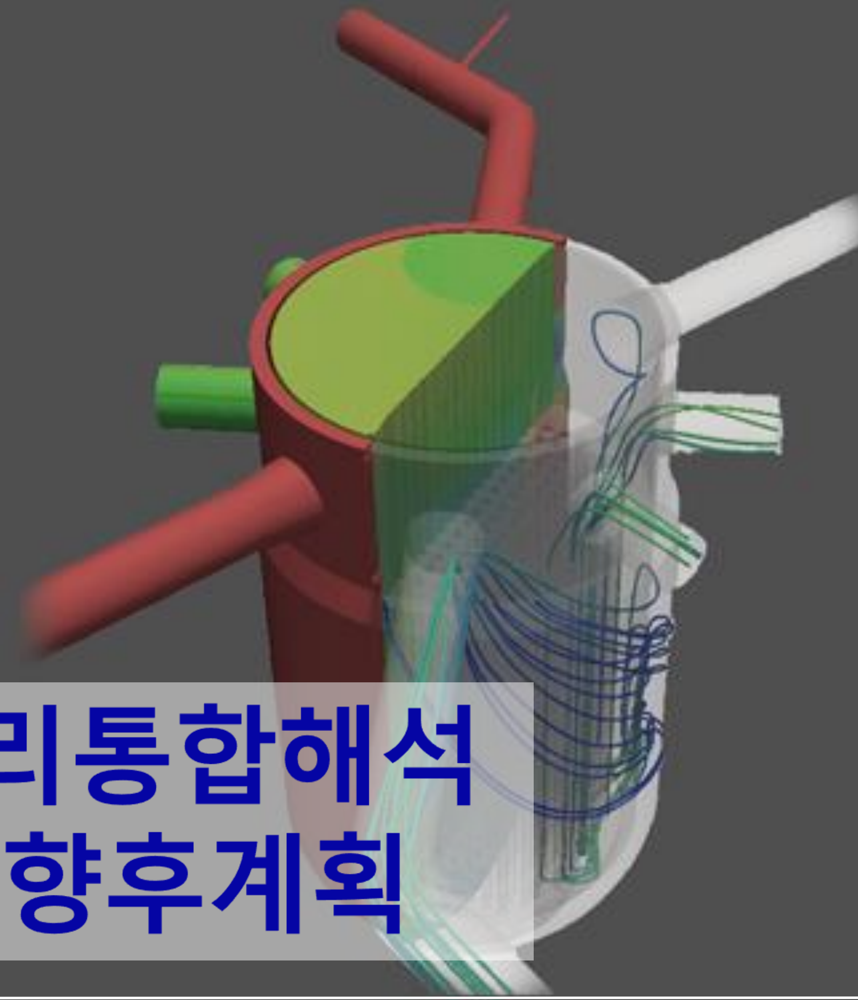
한국원자력학회 춘계학술대회, 워크숍 D, 2022.05.18, 제주국제컨벤션센터, 3층 한라홀 B



KNS Workshop

가동원전/SMR 다물리통합해석 플랫폼 개발 현황 및 향후계획

조윤제*, 이승준, 박익규, 이재룡, 도성주, 박소현, 윤한영

2022년 5월 18일

다물리계산과학연구실
한국원자력 연구원

KNS Workshop

CONTENTS

Main Features and Applications of CUPID

1

- Fast and Robust 3D 2-Phase Flow Solver
- Scalable Iterative Solver for a Large-scale Computing
- Multi-scale Simulation
- Multi-physics Simulation
- Etc. (RV, CT, SG, PAFS…)

Fast and Robust 3D 2-Phase Flow Solver

- Commercial CFD mainly focuses on 3D fluid dynamics and ***has limited applications for 2-phase flows especially when a large phase change is involved***

Commercial CFD

- Numerical Models of ***3D Fluid Dynamics***
- High Performance Computing (***HPC***) Technology

CUPID

- Unique ***Numerical Model for a large phase change***
- CFD- or Component-scale ***Analysis of RV, SG, and CT***

Models and Correlations for Nuclear Reactors

- ***2-Phase Interface*** Momentum and Energy Transfer Models
- ***Multi-Scale/ Physics*** models

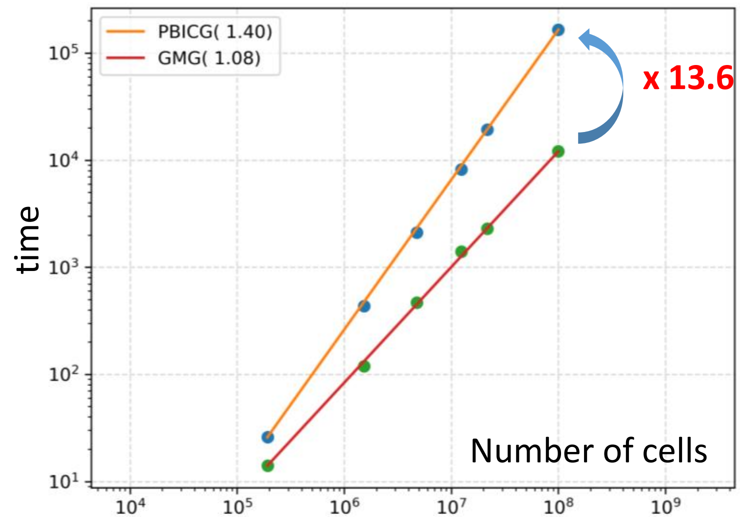
__RV__: Reactor Vessel, __SG__: Steam Generator, __CT__: Containment

Scalable Iterative Solver for a Large-scale Computing

- The most time-consuming part in CUPID is the ***"Pressure equation"*** solving module
  - The pressure equation takes more then ***90%*** of total computing time depending on the number of cells
  - The Conjugate Gradient ***(CG) solver is not scalable*** and we need to develop a ***new iterative solver*** which is ***scalable*** w.r.t the number of cells

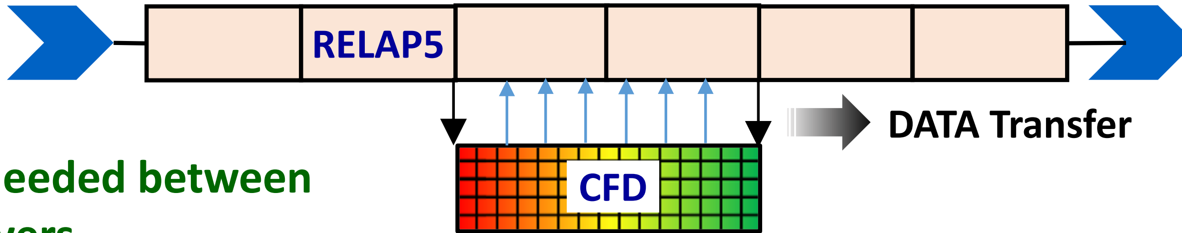
Number of Cells	time_pressure / time_total (%)
191,800	**78.8**
1,533,600	**75.7**
4,773,600	**81.6**
12,357,600	**86.2**
21,683,700	**90.2**
107,968,000	**92.9**

- Development of a ***Geometric Multi-Grid (GMG)*** solver for ***unstructured mesh***
  - CG solver: $\text{Time}_{\text{CG}} \propto N^{1.4}$
  - GMG solver: $\text{Time}_{\text{GMG}} \propto N^{1.0}$
  - The new GMG solver is ***Easy to use*** since the unstructured ***coarse meshes are generated automatically***



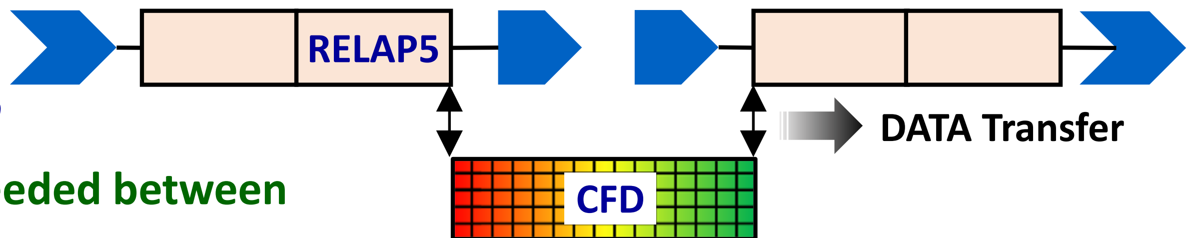
Multi-Scale Simulation for a Fast Transient

Domain Overlapping



Data Transfer is needed between Two separate solvers

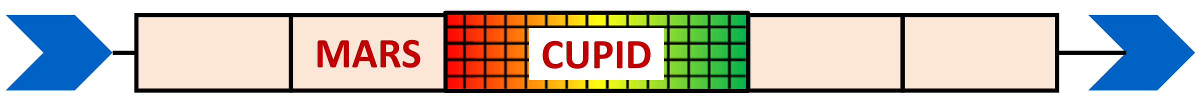
Domain Decomposition



Data Transfer is needed between Two separate solvers

Ex) RELAP5/ CFX, FLEUNT, STAR-CCM+

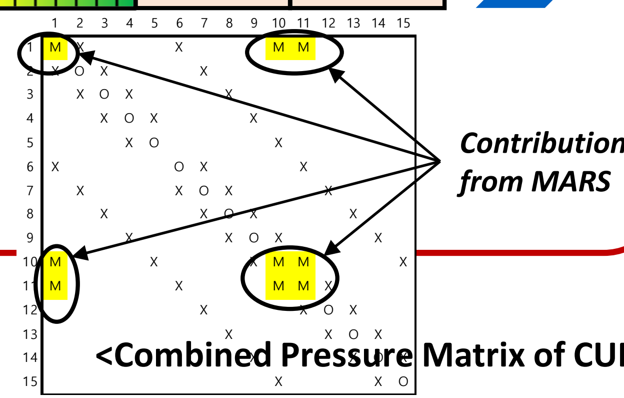
Single Domain



Single pressure solver matrix

: No need for the Data Transfer

⟶ *Versatile application to transient problems*



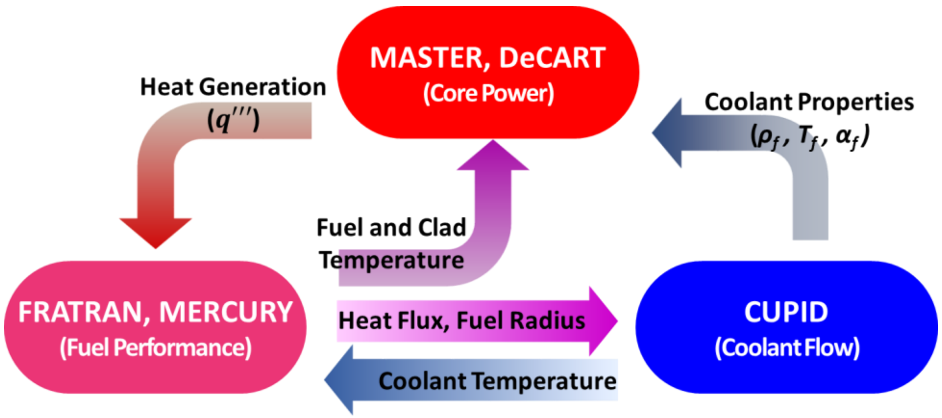
<Combined Pressure Matrix of CUPID>

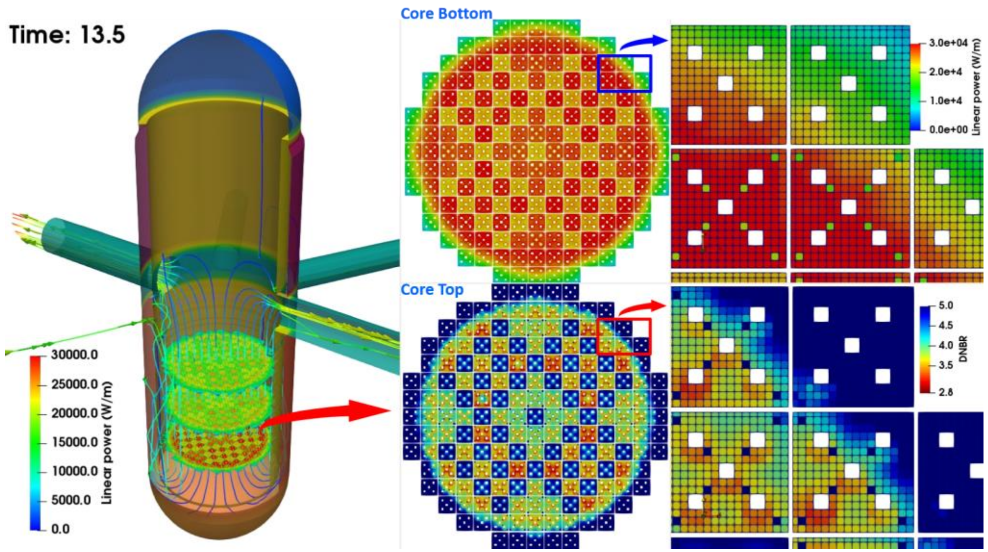
** I.K.Park et al., Annals of Nuclear Energy, 2013.*

Multi-Physics Simulation (TH/NK/FP)

Coupling of Multi-Physics Codes

- **Neutron Kinetics Codes:** ***MASTER, DeCART***
- **Thermal Hydraulics Code:** ***CUPID, MARS***
- **Fuel Performance Codes:** ***FRAPTRAN, MERCURY***



