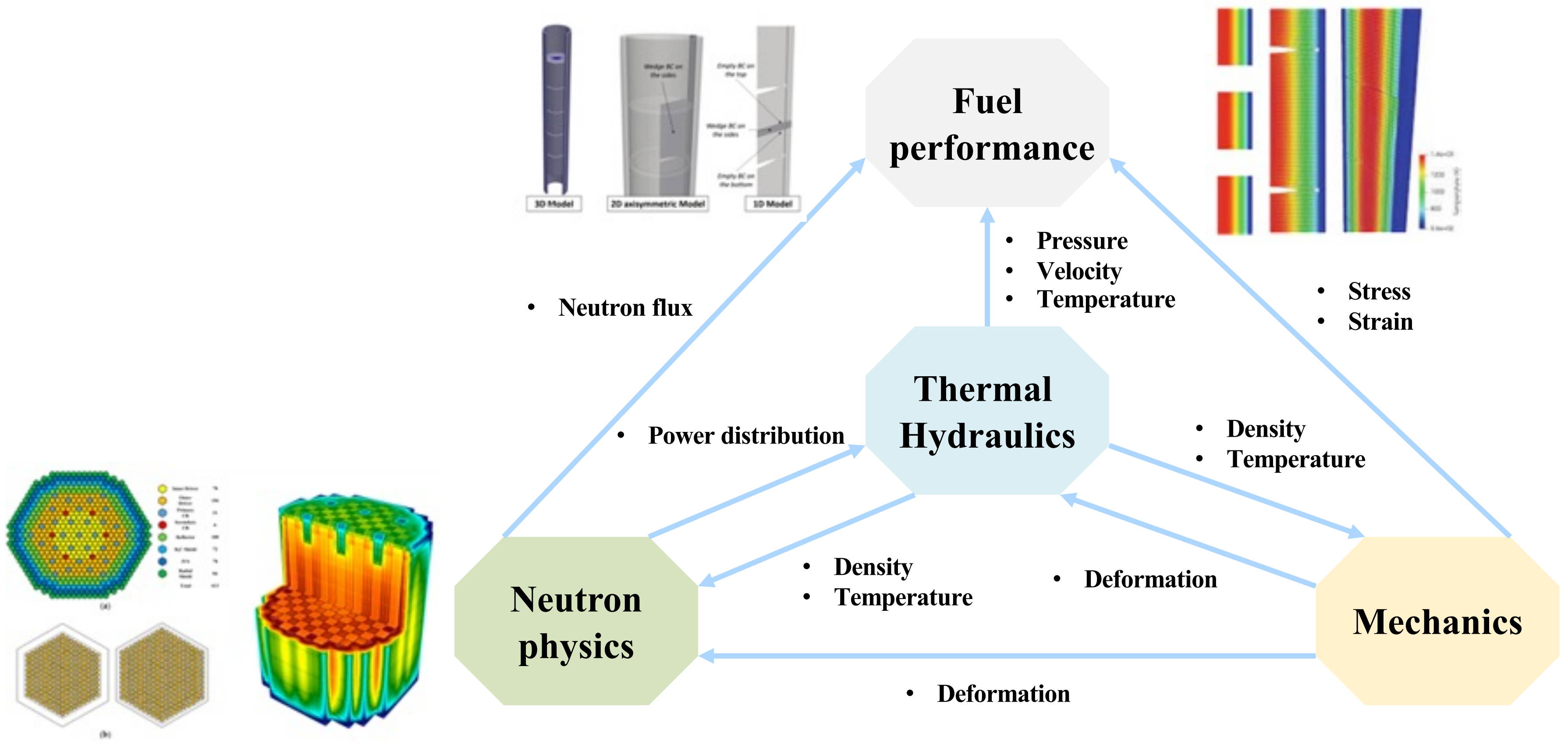
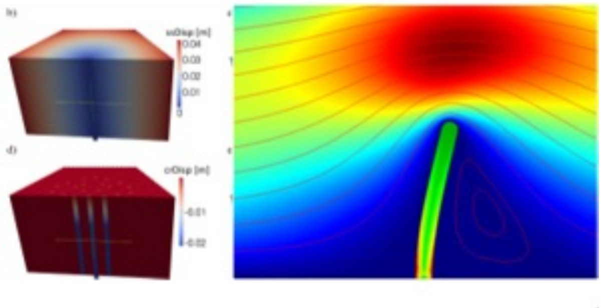
2.1 Technical routes to multiphysics

- As an energy generation and transport system, a nuclear reactor system is a **multi-physics** system centered on **thermal-hydraulics** and coupled with **neutronics**, **mechanics**, and related disciplines
- The **high-fidelity** multi-physics computational tools represents a critical direction for next-generation numerical simulation platforms for nuclear power systems

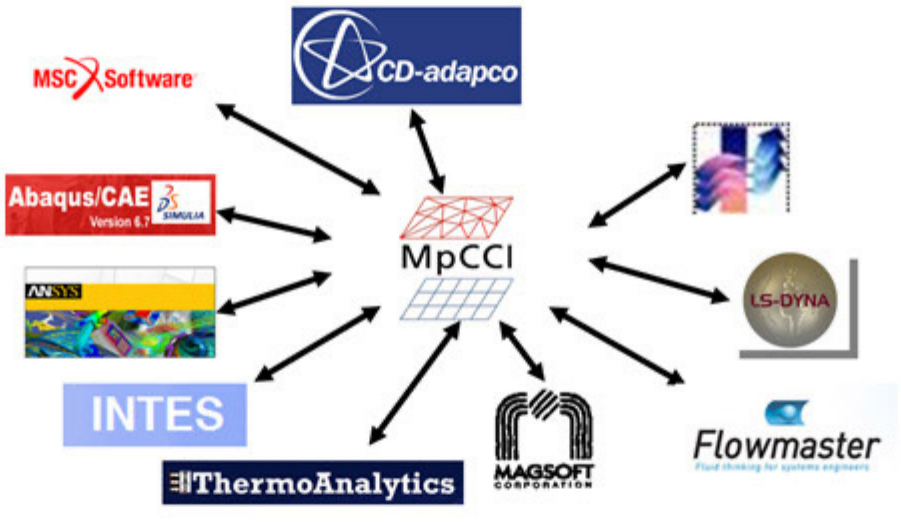


- ❑ Multidisciplinary direction
- ❑ Highly nonlinear
- ❑ Tight coupling

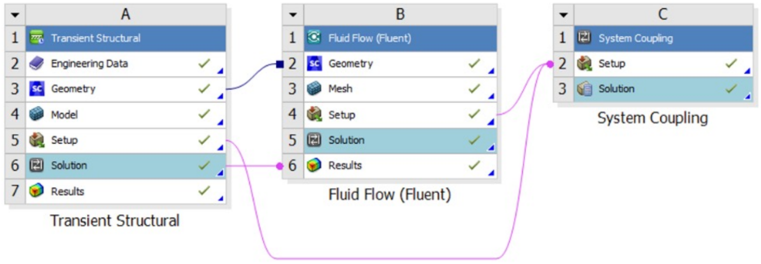


2.2 Route 1: Commercial softwares

- **Features:** Limited development using commercial software, or external coupling with dedicated codes.
- **Advantages:** Strong thermal-hydraulics and mechanics modules; complete documentation; user-friendly operation.
- **Limitations:** Commercial software usually lacks neutronics solvers; external neutronics codes or embedded interfaces are required.
- **Applications:** MpCCI-based coupling; Workbench-based coupling; COMSOL-based coupling.



MpCCI

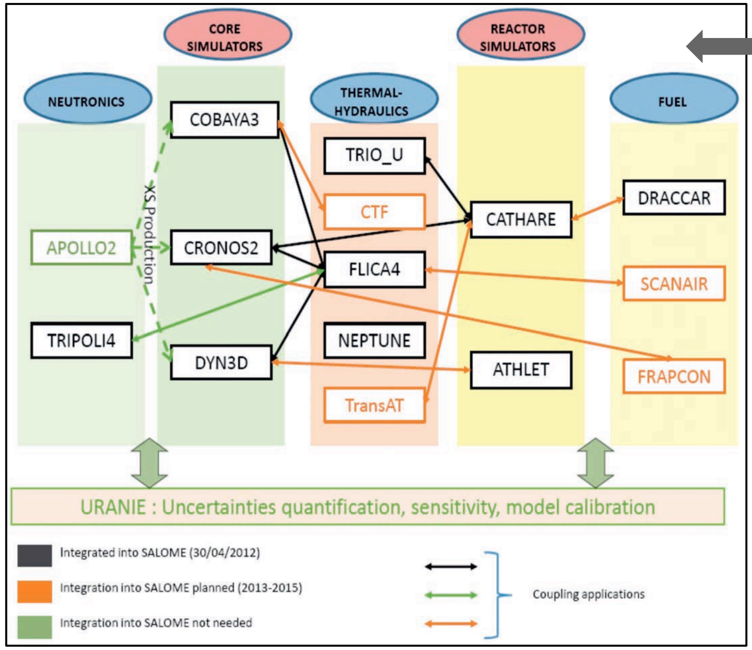


ANSYS Workbench

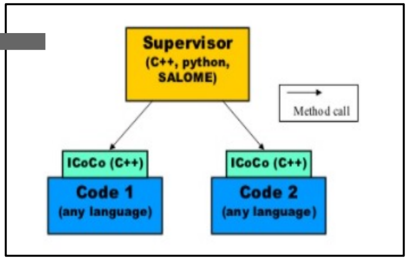
COMSOL

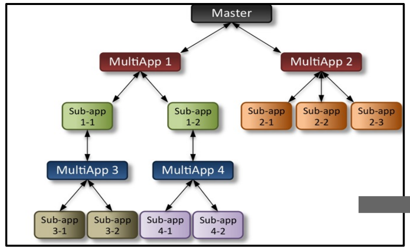
2.3 Route 2: Specified in-house codes

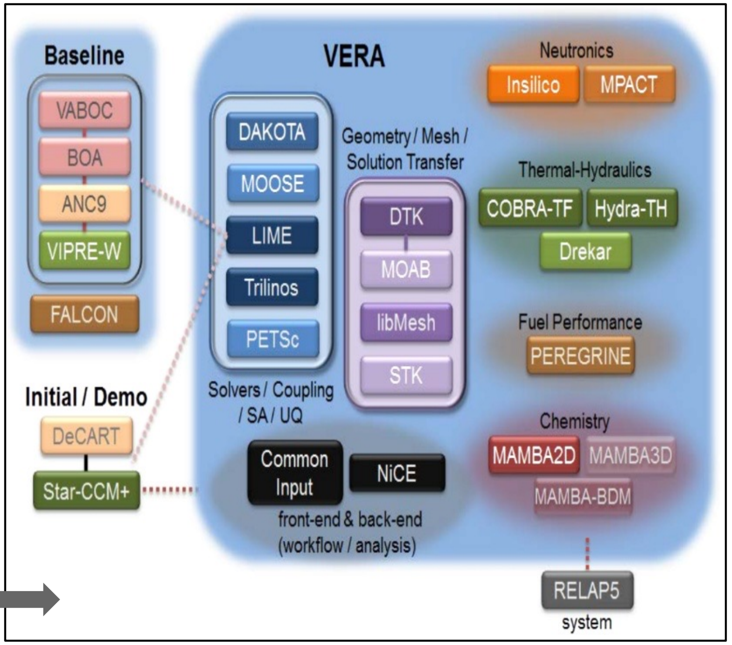
- **Features:** Adopts mature reactor codes with long-term V&V; only minor source-code changes are needed to build data-transfer interfaces.
- **Advantages:** Mature computational software system, with reliability verified over long-term use.
- **Limitations:** Three or more physics fields can create complex interaction logic; loose coupling converges slowly.
- **Applications:** The European NURESAFE program uses the ICoCo data interface; the U.S. CASL program uses the LIME framework.



NURESAFE







CASL

2.4 Route 3:General interface links different codes

- **Features:** Unified programming framework; different meshes for different physics fields; data transfer through mesh-mapping modules.
- **Advantages:** Shared framework facilitates extension and supports strong-coupling algorithms.
- **Limitations:** Mesh mapping introduces additional error sources; development effort is substantial.
- **Applications:** NEAMS uses MOOSE and MOBA for mesh management and mapping; NURESIM uses SALOME/MEDCoupling.

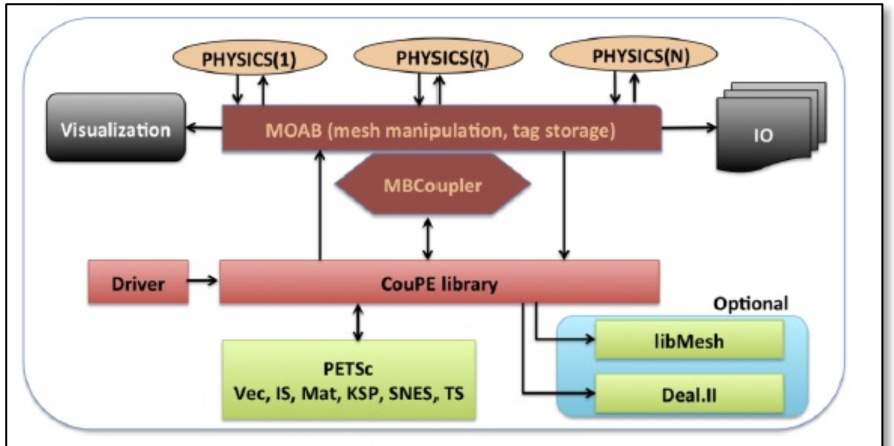
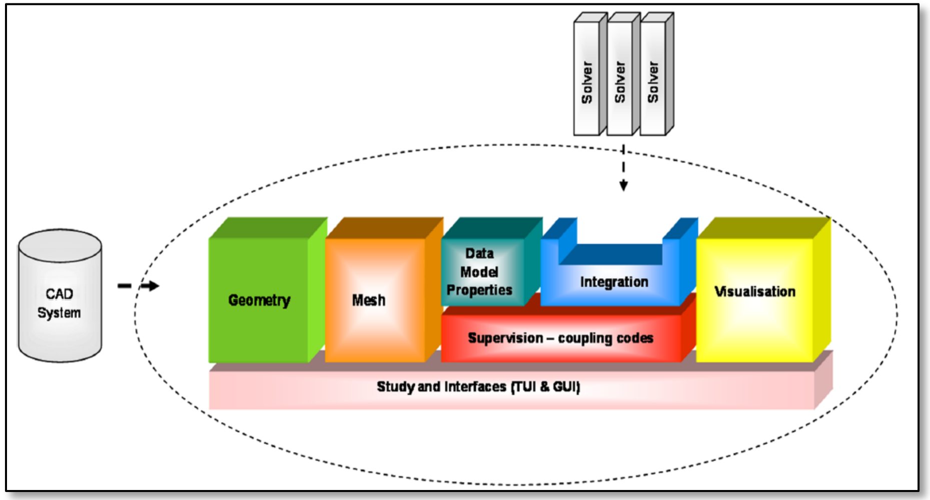


Figure 3.1. SHARP architecture.

