# 원전 다중스케일 열수력해석 현황 및 계획

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**한국원자력연구원**

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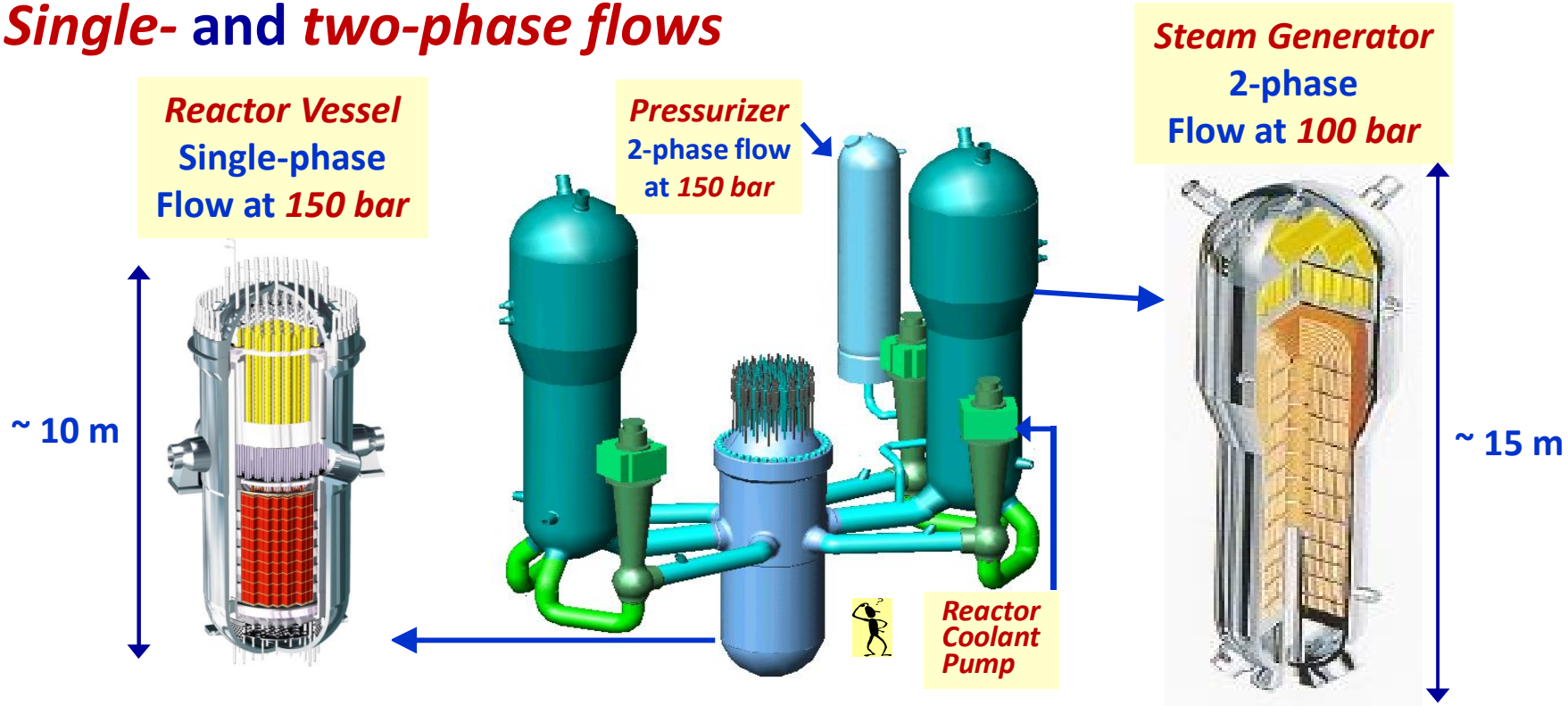
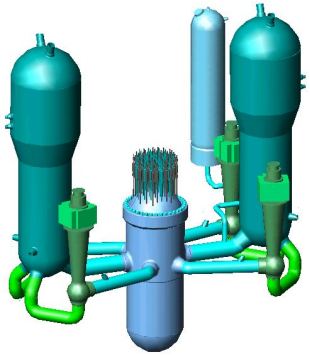
# Nuclear Reactor Thermal Hydraulics

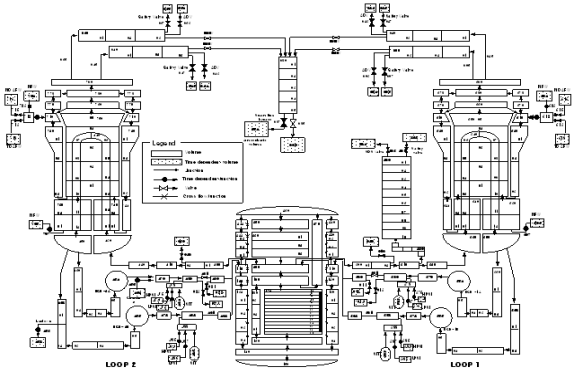
- *Big and complicated* system (Simplified analysis is needed)
- *Multi-physics*: reactor kinetics, fluid flow, heat transfer, I&C...
- *Steady-state* (performance) and *transient analysis* (safety)
- *Single-* and *two-phase flows*



# Length Scales in Nuclear Reactor TH Analysis

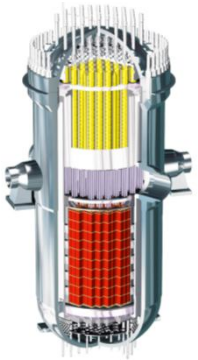
***System***

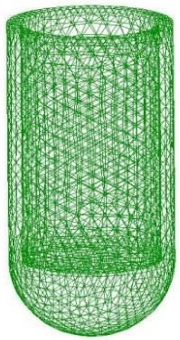




***~$10^0$ m****

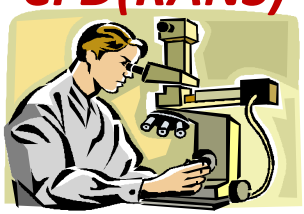
***Component***

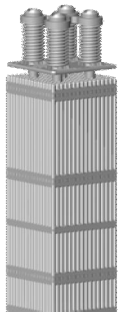


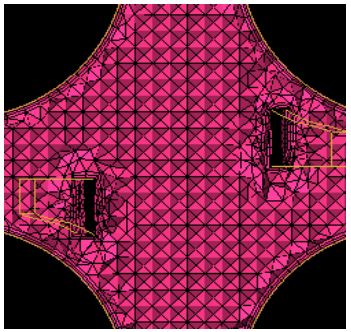


***~$10^{-1}$ m***

***CFD(RANS)***





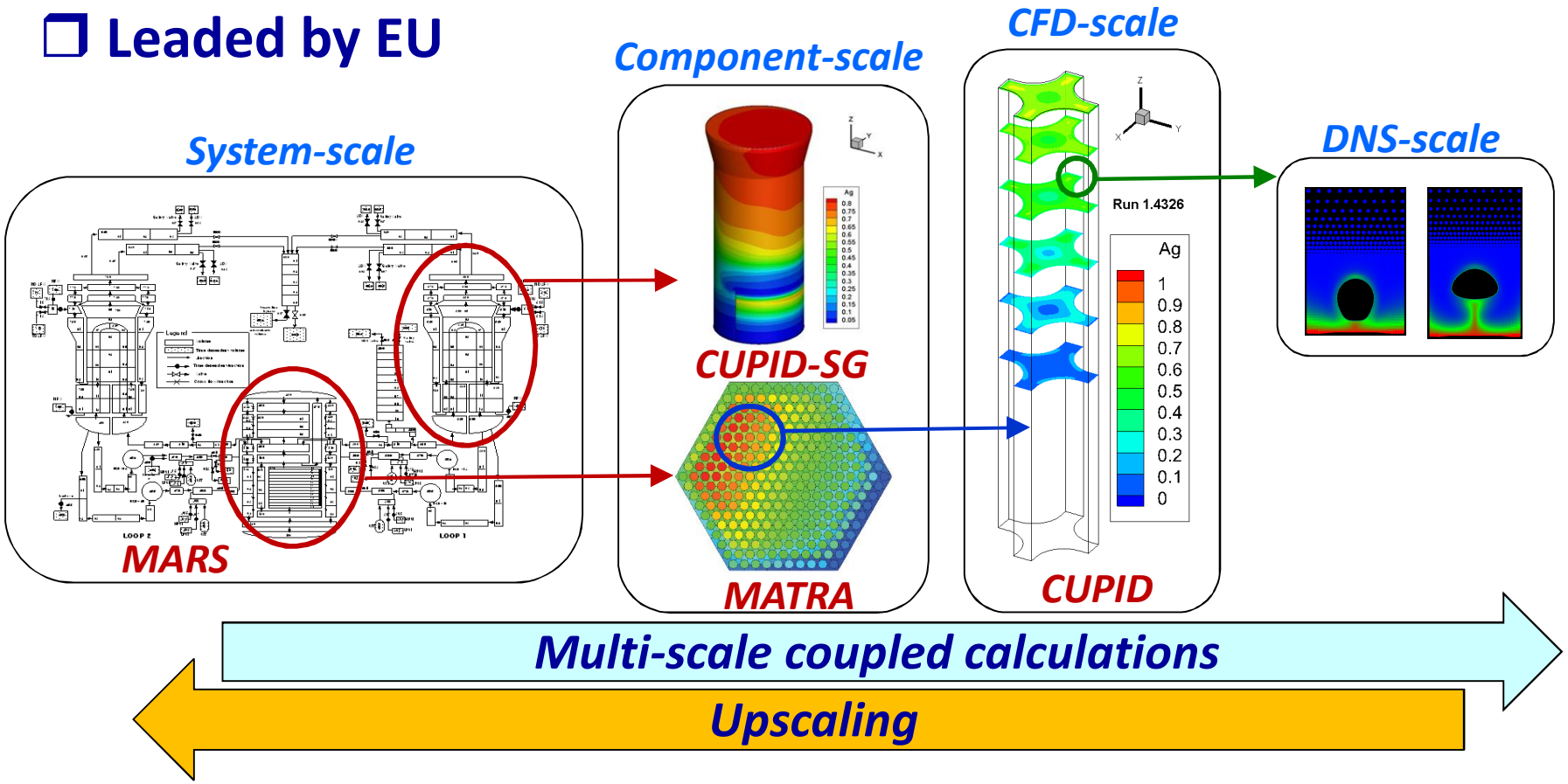


***< $10^{-2}$ m***

****Length Scale***

# Multi-Scale TH Analysis for PWRs

- Technologies providing high fidelity *TH predictions by combining codes* with different analysis scale
- *System*, *Component*, *CFD*, and *DNS* scale codes are used
- Leaded by EU



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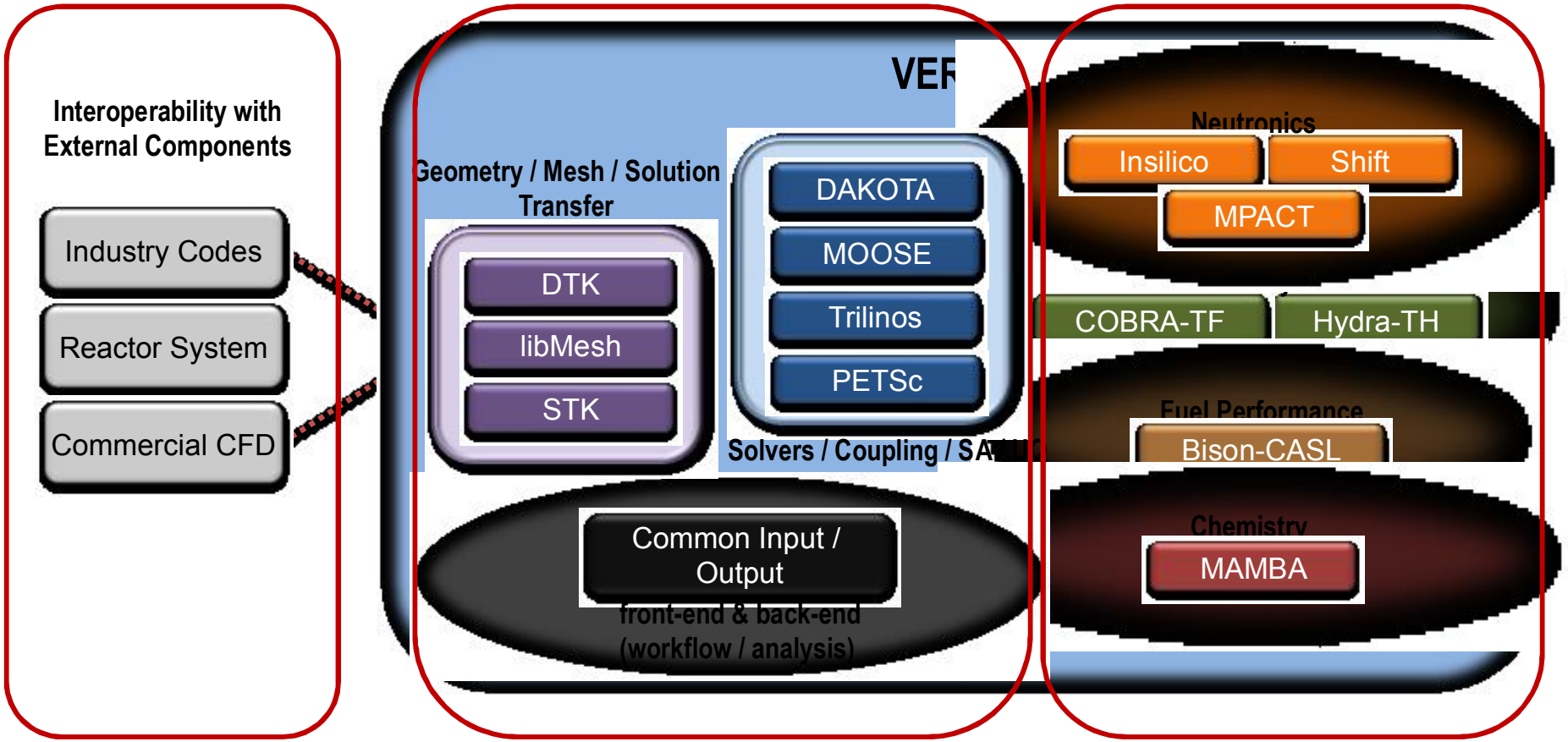
# CASL Project

