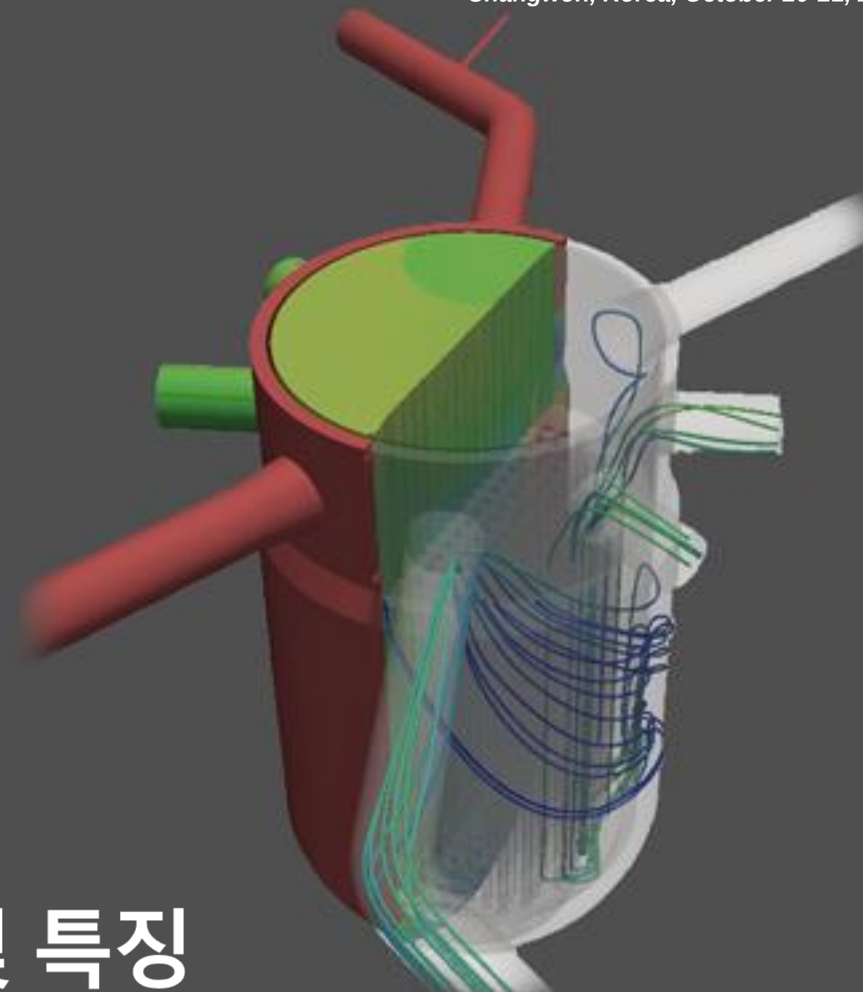
Transactions of the Korean Nuclear Autumn Spring Meeting
Changwon, Korea, October 20-21, 2022



KNS Workshop

원자력열수력 연구부회

한국원자력연구원
통합해석기술개발 현황 및 특징

Yun-Je Cho

October 19, 2022

KNS Workshop

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What is Integrated Analysis System?

1

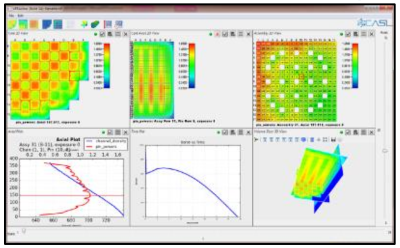
– Essential Components

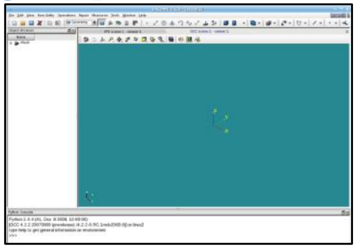
– MARU Platform

What is Integrated Analysis System?

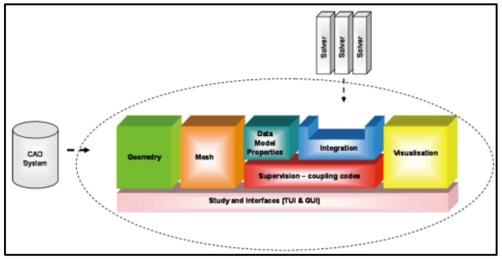
Essential Components

- User-friendly graphic interface



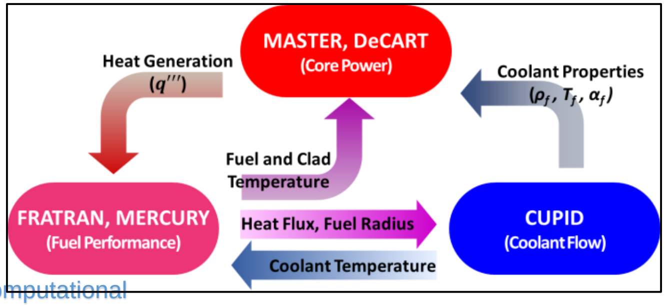


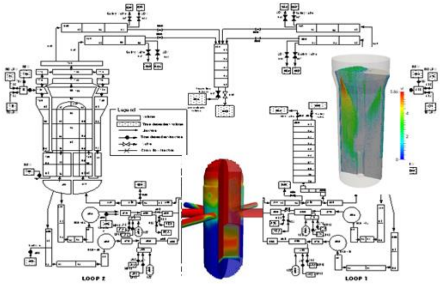
- Standardized numerical libraries



- ✓ Pre-processing
- ✓ Data Exchange
- ✓ Coupled computational schemes
- ✓ Job management and supervision (parallelism)
- ✓ Post-processing

- MSMP coupling technique





MARU (Multi-physics Analysis Platform for Nuclear Reactor SimUlation)

03
모든 것을 마루(MARU) 에 담다

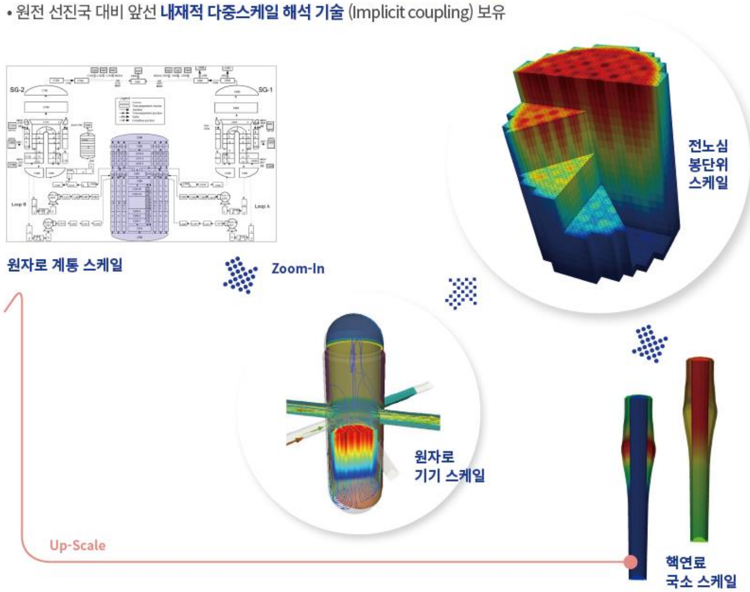
Multi-physics Analysis Platform for Nuclear Reactor SimUlation

MARU는 누구나 쉽게 사용할 수 있는 통합해석 플랫폼입니다.