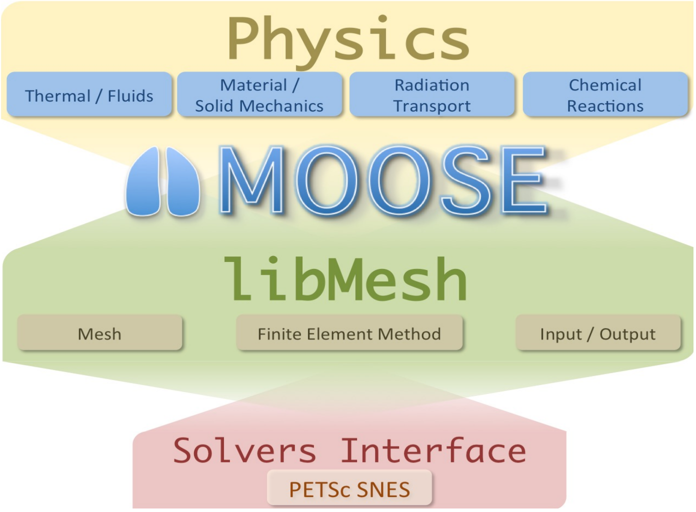
NEAMS-SHARP



NURESIM-SALOME

2.5 Route 4: All in one unified coupling frameworks

- **Features:** Unified programming framework with the same mesh for all physics fields, where PDEs are discretized and solved on a common mesh.
- **Advantages:** No mesh-mapping error; supports high-accuracy strong or fully coupled schemes.
- **Limitations:** Development effort is difficult and substantial.
- **Applications:** No mature applications; two mainstream exploratory frameworks are MOOSE and OpenFOAM.



MOOSE (Next talk)

OpenFOAM

2.6 Summary

Method	1. Commercial codes	2. In-house codes	3. General interface	4. Unified coupling framework
Coupling mode	Loose coupling	Loose coupling	Tight coupling	Tight coupling
Coupling method	OS（Operator separation）	OS	Picard	Picard/Newton
Coupling accuracy	Lower	Lower	Higher	Higher
Error	Errors introduced by data transfer and conversion between different programs		Grid interpolation errors	No grid interpolation error
Technical maturity	★★★★★	★★★★★	★★★	★★
Development difficulty	★	★★	★★★★	★★★★★
V&V	★★★★	★★★★	★★	★★

Routes 3 and 4 have emerged as the principal directions for the development of next-generation multi-physics coupling codes

2.6 Summary

		OpenFOAM	MOOSE	COMSOL	ANSYS	STAR-CCM+
Mode		Open source	Open source	Commercial		
Route		Route 2/3/4	Route 2/3/4	Route 1		
Discrete method		FVM	FEM	FEM	FVM/FEM	FVM/FEM
Multi-physics coupling platform		Unified framework / External data interface		Unified framework	External data interface based on the WorkBench platform	Internal data interface
Activity level in nuclear industry		★★★★★	★★★★★	★★★★	★★★★★	★★★★★
Scalability		★★★★★	★★★★★	★★	★★★	★★
Existing model maturity	Neutronics	★★★	★★★	--	--	--
	Thermal-hydraulics	★★★★★	★★★	★★★★	★★★★★	★★★★★
	Mechanics	★★★	★★★★	★★★	★★★★★	★★★
	Fuel performance	--	--	★★	★★	★
Copyright risks		★	★	★★★★	★★★★	★★★★

OpenFOAM and MOOSE constitute the technically mature, development-friendly, and legally low-risk open-source frameworks for strongly coupled multi-physics simulations

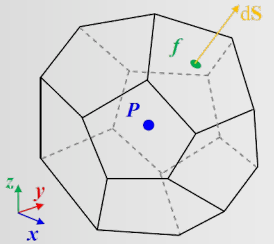
Contents

3.1 Introduction to OpenFOAM

- OpenFOAM, developed in 1989, is the **most popular open-source CFD** platform in finite volume method.
- It is compatible with several open-source pre/post-process codes, **showing a healthy community.**
- Users can **freely and conveniently develop** their solvers for specified physical problems with OpenFOAM.

Pre-process	Solver	Post-process
blender	OpenFOAM The OpenFOAM Foundation https://openfoam.org/	blender
FreeCAD	OpenFOAM https://www.openfoam.com/	ParaView
Meshlab	FOAM extend http:foam-extend.org	VisIt
gmsh		python
python		

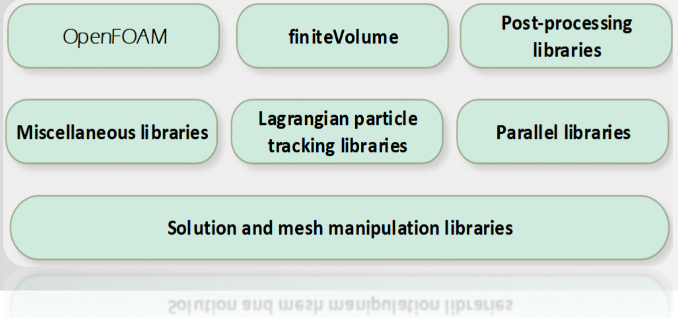
- FVM is naturally conservative.




```
fvVectorMatrix UEqn
(
    fvm::ddt(U)
  + fvm::div(phi, U)
  - fvm::laplacian(nu, U)
);

if (piso.momentumPredictor())
{
    solve(UEqn == -fvc::grad(p));
}
```

- Highly extendable for user-defined solvers



3.2 Glance of our works on OpenFOAM

- Based on OpenFOAM, we have developed 2 neutronics solvers and 2 thermal-hydraulics solvers, including the *neutron transport* and *space-time kinetics*, *subchannel analysis*, and *two-phase system thermal-hydraulics*. All the solvers are fully validated with experimental benchmarks.
- Besides, coupling analyses of 3 different types Gen-IV reactors (*LFR*, *FHR*, and *MSR*) are carried out.

Neutronics solvers (x2)

- SP3 neutron transport solver ***KaiyangCore***
- Improved quasi-statistic space-time kinetics solver ***KayangIQS***

\+

Thermal-hydraulics solvers (x2)

- CFD-based subchannel analysis solver ***YOGUANG***
- Two-phase system thermal-hydraulics solver ***STACO***

→

Coupling analyses (x3)

- LFR – ***MicroURANUS***
- FHR – ***FuSTAR***
- MSR – ***MOSART***

3.3 SP3 neutron transport – KaiyangCore

- **Our goal: use less computational workloads to get transport-like results – SP3 method.**
- **SP3 method is firstly proposed by *D. Geobard* in 1962, then *E. Larsen* strictly proved its theory in 1996.**

1. Diffusion-like transport

Approx: 3D operator to 1D operator

2. Heterogeneity revision

Approx: Even order to scalar

Approx: Odd order to vector

3. Scatter & fission sources

$$-D_g \nabla^2 \left(\psi_{0,g} + 2\psi_{2,g}\right) + \Sigma_{r,g}\psi_{0,g} = Q_g,$$

$$-\frac{27}{35} D_g \nabla^2 \psi_{2,g} + \Sigma_{t,g}\psi_{2,g} = \frac{2}{5}\left(\Sigma_{r,g}\psi_{0,g} - Q_g\right),$$

$$Q_g = \sum_{g' \neq g}^{G} \Sigma_{s,g' \to g}\psi_{0,g'} + \frac{\chi_g}{k_{eff}} \sum_{g'}^{G} \nu \Sigma_{f,g'}\psi_{0,g'},$$

Courtesy of Univ. Michigan

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Annals of Nuclear Energy 31 (2004) 1963–1986

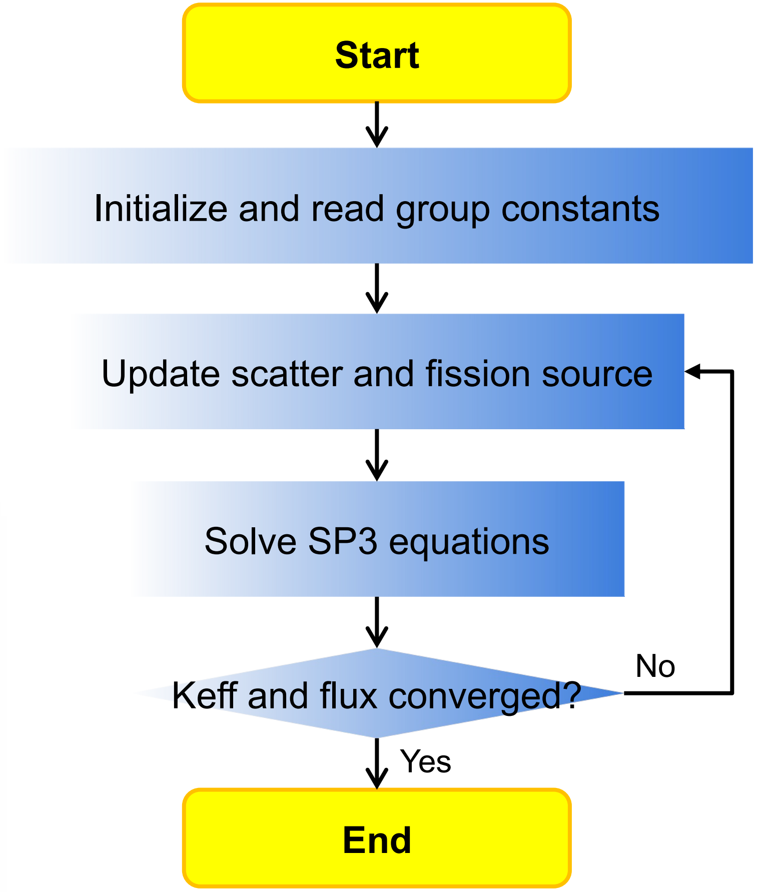
annals of NUCLEAR ENERGY

www.elsevier.com/locate/anucene

“I have an idea!” An appreciation of Edward W. Larsen’s contributions to particle transport

Marvin L. Adams *

Department of Nuclear Engineering, Texas A&M University, 129 Zachry, 3133 TAMU, College Station, TX 77843-3133, USA

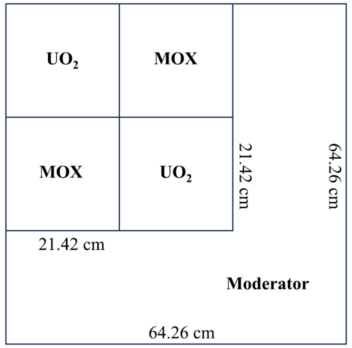


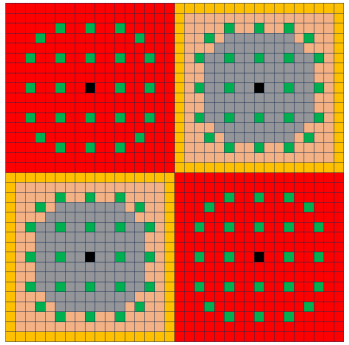
Celebration of 60 years birthday of E. Larsen on the journal Annals of Nuclear Energy (2004) ***gave the SP3 proof process introduction.***

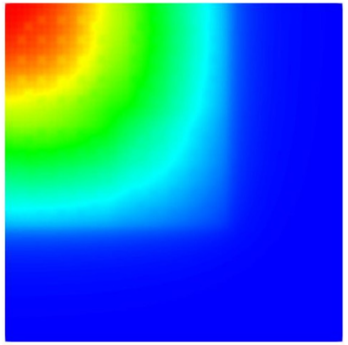
3.3 SP3 neutron transport – KaiyangCore

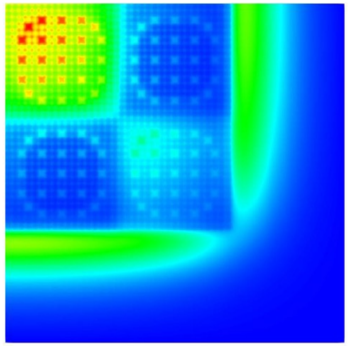
- KaiyangCore has been validated by several neutron transport benchmarks, such as C5G7, 3D-FBR, and BWR pin-by-pin cases, **showing a comparable numerical accuracy with high-order transport solvers.**