## ❒ CASL *(Consortium for the Advanced Simulation of Light Water Reactors)*

- 비젼: 원자로 성능 및 안전성의 신뢰도 향상을 위하여 계산과학에 기반한 모델/시뮬레이션 기술 개발 및 산업계 적용
- 목표: 가상원자로 개발, 원자로 운전 여유도 개선, 원자로 출력 증강 원전 수명 연장
- US DOE의 Energy Innovation Hub 사업
- ORNL(Oak Ridge Nat. Lab.) 주도로 약 20여개 산학연 기관 참여
- 제2의 Manhattan Project로 불리는 대형 사업
  - 1 단계: 2010-2015 (예산: 약 1400 억원)
  - 2 단계: 2015-2020 (예산: 약 1400 억원)
- 1단계 개발 목표 성공적 완수 및 2단계 진행 중

# Virtual Environment for Reactor Applications (VERA)




상용 소프트웨어

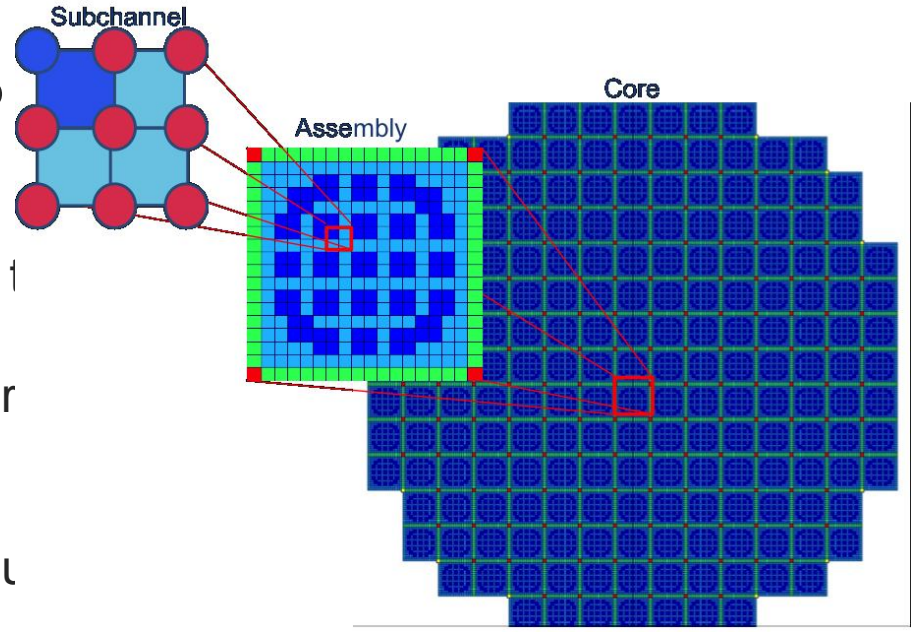
계산과학 전문 소프트웨어

원전 시뮬레이션 소프트웨어

# 원자로 열수력 해석

## ❒COBRA-TF Subchannel T/H Provides Pin-Resolved Capability

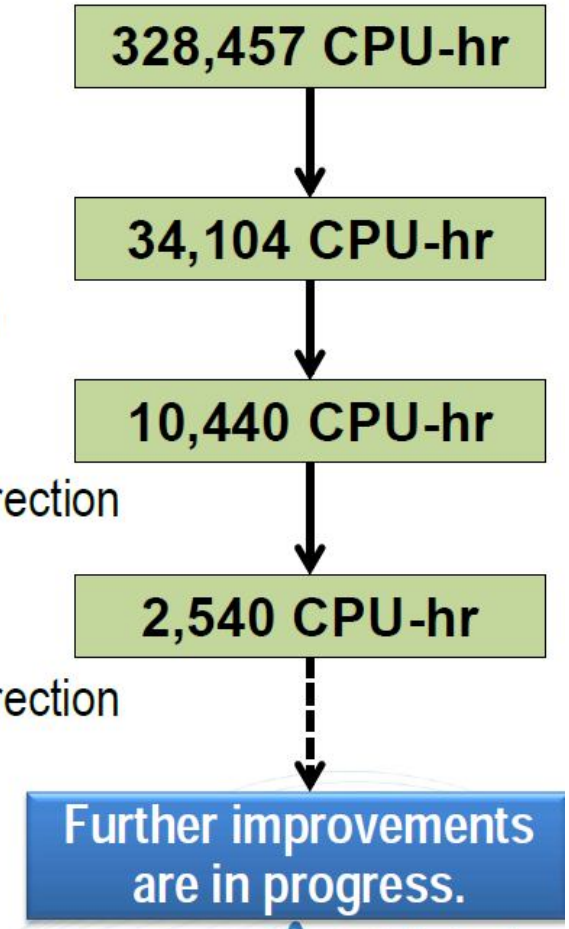
- **Core simulator T/H provided by *subchannel T/H* using COBRA-TF (CTF) code being jointly developed by Penn St. and ORNL**
- **CTF is a *two fluid, three-field model* (liquid, droplets, vapor)**
- **Several developments required to support full core pin-cell level resolution:**
  - ***Optimization of COBRA-TF solvers*** t reduce memory and execution time
  - Spatial decomposition ***parallelism*** to r run time
  - ***Preprocessor*** to automate input development from VERA common inpu



# 가상원자로 성능 개선

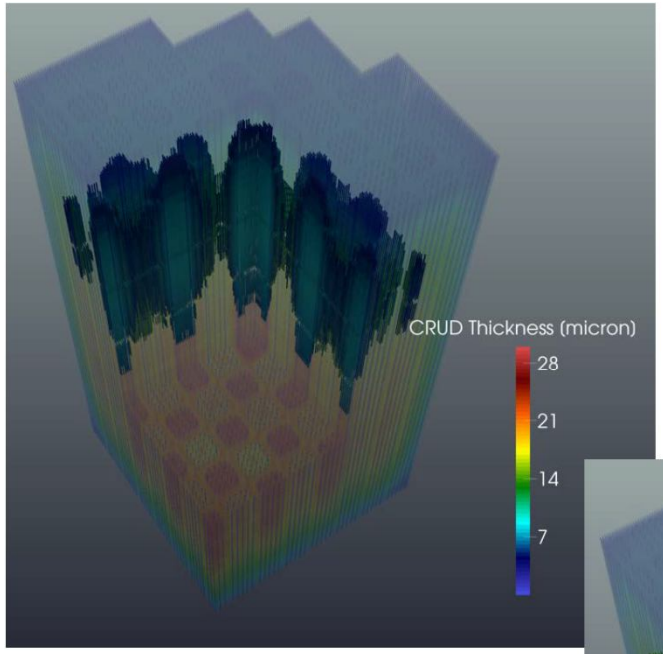
## VERA-CS performance improvement over last 15 months.

- Dec 2013
  - Insilico/CTF – 56/8 energy groups
  - 18,769 cores, 17.5 hours wall time
- Apr 2014
  - MPACT/CTF – 56 energy groups, P2 scattering
  - 2,784 cores, 12.25 hours wall time
- Aug 2014
  - MPACT/CTF – 56 energy groups, transport correction
  - 2,784 cores, 3.75 hours wall time
- March 2015
  - MPACT/CTF – 47 energy groups, transport correction
  - Direct Coupling
  - 4,234 cores, 36 minutes wall time

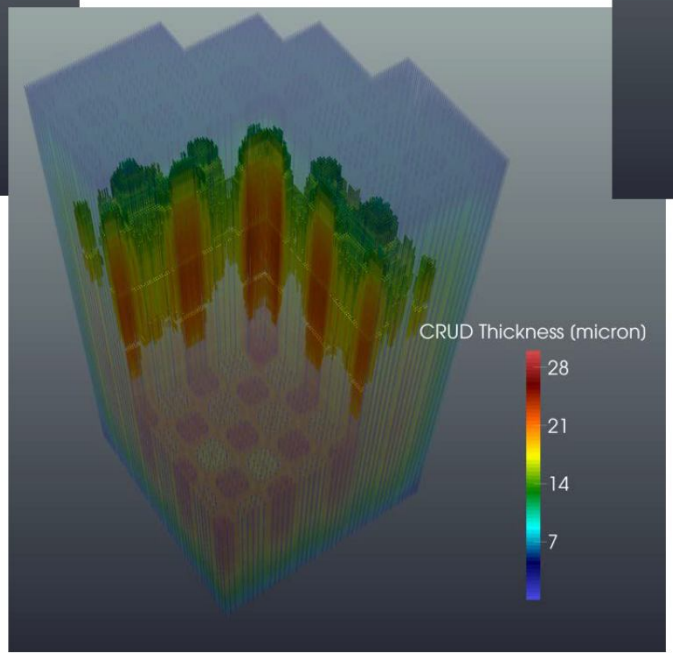


# CRUD Induced Power Shift (CIPS)

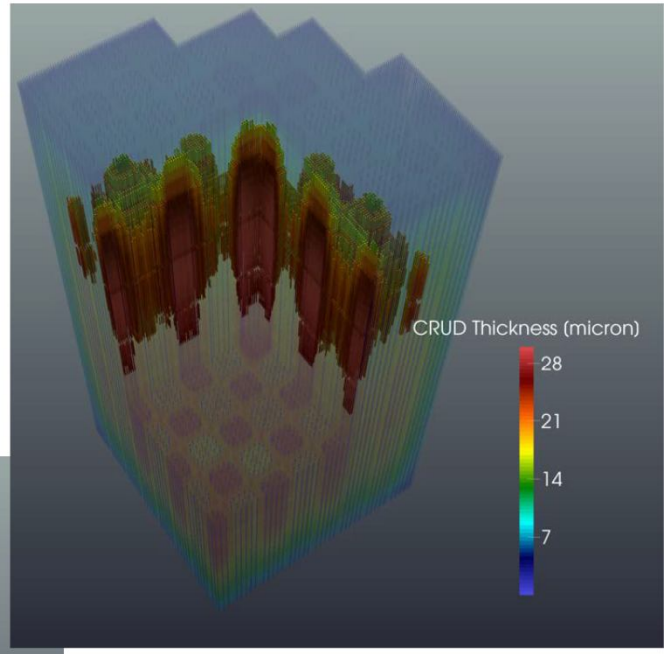
- CRUD thickness over time in regions with subcooled boiling