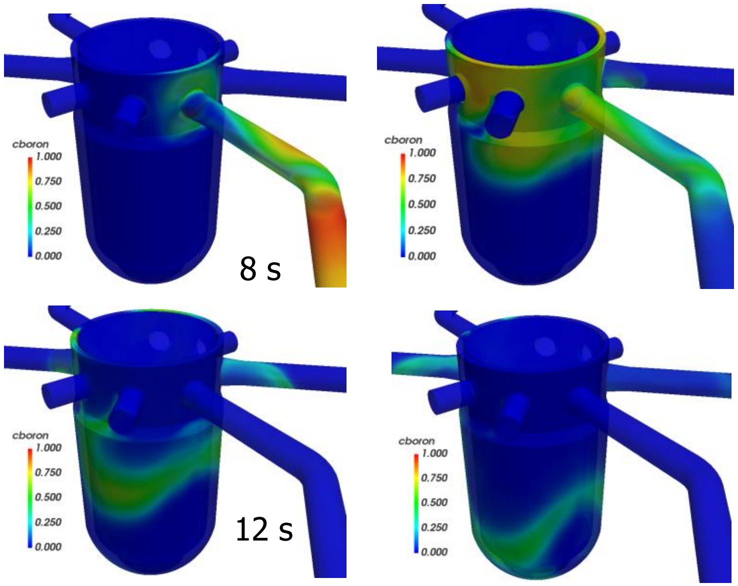


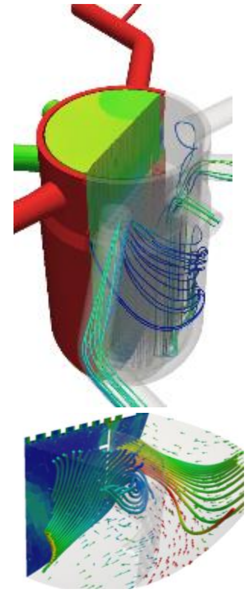
Full Core Pin-wise Simulation of the Steam Line Break Accident of OPR1000

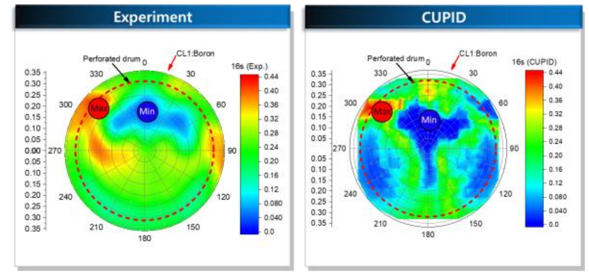
** H.Y.Yoon et al., Nuclear Science and Engineering, 2020.*

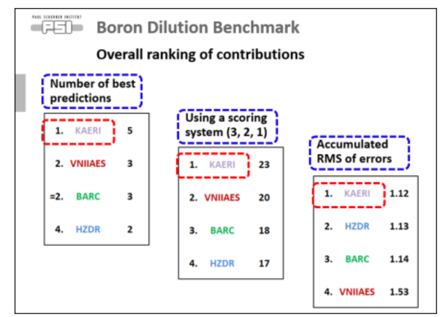
Reactor Vessel

» Simulation of the *ROCOM (HZDR) flow mixing experiment* (IAEA/CRP)



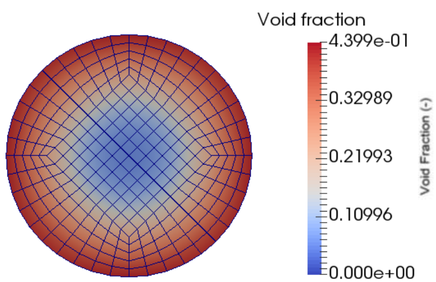


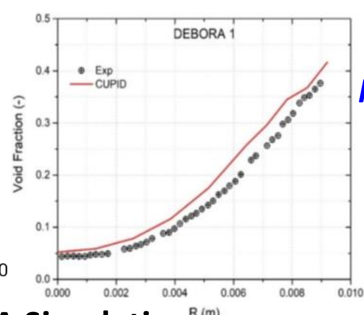




**** Y.J.Cho et al., Nuclear Engineering and Design, 2019.***

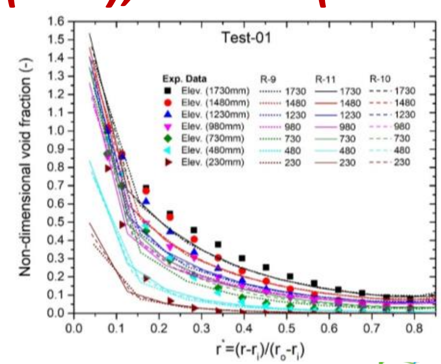
» Validation of wall boiling models against *DeBORA (CEA), F-SUBO(KAERI)*





<DeBORA Simulation>

**** Y. Alatrash et al., Nuclear Engineering and Technology, 2021.***



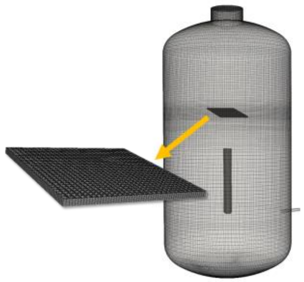
<F-SUBO Simulation>

Containment

OECD/NEA *HYMERES-2*

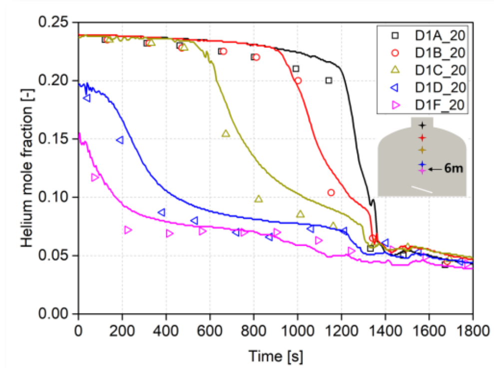
- Helium layer erosion test using ***PANDA*** facility of PSI
- Vertical steam jet with obstructions

<PANDA>

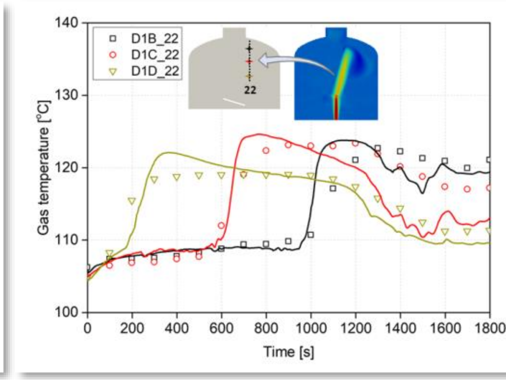


- ✓ ***Non-condensable gas***
- ✓ ***Radiation*** model

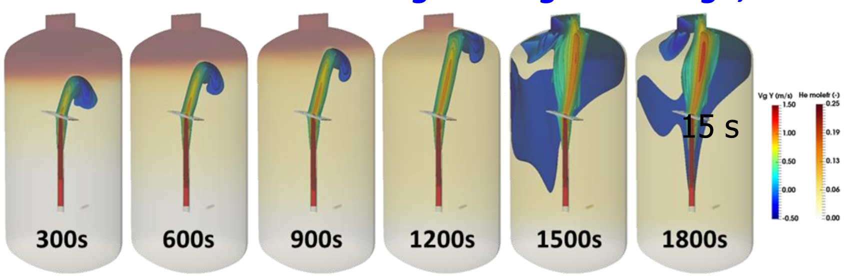
** J.H.Sohn et al., Nuclear Engineering and Design, 2021.*



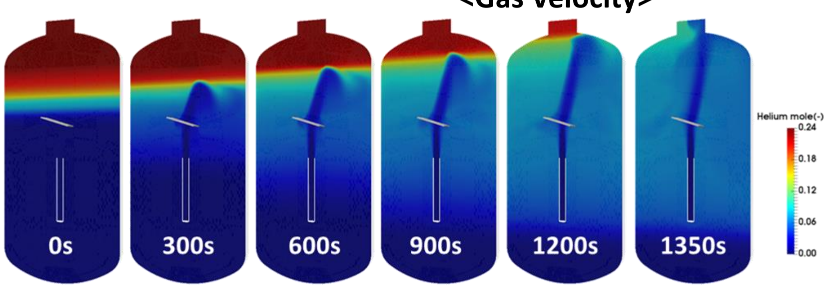
<Helium Moral Fraction Transient>



<Gas Temperature Transient>



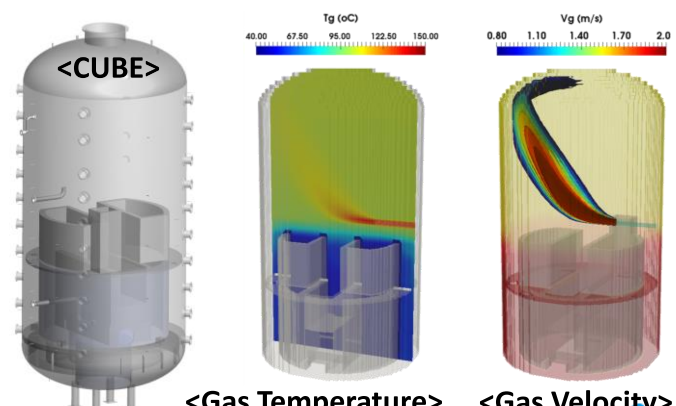
<Gas Velocity>



<Helium Moral Fraction>

ATLAS-CUBE (KAERI)

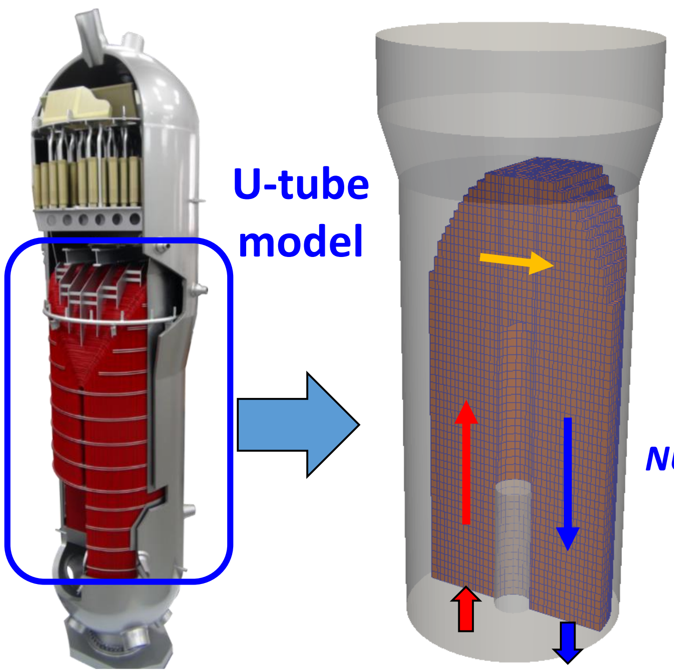
- Steam injection test using **CUBE** facility connected with **ALTAS**
- Thermal stratification / Effect of structures as a passive heat sink
  - ✓ ***Condensation*** models



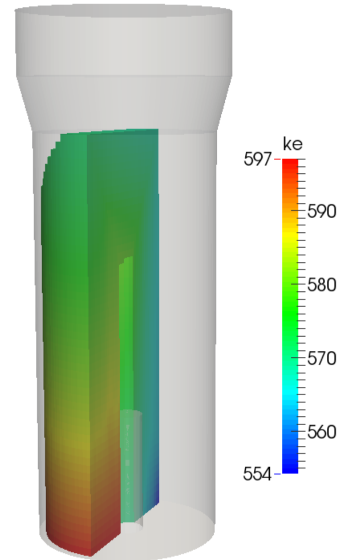
<Gas Temperature> <Gas Velocity>

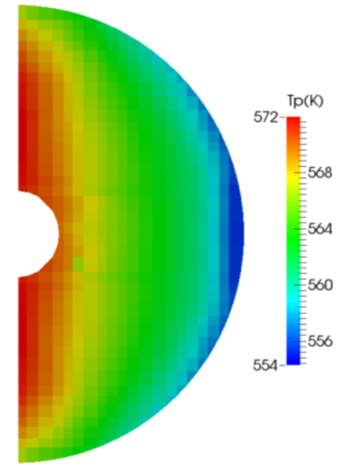
Steam Generator

- **PWR SG analysis code (*CUPID-SG*) has been developed based on the CUPID code**
- **All regions for *riser, downcomer, separator, and steam dome* are modeled**
- **A *U-tube model has been developed* where all U-tubes are grouped and connected with the secondary fluid cells**