- 다물리/다중스케일 통합 해석기술 제공
- 계산과학 기술을 활용한 원자로 내부 현상 실시간 구현

다중 스케일 해석 기술을 제공 합니다.

- 원자로 내의 해석 영역과 모의해야 할 현상에 따라 **계통 / 기기 / 봉단위 / 국소** 스케일 해석이 가능
- 원전 선진국 대비 앞선 **내재적 다중스케일 해석 기술** (Implicit coupling) 보유



다물리 연계 해석 기술이 탑재 되었습니다.

- 원자로의 열수력 이상유동 / 노물리 동특성 / 핵연료 연소 현상의 상호작용을 정밀 예측 가능
- 전노심 봉단위의 고해상도 다물리 연계 해석 기능 지원

비전문가도 쉽게 사용할 수 있습니다.

- MARU 는 원자로 통합 해석을 위한 Turnkey solution입니다.
- 언제, 어디서나, 한 번의 클릭으로 원자로에 따른 격자 생성부터, HPC 기반 다물리/다중스케일 계산 및 후처리 까지 MARU를 통해 수행 가능합니다.

WORK FROM ANYWHERE
MARU

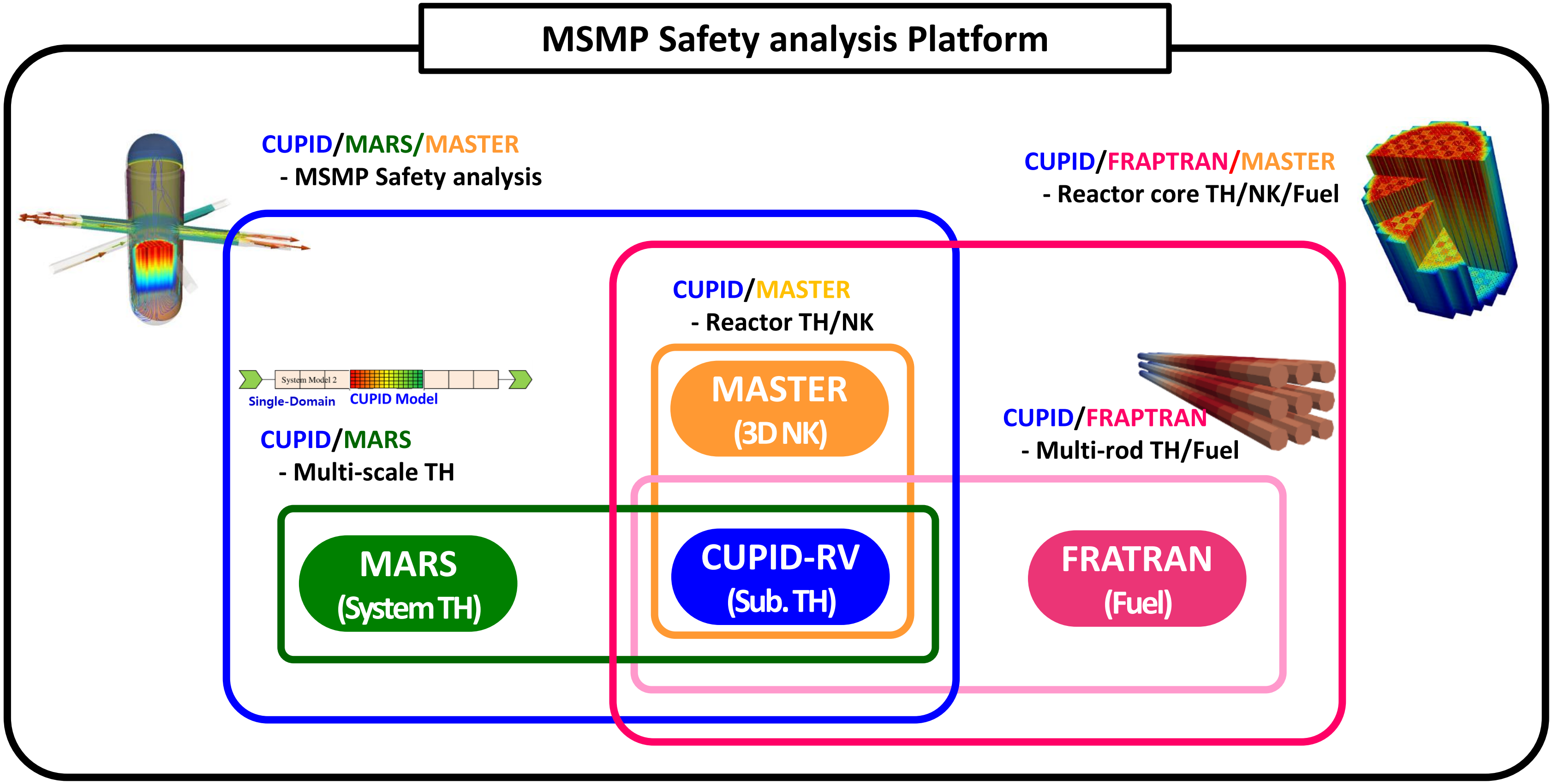
HPC 통합 환경
다물리연계 해석 / 다중스케일 해석

사용자 친화적 환경
GUI 기반 입출력 파일 생성
GUI 기반 해석 후처리

MARU Platform (1/2)

Platform for 3D MSMP Safety analysis

Capability of MARU



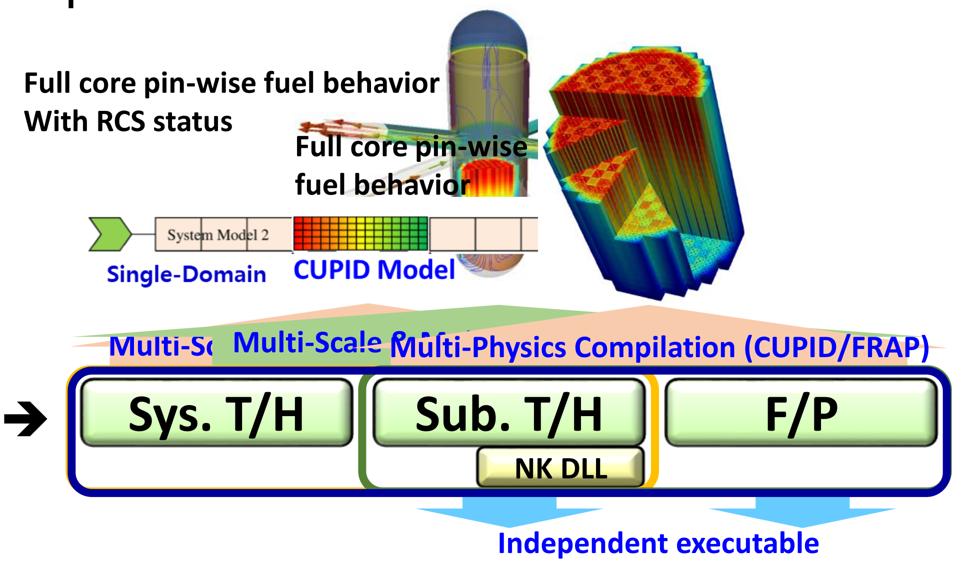
MARU Platform (2/2)