90 EFPD




270 EFPD




360 EFPD

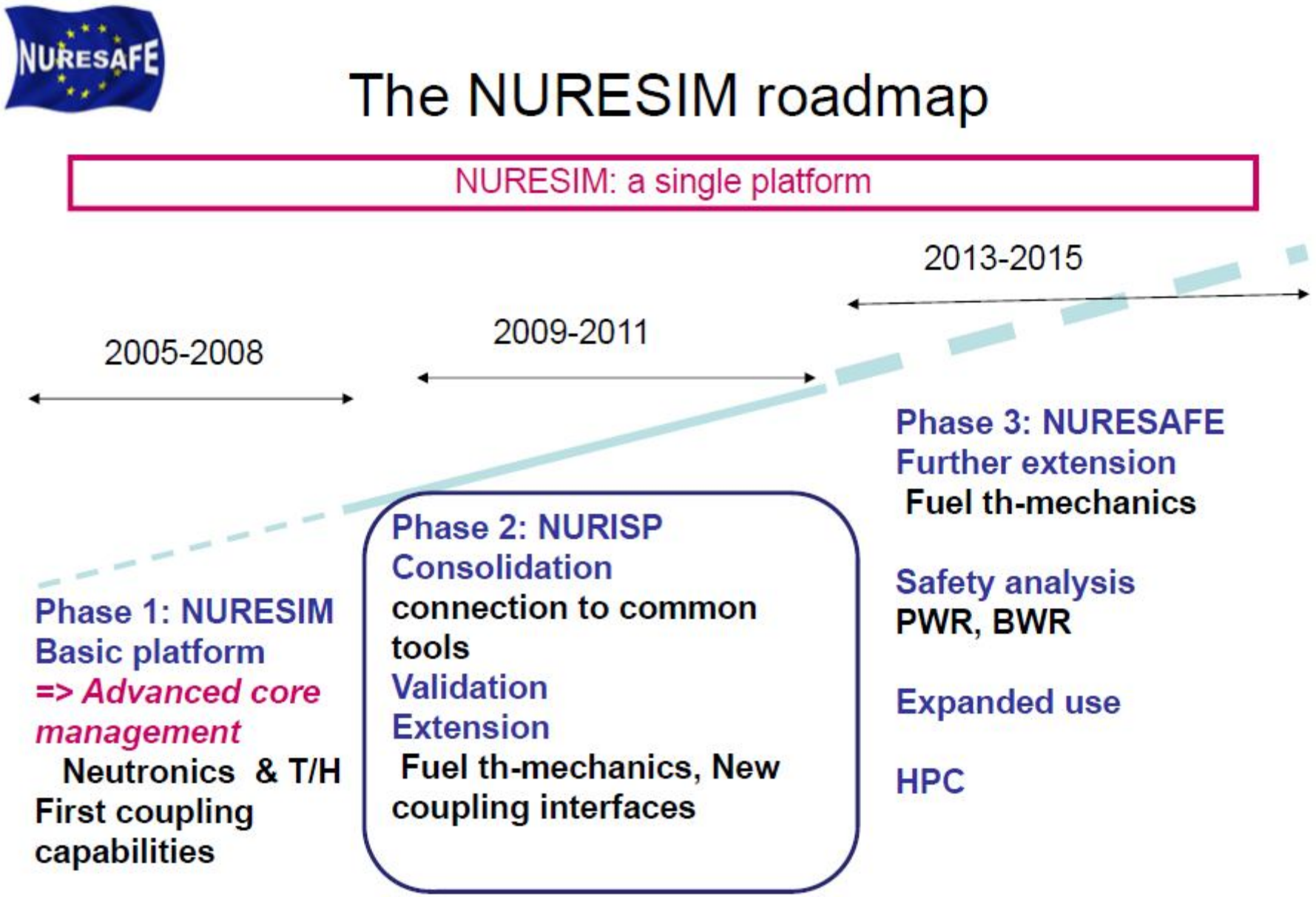
# NURESIM (2005~)

## (NUclear Reactor European SIMulation platform)

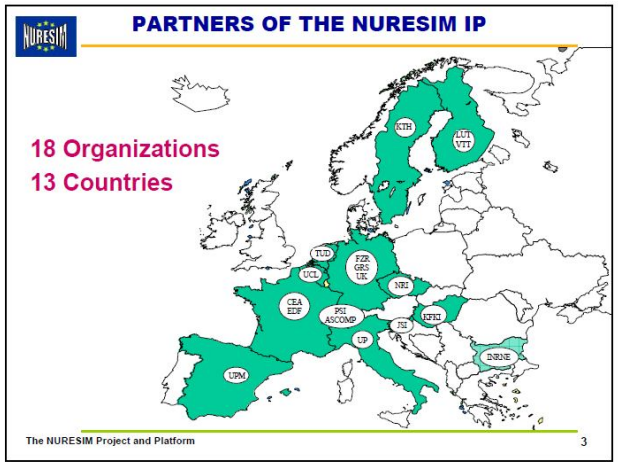
### ❒ NURESIM Target

- ***Integrated*** **Platform**
  - ✓ Common functions, ***multi-scale/physics***, user friendly
- ***Sate of the art*****, covering most disciplines**
  - ✓ SOA or beyond, well validated, including different physics
- ***European***
  - ✓ A common European development to meet requirements from stakeholders, share tools, knowledge and best practices
- **For Simulation of** ***Light Water Nuclear Reactors***
  - ✓ GEN-II, GEN-III, GEN-III+

# NURESIM Road Map



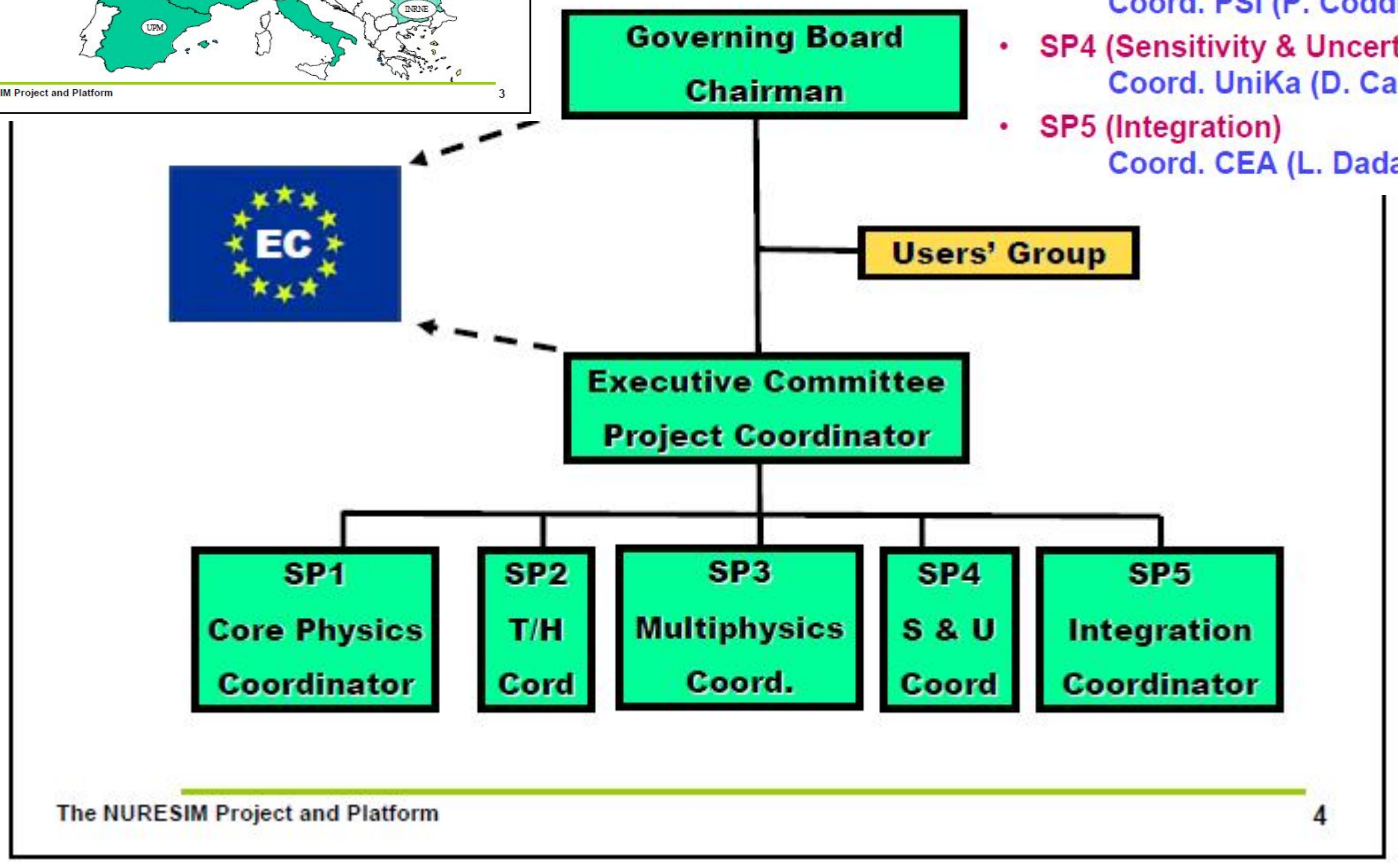
# NURESIM 연구 개발 분야




18 partners

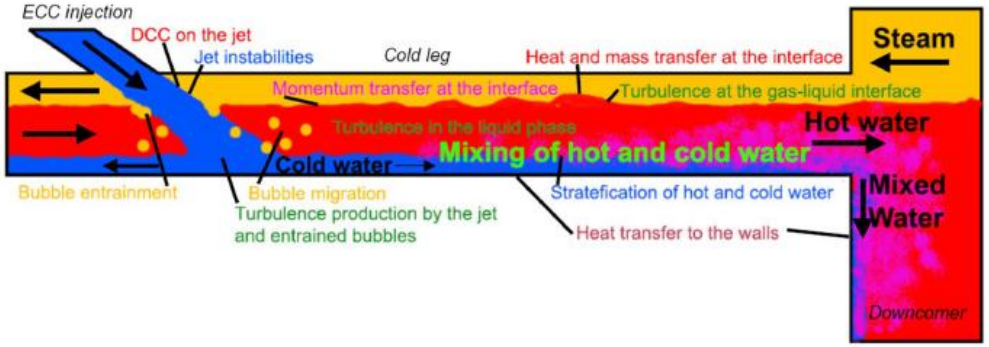
- SP1 (Core Physics) 40% of manpower
  Coord. UPM (JM Aragonés) 10 Partners
- SP2 (Thermalhydraulics) 40%
  Coord. CEA (D. Bestion) 14 Partners
- SP3 (Multi-Physics) 5%
  Coord. PSI (P. Coddington) 3 Partners
- SP4 (Sensitivity & Uncertainty) 9%
  Coord. UniKa (D. Cacuci) 3 Partners
- SP5 (Integration) 6%
  Coord. CEA (L. Dada) 1 Partner

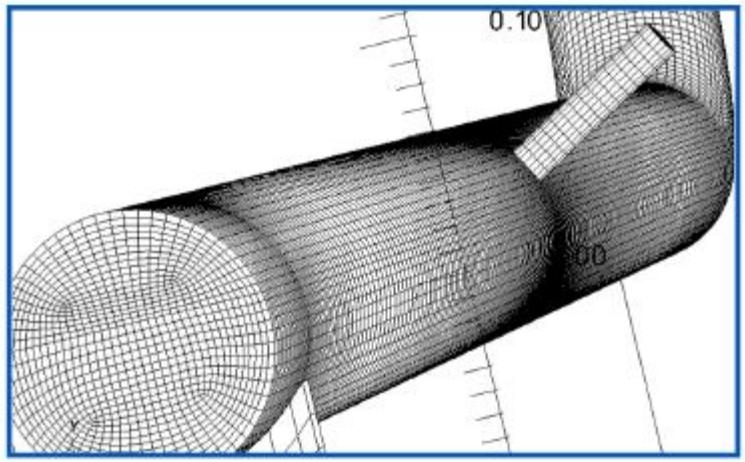
## M ORGANIZATION



# NURESIM: 원자로 배관 열충격 해석

## ❒ NEPTUNE-CFD Assessment of PTS (Pressurized Thermal Shock)

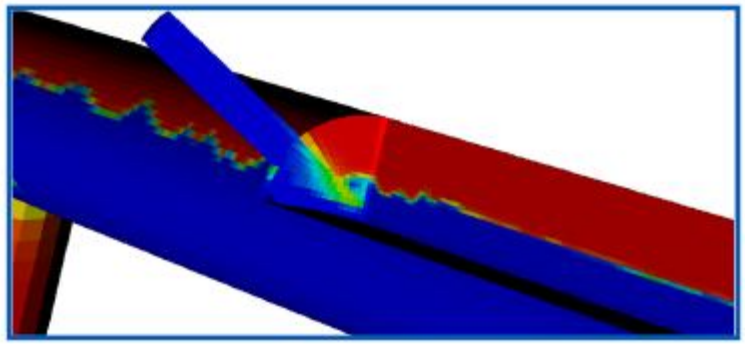



Objective: predict the temperature field following ECCS injection in an uncovered cold leg for an evaluation of mechanical and thermal loading on PV walls.