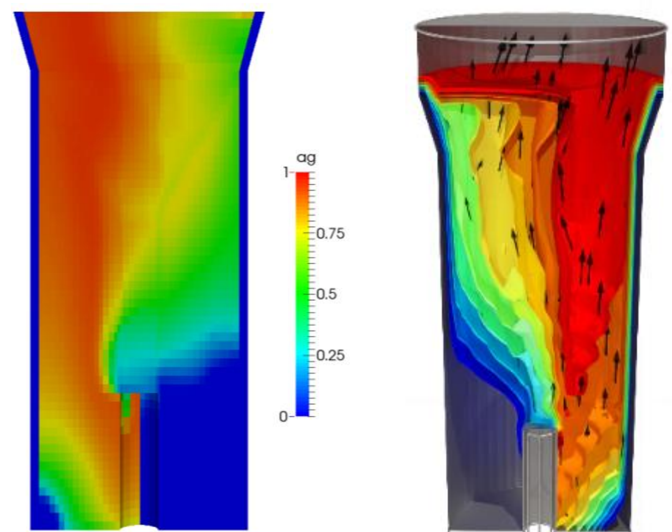


** H.Y.Yoon et al., NURETH-17, 2017.*





<Primary Coolant Temperature>

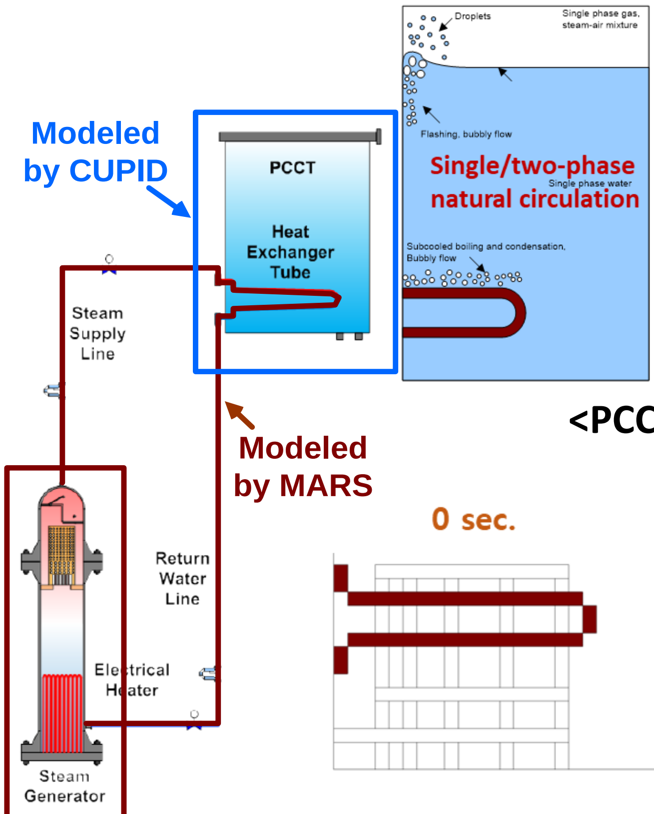


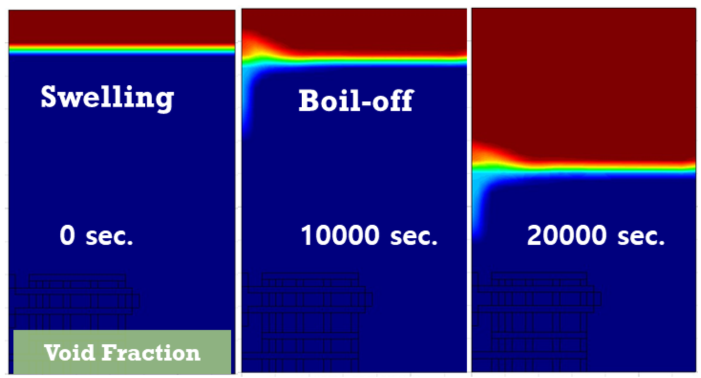
<Secondary Side Void Fraction and Velocity Vectors>

Special Component – PAFS (APR+)

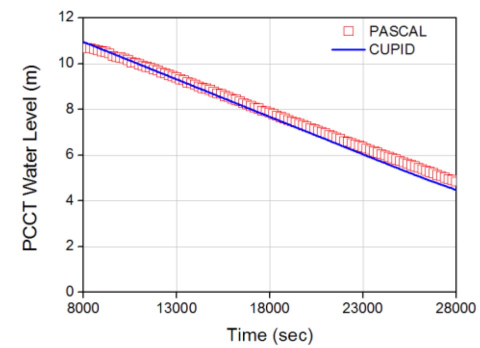
** H.K.Cho et al., Nuclear Engineering and Design, 2014.*

- ***PAFS*** **(Passive Auxiliary Feedwater System)**
  - Removes residual heat by a *natural circulation loop*
  - Validation Experiment: *PASCAL (KAERI)*
- **Simultaneous application of component and system scales (*CUPID/MARS*)**

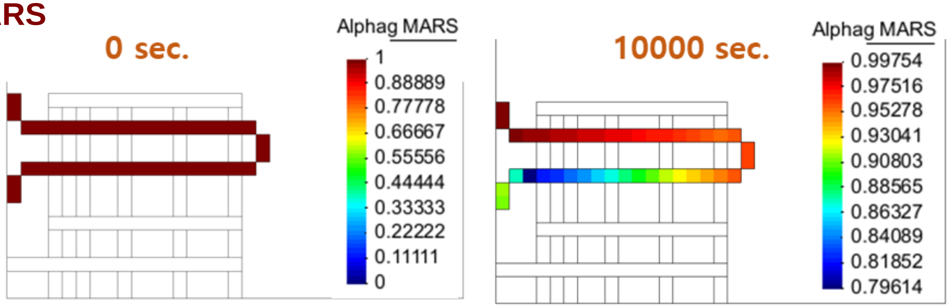




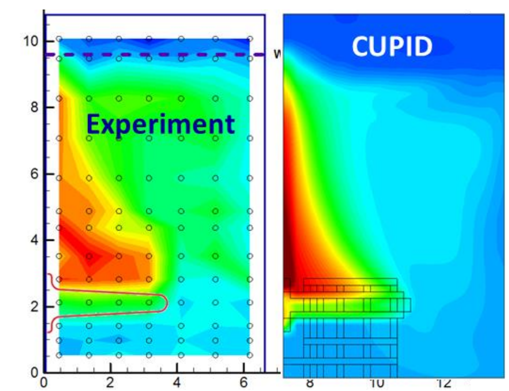
<PCCT Boil-off Transient by CUPID>



<Prediction of Water Level>



<HTX Tube Inside Condensation by MARS>



<Prediction of Water Temperature>

iSMR-
MSMP Platform
(MARU)

2

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

03
모든 것을 마루(MARU) 에 담다

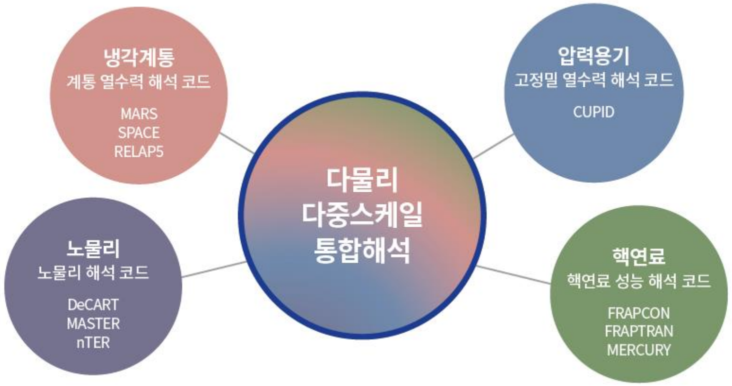
Multi-physics Analysis Platform for Nuclear Reactor SimUlation

MARU는 누구나 쉽게 사용할 수 있는 통합해석 플랫폼입니다.

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

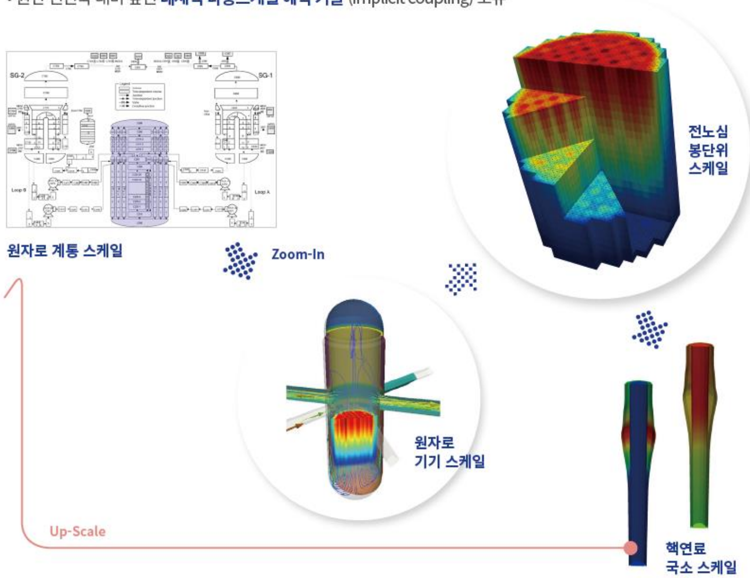
다물리 연계 해석 기술이 탑재 되었습니다.

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



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



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.

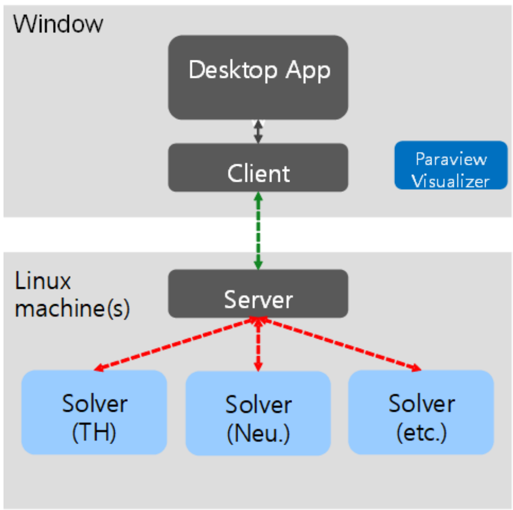
WORK FROM ANYWHERE
MARU

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

HPC 통합 환경
다물리연계 해석 / 다중스케일 해석

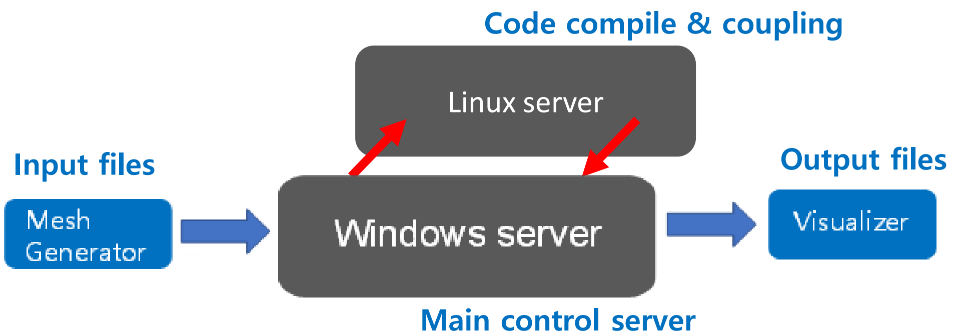
Development of MARU Platform

Design Features of MARU



[Windows(Client)/Linux(Server) application]

- Windows(client)/Linux(Server) application (TCP/IP socket communication)
- Pre-processing in Windows system
  - Input file and grid generation
  - Post-processing
- Coupling and calculation in Linux system



[Structure of data IO]

Technical Requirements for MARU

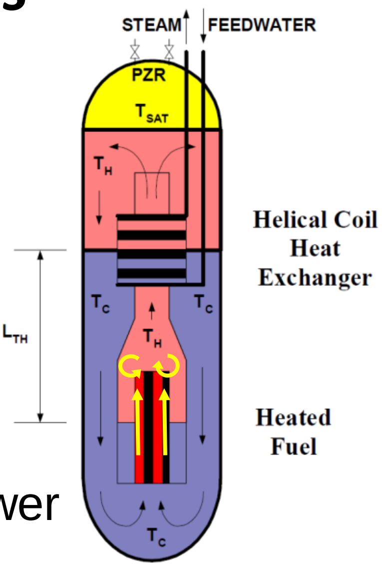
3

- 3D Flows in Single-Phase Natural Circulation
- 3D Flows in Two-Phase Natural Circulation
- Required Models for iSMR
- Model Development

3D Flows in Single-Phase Natural Circulation

Natural Circulation is the major characteristic of SMRs

- **Low driving force**
- **To increase flow rate at a fixed power**
  - Increase the loop height or decrease the loop resistance



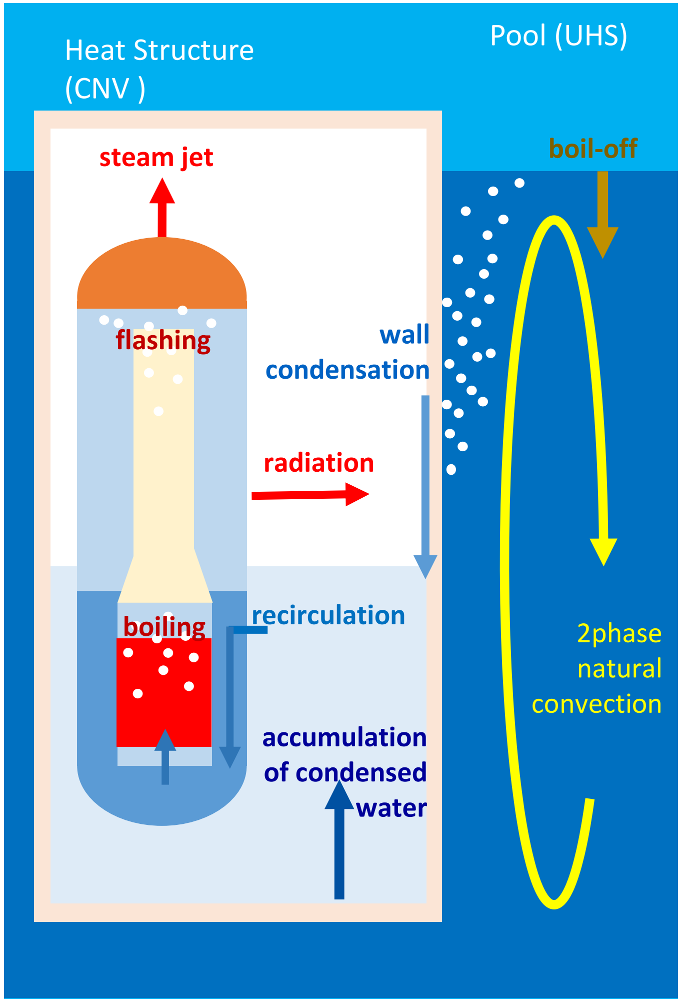
3D Flows in Natural Circulation

- **Flow instability in low flow rate**
  - Low flow rate leads to lower allowable maximum channel power
  - Inherently less stable due to nonlinear nature of NC flow
- **Power transient by load follow operation**
  - Local eddy flow at core outlet during power transition (or low power condition)
  - Long time to steady state condition
- **Mixed Convection: RCP + natural circulation**
  - Asymmetry flow in the core when local RCPs are off
  - Transition of forced-to-Natural circulation flow when all the RCPs are off

* IAEA, Natural circulation in water cooled nuclear reactor power plants, IAEA-TECDOC-1474, 2005.