✓ OECD-C5G7 benchmark



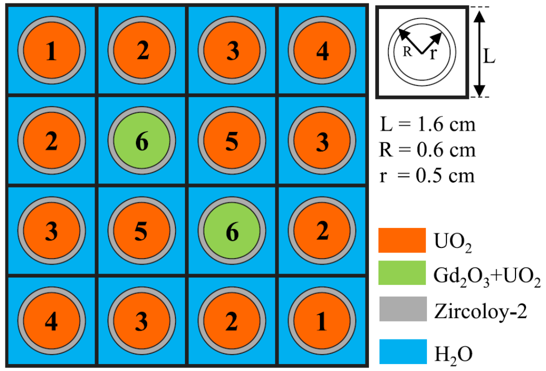


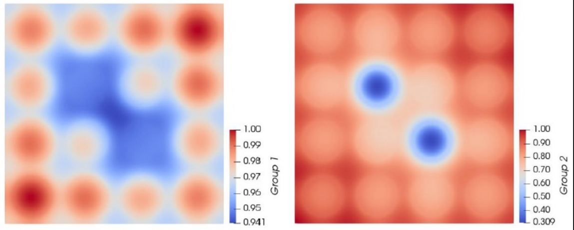




Code	Method	Global max (%)
APOLLO2	MOC	4.16
CRONOS2 -SN	SN	4.98
PARTISN	SN	5.23
OpenFOAM	**SP3**	**6.18**
COHINT	CP/IC	11.36

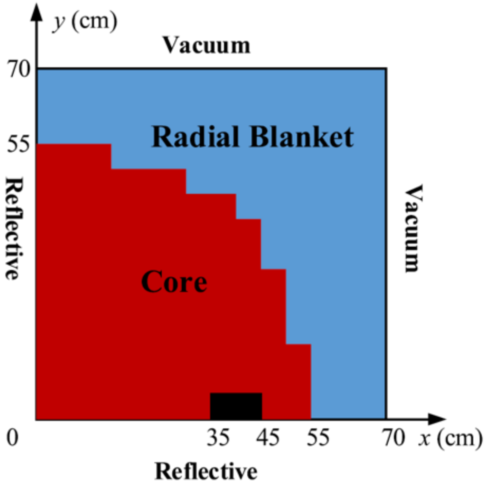
✓ BWR pin-by-pin case

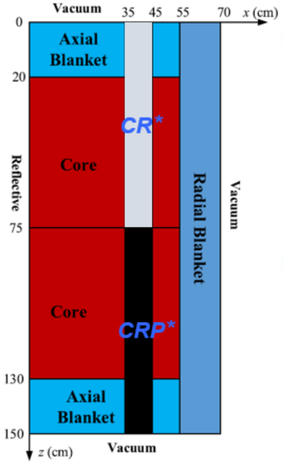


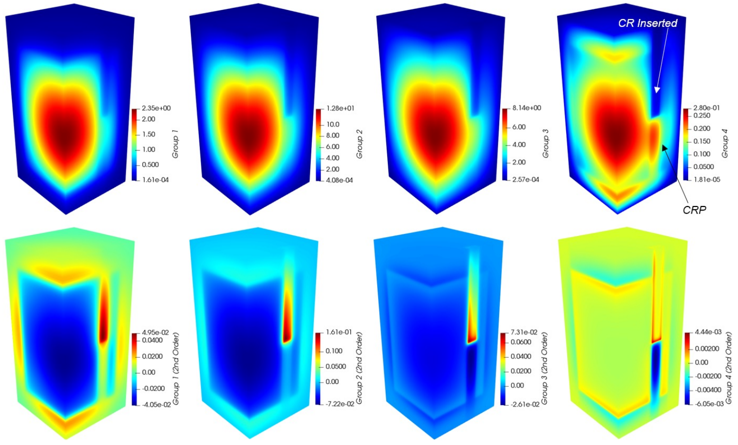


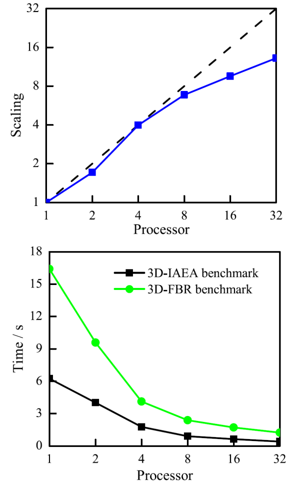
Solver	Pin 1	Pin 2
DRAGON	0.190448	0.181816
DIAMOND	0.190587	0.181753
OpenFOAM	0.189707	0.181754
Deviation	−0.389%	−0.034%

✓ 3D-FBR benchmark









3.4 Space-time kinetics – KaiyangIQS

- Improved quasi-static method (IQS) decomposes the neutron scalar flux to amplitude function (rapid) and shape function (slow), which allows us to use small and large time steps for space-time kinetics simulation coupling with adjoint neutron transport equation.

$$\frac{1}{v_g}\frac{\partial \phi_g(\vec{r},t)}{\partial t} = D_g\nabla^2\phi_g(\vec{r},t) - \Sigma_{t,g}\phi_g(\vec{r},t) + \sum_{g'=1}^{G}\Sigma_{s,g'\to g}\phi_{g'}(\vec{r},t) + \frac{(1-\beta)\chi_{p,g}}{k_{eff}^{(0)}}\sum_{g'=1}^{G}\nu\Sigma_{f,g'}\phi_{g'}(\vec{r},t) + \sum_{i=1}^{6}\chi_{d,i,g}\lambda_i\hat{C}_i(\vec{r},t)$$

$$\frac{\partial \hat{C}_i(\vec{r},t)}{\partial t} = \frac{\beta_i}{k_{eff}^{(0)}}\sum_{g=1}^{G}\nu\Sigma_{f,g}\phi_g(\vec{r},t) - \lambda_i\hat{C}_i(\vec{r},t), \quad i=1,\cdots,6$$

Quasi-static decomposition

$$\phi_g(\vec{r},t) = n(t)\cdot\psi_g(\vec{r},t)$$

Scalar flux

Shape:

$$\frac{n}{v_g}\frac{\partial\psi_g}{\partial t} + \frac{\psi_g}{v_g}\frac{dn}{dt} - n\cdot D_g\nabla^2\psi_g + n\cdot\Sigma_{t,g}\psi_g = n\cdot\sum_{g'=1}^{G}\Sigma_{s,g'\to g}\psi_{g'} + n\cdot\frac{(1-\beta)\chi_{p,g}}{k_{eff}^{(0)}}\sum_{g'=1}^{G}\nu\Sigma_{f,g'}\psi_{g'} + \sum_{i=1}^{6}\chi_{d,i,g}\lambda_i\hat{C}_i$$

Amplitude:

$$\frac{dn(t)}{dt} = \frac{\rho(t)-\bar{\beta}(t)}{\Lambda(t)}n(t) + \sum_{i=1}^{6}\lambda_i\bar{C}_i(t)$$

$$\frac{d}{dt}\bar{C}_i(t) = \frac{\bar{\beta}_i(t)}{\Lambda(t)}n(t) - \lambda_i\bar{C}_i(t), \quad i=1,\cdots,6$$

- Implementation in OpenFOAM: mainly consist of 3 sub-solvers, 1 process solving strategy code.

Amplitude function → ODE solver in Rosenbrock method — *1 sub-solver*

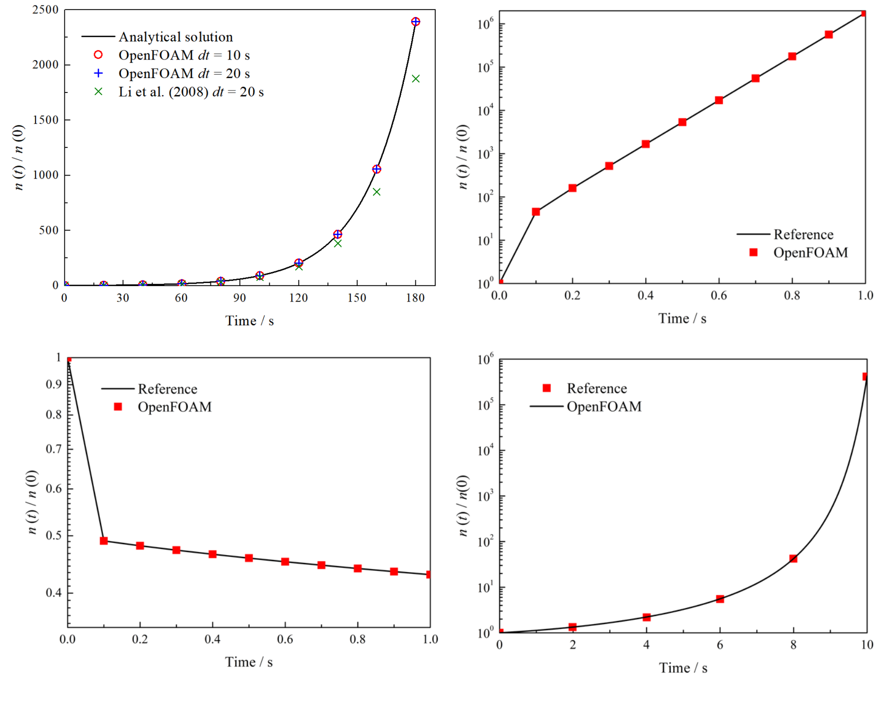
Adjoint and shape equations → Developed from KaiyangCore (SP3) — *2 sub-solvers*

Space-time kinetic parameters → Overall solving strategy code — *1 strategy control code*

3.4 Space-time kinetics – KaiyangIQS

- **Sub-solvers in KaiyangIQS are carefully verfied first, such as amplitude and adjoint neutronics solvers. The comprehensive validations of KaiyangIQS are carried out with 1D/2D/3D benchmarks.**
- **We adopt high-order *Rosenbrock* algorithm to solve stiffness problems, the numerical accuracy of space-time kinetics is promising.**

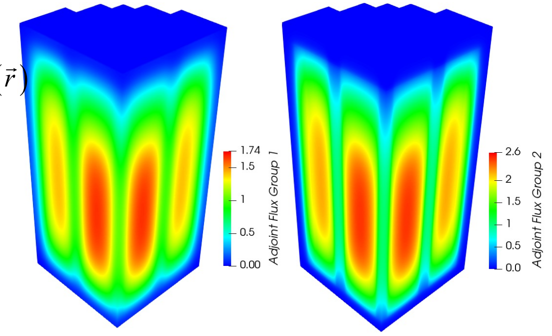
✓ Amplitude solver



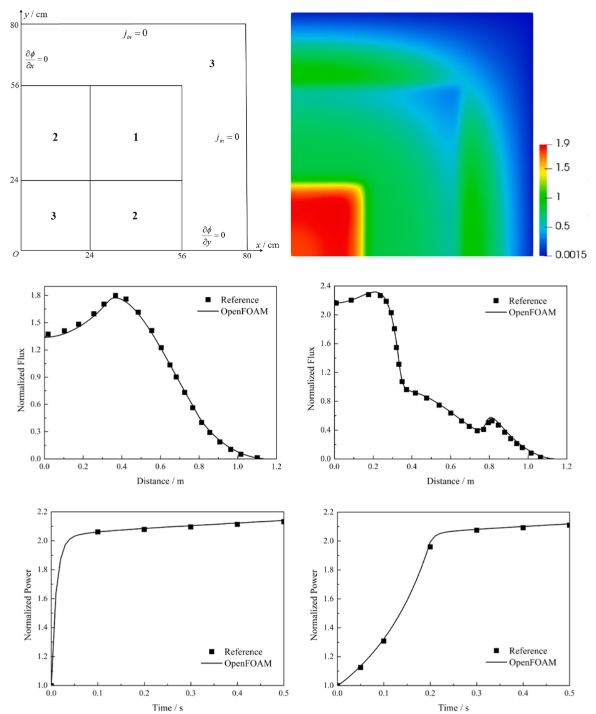
✓ Adjoint neutronics solver

$$-D_g\nabla^2\phi_g^*(\vec{r})+\Sigma_{t,g}\phi_g^*(\vec{r})=\sum_{g'=1}^{G}\Sigma_{s,g\to g'}\phi_{g'}^*(\vec{r})+\frac{\nu\Sigma_{f,g}}{k_{eff}^*}\sum_{g'=1}^{G}\chi_{g'}^*\phi_{g'}^*(\vec{r})$$

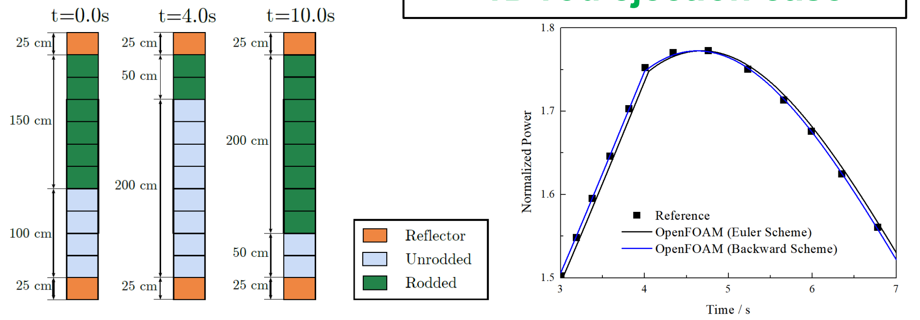
$$k_{eff}^{*,n}=k_{eff}^{*,n-1}\cdot\frac{\left(\int_{\partial V}\sum_{g=1}^{G}\chi_g^*\phi_g^*dV\right)^n}{\left(\int_{\partial V}\sum_{g=1}^{G}\chi_g^*\phi_g^*dV\right)^{n-1}}$$



✓ TWIGL benchmark



✓ 1D rod ejection case



3.5 Subchannel analysis – YOGUANG

- **Considering the advantages of OpenFOAM, we develop a CFD-based subchannel code – YOGUANG for Gen-IV wire-wrapped liquid metal cooled reactors. General mesh system is adopted to solve a CFD-like thermal-hydraulics. The empirical models are supplemented to close the source terms.**