Required space resolution: a few cm
Required time resolution: >1s
Required accuracy (depends on reactor age)

requires CFD
both URANS & LES are possible
of the order of tens of K



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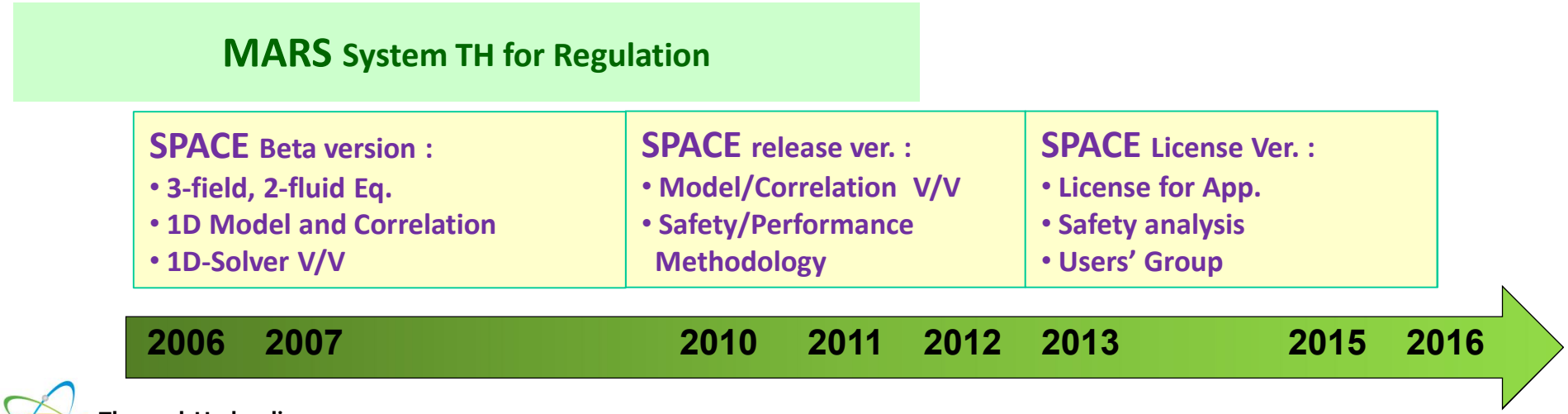
IV. 향후 연구 개발 전략

## ❒ System Thermal-Hydraulics Codes

- ***Developed and validated since 1960s***
- ($700 million spent by US nuclear regulatory commission)
- A ***one-dimensional two-fluid model*** for two-phase flows
- Essential tool for safety and performance analysis
- In Korea, ***MARS, SPACE*** codes have been developed by KAERI

## ❒ **MARS** code for ***Regulatory Utilization*** (KINS)

## ❒ **SPACE** code development ***lead by industry*** (supported by MOTIE)



# System Scale TH Analysis for PWRs

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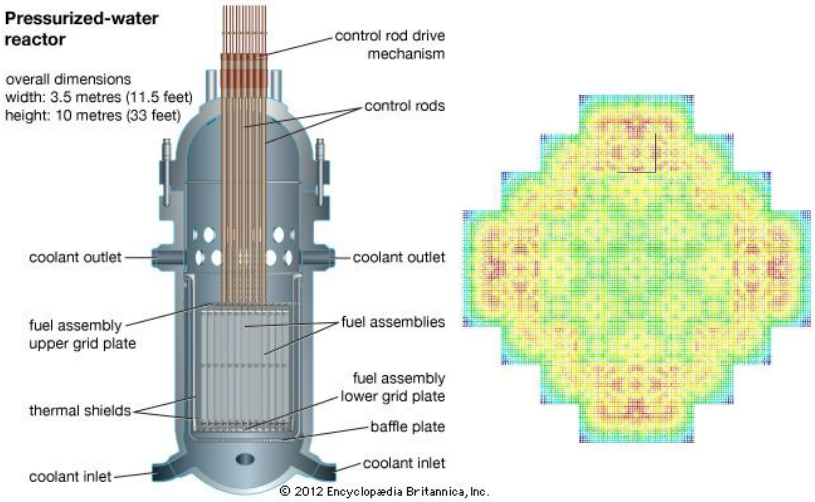
# Component Scale TH Analysis for PWRs

## ❒ Component Scale TH Codes

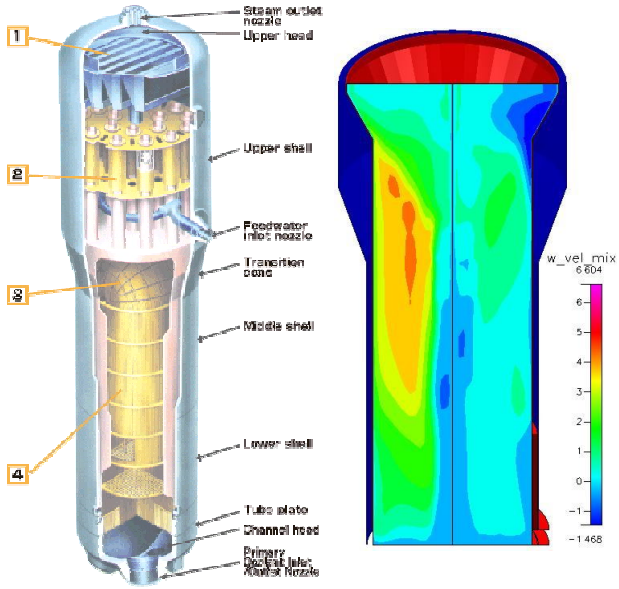
- Developed for ***component design***
- Equipped with ***component specific physical models***
- A tool for a ***multi-scale TH*** analysis

***Containment***

***Reactor Core***




***Steam Generator***



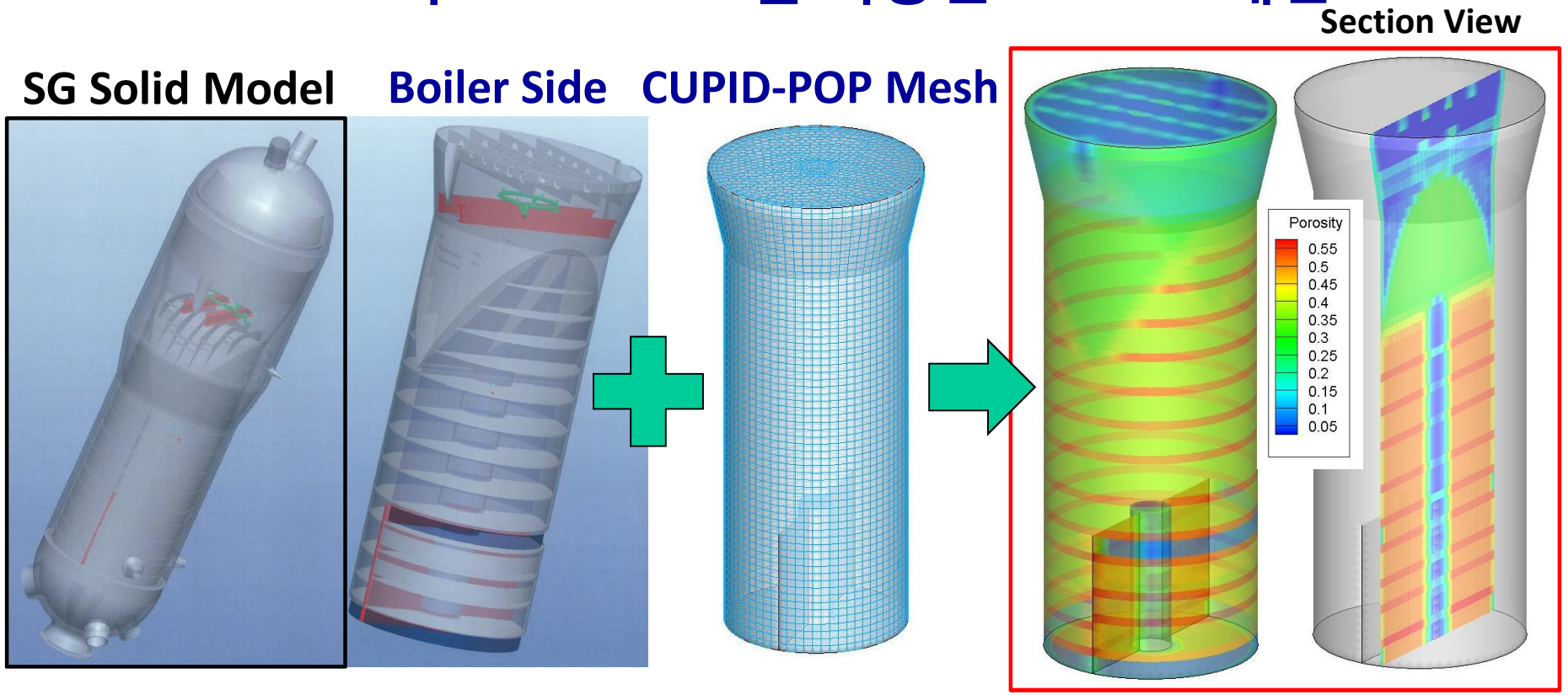

***MATRA***
***(KAERI, Korea)***

***ATHOS***
***(EPRI, US)***

***COM3D***
***(KIT, Germany)***

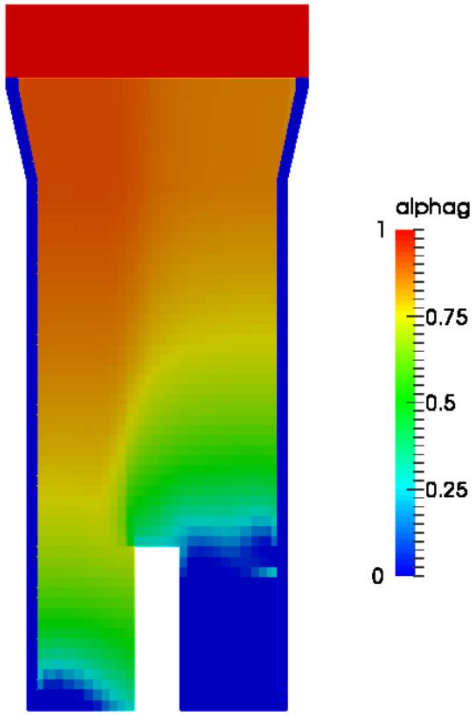
# CUPID-SG : 신고리 3/4 SG 해석 (1)

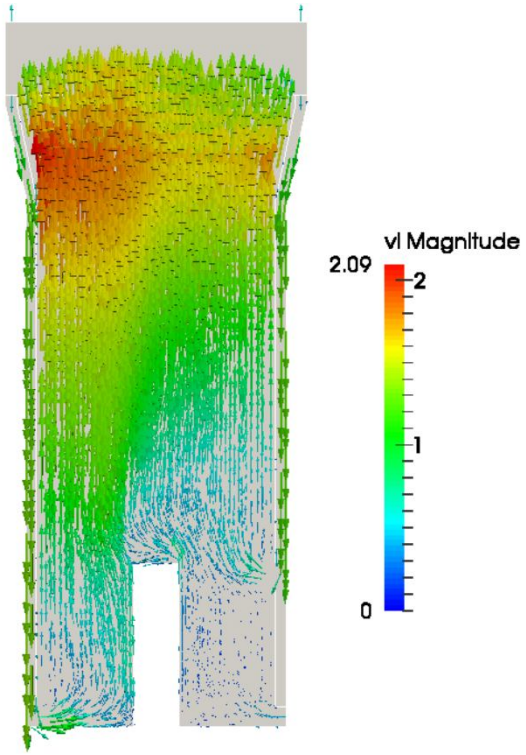
## ❖ CAD (PRO-E.) 와 Solid Model을 이용한 Porosity 계산



# CUPID-SG : 신고리 3/4 SG 해석 (2)

- ❖ CUPID 기반 증기발생기 해석 코드 기술 사업화 (‘16.7~’17.6)
- ❖ 일차계통, 강수부, 습분분리기 모델 포함
- ❖ GUI 입력 기능 개발