3D Flows in Two-Phase Natural Circulation

***Two-Phase* Transient Phenomena under Accident Condition**



➢ Reactor Pressure Vessel (RPV) Side
- LOCA (RVV, RRV)
- Boiling and flashing

➢ Containment Vessel (CNV) Side
- Steam condensation on heat structure surface
- Radiation heat transfer

➢ Pool Side
- Two-phase natural convection
- Boil-off

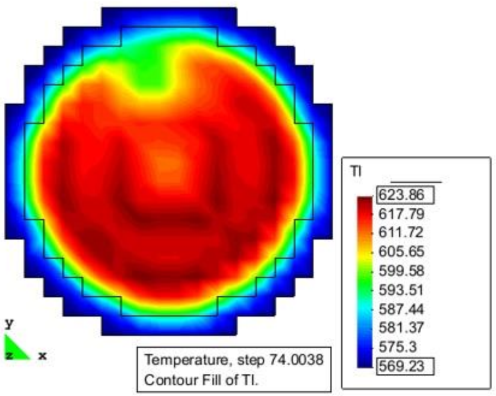
Two Natural Circulation Modes in One System
- **Mode1: Two-phase natural convection in a pool**
- **Mode2: Recirculation via RVV & RRV**

Multi-Physics Issues in SMR

Multi-Physics Coupled Analysis

- **Load follow operation**
  - TH analysis for elaborate control of power
- **Control rod ejection/drop accident**
  - Cross flow mixing phenomena
  - 3D power distribution and void generation
- **Various LOCA/non-LOCA Scenarios**
  - Validation of SMR safety control procedure
- **CUPID/MASTER/FRAPTRAN**
  - 3D TH/Neutronics/Fuel performance code coupling

Liquid temperature



Performance of the MARU Platform

- **Realization of almost real-time calculation**
  - **MPI domain decomposition** algorithm for massive computations
  - 1D/3D **multi-scale coupling** method

Required Models for iSMR

Component Models

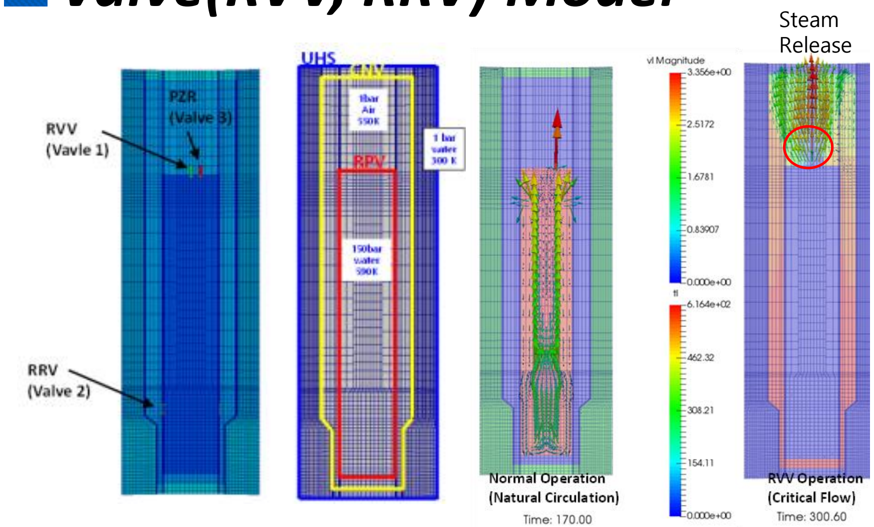
- **Valve(RVV, RRV): Blockage, on/off timing control algorithm**
- **MCP : Homologous curve MCP model, flow rate control by RPM**
- **Steam generator: pressure drop model (primary side), heat transfer coefficient model inside/outside helical tube**

Physical Models

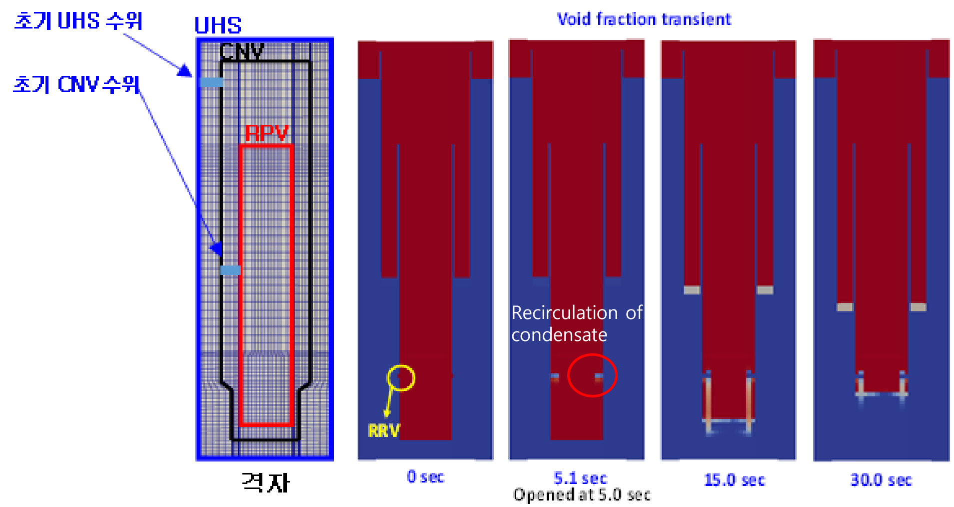
- **Porous model: flow resistance model outside Rx core**
- **Sub-channel model: pressure drop model, turbulence mixing model**
- **Condensation model in containment vessel**
- **Radiation model in containment vessel**
- **Critical flow: 2-phase critical flow model based on cell-centered mesh system**

Model Development (1/5)

Valve(RVV, RRV) Model

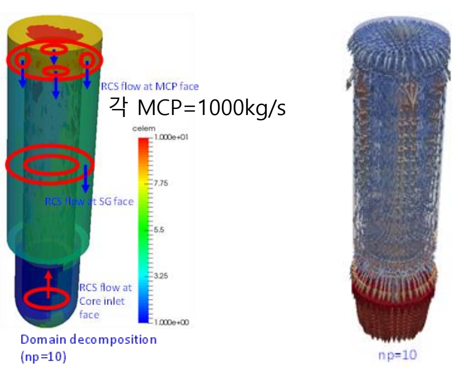


[Test calculation of NuScale RVV]

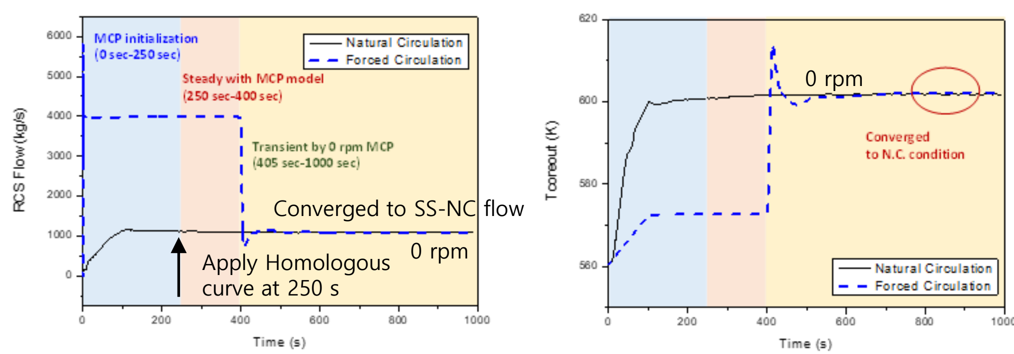


[Test calculation of NuScale RRV]

MCP Model



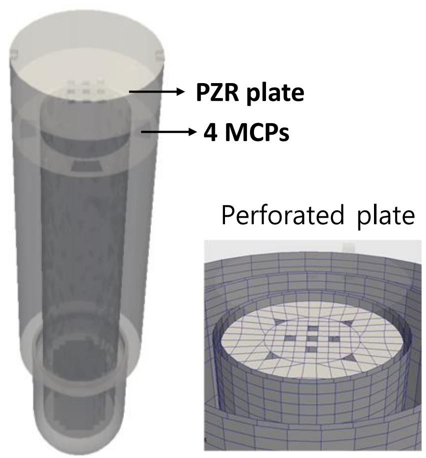
[Locations 4 MCPs] [Flow pattern by MCP]



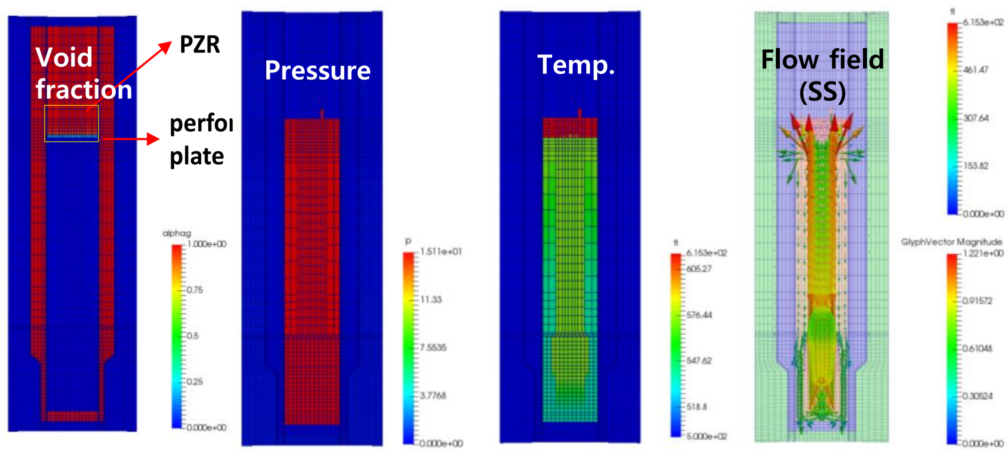
[Transition from forced- to natural- convection by MCP RPM control]

Model Development (2/5)

PZR Model



[PZR plate modeling]



[Steady state calculation with NuScale condition]

Porous Approach-based Inner Structure Model

- Porosity and permeability: flow volume area in governing eqs.
- Three pressure drop models: similar calculation results

$$F_{wk} = \frac{dp/dz}{V_{steady}^2} V$$

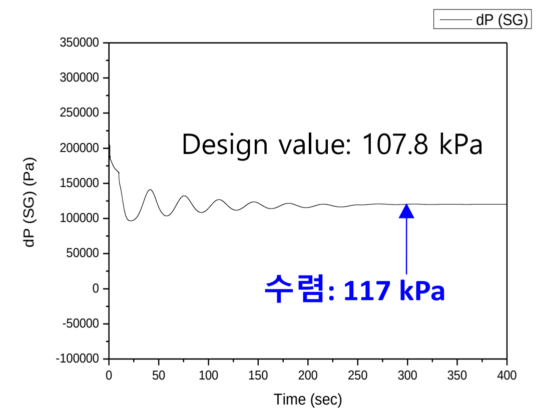
1.SS state-based K-factor

$$F_{wk} = \frac{(dp + dp_{control})/dz}{V_{steady}^2} V$$

2. P-based adaptive K-factor

$$F_{ix} = f_{cH} C_{AH} C_{VH} A_{SH} \rho u_{ix} |u_{ix}|$$

3. Friction-based physical model



[Calculation result with Friction-based model]

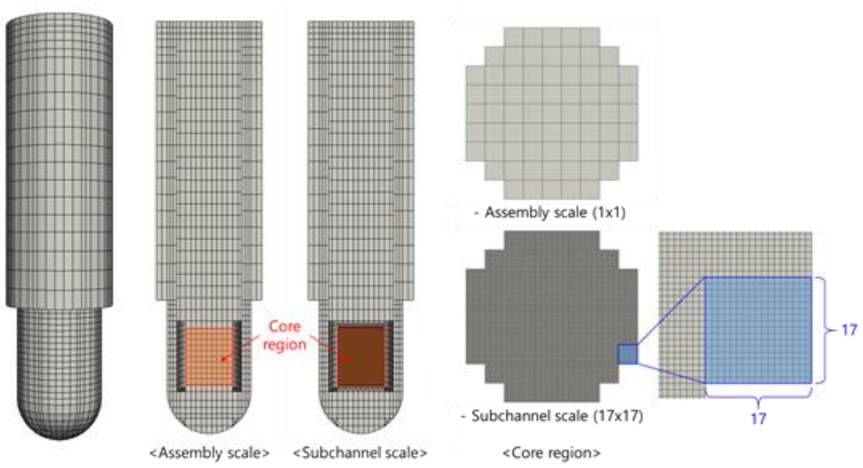
Model Development (3/5)