Continuity equation

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

Momentum equation

$$\nabla\cdot(\rho\mathbf{u}\mathbf{u})=-\nabla p+\nabla\cdot(\mu_t\nabla\mathbf{u})+\nabla\cdot(\mu\nabla\mathbf{u})-\mathbf{K}\cdot\mathbf{u}+\rho\mathbf{g}$$

Todreas-Nishimura model

$$\kappa_t=f_{scale}\cdot\left[\underbrace{S(\mathrm{Re},\mathbf{u})}_{sweep}+\underbrace{P(\mathrm{Re},Gr,\mathbf{u})}_{plume}\right]\qquad \mu_t=\rho\kappa_t\cdot\mathrm{Pr}_t$$

$$-\rho\overline{\mathbf{u}'T'}=\Gamma_t\nabla T,\quad \mathrm{Pr}_t=\frac{\mu_t}{\Gamma_t}\qquad \kappa_t=\frac{\Gamma_t}{\rho}$$

Friction drag tensor

$$\mathbf{M}=\begin{bmatrix}\mu\cdot f_x & & \\ & \mu\cdot f_y & \\ & & \mu\end{bmatrix}$$

Cheng-Todreas model

$$\mathbf{K}=\begin{bmatrix}k_x & & \\ & k_y & \\ & & k_z\end{bmatrix}\qquad \mathbf{k}=\frac{f_D\rho|\mathbf{u}|}{2D_h}$$

Energy equation

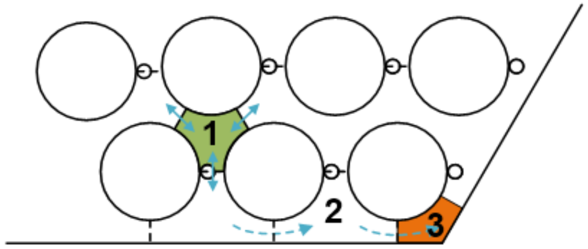
$$\nabla\cdot(\rho C_p\mathbf{u}T)=\nabla\cdot(\mathbf{A}\cdot\nabla\rho C_pT)+\nabla\cdot(\kappa_t\nabla\rho C_pT)+Q$$

Todreas-Nishimura model

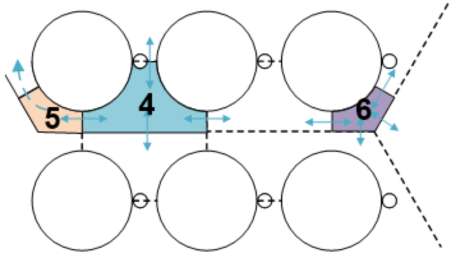
$$\kappa_t=f_{scale}\cdot\left[\underbrace{S(\mathrm{Re},\mathbf{u})}_{sweep}+\underbrace{P(\mathrm{Re},Gr,\mathbf{u})}_{plume}\right]$$

Shape conduction

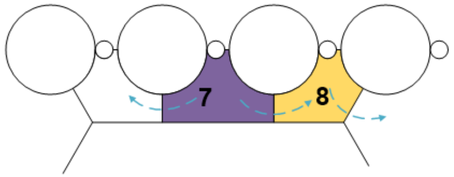
$$\mathbf{A}=\begin{bmatrix}\alpha\cdot f_x & & \\ & \alpha\cdot f_y & \\ & & \alpha\end{bmatrix}$$



Inner, side, and corner subchannels



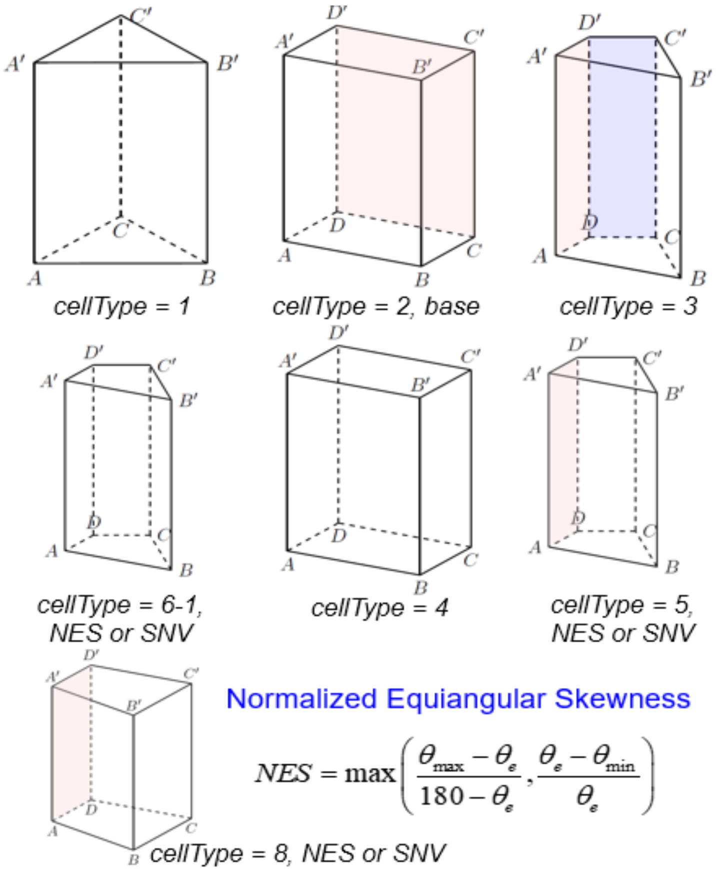
New-added open subchannels



Irregular shape subchannels

3.5 Subchannel analysis – YOGUANG

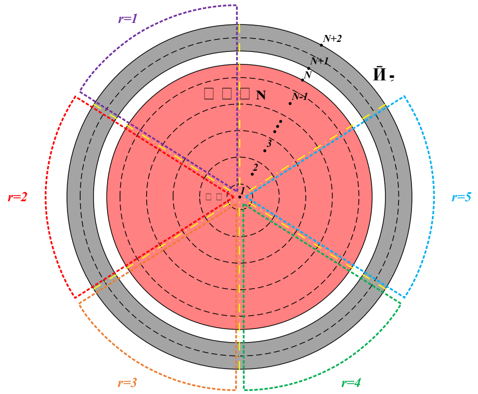
- **Three novel rapid modelling techniques are proposed: 1. subchannel auto-identification, 2. fuel pin radial temperature calculation, and 3. fuel pin two-layer auto-location. The merits of YOGUANG allow to make a quick core-level subchannel analysis with robust numerical methods for Gen-IV reactors.**

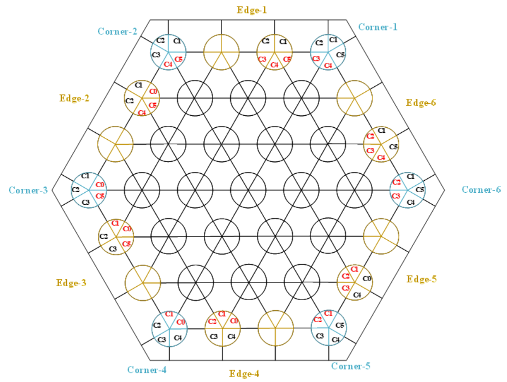


Normalized Equiangular Skewness

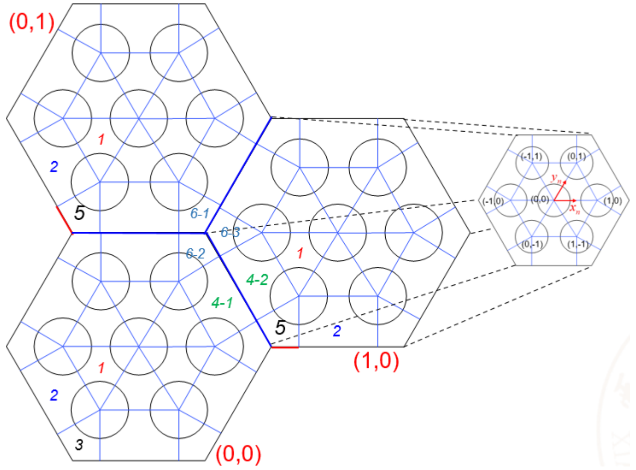
$$NES = \max\left(\frac{\theta_{\max} - \theta_e}{180 - \theta_e}, \frac{\theta_e - \theta_{\min}}{\theta_e}\right)$$

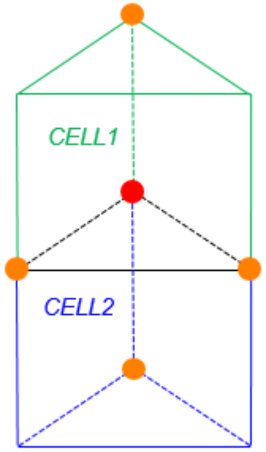
Subchannel auto-identification





1D fuel pin radial temperature calc.





Fuel pin two-layer auto-location

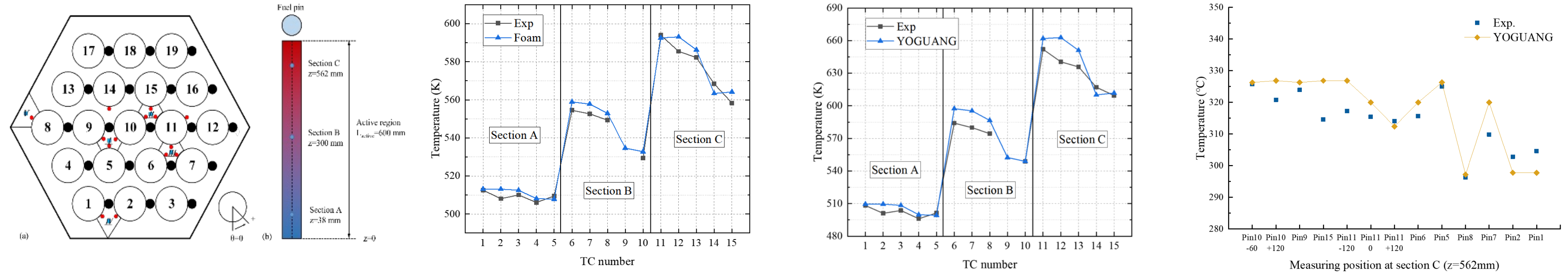
Advantages & advancements

1. **Quick core-level subchannel modeling ability.**
2. **More precise fuel pin temperature prediction.**
3. **More robust and flexible numerical scheme and solving algorithm.**

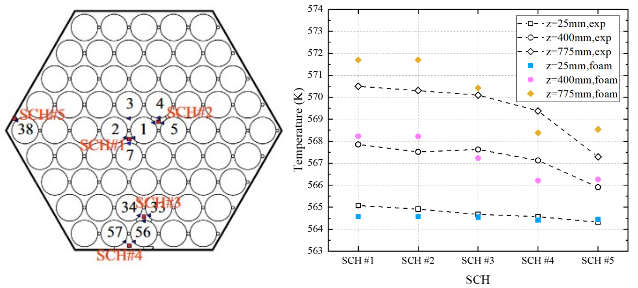
3.5 Subchannel analysis – YOGUANG

- **YOGUANG is validated with several well-known LBE experiments, such as NACIE-UP, KIT-THEADES, and KYLIN, showing the good numerical predictions when compared with benchmark code – COBRA.**
- **YOGUANG strongly supports the coarse-mesh CFD subchannel method, which is expected to give new insights on subchannel analysis of thermal-hydraulics.**