Platforms Structure

➢ Multiple source-to-source compilation among codes as user needs

- Equivalent source level between T/H and F/P

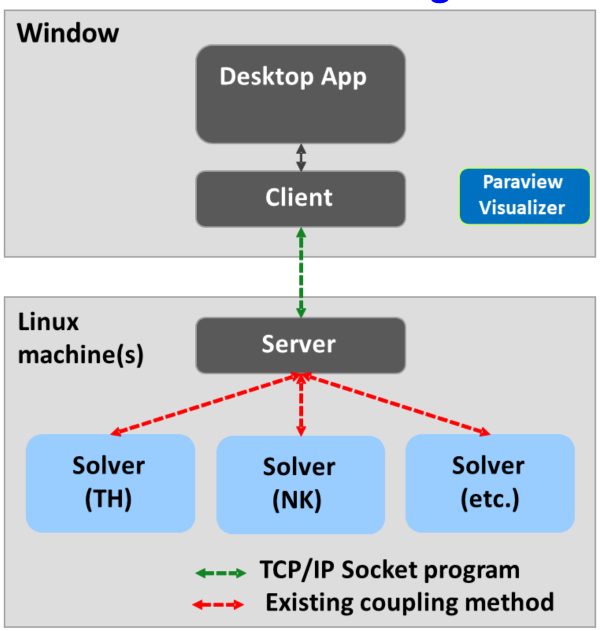
Source level →



➢ TCP/IP socket communication

- Server (Linux) ←→ Client (Windows)
- No need to access 'Linux machine'

MARU configuration



Multi-Scale and Multi-Physics (MSMP) Simulations

2

- MSMP Approach
- MSMP Simulation of OPR1000 SLB Accident
- Improvement of Safety Margin (DNBR)

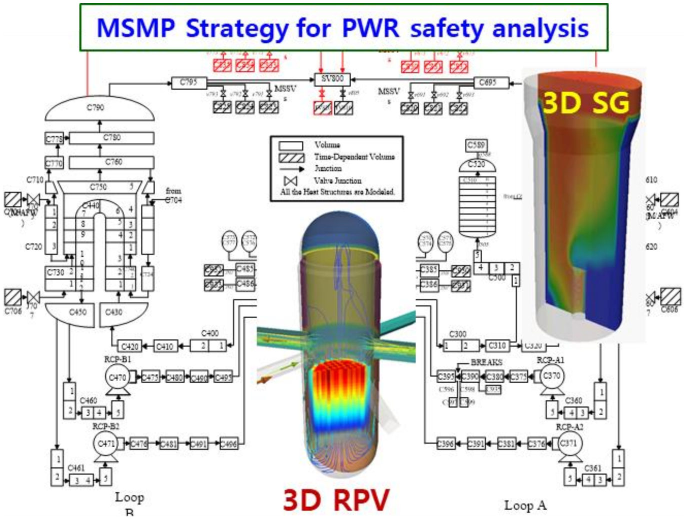
Multi-Scale & Multi-Physics (MSMP) approach

Multi-Scale T/H

- ***3D (subchannel T/H)*** **resolution for region of interest**
  - **Reactor pressure vessel**, steam generator
  - Desirable spatial resolution for 3D resolution
    - ✓ Ex. **Subchannel scale** for core
  - Realistic multi-dimensional flow behavior
    - ✓ Radial flow behavior in core, two-phase flow in secondary side of SG
- ***1D (Sys. T/H)*** **resolution for the rest of RCS**

Multi-Physics (N/K, F/P)

- ***Pin-wise fuel behavior***
  - 3D power distribution
    - ✓ Neutron kinetics (N/K) code
  - Realistic fuel rod status
    - ✓ Fuel performance (F/P) code



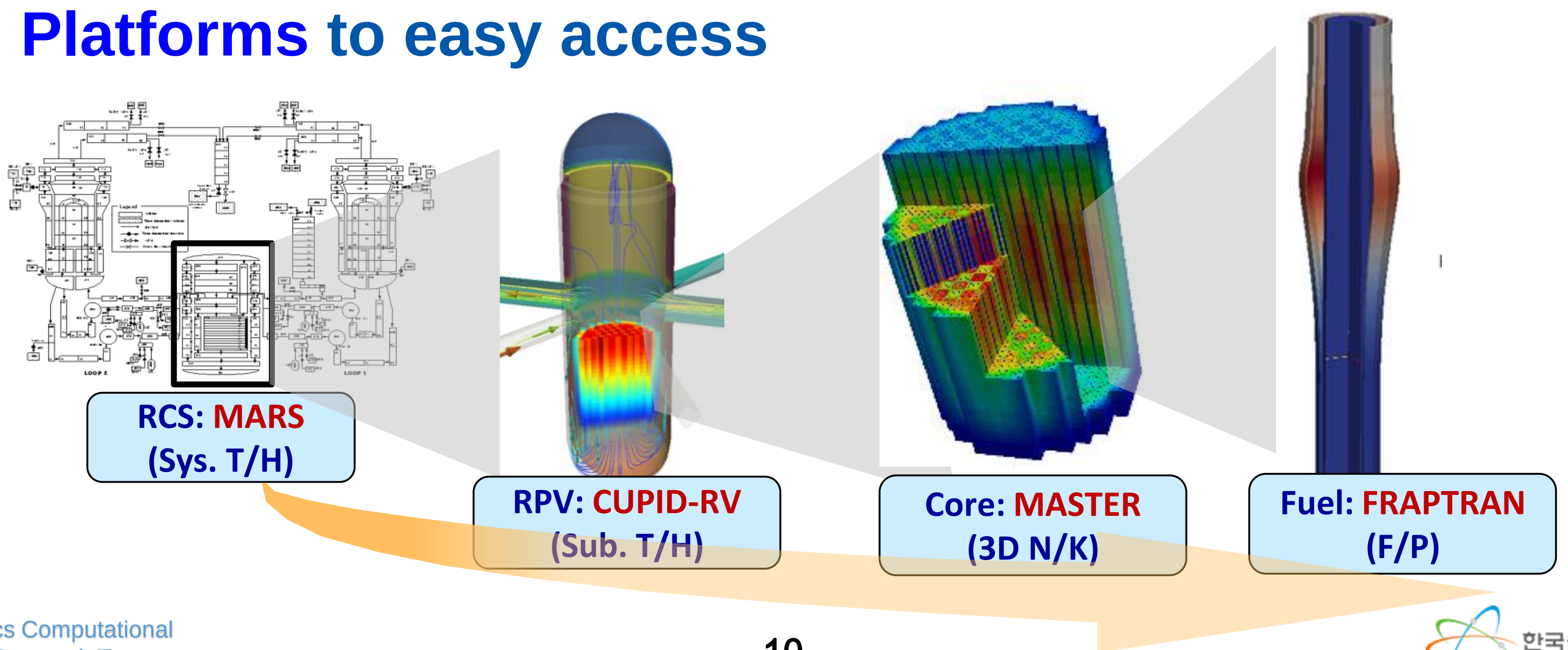
Multi-Scale & Multi-Physics (MSMP) Strategy