Reactor Core TH Model

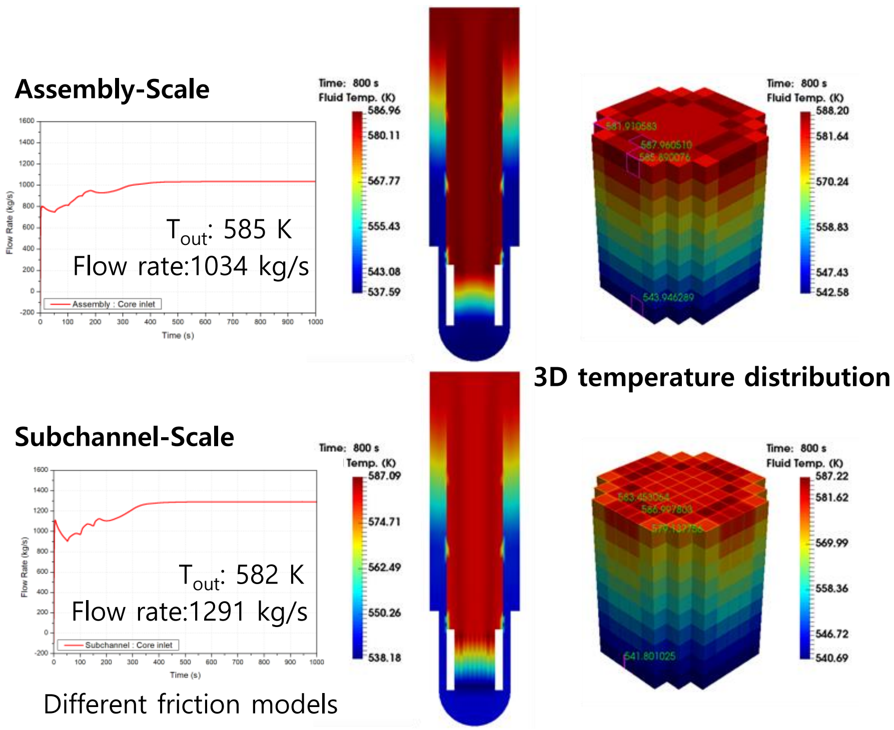
- Assembly-scale: reactor core model package (PWR based)
- Subchannel-scale: reactor core model package (PWR based) + subchannel model (friction & turbulence mixing models)

[Calculation conditions]

Initial condition	Pressure : 150 bar
	Fluid temperature : 560 K
	Fuel rods temperature : 594 K
Volumetric heat	Core : distributed into each channel, Total 259 MW
	SG : simple model, Total 259 MW
Simulation time	1,000s



[Assembly-, Subchannel-scale Full-core meshes]



[Assembly-, Subchannel-scale SS calculation results]

Model Development (4/5)

Condensation model

- ***Colburn-Hougen model, modified shah(KAIST data)***
- ***Effect of NC gas property***
  - *Diffusion coefficient: function of molar weight, atomic diffusion volume*

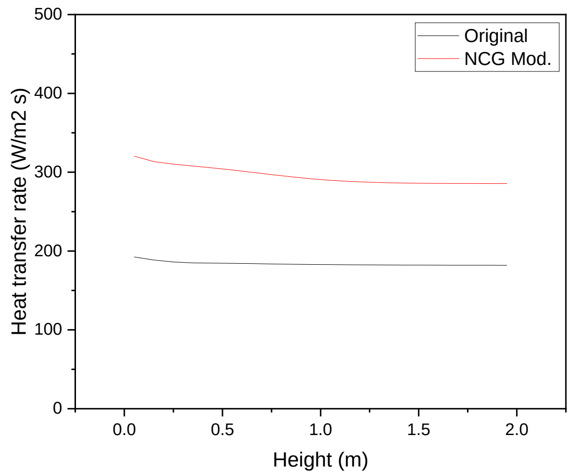
$$D_{AB} = \frac{0.00266 T^{3/2}}{P M_{AB}^{1/2} \sigma_{AB}^2 \Omega_D}$$

where D_{AB} = diffusion coefficient, cm^2/s
T = temperature, K
P = pressure, bar
σ_{AB} = characteristic length, Å
Ω_D = diffusion collision integral, dimensionless

coef_diff(1) 3.416486781592469D-005
Steam+air

coef_diff(1) 7.364200245279183D-005
Steam+air+H_2

Diffusion coefficient 가 응축열전달 계수에 미치는 영향

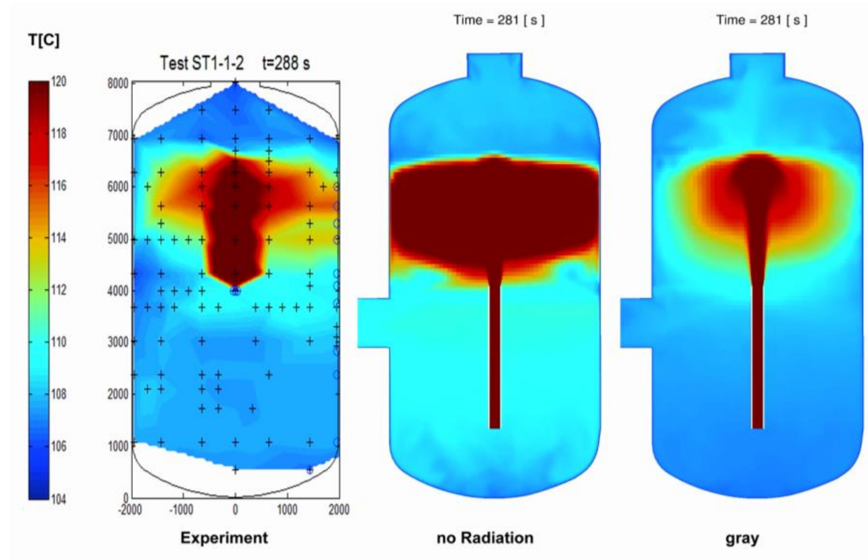


Model Development (5/5)

Radiation model

- Radiation heat transfer in containment vessel (CV)
- P1 model
  - Transport equation of incident radiation (G)

$$\nabla \cdot \left(\frac{1}{3(\kappa + \sigma_s) - A_1 \sigma_s} \nabla G \right) - \kappa G + 4\kappa\sigma T^4 = 0$$

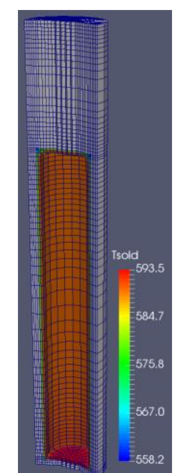


[Effect of radiation model-HYMERES2 project]

Radiation HT in CV

- Effect of gas species (absorptivity)
- Effect of emissivity

RV_ϵ, CNV_ϵ	Convection + Conduction(MW)	Radiation(MW)	Total (MW)	Ratio (Rad/Total)
0.5, 0.5	0.89	1.13	2.02	0.56
1.0, 1.0	0.88	2.29	3.17	**0.72**
0.82, **0.2**	1.11	0.65	1.76	**0.37**
0.82, 0.6	0.95	1.54	2.49	0.62
0.20, **0.2**	0.86	0.44	1.30	**0.34**



Application to SMR Conceptual Design

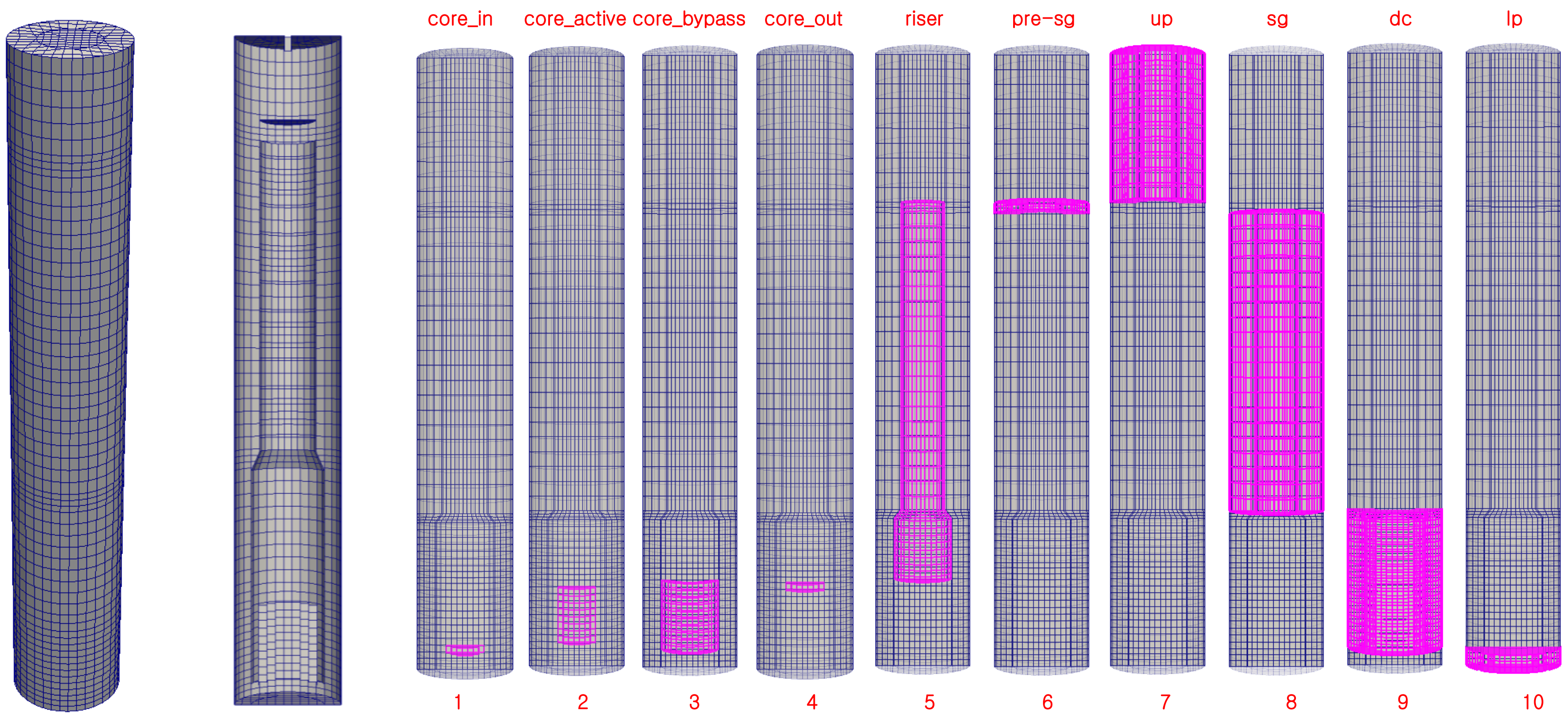
4

- Natural Circulation of NuScale and iSMR
- 3D Full Core Analysis Using Subchannel Model
- Conceptual SMR LOCA Anlysis

Mesh Generation for NuScale Reactor

Mesh for Natural Circulation Tests

- Unstructured mesh with orthogonality for numerical stability
- 9624 cells for component scale calculations



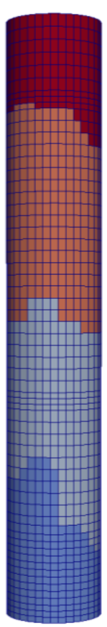
Total Mesh   Wall BC   Zone for components

Steady State Calculation of NuScale

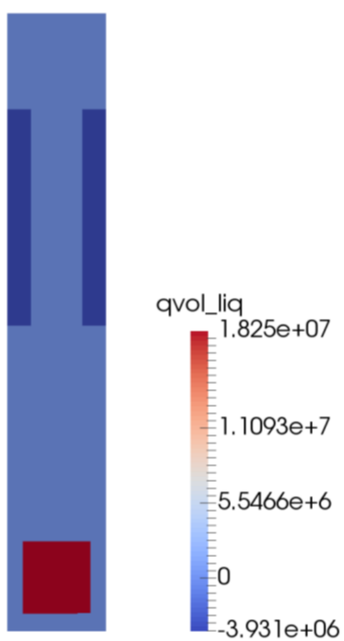
MPI Domain Decomposition: 6 cores

Analysis Conditions:

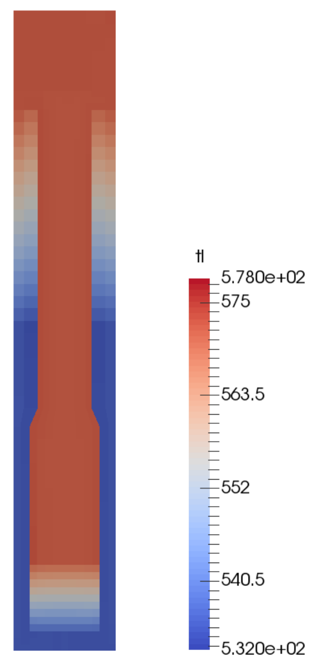
- Power=100 MWth
- Uniform heat source and sink (Core and SG)
- Problem time=100 sec (wall clock time=180.3 sec)