✓ NACIE-UP experiment

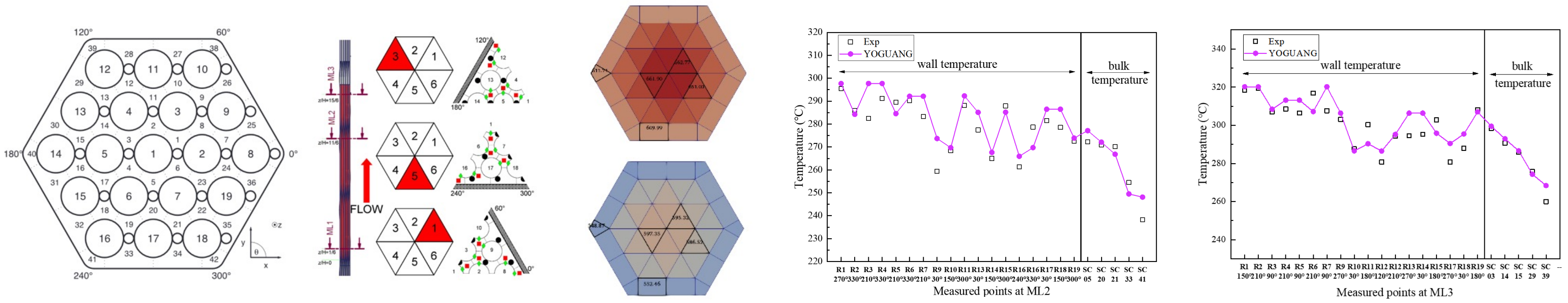


✓ KYLIN-61 experiment



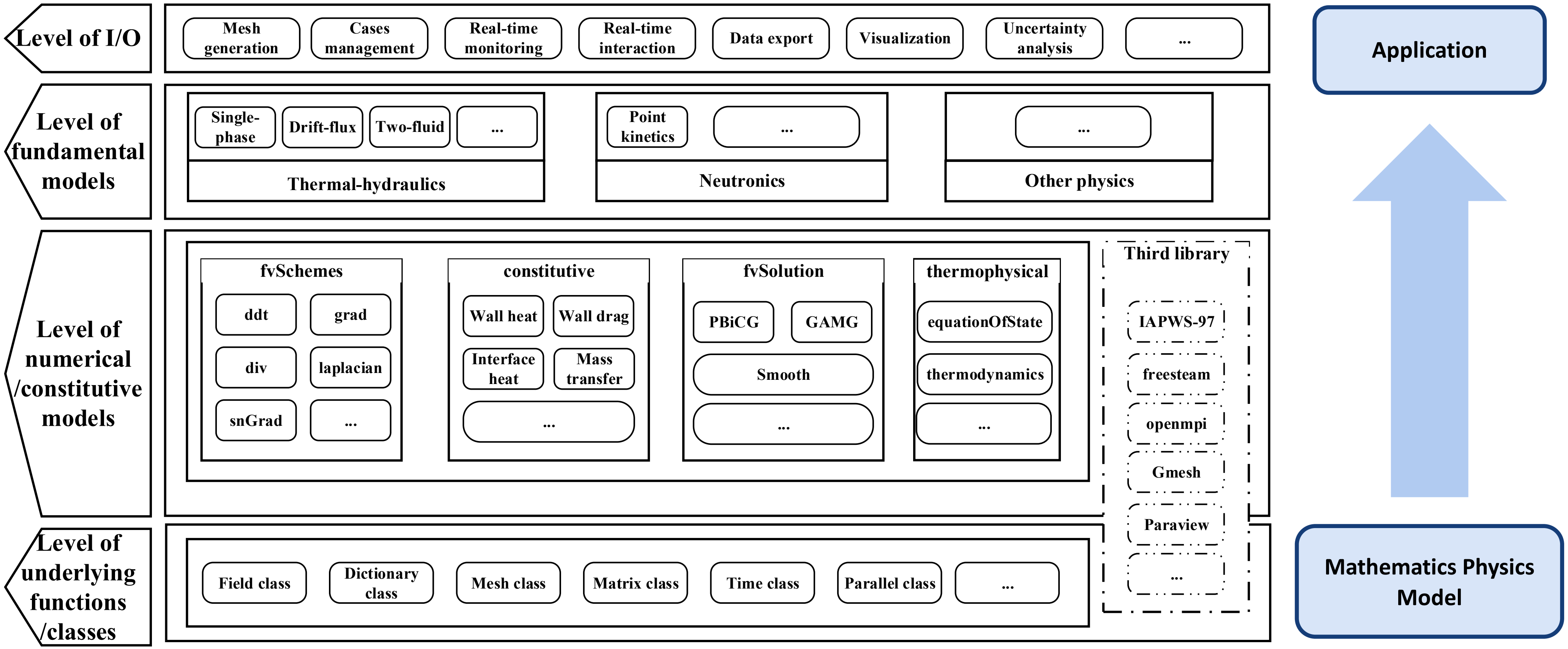
Error	MRE%	MAE(°C)	RMSE(°C)	MaxE(°C)
ML1				
SACOS	3.76	3.175	3.874	8.211
COBRA-YT	4.10	3.458	4.407	10.019
Foam	5.26	4.440	5.430	12.496
ML2				
SACOS	7.253	6.118	7.658	18.005
COBRA-YT	6.741	5.686	7.373	15.516
Foam	7.156	6.036	7.556	14.778
ML3				
SACOS	7.516	6.331	8.107	19.783
COBRA-YT	7.236	6.104	7.784	15.533
Foam	6.170	5.205	6.291	14.485

✓ KIT-THEADES experiment



3.6 System-level two phase flow – STACO

- We also develop **a CFD-based system code** – STACO (**S**ystem-level **T**hermal-hydraulic **A**nalysis **C**ode based on **O**penFOAM)
- This tool supports the partial non-equilibrium **drift-flux** model and the non-equilibrium **two-fluid** model



Program development level

3.6 System-level two phase flow – STACO

- **Governing equations of two-fluid model**

- Continuity equations $$\frac{\partial(\alpha_k \rho_k)}{\partial t} + \nabla \cdot (\alpha_k \rho_k \boldsymbol{u}_k) = \Gamma_k$$

- Momentum equations $$\frac{\partial(\alpha_k \rho_k \boldsymbol{u}_k)}{\partial t} + \nabla \cdot (\alpha_k \rho_k \boldsymbol{u}_k \boldsymbol{u}_k) = -\alpha_k \nabla p + \boldsymbol{F}_{\boldsymbol{w,k}} + \alpha_k \rho_k \boldsymbol{g} + \boldsymbol{F}_{i,k} + \Gamma_k \boldsymbol{u}_{\boldsymbol{i}}$$

- Energy equations $$\frac{\partial(\alpha_k \rho_k h_k)}{\partial t} + \nabla \cdot (\alpha_k \rho_k \boldsymbol{u}_k h_k) = Q_{w,k} + \alpha_k \frac{Dp}{Dt} + h_{i,k}\Gamma_k + Q_{i,k}$$

- Constitutive models

$$\boldsymbol{F}_{\boldsymbol{w,k}} = -C_{w,k} |\boldsymbol{u}_{\boldsymbol{k}}| \boldsymbol{u}_{\boldsymbol{k}}$$

wall shear

$$\boldsymbol{F}_{\boldsymbol{i,k}} = C_i |\boldsymbol{u}_{1-k} - \boldsymbol{u}_k| (\boldsymbol{u}_{1-k} - \boldsymbol{u}_k)$$

interphase shear

$$Q_{i,k} = H_{i,k} A_i (T_i - T_k)$$

interfacial heat transfer

$$Q_{w,k} = H_{w,k} A_w (T_w - T_k) + H_{w,sat,k} A_w (T_w - T_{sat})$$

wall heat transfer

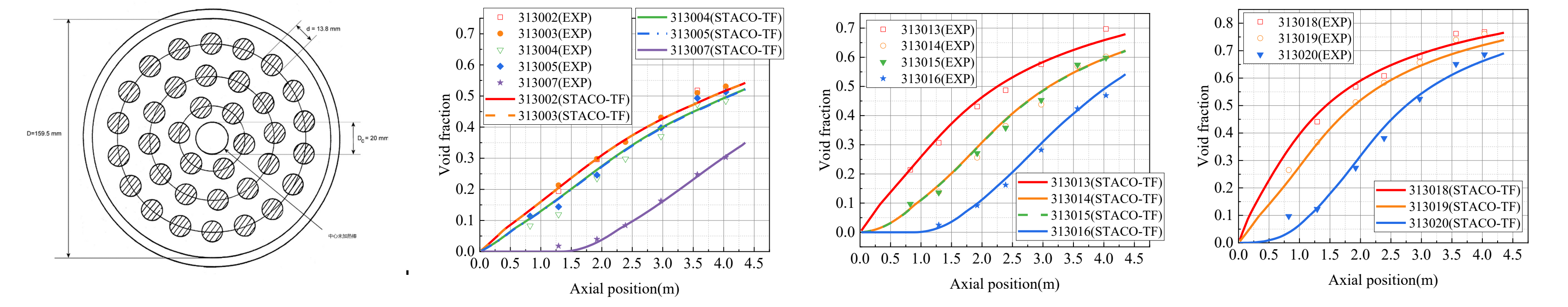
$$\Gamma_k = \frac{Q_{i,k} + Q_{i,1-k}}{h_{i,k} - h_{i,1-k}} + \Gamma_w$$

mass transfer

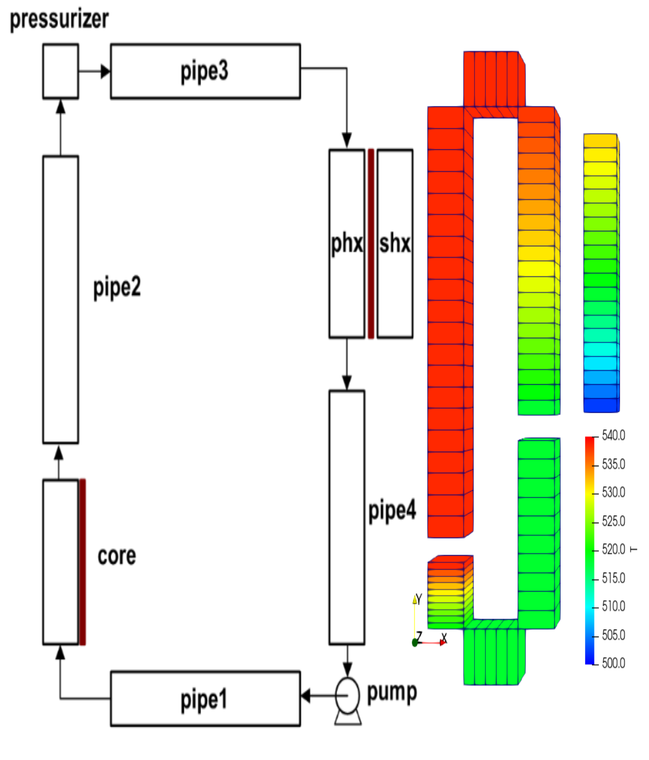
3.6 System-level two phase flow – STACO

- **STACO is validated with several well-known two-phase experiments, such as FRIGG, Bartolomei , showing the good numerical predictions.**
- **STACO supports the 1D-mesh CFD system method, which is expected to give new insights on system analysis of thermal-hydraulics.**