MSMP Integrated Simulation Scope

➢ Entire RCS is considered

Region	features	Code	Coupling
RCS	System-scale T/H	MARS, SPACE	Source-to-source
RPV	Subchannel-scale T/H	CUPID-RV	
Reactor core	Fuel performance	FRAPTRAN	
	3D neutron diffusion	MASTER	Dynamic Link Library (DLL)

➢ Platforms to easy access

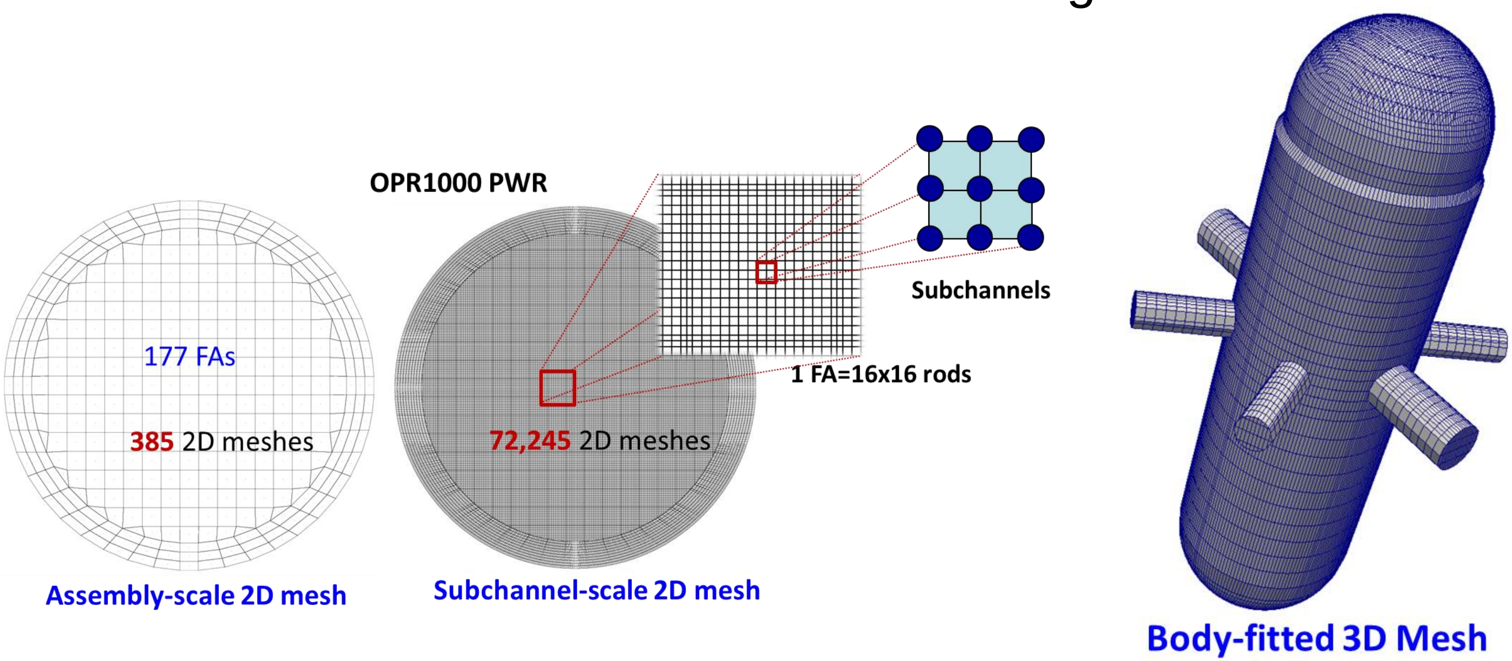


3D Reactor Pressure Vessel Modeling

Subchannel-scale RPV Computational Geometry

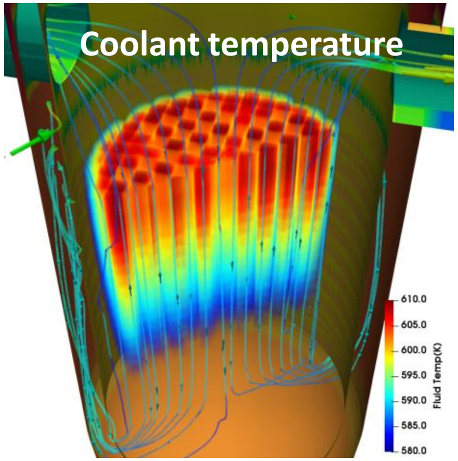
➢ Body-fitted RPV mesh

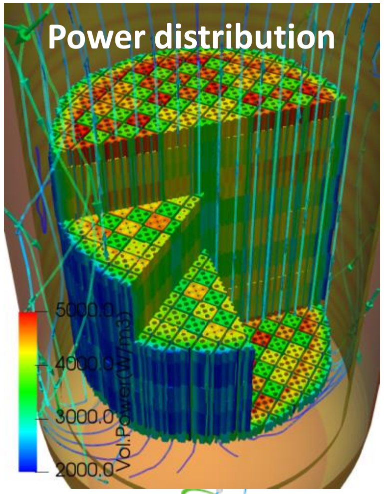
- **In-house** RPV mesh generator (***RVMesh3D***)
- Reactor core, downcomer, upper/lower plenum, and hot/cold leg
- Practical number of meshes (Currently **1.3M**)
- **Subchannel T/H resolution** for core region



MSMP Simulation of OPR1000 SLB Accident

Steady State (End of Cycle Full Power)