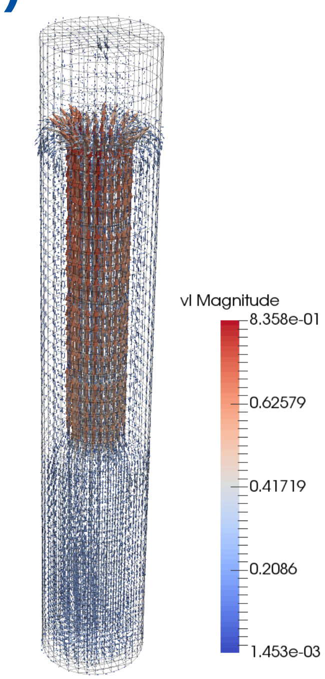
6 MPI Processors



Volumetric Power



Liquid Temperature



Liquid Velocity

Sensitivity Study for Natural Circulation Flows

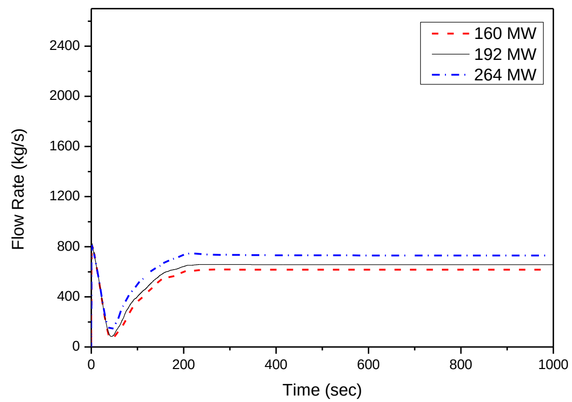
Effect of Reactor Power

Subcooling of Shinkori 3,4 =18.2 °C

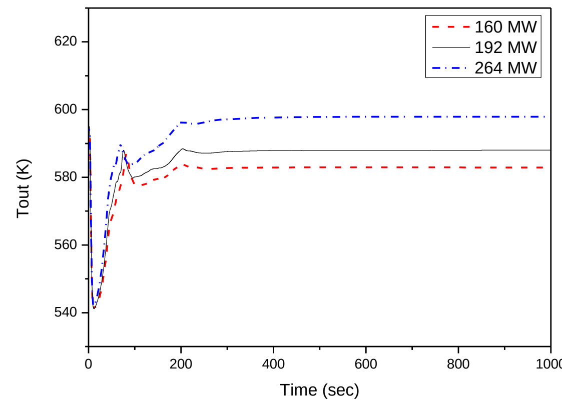
- *Total Pressure Drop=11.2 kPa*

Power (MWth)	Power (MWe)	Flow Rate (kg/s)	Tout (K)	Tsub (K)	ΔT (K)
160	50	617.3	582.9	25.1	44.7
192	60	656.2	587.9	20.1	49.7
264	77	730.5	597.9	10.1	59.7

← Ref.



Natural Circulation Flow Rate



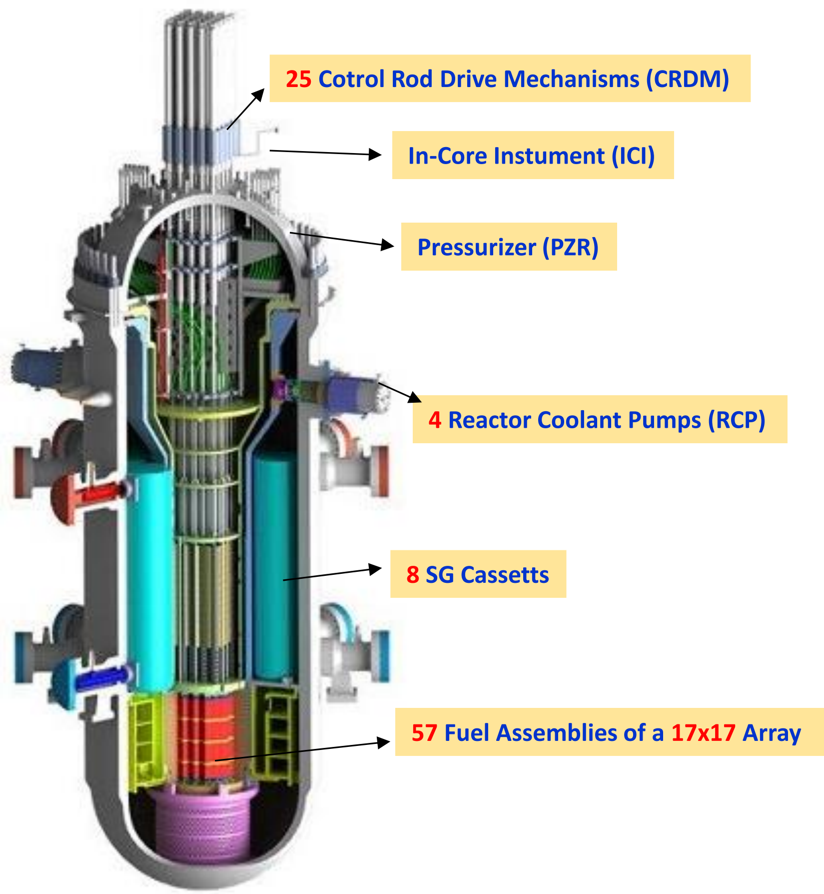
Core Exit Temperature

(Ref) Pressure=13.80 MPa (Tsat=608 K)
Flow rate=641.5 kg/s
$T_{core,in}$=538.15 K
$T_{core,out}$=594.15 K

Difference with design value	
Flow Rate	2.29 %
$T_{core,out}$	1.05 %

Preliminary Calculation for iSMR Design

Design Specification of SMART

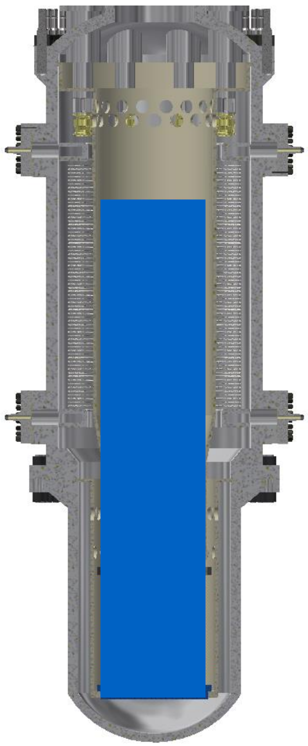


	SMART	NuScale
System Pressure (MPa)	15	13.8
Core Inlet Temperature (K)	568	538
Core Outlet Temperature (K)	596	594
RCS Flow Rate (kg/s)	2090	641
Power(Electric/Thermal)	100/330	60/192
No. of Steam Generators (Type)	8 (heilcal coil cassette)	2 (heical coil)
No. of RCPs	4	0
No. of FAs (Array)	57 (17x17)	37 (17x17)

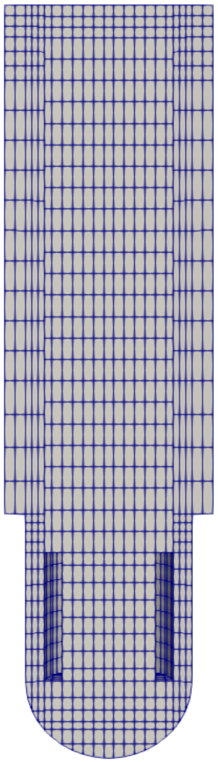
iSMR Mesh Generation

Conceptual iSMR Configuration and Mesh Generation

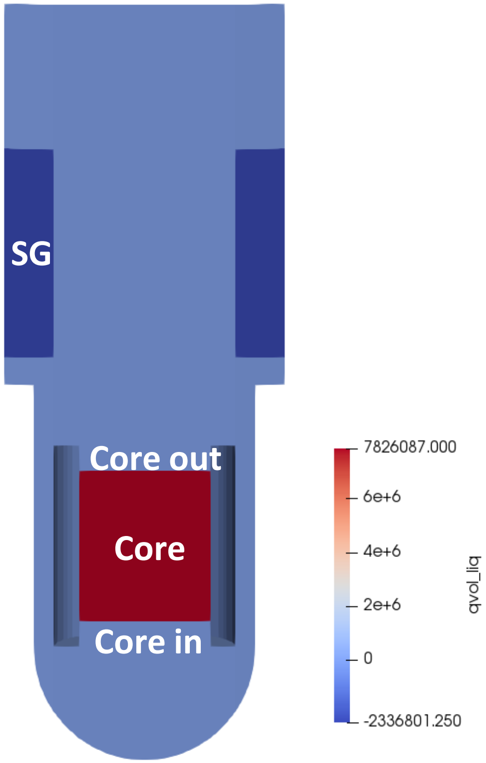
- 15 MPa single-phase water
- Test power=100 MWe, 133MWe, 166 MWe
- Problem time=1000 sec.



Conceptual iSMR configuration



The number of cells : 14,153

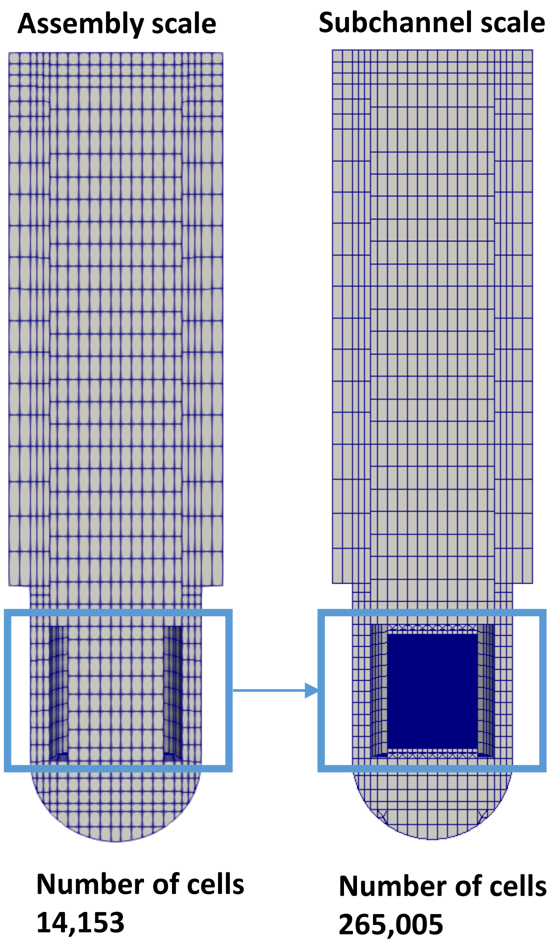


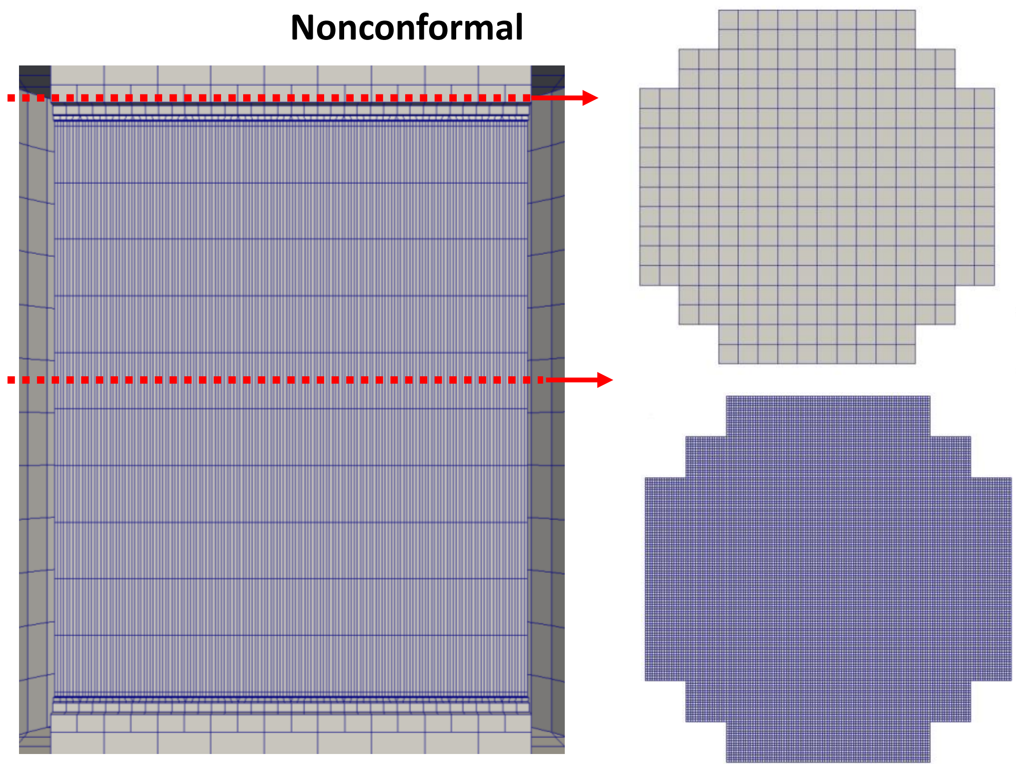
Uniform Heat Source/Sink (Core/SG)