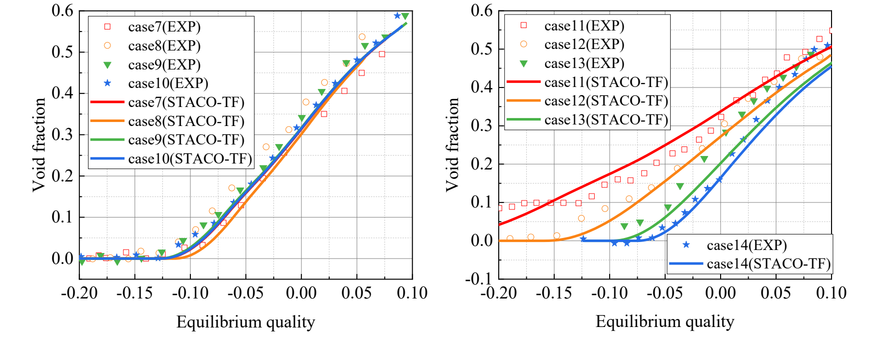
✓ FRIGG experiment



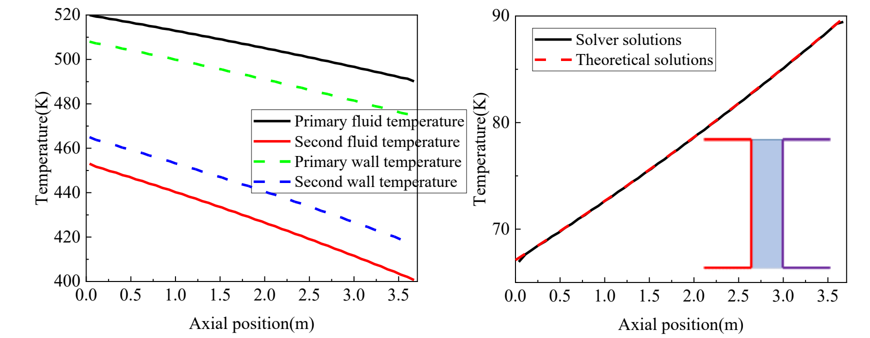
✓ Loop simulation



✓ Bartolomei experiment

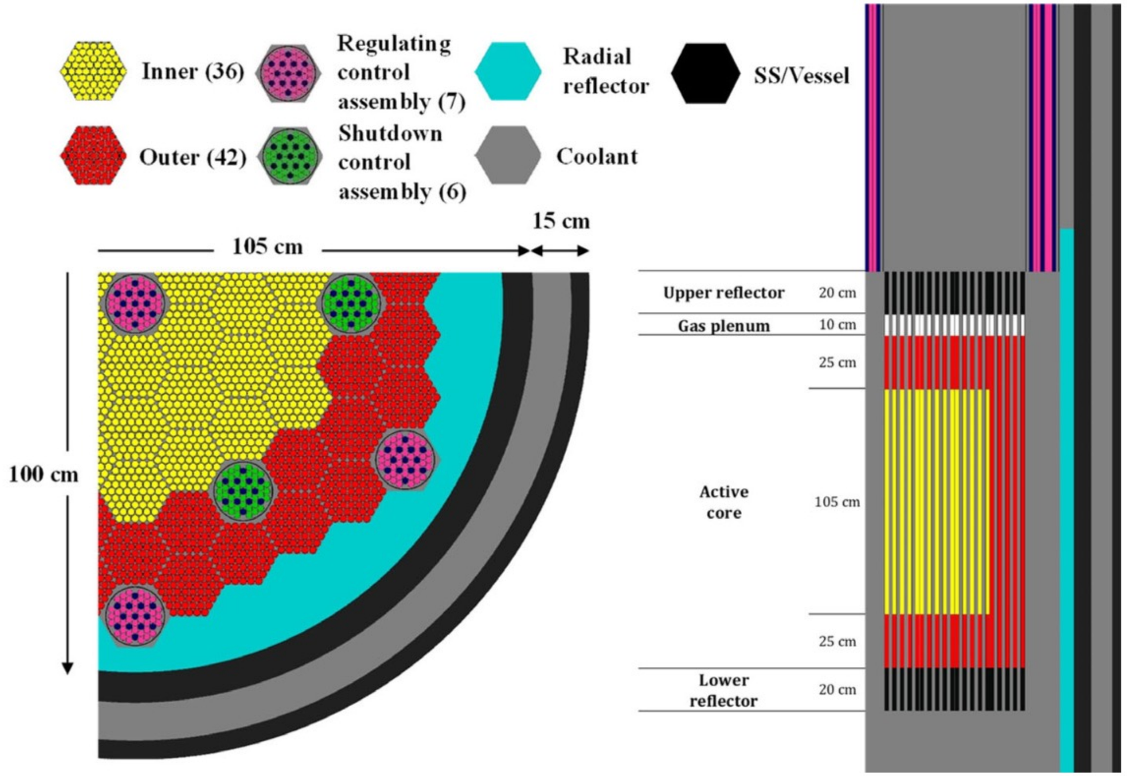


✓ Component validations

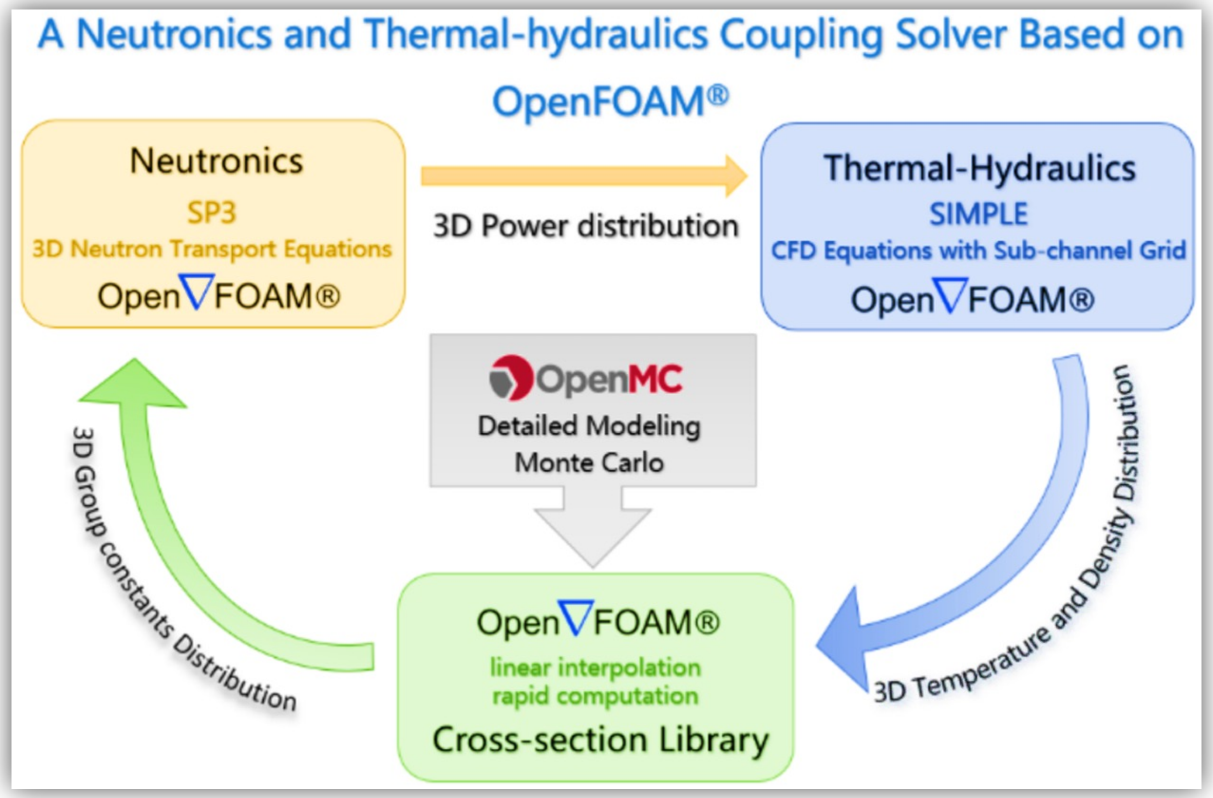


3.7 Coupling analysis for LFR

- MicroURANUS is a small-modular LFR for all-weather zero-carbon energy. However, the fission power distribution is coupled with thermal-hydraulics, required to be studied for safety assessment.
- We couple KaiyangCore (SP3) and YOGUANG (subchannel) to make the 3D core-level N/TH analyses. The group constants are generated from OpenMC.



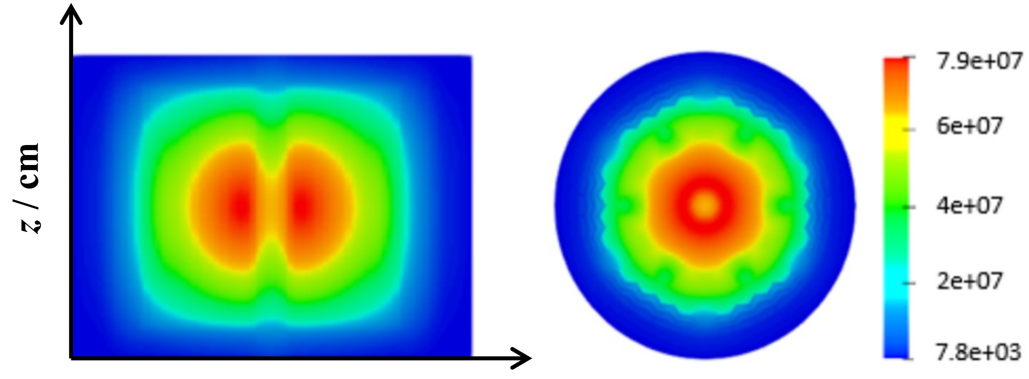
MicroURANUS reactor layout (Nguyen et al 2021)



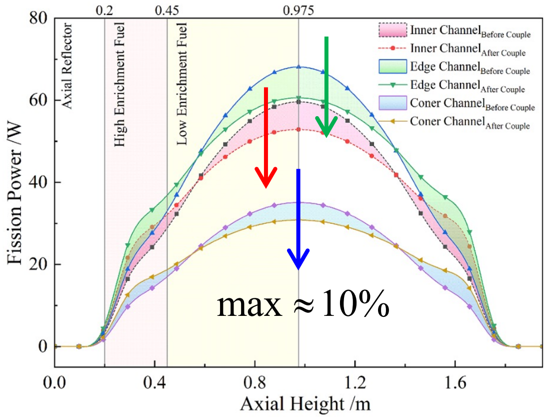
Neutronics/Thermal-hydraulics coupling strategy

3.7 Coupling analysis for LFR

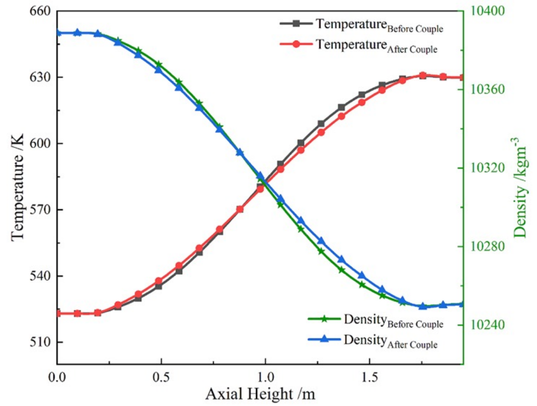
- The neutronics behaviors solved by KaiyangCore are conducted and validated by Monte-Carlo method.
- **The coupling effect of MicroURANUS is pronounced.** The **axial power is flattened** with the **max variation of 10% after the coupling**, because of remarkable changes of fission and transport group constants.



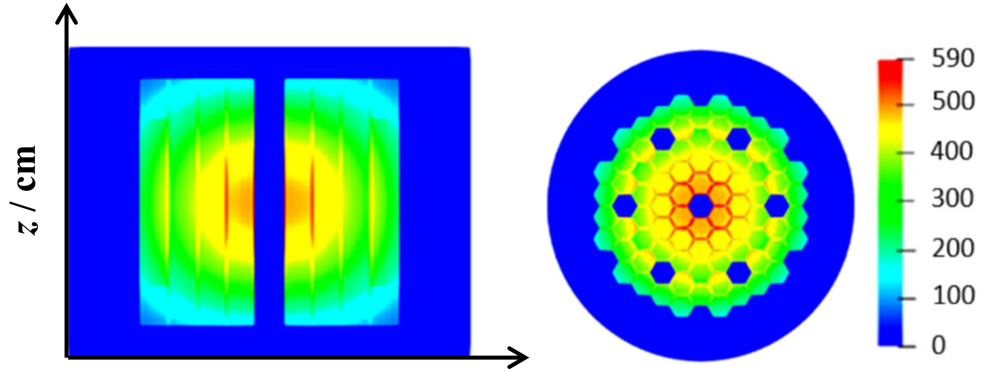
Fast neutron flux



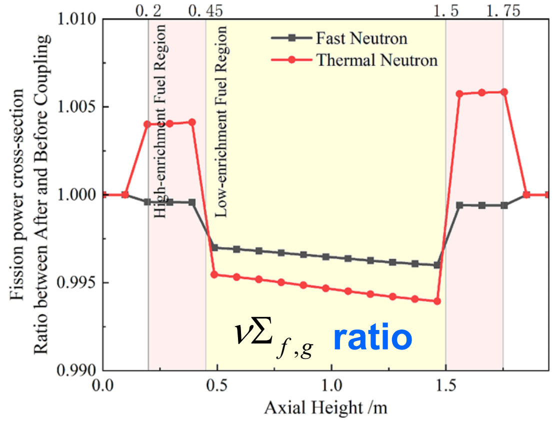
Axial power variation

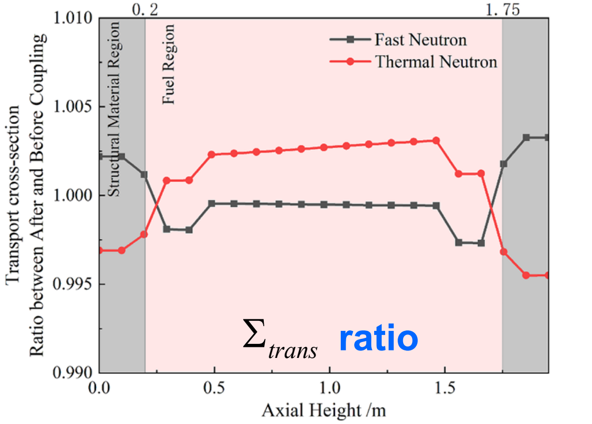


Axial temperature variation



Fission power density



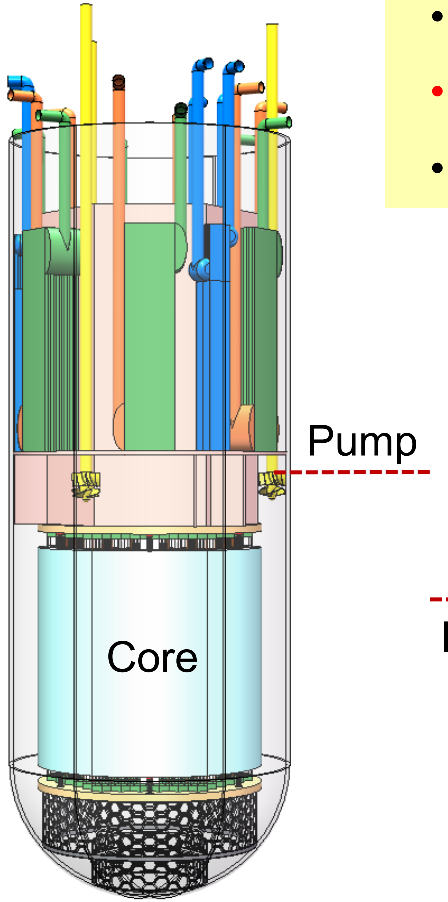


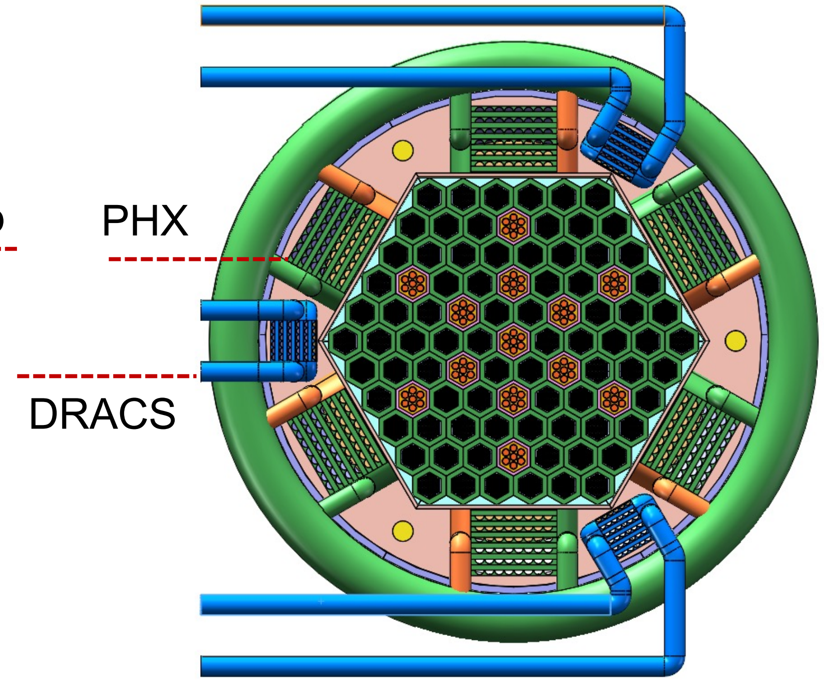
3.8 Coupling analysis for FHR

固有安全一体化小型氟盐冷却高温堆－“福星”

FLUORIDE-SALT-COOLED HIGH-TEMPERATURE ADVANCED REACTOR (***FuSTAR***)

- Integrated and modular core design
- Core weight < 60 tons
- Diameter: 3.5m; Height: 10m





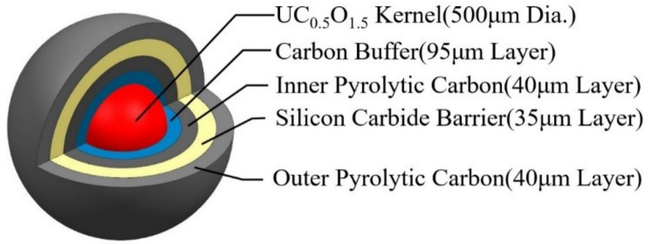
- Highway

- Railway

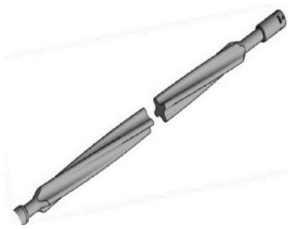
- 125 MWth with 973 K outlet

3.9 Coupling analysis for FHR

➢ **FUSTAR: A graphite-moderated thermal spectrum core scheme using TRISO particles as fuel, helical cruciform fuel elements, and FLiBe as coolant**