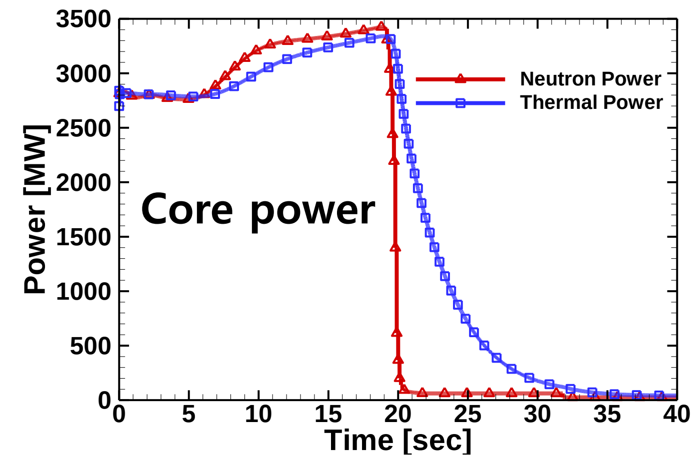
MSMP Simulation of OPR1000 SLB Accident

Sequence of Events and Major Parameters

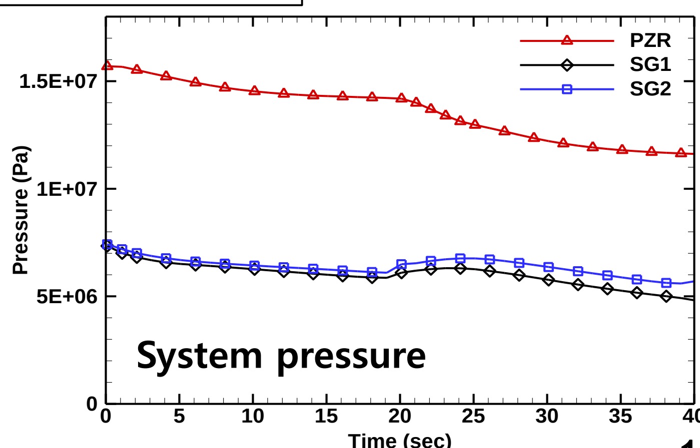
Sequence of events

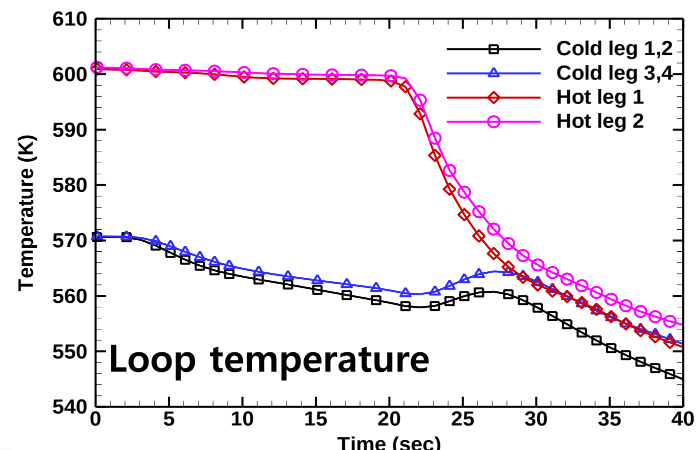
Time(sec)	Event	Setpoint
0.0	Steam line break occurs	
18.4	**Overpower trip setpoint reached**	**121 %**
18.6	Turbine Trip	
19.1	Rod begins to drop	
34.0	Low SG1 setpoint reached	5.44 MPa
35.1	MSIV1 closed	

MSMP result



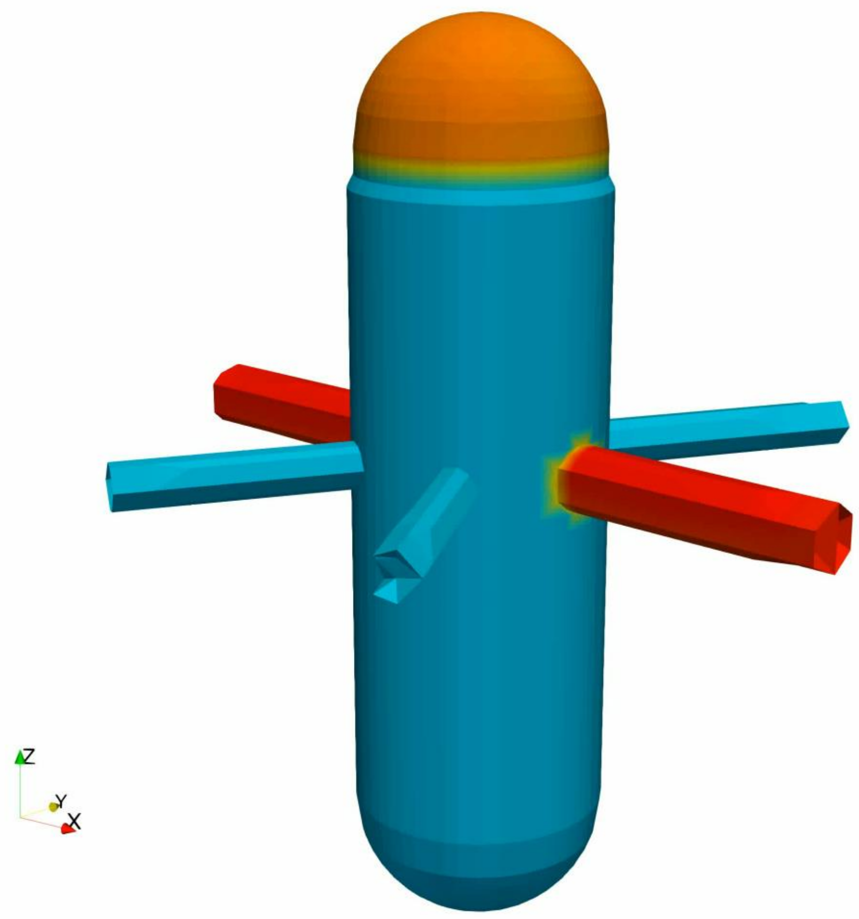
System TH result





MSMP Simulation of OPR1000 SLB Accident

» Power & DNBR Distribution



Sequence of events

Time(sec)	Event
0.0	Steam line break occurs
18.4	**Overpower trip setpoint reached**
18.6	Turbine Trip
19.1	Rod begins to drop
31.0	Void begins to form in RV Upper P.
34.0	Low SG1 setpoint reached
35.1	MSIV1 closed

Performance	
Problem time	**100 sec**
Resources	Intel® Xeon® Gold 6230R CPU @ 2.10GHz
Number of Procs	300
Computing time	**120 min**

Improvement of Safety Margin (DNBR)