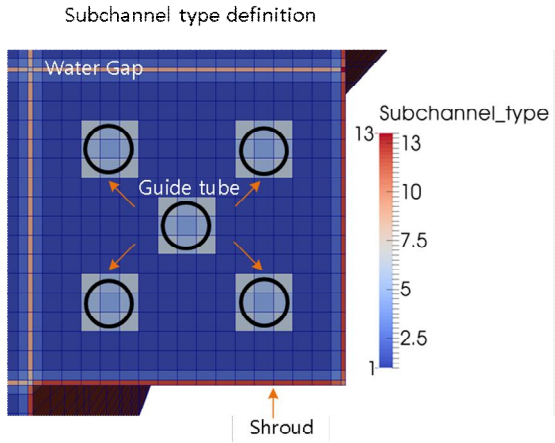


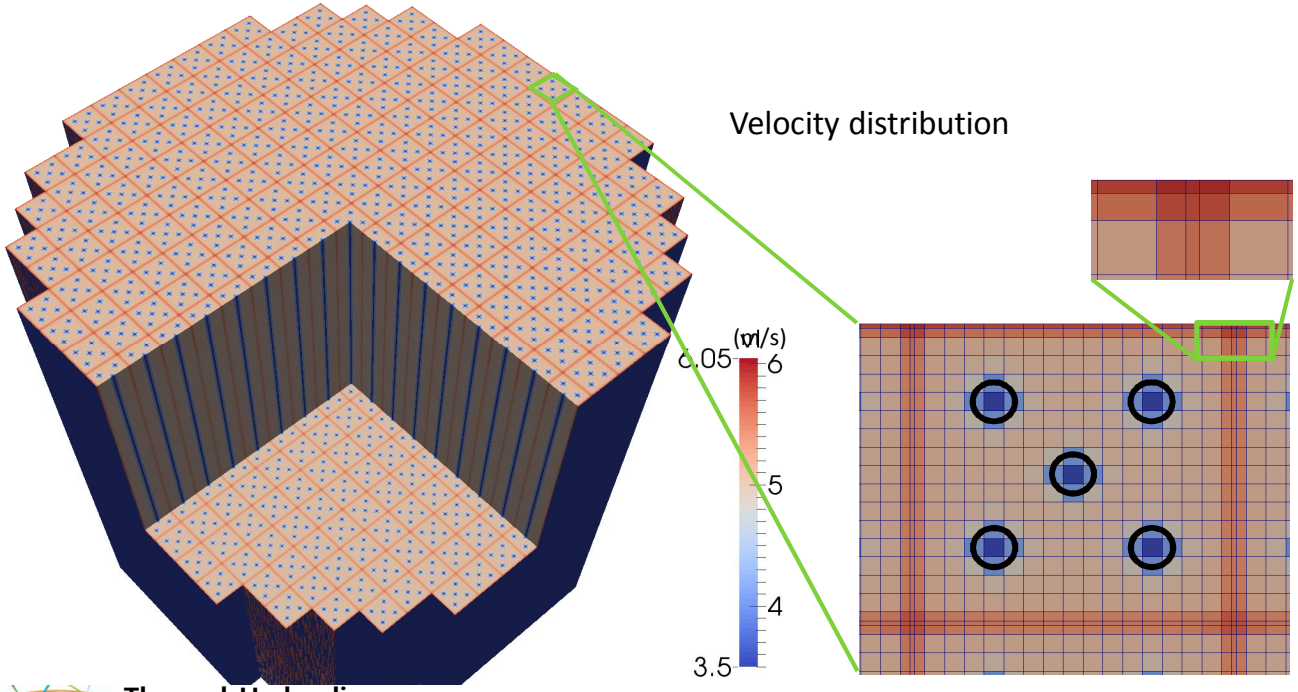



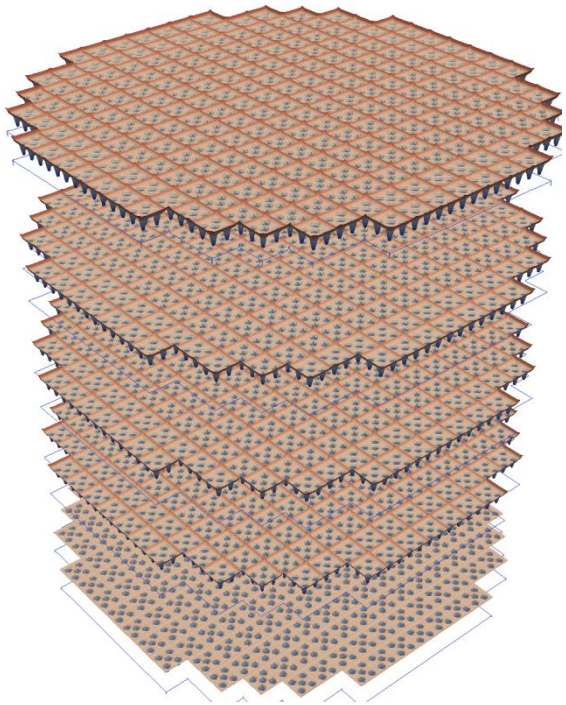
# CUPID (NuTHEL): APR1400 부수로스케일 전노심 해석

## Preliminary steady-state calculation

- Adiabatic condition
- Geometry modelling
  - Guide tubes, water gaps, core shroud, etc.
- Total computational cells: ~2.7 millions
  - 241 assemblies, 56,876 fuel rods
  - 78697×34 (number of planes)



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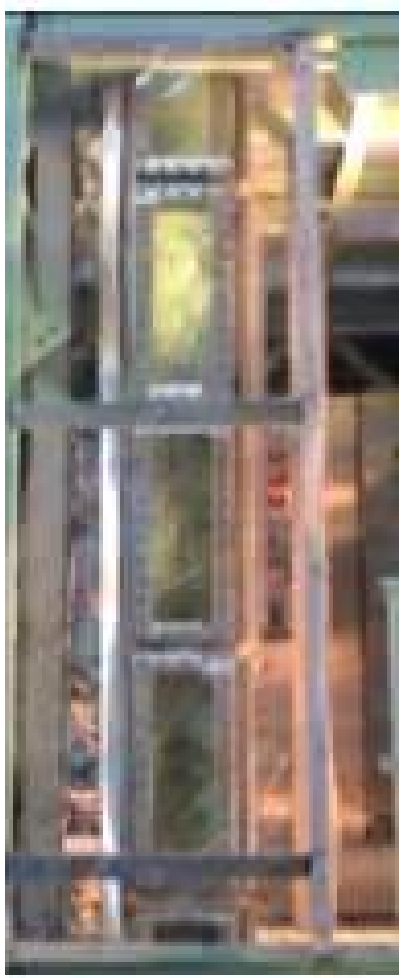
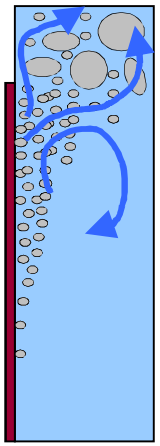
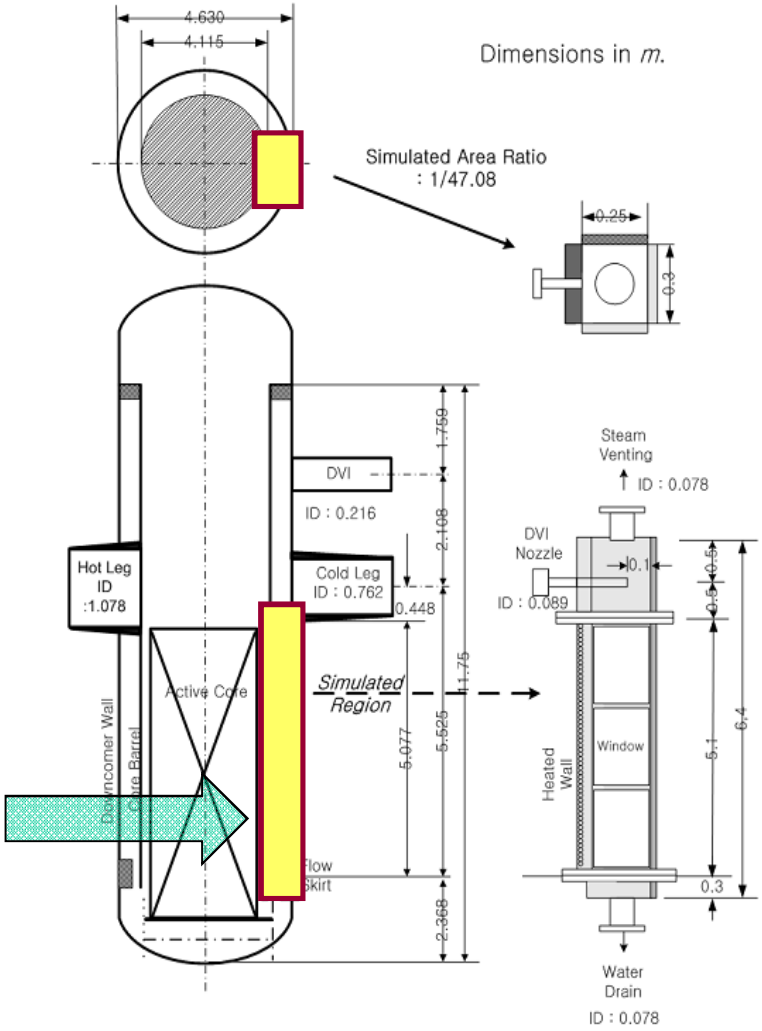
# CUPID: DOBO Analysis (1)

**DOBO Experiment KAERI**



**Downcomer Boiling**



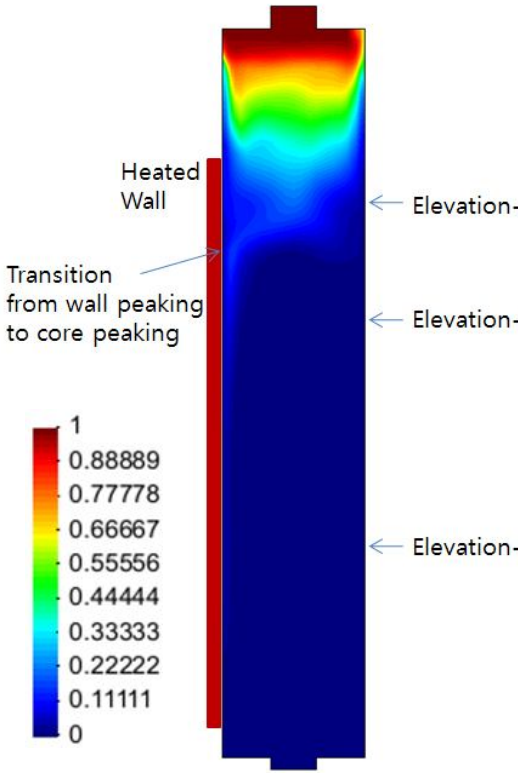


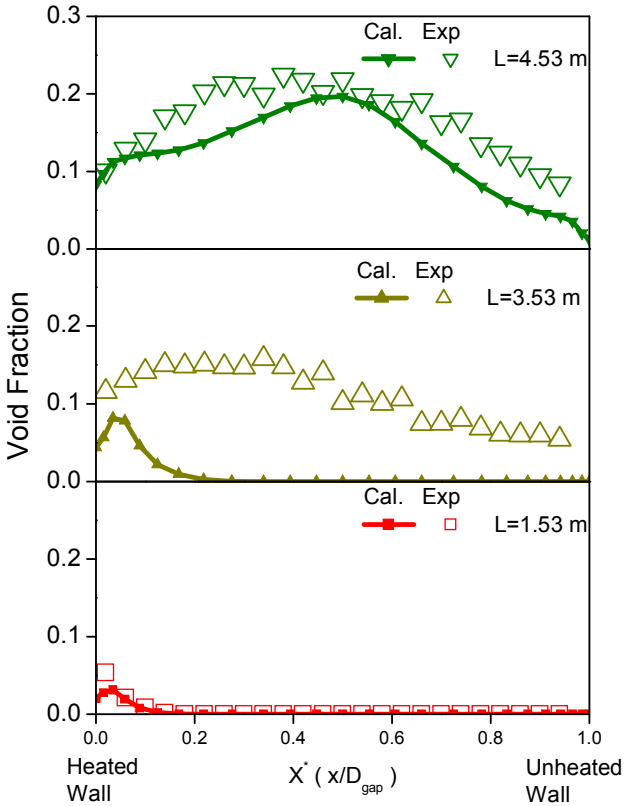
# CUPID: DOBO Analysis (2)