3D Full Core Mesh Generation for iSMR

Mesh for the Subchannel Scale iSMR

- **Full core analysis with local resolution control: nonconformal mesh**



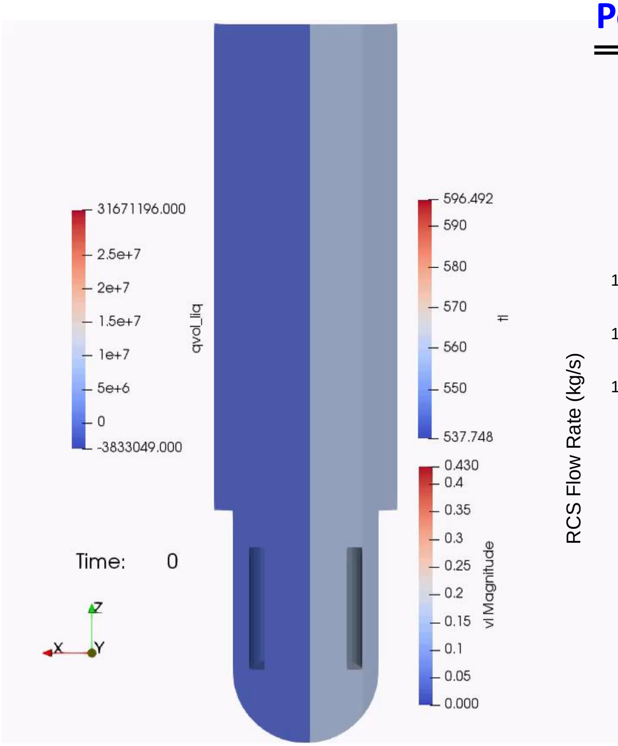


Subchannel mesh for the reactor core

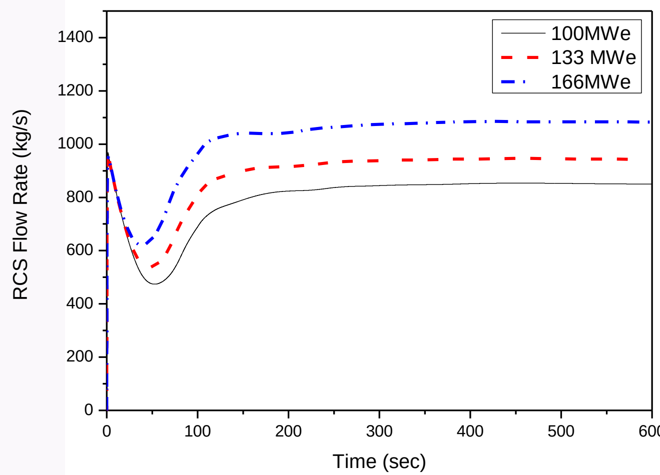
Sensitivity Study for Natural Circulation Flows

Natural Circulation Calculation

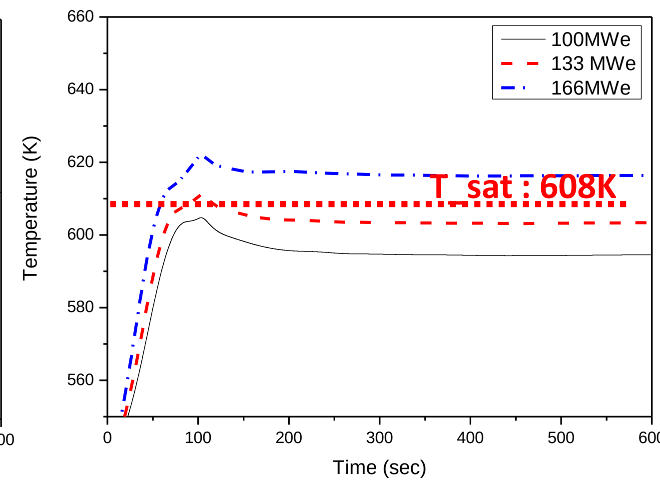
➢ 25% of SMART Pressure drop



Power (MWe)	Flow Rate (kg/s)	Tout (°C)	Tsub (°C)	ΔT (°C)
100	892	319	16	54
133	938	323	12	58
166	1082	338	-3	73



Natural Circulation Flow Rate



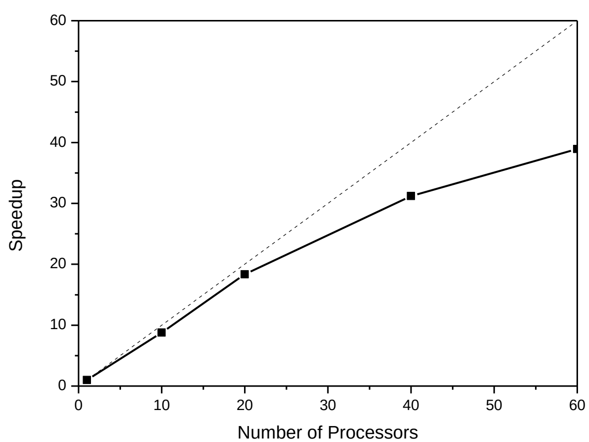
Core Exit Temperature

Implementation of Subchannel Model

Subchannel Model

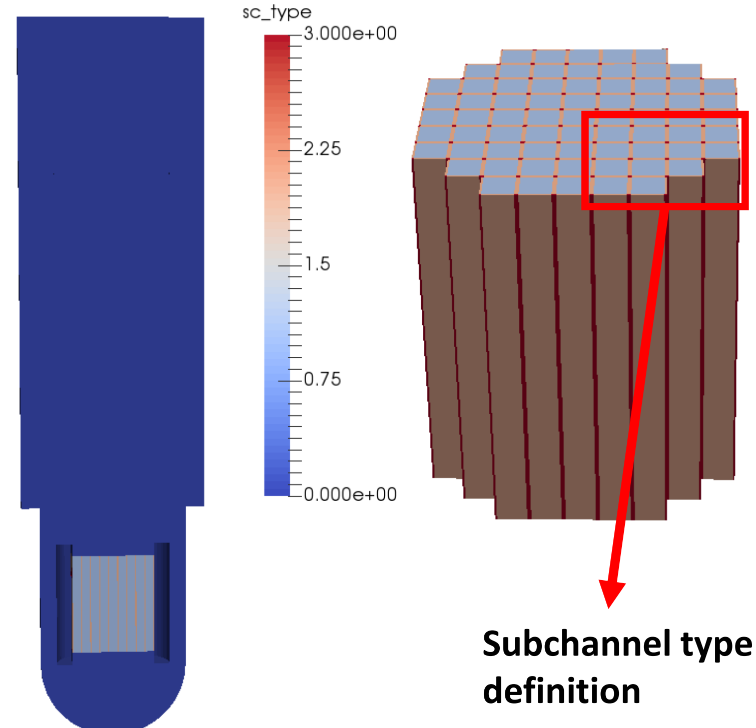
- ➤ **Friction Model from MATRA code**
- ➤ **Turbulence Mixing Model=EVVD**

Model	Note
Friction factor	$\Delta P = -\frac{1}{2}\left(\frac{f}{d_{hy}} + K'\right)\left(\frac{G_k^2}{\rho_k}\right)$
Form loss	$\Delta P_L = -\frac{K_G}{2}\left(\frac{W_{IJ,k}\lvert W_{IJ,k}\rvert}{l_{IJ}\rho_k s_{IJ}}\right)$
Turbulent mixing and void drift	• EM (Equal Mass exchange) • EVVD (Equal Volume exchange and Void Drift)
Grid spacer	$\Delta P = -\frac{K}{2}\left(\frac{G_k^2}{\rho_k}\right)$

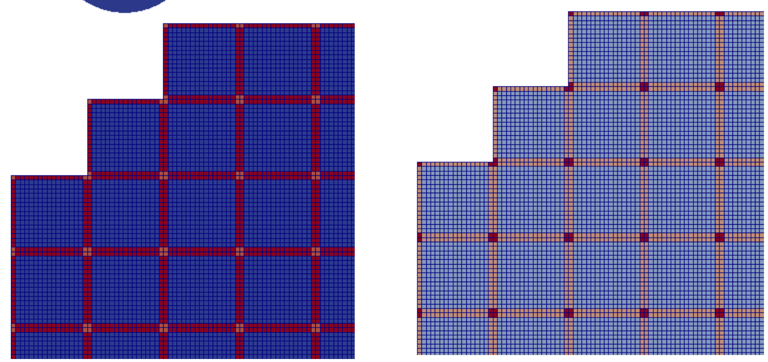


Speedup Test

Real time calculation for 1000 sec : **983 seconds** (wall clock time, CPUs)



Subchannel type definition

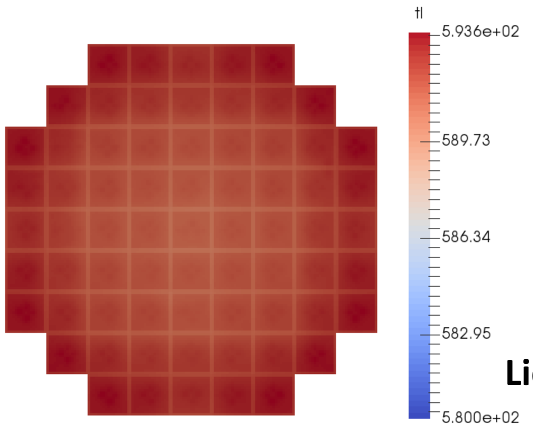


Hydraulic diameter

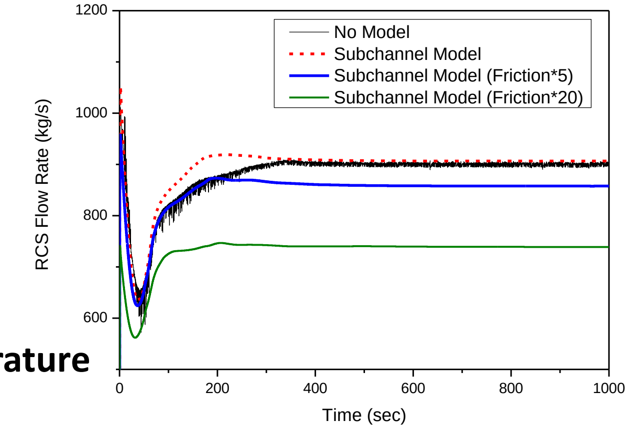
Full Core Analysis with Subchannel Model

Test Calculation of Subchannel Model

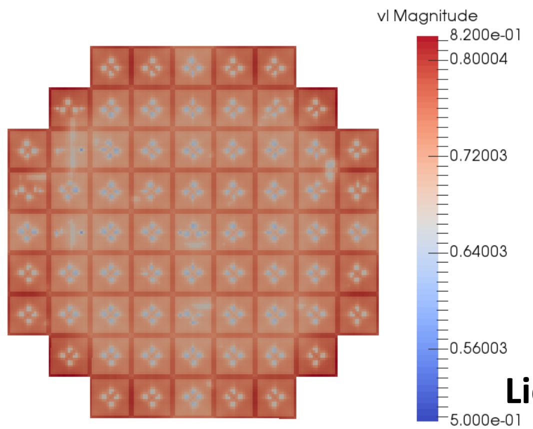
- Uniform heat source at the reactor core
- Turbulence Mixing by EVVD model, Friction by MATRA model



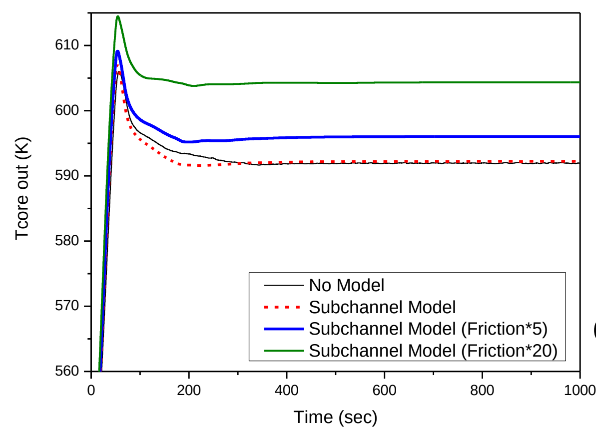
Liquid Temperature



RCS Flow Rate



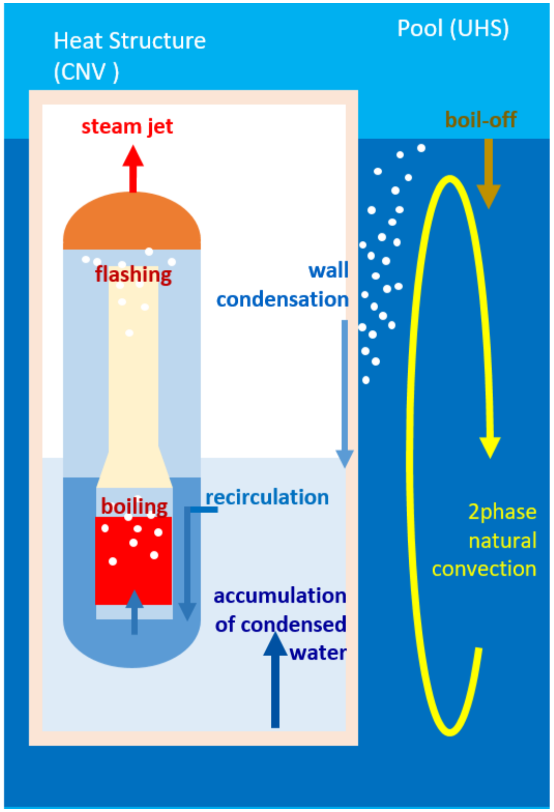
Liquid Velocity



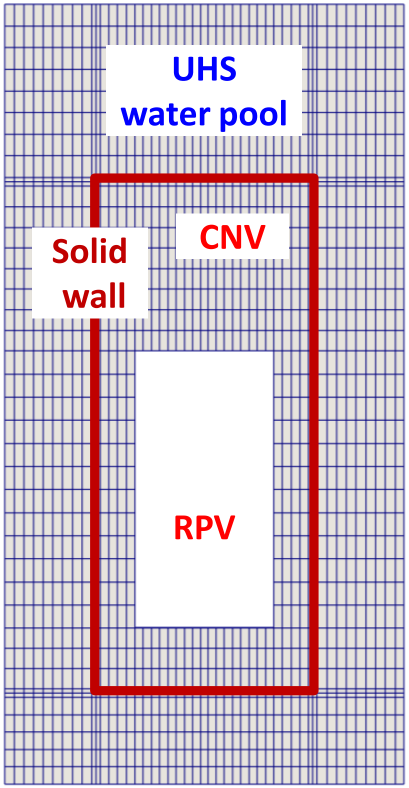
Core Exit Temperature

Conceptual Problem for SMR LOCA Analysis (1/3)