Safety Margin in SLB Accident

Minimum DNBR in fuel assembly

※ DNBR: Departure from Nucleate Boiling Ratio

- Key parameter to ensure safety margin for SLB accident

Enhancement of safety margin for MSMP approach

- 30% larger than 1D result

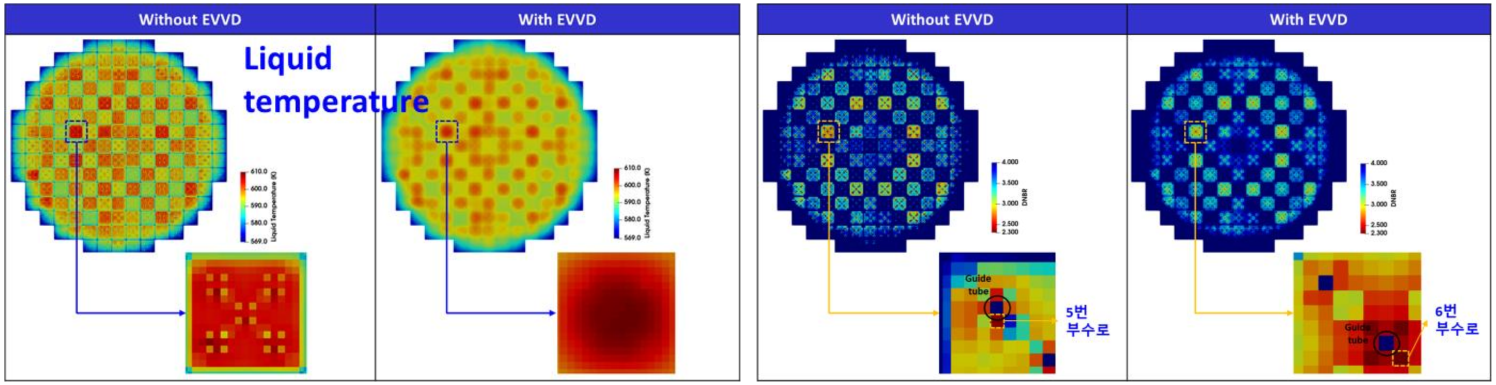
Methodology	MDNBR
1D System-scale TH	2.020
MSMP (without Turbulent mixing)	2.331
MSMP (with Turbulent mixing)	2.615

Enhancement of Safety Margin

Key parameters to enhance MDNBR in MSMP

Key parameter 1: 3D Coolant Flow

- **3D radial flow dispersion with turbulent mixing**
  - Impossible to consider radial flow mixing in 1D safety analysis
  - **3D Radial flow including turbulent mixing enhances coolability**
  - **Ensure additional safety margin**

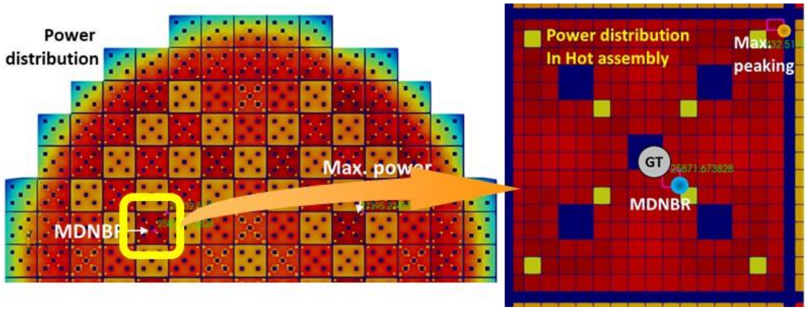


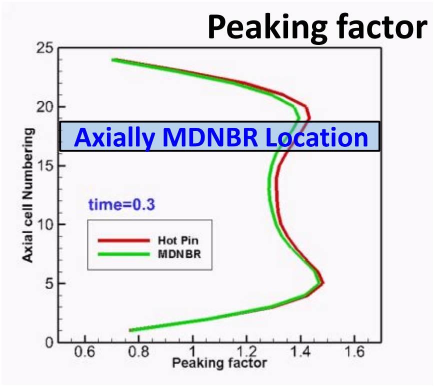
Key parameters to enhance MDNBR in MSMP

Key parameter 2: Realistic fuel power (with N/K code)

Power output of fuel assembly (pin-wise power)

- Co-simulation with N/K produces detailed rod-scale power
- MDNBR does not meet the Hot Pin assumption
  - ✓ 1D Safety analysis: Hot pin assumption to occur MDNBR
- Mitigate 1D conservative assumption
- **Ensure additional safety margin**





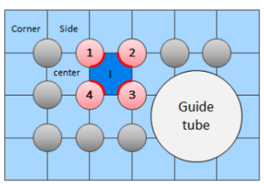
Key parameters to enhance MDNBR in MSMP

Key parameter 3: Non-identical geometric parameters

Various subchannel information

- Subchannel-scale resolution yields various geometric parameters
- CHF can be evaluated according to subchannel type
- **Ensure additional safety margin**

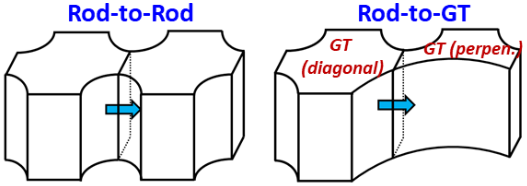
Various heated diameters



Subchannel type	Heated dia. [m]
Rod-to-Rod	0.012637
1D System TH	0.013012
Rod-to-GT (perpendicular)	0.013855
Rod-to-GT (diagonal)	0.016922

Rod-to-Rod

Rod-to-GT



MDNBR distribution for subchannel type

Subchannel type	Heated dia. [m]	K1	q''_{CHF}	MDNBR
Rod-to-Rod	0.012637			
1D System TH	0.013012			
Rod-to-GT (perpendicular)	0.013855			
Rod-to-GT (diagonal)	0.016922			

Full core Pin-wise Fuel Performance

3

— Pin-wise F/P code Coupling

— Evaluation of Pin-wise Fuel Performance in SLB Accident

Pin-wise Fuel Performance code Coupling (1/4)

Fuel Performance Code

US NRC FRAPTRAN code

- Single fuel rod behavior
- Coupled with system T/H code

How to Couple for Source Level Multiple Fuels

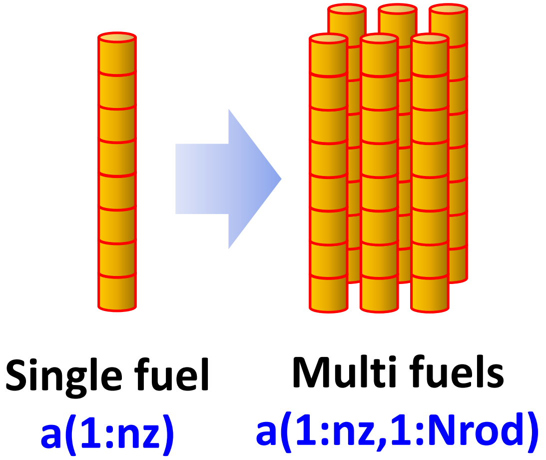
Mapping between fuel's cell and fluid cell

- **CUPID** (sub. T/H): Fuel nodes of Internal heat structure model
- **FRAPTRAN** (F/P): Single-rod Fuel nodes

Extend fuel code for multiple fuels

- Extend coupling variables for multi-rods
  - ✓ Including modification of F/P code (variables' array)
- Call fuel code as many as the number of fuels