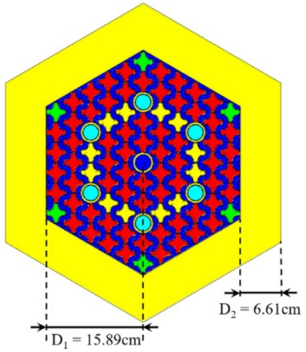


TRSIO



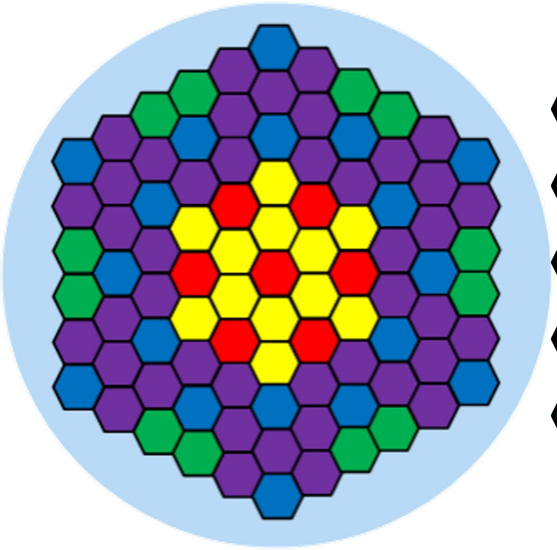
Helical cruciform fuel element

FLiBe

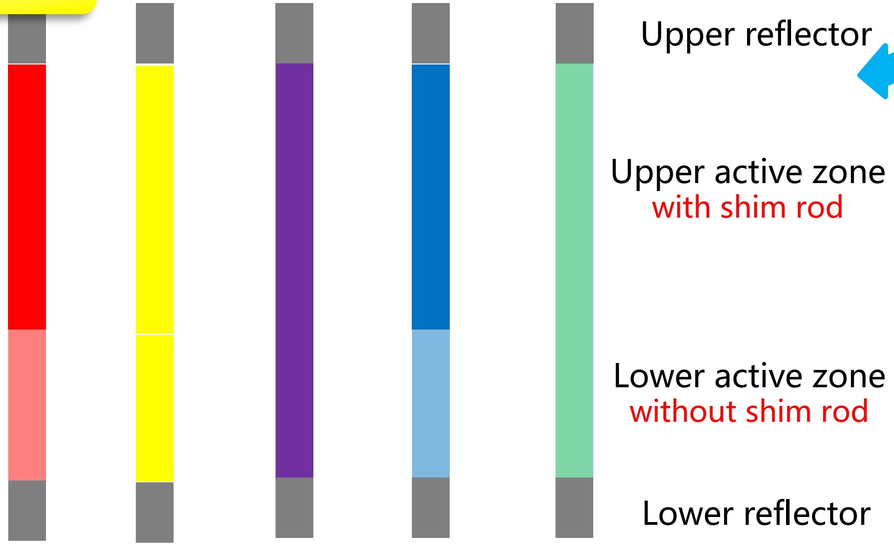


Graphite moderator

Core configuration



- Enrichment: 15%, shim rod
- Enrichment: 15%, without control rod
- Enrichment: 17.5%, without control rod
- Enrichment: 17.5%，shim rod
- Enrichment: 17.5%，safety rod



3.9 Coupling analysis for FHR

- **GeN-FOAM is a multi-physics solver developed by PSI and EPFL, including thermal-hydraulics, neutronics, and mechanics.**

$$\frac{\partial \gamma\rho}{\partial t} + \nabla\cdot(\gamma\rho\boldsymbol{u}) = 0$$

$$\frac{\partial \gamma\rho\boldsymbol{u}}{\partial t} + \nabla\cdot(\gamma\rho\boldsymbol{u}\boldsymbol{u}) = \nabla\cdot(\mu_{eff}\nabla\boldsymbol{u}) - \gamma\nabla p + \gamma\boldsymbol{F}_{g} + \gamma\boldsymbol{F}_{ss}$$

body force

drag force

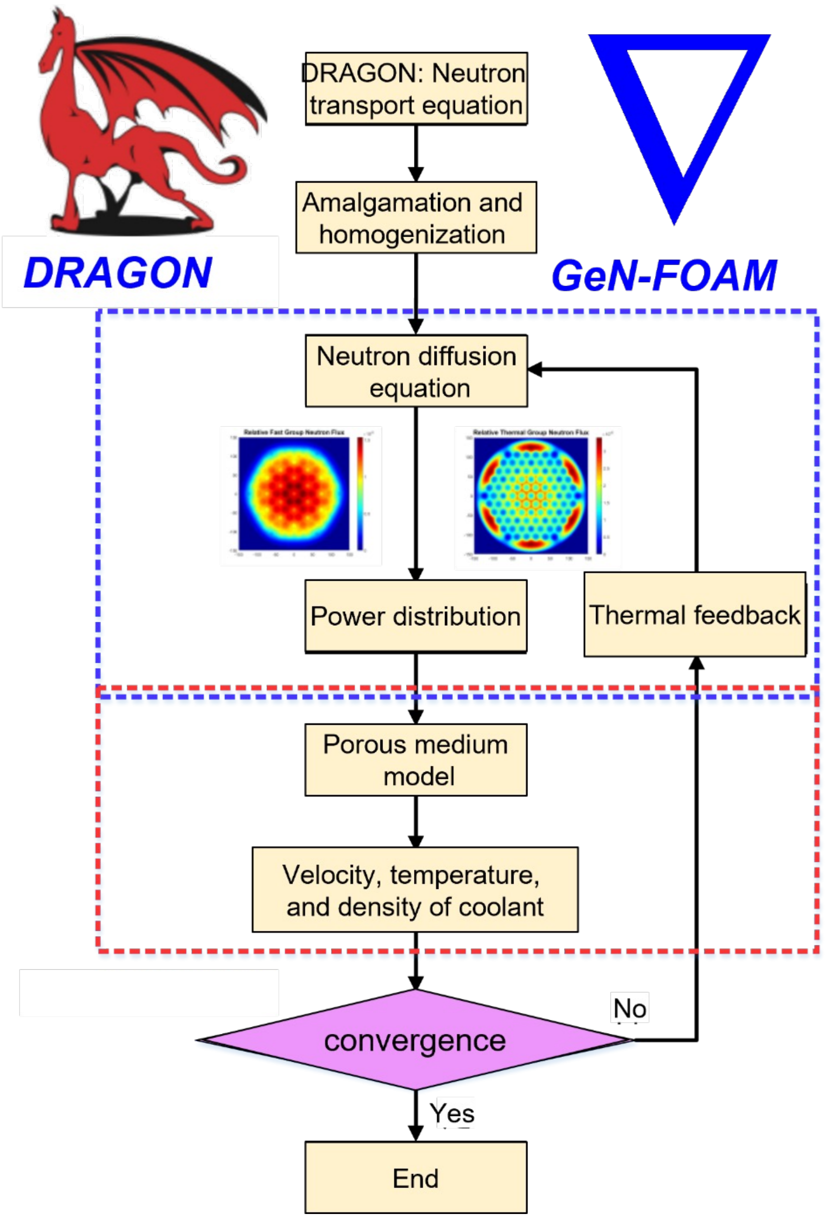
$$\frac{\partial\gamma\rho e}{\partial t} + \nabla\cdot\left(\gamma\boldsymbol{u}(\rho e + p)\right) = \nabla\cdot(\gamma k_{eff}\nabla T) + \gamma Q_{ss} + Q_F + \gamma\boldsymbol{F}_{ss}\cdot\boldsymbol{u}$$

heat source from structure

heat source from fuel salt

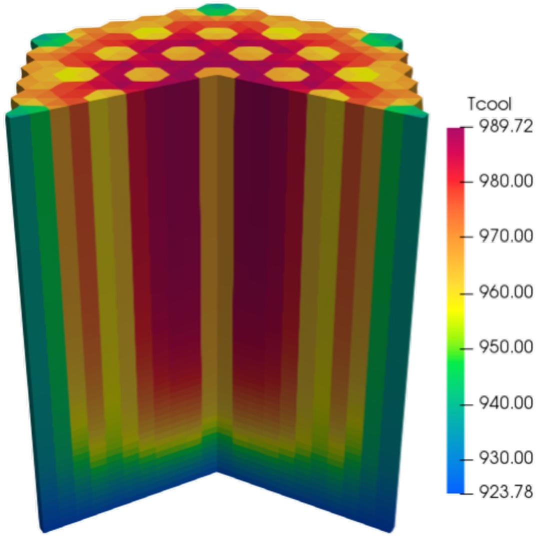
$$\frac{1}{v_g}\left(\frac{\partial\phi_g}{\partial t} + \nabla\cdot\boldsymbol{u}\phi_g\right) = \nabla\cdot D_g\nabla\phi_g - \Sigma_{t,g}\phi_g + \sum_{g'\neq g}^{G}\Sigma_{g'\to g}\phi_{g'} + \chi_{p,g}(1-\beta)\sum_{g'=1}^{G}\nu\Sigma_{f,g'}\phi_{g'} + \sum_{i=1}^{I}\chi_{d,i,g}\lambda_i C_i$$

$$\frac{\partial C_i}{\partial t} + \nabla\cdot(\boldsymbol{u}C_i) = \nabla\cdot\left(\frac{\nu}{Sc}+\frac{\nu_t}{Sc_t}\right)\nabla C_i + \beta_i\sum_{g'=1}^{G}\nu\Sigma_{f,g'}\phi_{g'} - \lambda_i C_i$$

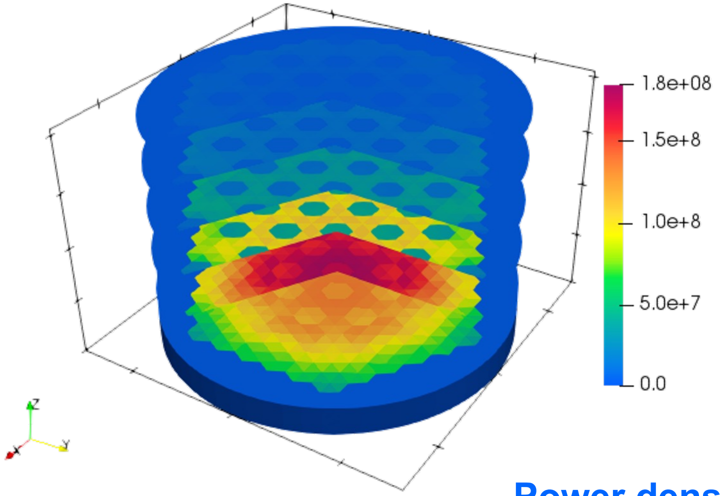


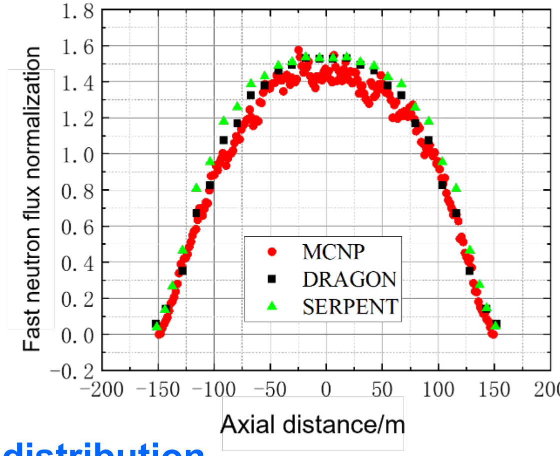
3.9 Coupling analysis for FHR

- **The neutronics behaviors are conducted and validated by Monte-Carlo method.**
- **The overall temperature rise of the core was approximately 50K, which met the design requirements.**