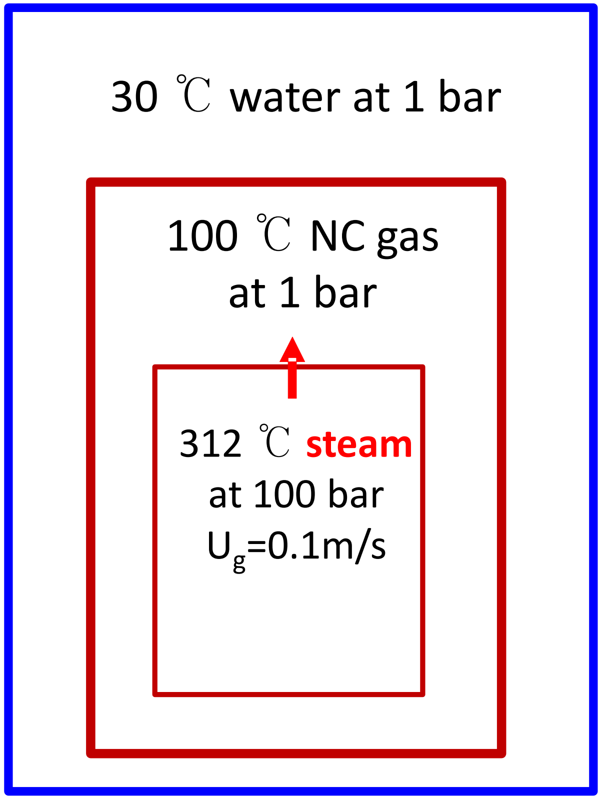
- ***Setup a conceptual problem to verify the CUPID code capability for the application to SMR LOCA analysis***
- ***2D mesh model for RPV, CNV, CNV solid wall, and UHS***



SMR LOCA Phenomena



2d Mesh Model



Initial Conditions

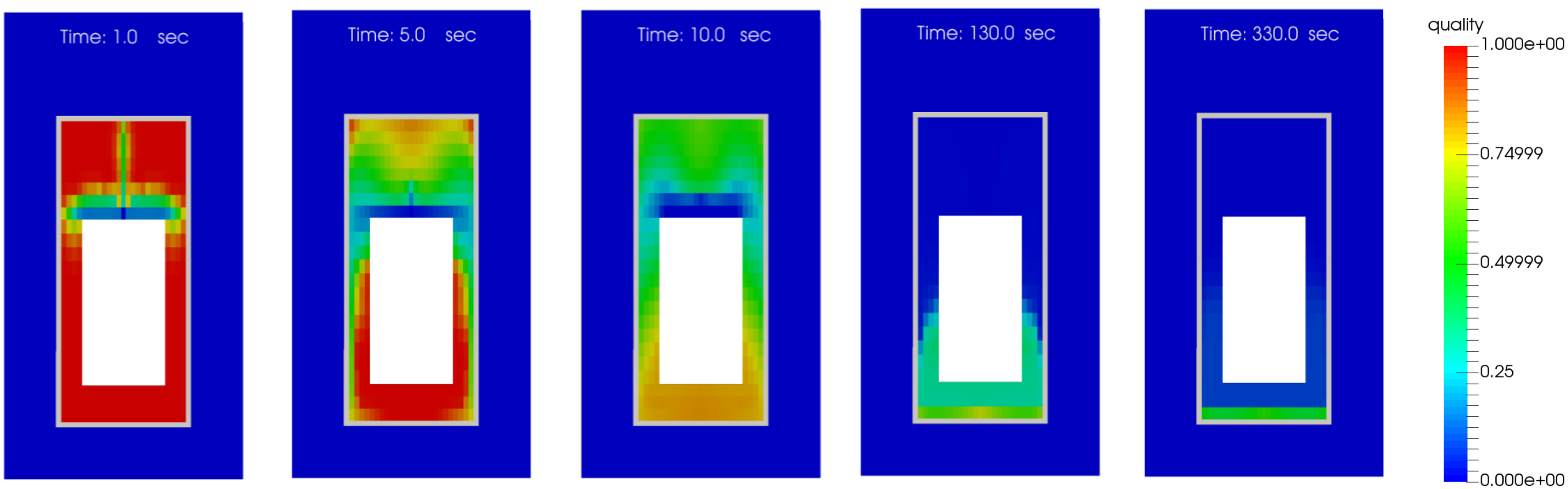
Conceptual Problem for SMR LOCA Analysis (2/3)

Verification of physical models

- Wall condensation in CNV (water level increase)
- Heat conduction of the CNV wall
- Natural circulation in UHS
- Boil-off in UHS (water level decease)

Verification of numerical stability for

- Simultaneous calculation of the two fluid regions separated by a solid wall

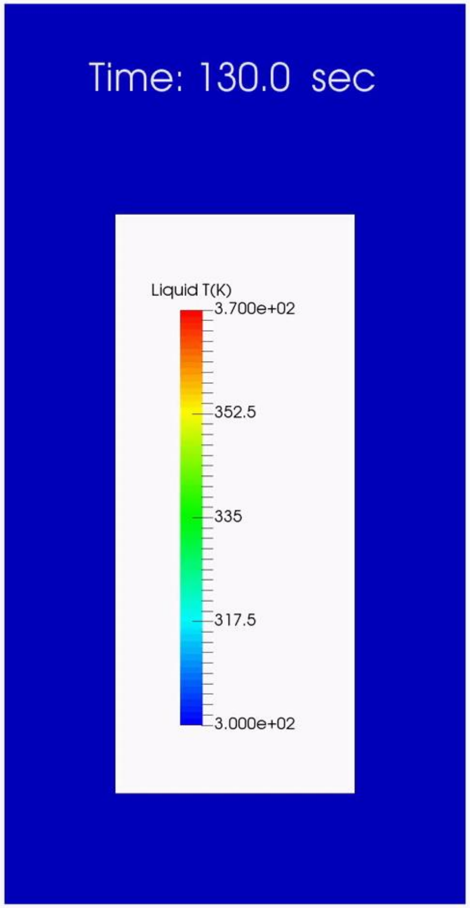


Non-condensable gas transient in CNV up to 330 s

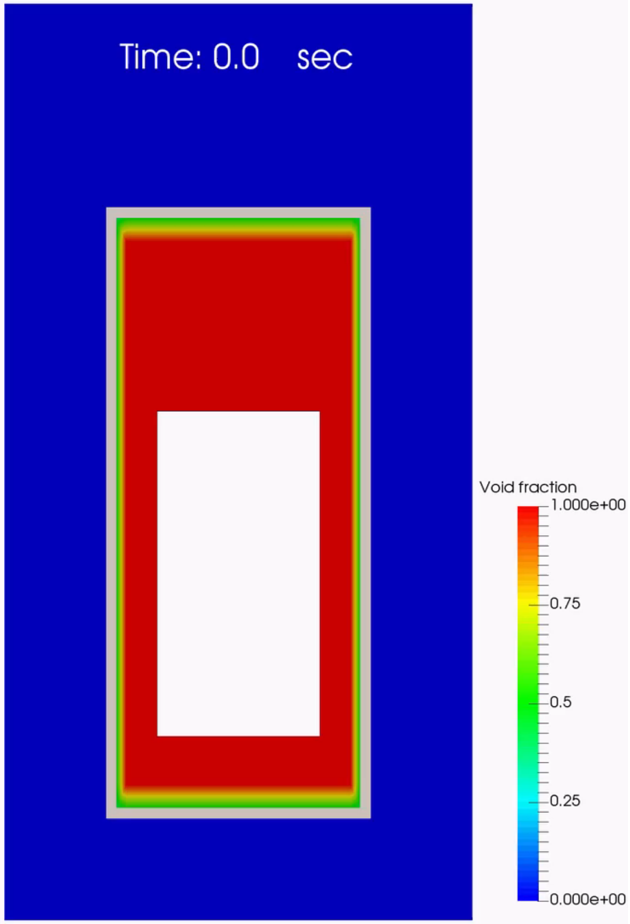
Conceptual Problem for SMR LOCA Analysis (3/3)

- ***10^5 seconds (27.7 hours) of long transient* was successfully simulated**
  - **Water lever increase in CNV due to condensation**
  - **Water lever decease in UHS due to boil-off**
- ***Numerical stability***
  - **Simulation took 4300 seconds with 4 CPUs**
  - **Practical application to Full 3D analysis is achievable**

Liquid temperature in UHS



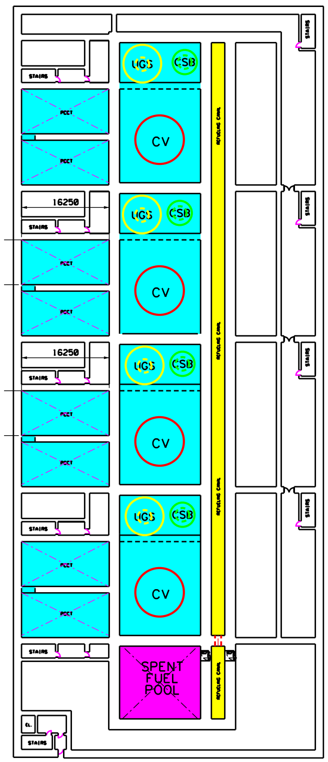
Gas volume fraction



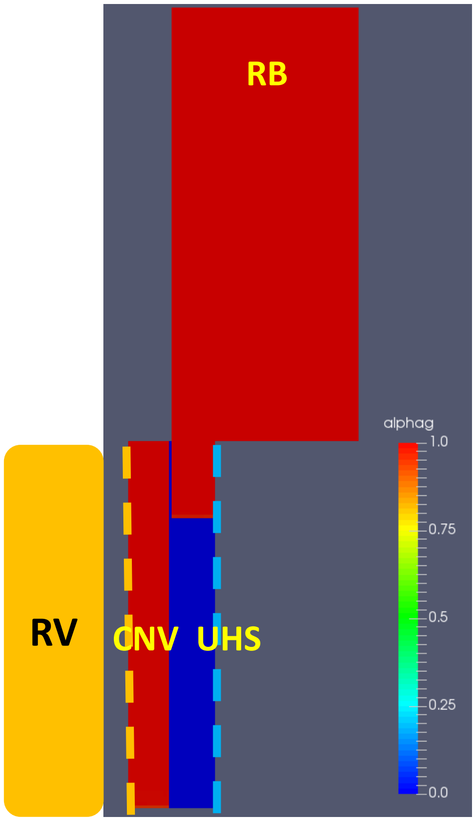
Long Tern Cooling Capability

Turbulence mixing in RB

- Long term (infinite) cooling
- Air circulation in RB

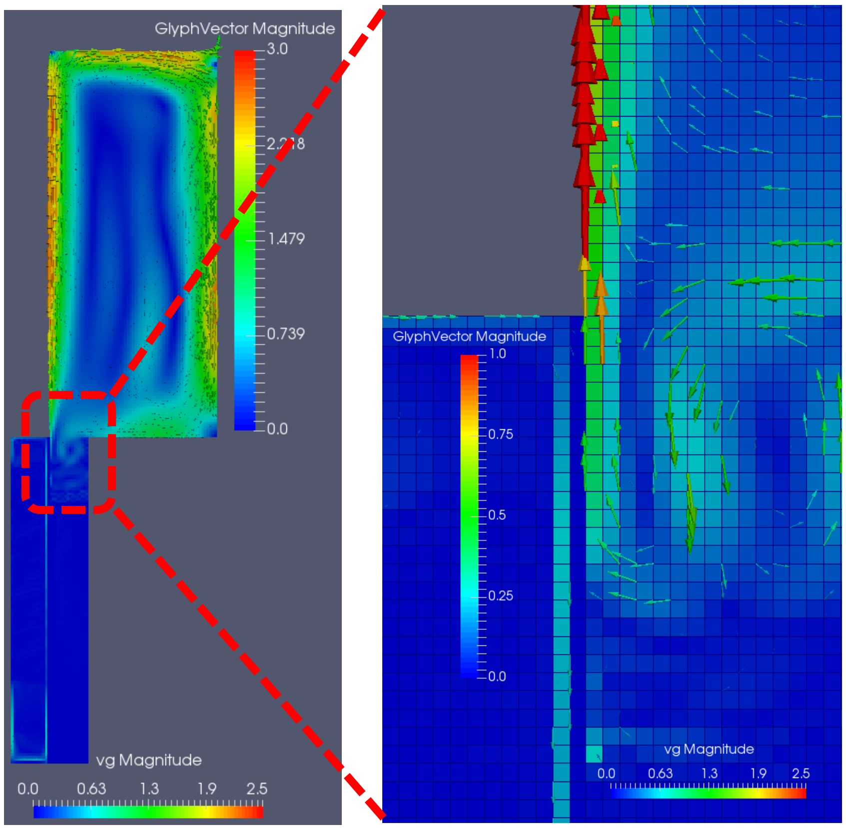


Arrangement of iSMR module (ex.)



Tw=530K- Tw=300K

Conceptual diagram



Natural circulation in upper part of USH pool

Summary

5

Summary

MSMP integrated platform MARU

- *Multi-scale and multi-physics* coupled calculation
- *HPC* by MPI, OpenMP, and GMG
- Client-Server socket communication in *Windows PC*
- Use of high performance *Linux cluster*
- Turnkey solution from pre- to post-processing

Development of models for iSMR

- *Grid generator*: assembly/subchannel scale
- *Component models*: SG, PZR, MCP, RVV/RRV, and PAFS
- *Physical models*: mixed convection, condensation, conjugate heat transfer and radiation heat transfer

THANK YOU

yjcho@kaeri.re.kr