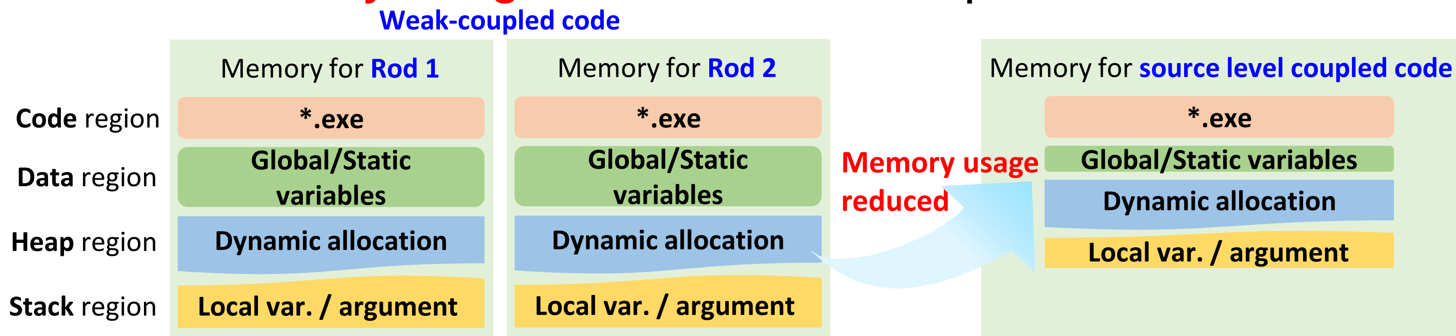
```
DO i=1,Nrods
  Call FRAPTRAN(i)
ENDDO
```



Pin-wise Fuel Performance code Coupling (2/4)

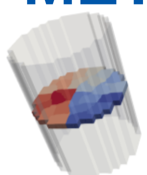
Parallel Computing in HPC Environment

- **SPMD (Single Program, Multiple Data)**
  - Source-to-source compilation
  - Efficient memory usage for massive multiple fuels calculation.



Parallel for Pin-wise Full Core Simulation

- **Prerequisite for simple mapping**
  - Single fuel is not partitioned
- **Domain partitioning by METIS**
  - Partitioned 2D plane
  - Extrude along fuel height



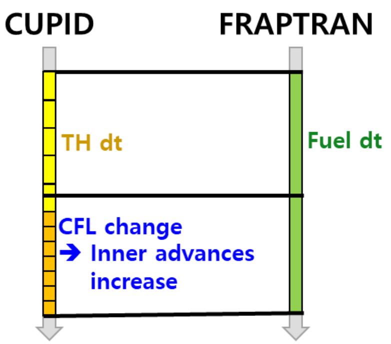
Performance	
Problem time	**100 sec**
Resources	Intel® Xeon® 6230R CPU @ 2.10GHz
# Procs.	300
Computing time	**160 min (w/I FRAPTRAN)**
	120 min (w/o FRAPTRAN)

Pin-wise Fuel Performance code Coupling (3/4)

Time Advance

Time-step control between TH and Fuel code

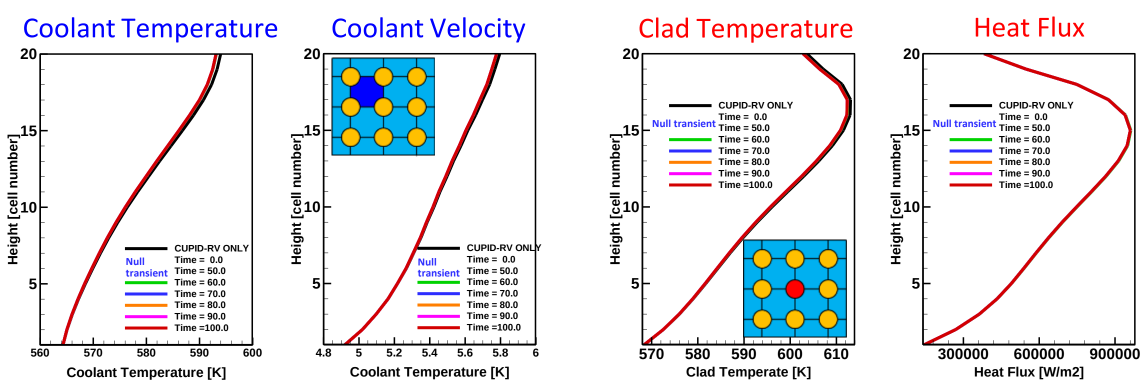
- Time-marching scheme is implemented
  - ✓ Time marching between CUPID and FRAPTRAN
  - ✓ The number of inner advances determined

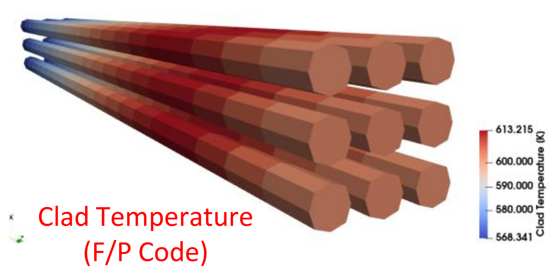


Verification(1) – 3x3 Fuel Rods

CUPID-RV/FRAPTRAN

- Fuel behavior from FRAPTRAN



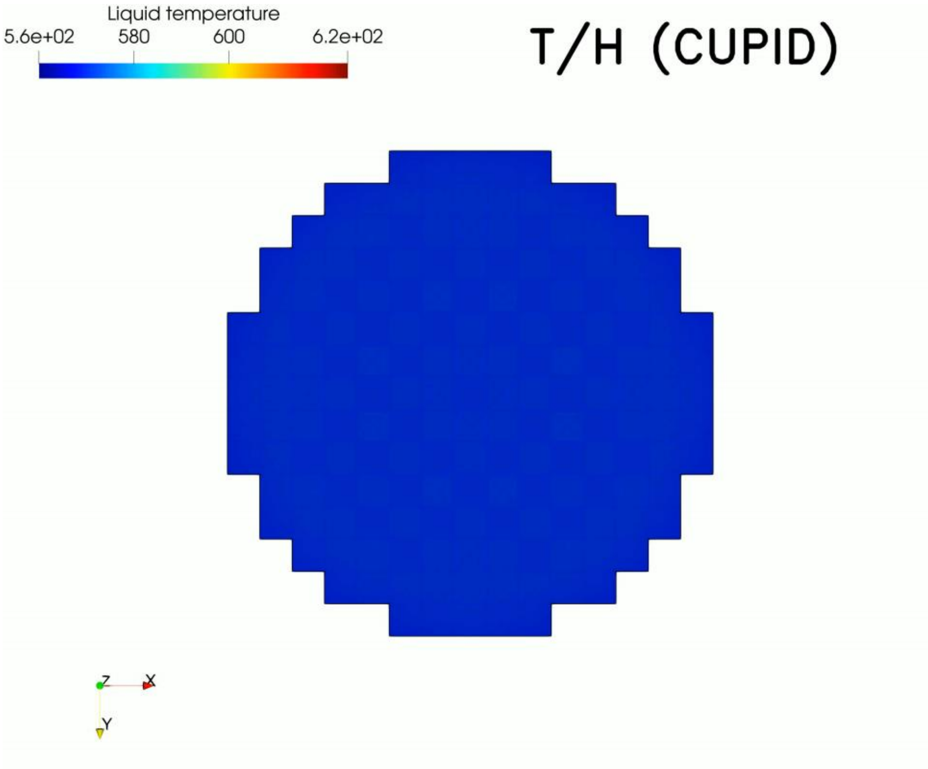


Clad Temperature (F/P Code)