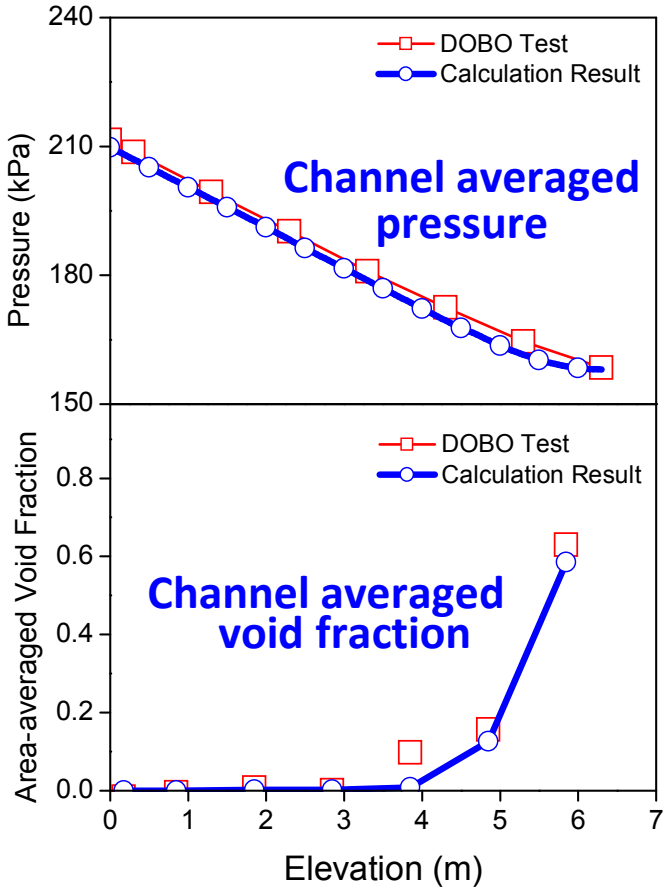
## Void fraction

- Transition from wall peaking to core peaking

- DP estimation error < 5%
- The error is about 100% with a system analysis code



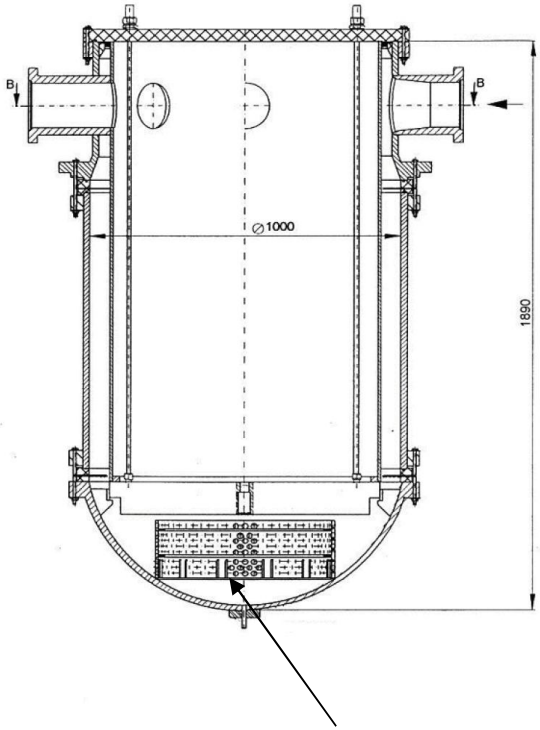



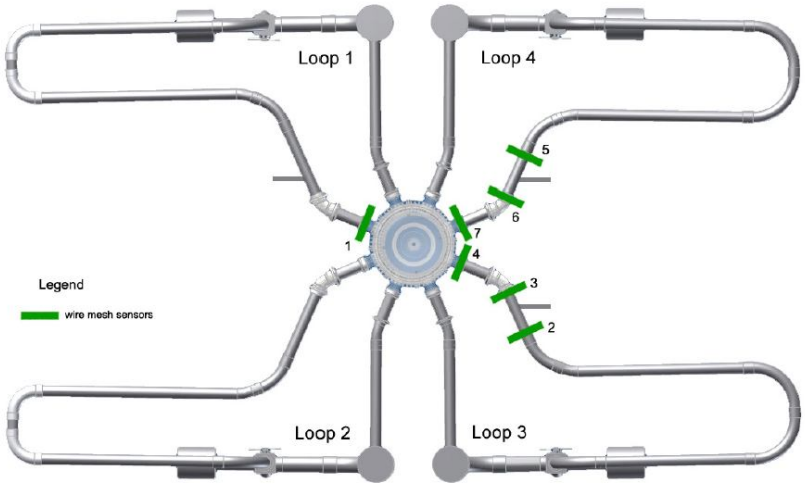


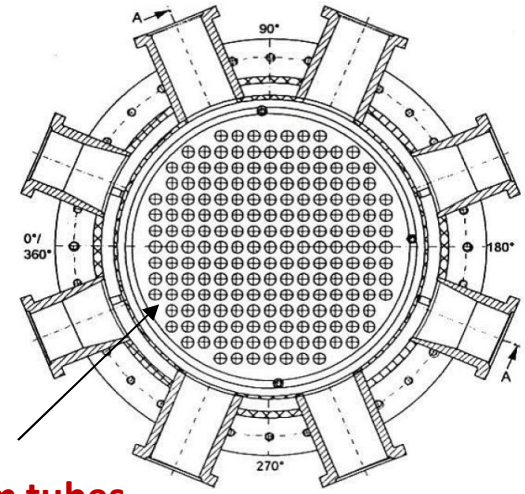

** Cho et al., Journal of Nuclear Science and Technology, 2012.*

# CUPID: ROCOM Analysis (1)

- ROCOM (ROssendorf COolant Mixing)
  - OECD PKL 2 Project
    - PKL test: fast cool down transient
    - ROCOM: coolant mixing in RPV
  - Overview of ROCOM
    - German KONVOI type PWR (1:5 length scale)
  - IAEA/CRP Benchmark 해석 참여 (2017)




193 aluminum tubes

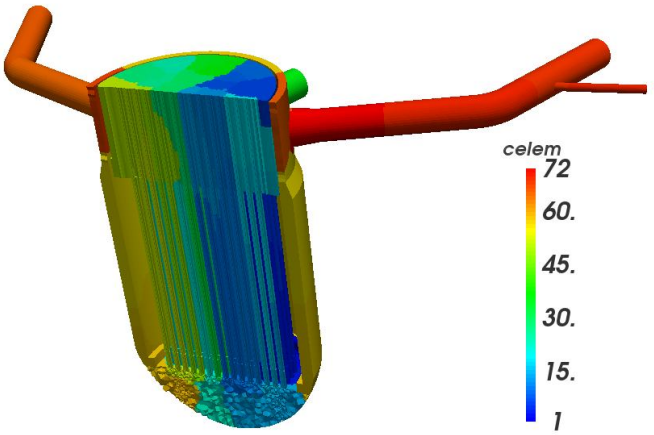
Sieve drum

# CUPID: ROCOM Analysis (2)

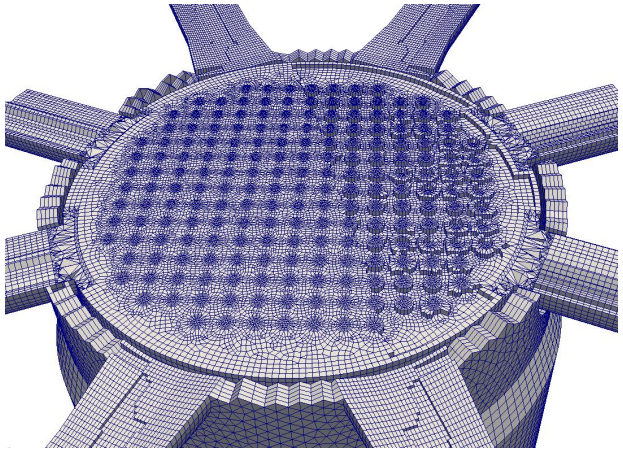
## ❑ Grid Generation

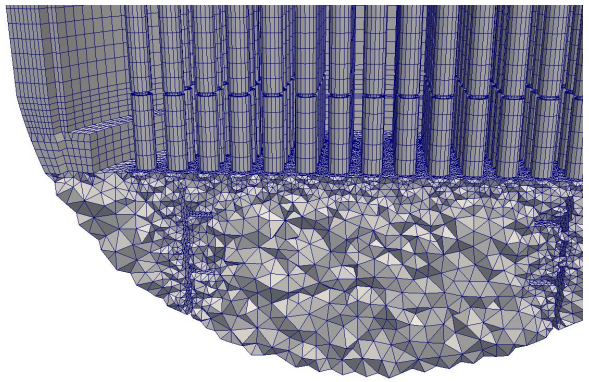
- *SALOME* (open source software)
- Developed by CEA/DEN, EDF R&D and OPEN CASCADE
- SALOME 7.7.1 (Current version = 7.8.0)
- Hexahedron + Tetrahedron:

  *3,434,527 cells*



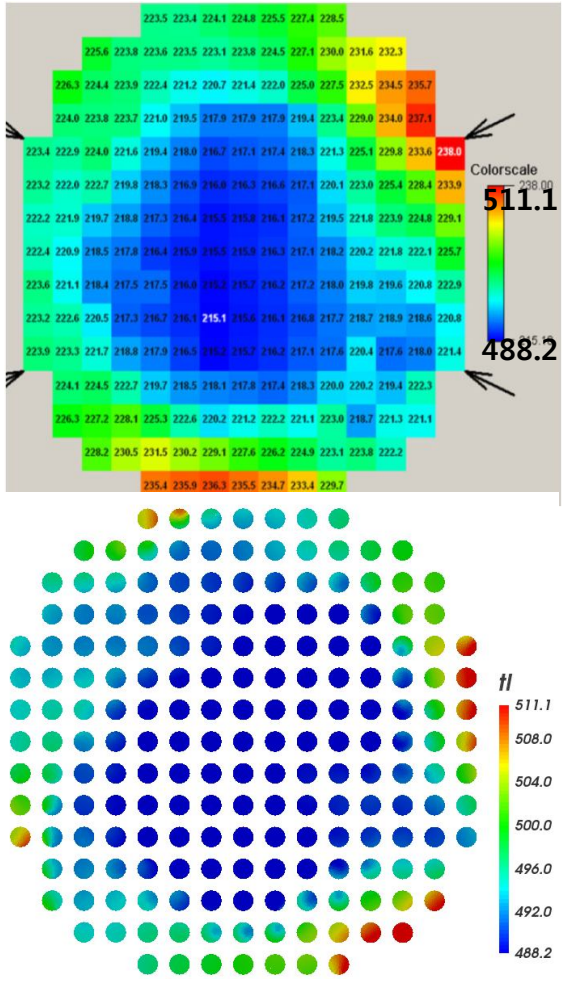

72 CPUs used



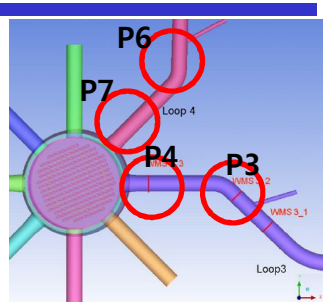


# CUPID: ROCOM Analysis (3)

- Temperature field in core inlet

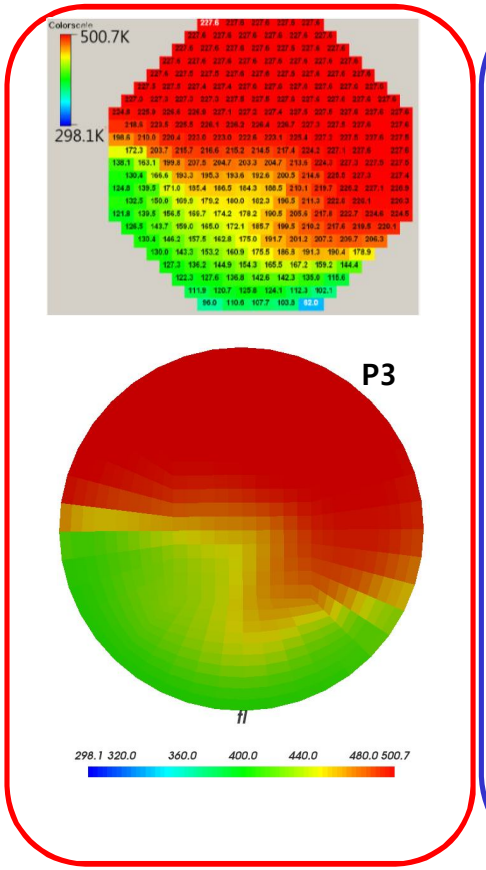



- Temperature field in cold leg

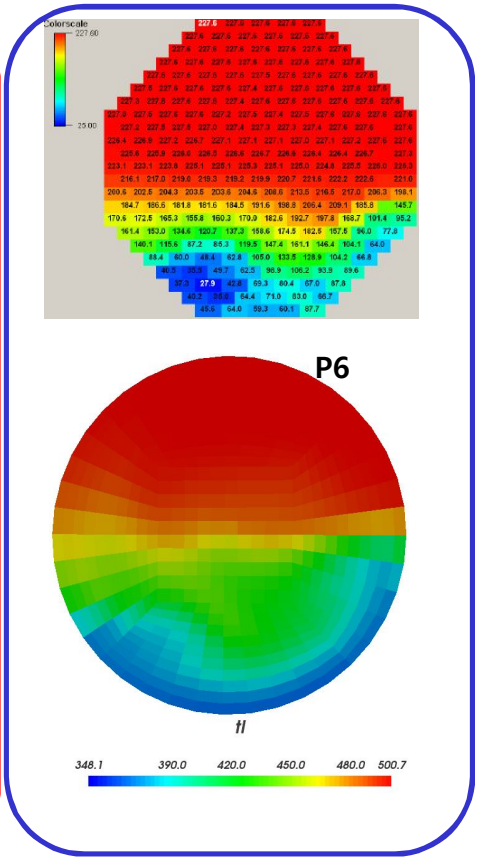



ROCOM

CUPID




Loop3(High flow rate)