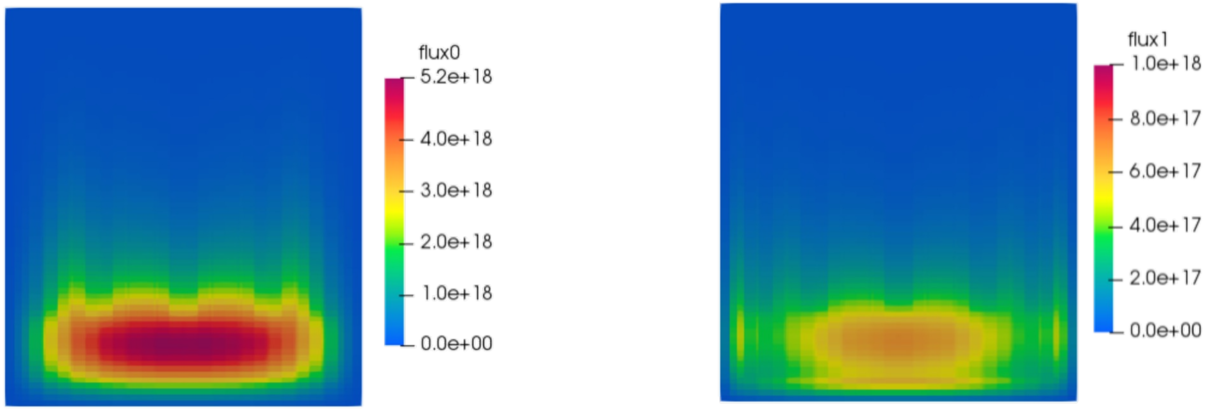


Coolant temperature field





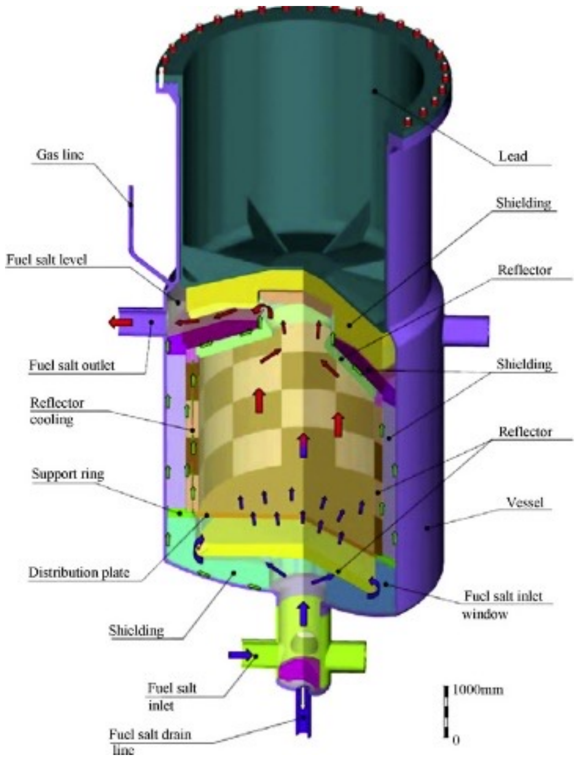
Power density distribution



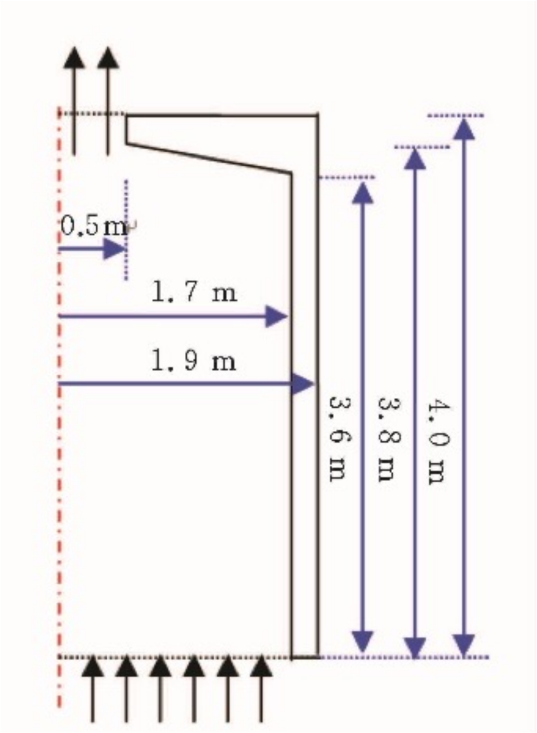
Neutron flux distribution

3.9 Coupling analysis for MSR

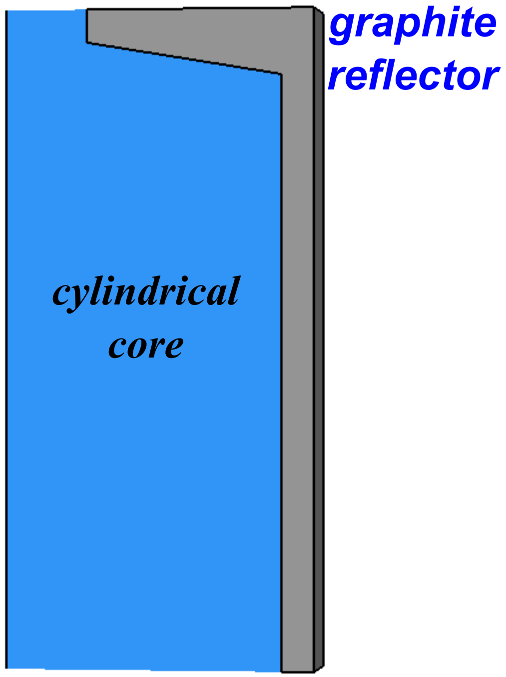
- The concept of MOSART was first proposed by the Russian RPC-KI
- MOSART is a fast spectrum reactor with a cylindrical core surrounded by a graphite reflector



MOSART



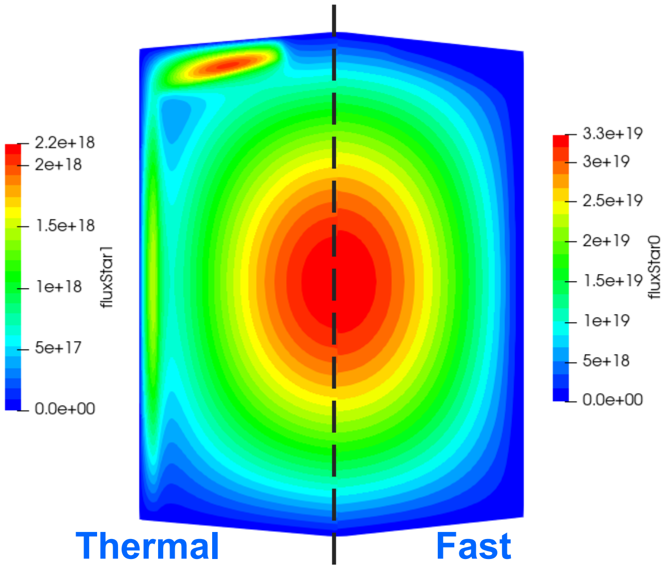
Simplified structure



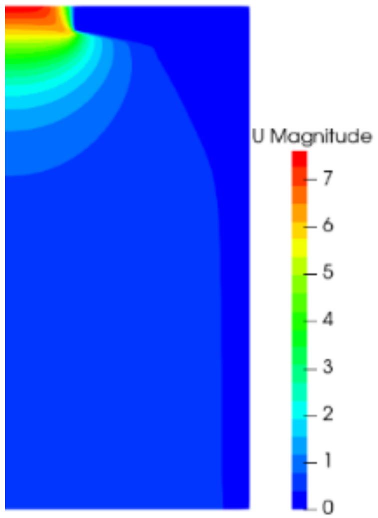
2D axisymmetric model

3.9 Coupling analysis for MSR

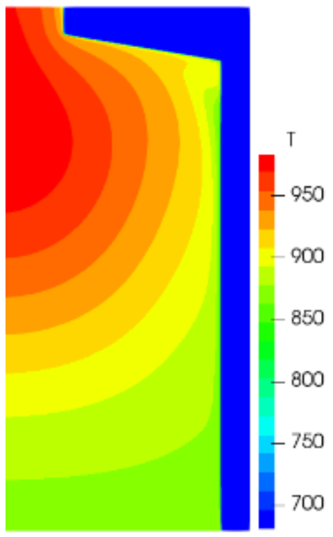
- The **peaks** of both fast and thermal neutron flux occur at the center of the reactor core.
- The flow of molten salt is uniform with the **recirculation** zone forming at the corner.
- **DNPs** move downstream along the flow.



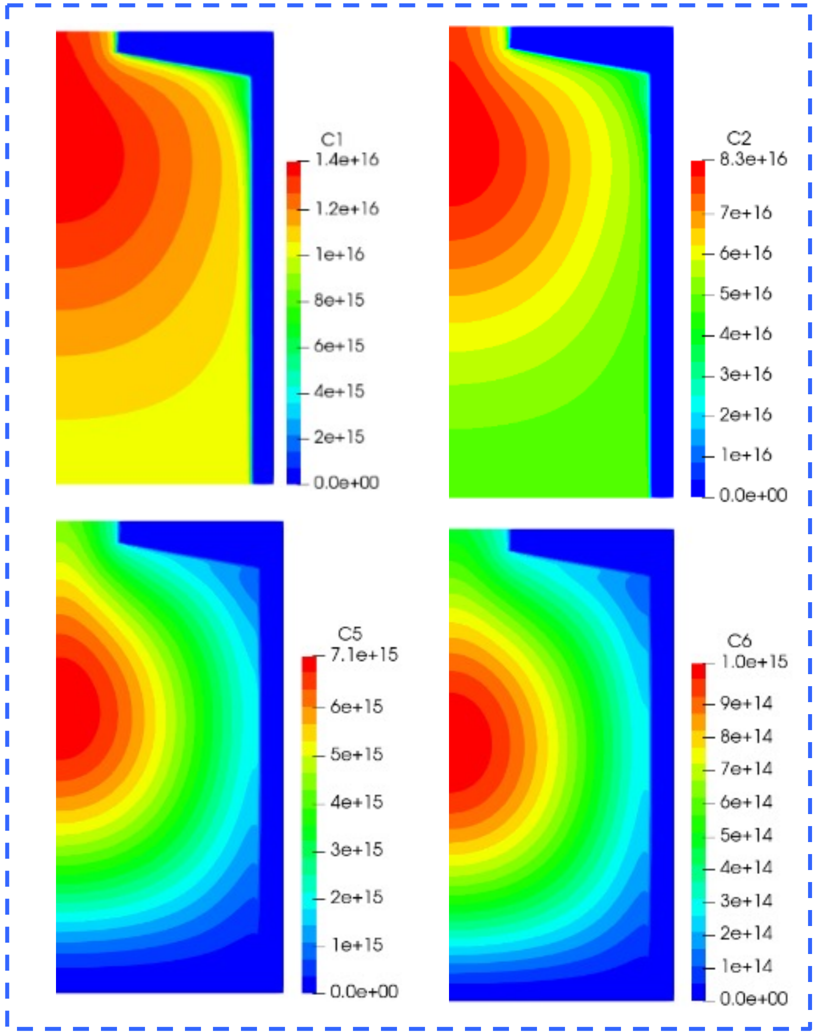
Thermal neutrons | Fast neutrons



Velocity



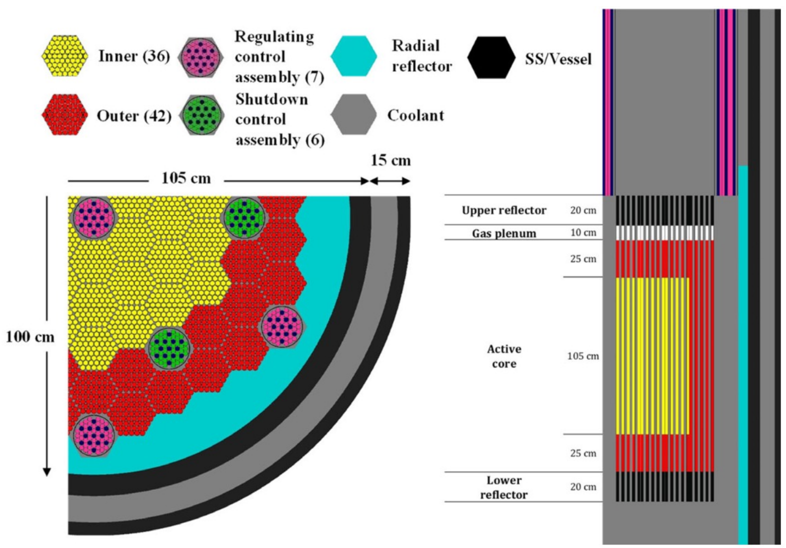
Temperature



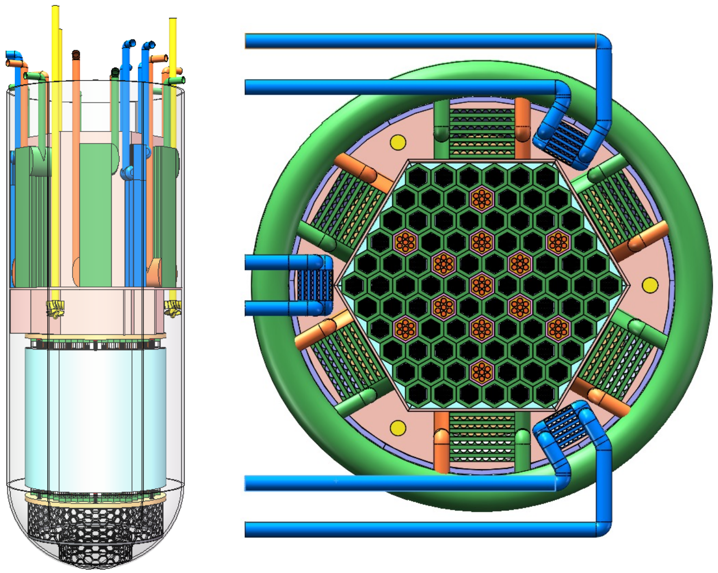
DNPs (C1 C2 C5 C6)

3.10 Summary

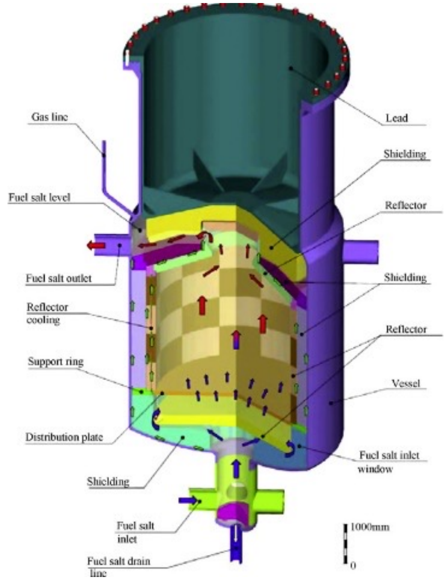
- In the first talk, we mainly focus on the multiphysics modeling of Gen-IV reactors based on OpenFOAM.
- Given the merits of powerful FVM operator, equation discretization, and matrix solver, we can flexibly develop our own neutronics and thermal-hydraulics solvers.
- Coupling under a unified framework shows advantages on compact and high-fidelity solving, which is practical and conducted on the examples of LFR, FHR, and MSR.



MicroURANUS



FuSTAR



MOSART

Thank You!