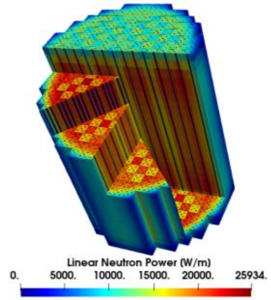
Pin-wise Fuel Performance code Coupling (4/4)

Verification(2) – LWR Full Core

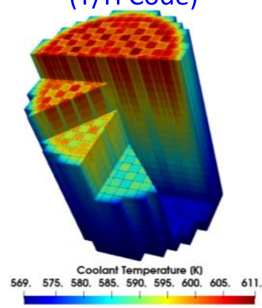
- **Steady state of OPR1000 core region**
- **CUPID-RV/MASTER/FRAPTRAN**
  - **Sub. T/H** & **N/K** & **F/P** coupled simulation



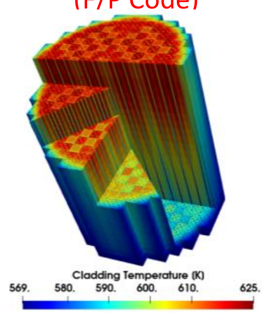
Neutron Power
(N/K Code)



Coolant Temperature
(T/H Code)



Clad Temperature
(F/P Code)



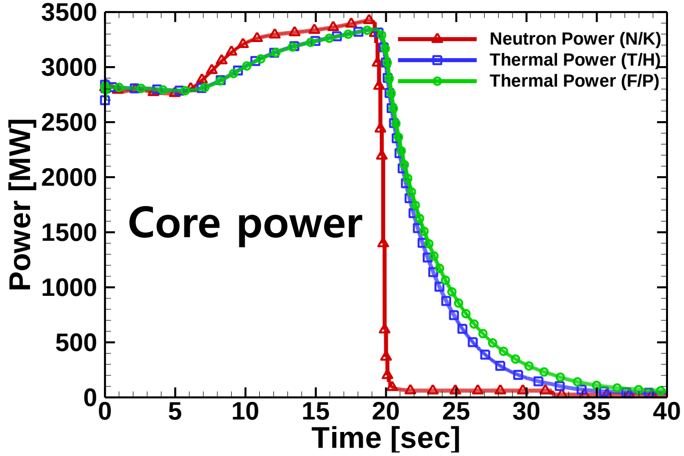
Evaluation of Pin-wise F/P in SLB Accident

Evaluation by Fuel code

Steam line break accident (SLB)

- Fuel behavior calculated by FRAPTRAN
- Radial conduction is dominant
- Similar pattern with simple heat structure model of T/H code
- MDNBR expected lower slightly

Methodology	MDNBR
1D System-scale TH	2.020
MSMP (w/o F/P)	2.615
MSMP (w/i F/P)	**2.563**



Capability for pin-wise fuel behavior

- Other accidents such as RIA can be accessed (On-going)
  - ✓ F/P code becomes considerably important in safety analysis for RIA accident

Summary

4

Summary

Necessity for 3D MSMP Simulation

- **Detailed information inside of RPV**
  - **3D** Visualization of **full core fuel power** distribution
- **Enhancement of safety margin**
  - Realistic **MDNBR evaluation**
  - **Improvement of MDNBR** designed by 1D safety analysis

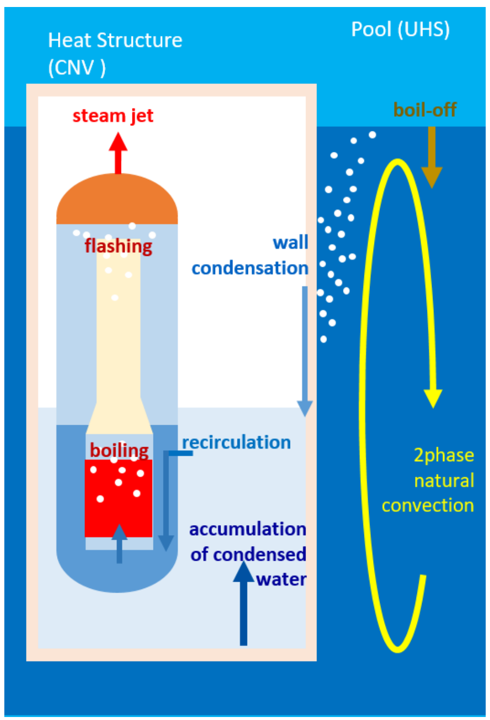
MARU Platform

- **MSMP (Multi-scale & Multi-Physics) simulation**
- **User interface & Numerical models are under development**

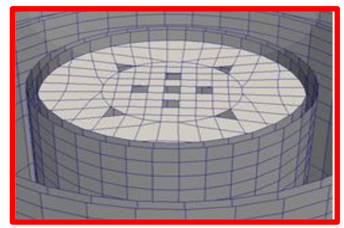
Future Works

MARU for iSMR

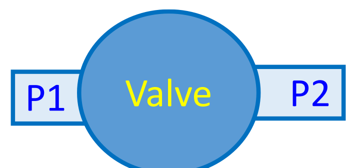
- **Physical models & components**
- **N/K(RAST-K, MASTER)-CUPID coupled simulation**
- **LOCA simulation of NuScale**



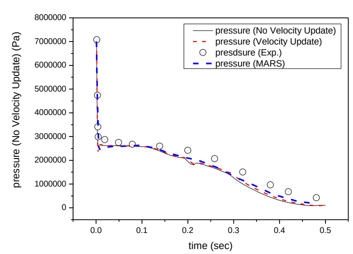
RCP model



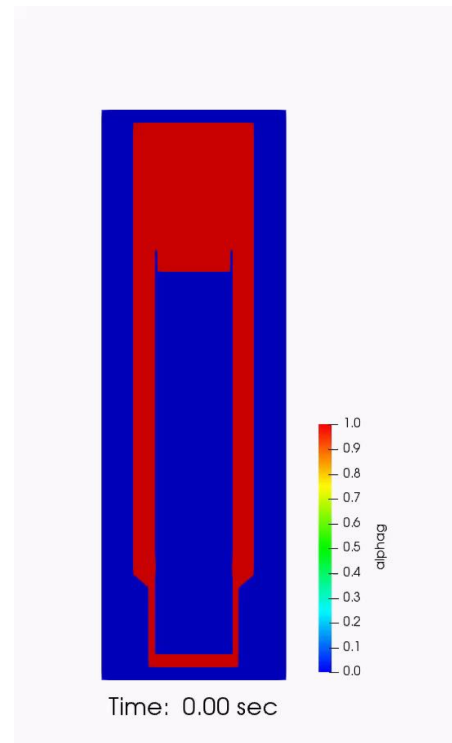
PZR model



Valve model



Critical flow model



THANK YOU

yjcho@kaeri.re.kr