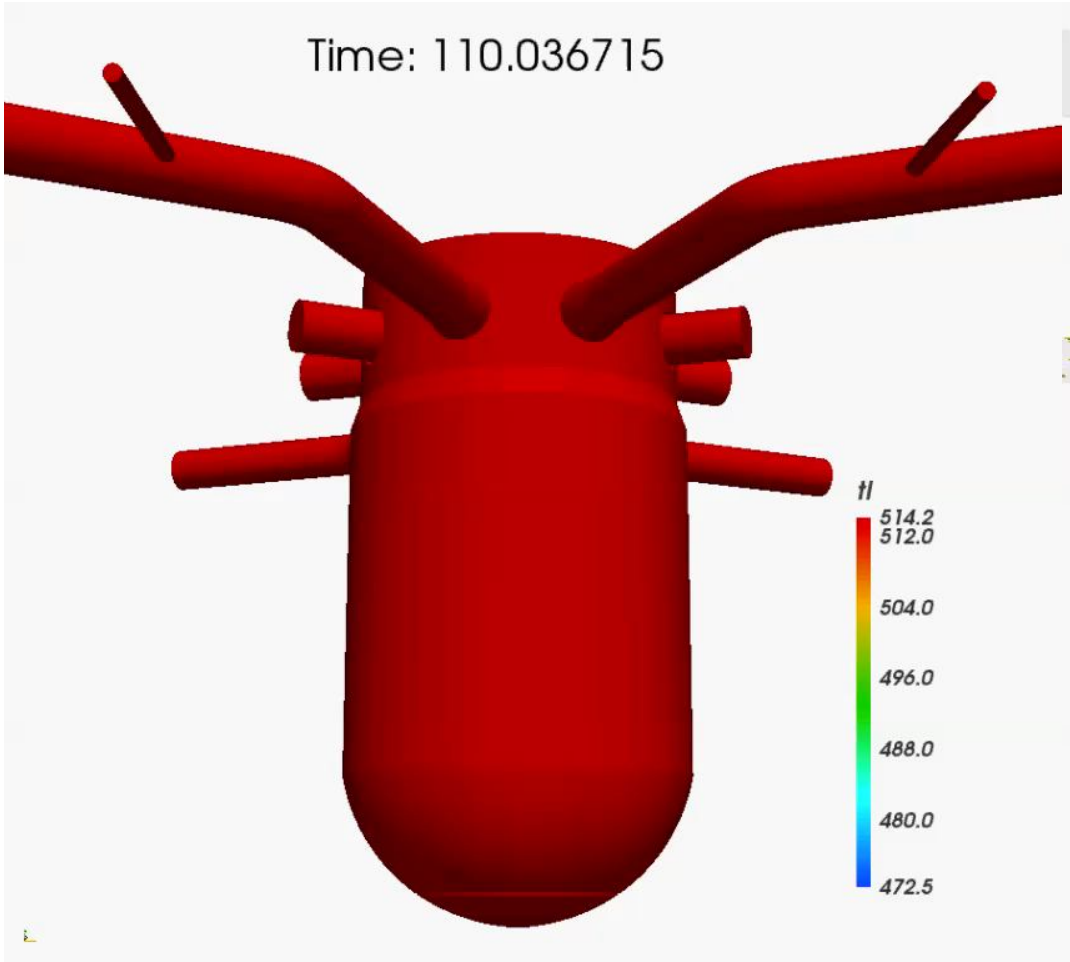



Loop4(Low flow rate)

# CUPID: ROCOM Analysis (4)

## ❑ Transient Calculation (T2.1)

- **Cold leg injection (110s to 270s)**




# CUPID (SeoulTech): OECD/NEA PSI IBE-4 (1)

## ❑ The *GEMIX* (GEneral MIxing eXperiment) Exercise of PSI

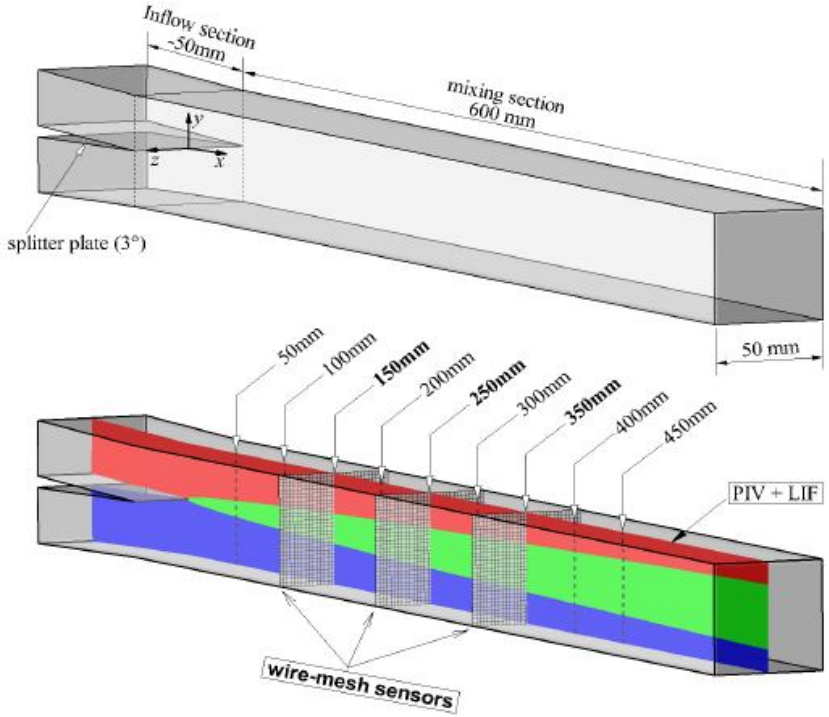



**Table 2.** Experimental matrix for this benchmark.

| Inlet mean velocity | 0.6 m/s | 1 m/s |
|---|---|---|
| Global Re-number | 30000 | 50000 |
| $\Delta\rho = 0\%, \Delta T = 0K$ | N339 | N337 |
| $\Delta\rho = 1\%, \Delta T = 5K$ | N320 | **N318** |

## ❑ 13 submissions

### CFD-CODE

| | |
|---|---|
| ANSYS (CFX) | 3 |
| ANSYS (FLUENT) | 2 |
| STAR-CCM | 2 |
| Code_Saturne | 2 |
| CUPID | 1 |
| TrioCFD | 1 |
| P2REMICS | 1 |
| OpenFOAM | 1 |

### TURBULENCE MODEL

| | | |
|---|---|---|
| k-eps | 7 | CUPID |
| k-omega | 4 | |
| LES | 2 | |
| RSM | 1 | |

### Number of grid

| | | |
|---|---|---|
| | 59850 (2D) | ← *minimum* |
| CUPID | 156260 | |
| | 300000 | |
| | 20644596 | ← *maximum* |
| | 3696000 | |
| | 5753458 | |
| | 3596992 | |
| | 675168 | |
| | 712704 | |
| | 62418 (2D) | |
| | 1637784 | |
| | 652320 | |
| | 813276 | |

# CUPID (SeoulTech): OECD/NEA PSI IBE-4 (2)

## ❑ Ranking for *concentration*

| | User | FoM | Ranking |
|---|---|---|---|
| | 1 | 3.074881 | 1 |
| | 2 | 6.414524 | 5 |
| | 3 | 6.179881 | 4 |
| | 4 | 9.228452 | 12 |
| CUPID | 7 | 7.380238 | 9 |
| | 9 | 5.467262 | 3 |
| | 10 | 6.859762 | 6 |
| | 11 | 8.697976 | 10 |
| | 15 | 7.086429 | 8 |
| | 16 | 6.982024 | 7 |
| | 18 | 9.715 | 13 |
| | 19 | 5.013929 | 2 |
| | 20 | 8.899643 | 11 |

## ❑ Ranking for *thickness of mixing layer*

| | user | FoM | Ranking |
|---|---|---|---|
| | 1 | 0.031418 | 2 |
| | 2 | 0.186935 | 7 |
| | 3 | 0.02999 | 1 |
| | 4 | 0.476981 | 13 |
| CUPID | 7 | 0.156025 | 6 |
| | 9 | 0.09458 | 5 |
| | 10 | 0.069638 | 4 |
| | 11 | 0.274574 | 11 |
| | 15 | 0.203641 | 8 |
| | 16 | 0.215331 | 10 |
| | 18 | 0.294725 | 12 |
| | 19 | 0.033593 | 3 |
| | 20 | 0.213123 | 9 |

## ❑ Ranking for *mean velocity*

| | User | FoM | Ranking |
|---|---|---|---|
| | 1 | 4.727778 | 3 |
| | 2 | 6.477778 | 5 |
| | 3 | 4.627778 | 2 |
| | 4 | 8.522222 | 10 |
| CUPID | 7 | 9.033333 | 11 |
| | 9 | 4.844444 | 4 |
| | 10 | 7.155556 | 7 |
| | 11 | 7.966667 | 9 |
| | 15 | 6.811111 | 6 |
| | 16 | 9.072222 | 12 |
| | 18 | 9.7 | 13 |
| | 19 | 4.422222 | 1 |
| | 20 | 7.638889 | 8 |

## ❑ Ranking for *turbulent kinetic energy*

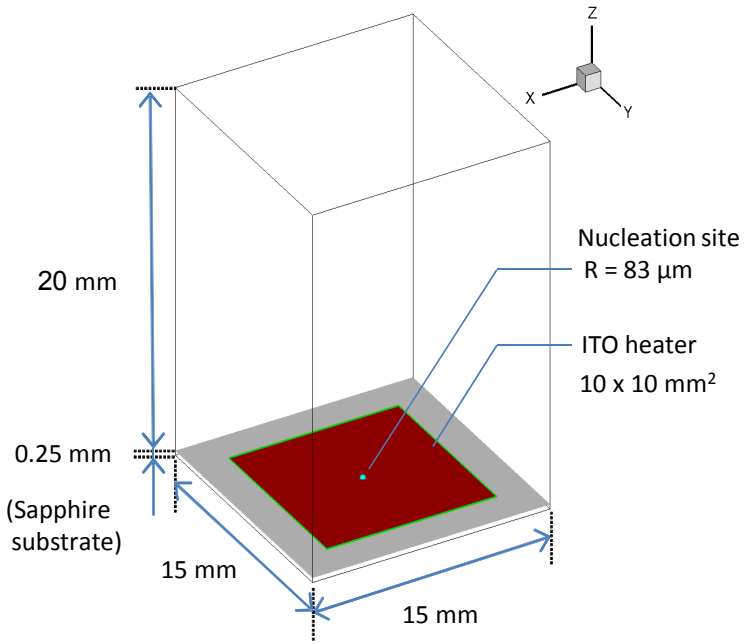
| | user | FoM | Ranking |
|---|---|---|---|
| | 1 | 3.867411 | 2 |
| | 2 | 6.002381 | 6 |
| | 3 | 3.463244 | 1 |
| | 4 | 6.352827 | 7 |
| CUPID | 7 | 4.662649 | 4 |
| | 9 | 4.86622 | 5 |
| | 10 | 11.21324 | 12 |
| | 11 | 12.31548 | 13 |
| | 15 | 6.523958 | 8 |
| | 16 | 4.401786 | 3 |
| | 18 | 10.81458 | 11 |
| | 19 | 7.109226 | 9 |
| | 20 | 9.406994 | 10 |

# PSI-Boil: DNS of Boiling (1)

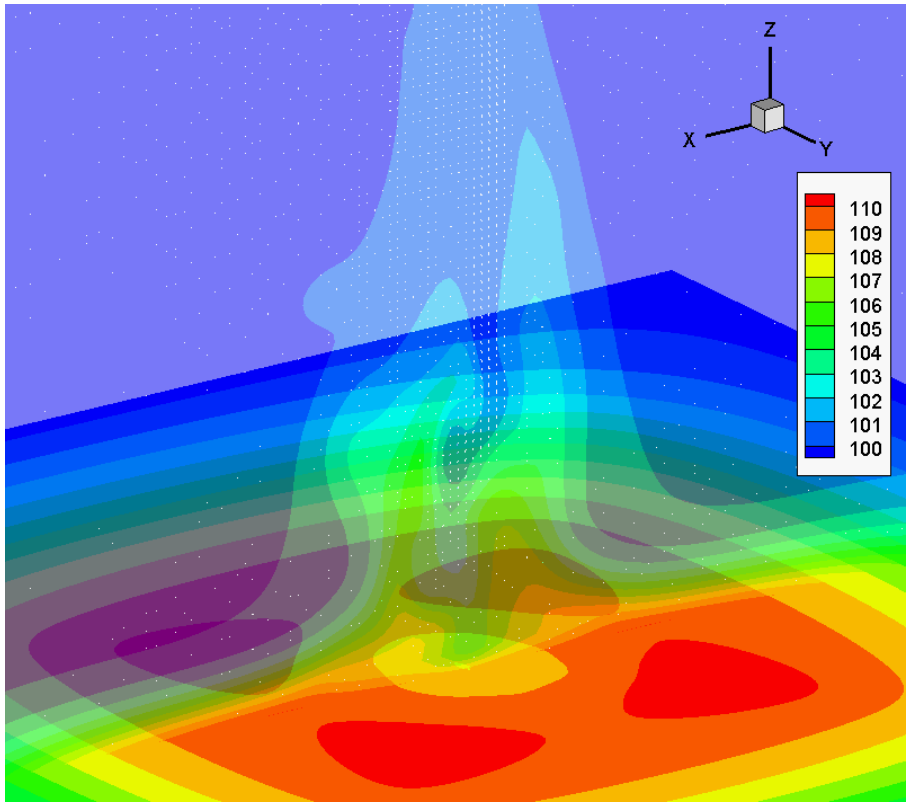
## Pool Boiling from Single Nucleation Site

### ❒ Simulation results

- **Grid: 76x176x224 (~3M)**
- **Δ=62.5 microns**

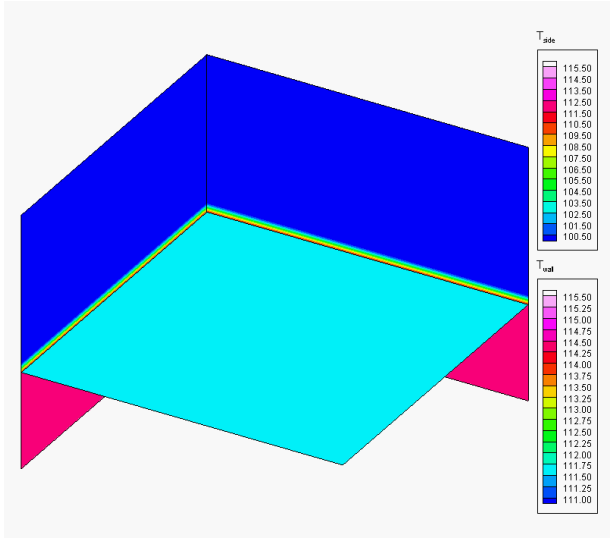



***Computational domain***

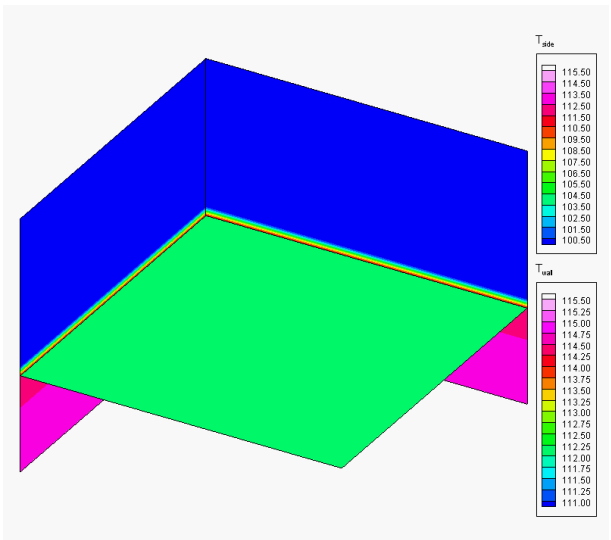



***Evolution of th 12th bubble: chromatic colors are temperature, gray is the bubble interface***

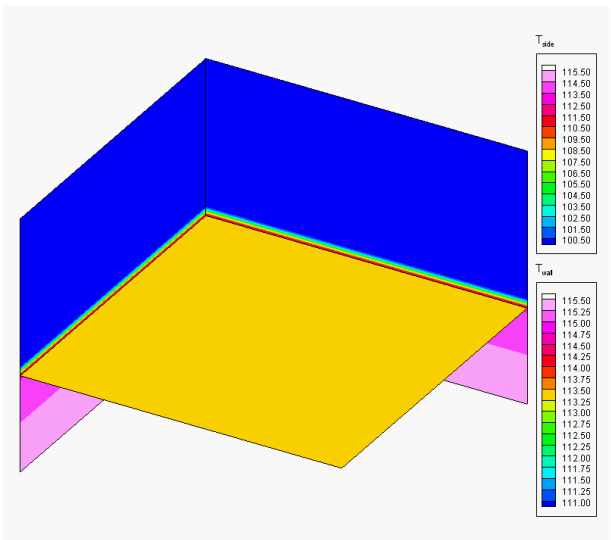
# PSI-Boil: DNS of Boiling (2)



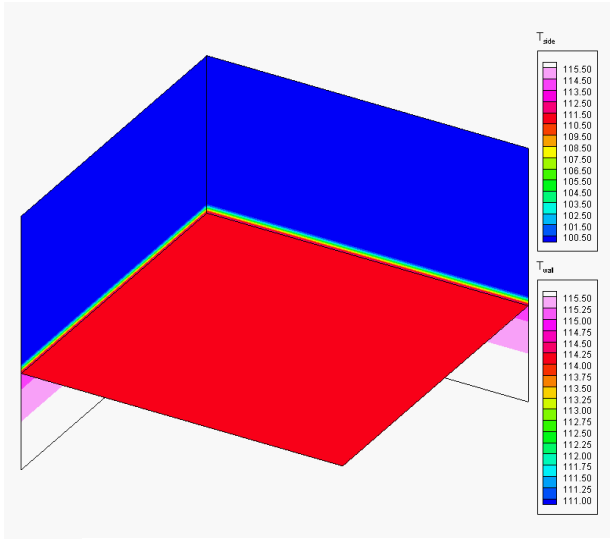
50*kW/m²*



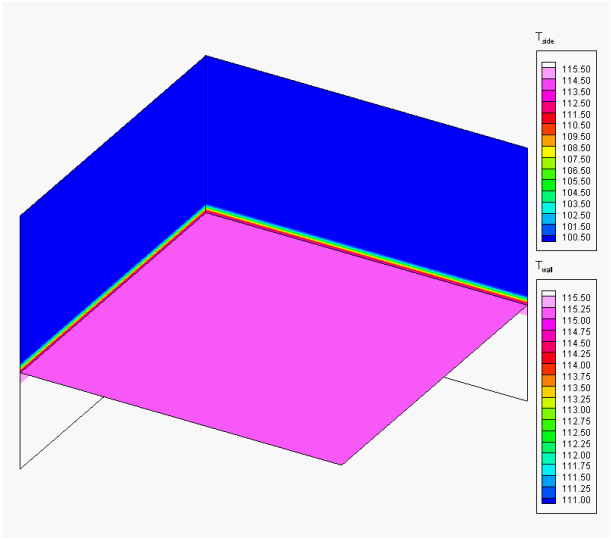
100*kW/m²*



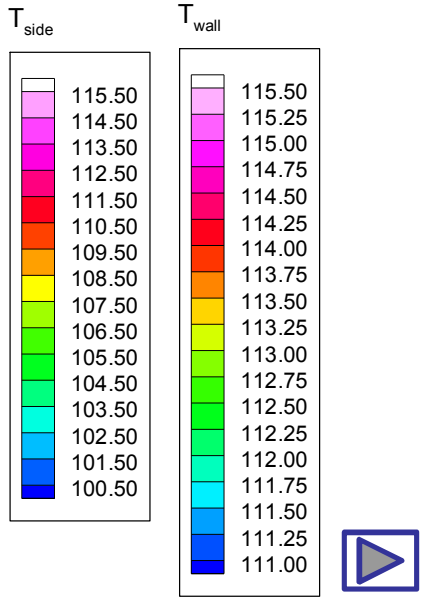
150*kW/m²*



200*kW/m²*

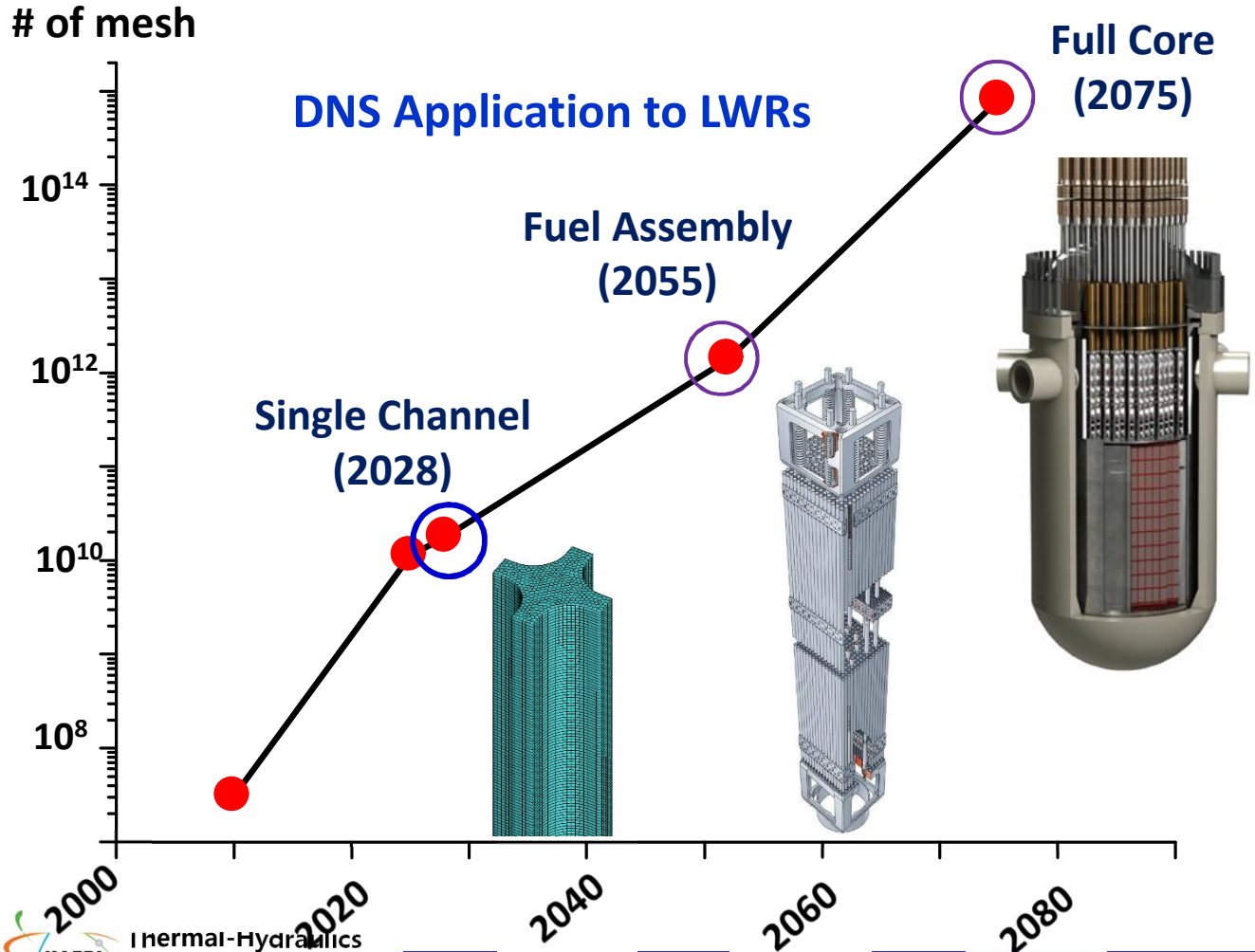


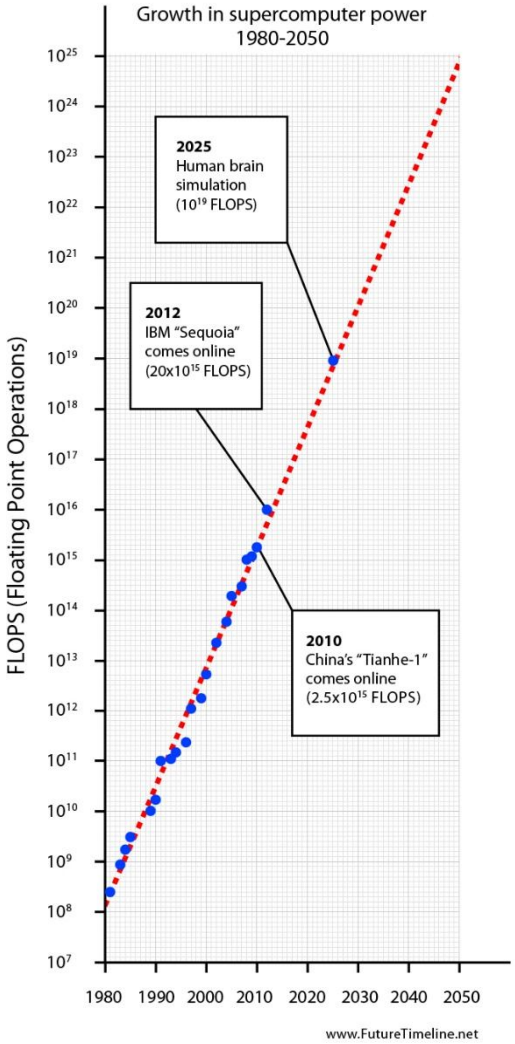
300*kW/m²*



# CFD/DNS Scale TH Analysis – *Single-phase*

- CFD codes based on *RANS* has been used for *component design*
- *LES and DNS* have been developed, but these are *not matured* for industrial applications

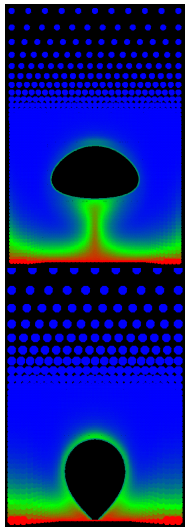


# CFD/DNS Scale TH Analysis – *Two-phase*

- Two methods for two-phase flows
  - *CFD-scale*: Time-averaged *two-fluid model*
  - *DNS-scale*: Single-phase CFD plus *interface tracking method*
- Limited application to bubbly, mist, and stratified flows
- *Development of interface models and systematic validation* are needed

| | 1-phase CFD/DNS | 2-phase CFD/DNS |
|---|---|---|
| DNS | ○ | △ (Pseudo-DNS) |
| Phase change | X | ○ |
| Validation of Physical Models | ○ | △ |
| Major Uncertainty | Turbulence Models | Phase Interface Models |
| Design Applications | ○ | △ |



*DNS for Subcooled Nucleate Boiling*

** Yoon et al., Int. J. Multiphase Flow, 1999*

I. 원전다중스케일 열수력 해석 개요

II. 국외 원전 모델 및 시뮬레이션 현황

## III. 국내 다중스케일 열수력 해석 현황

1. 계통스케일 해석

2. 기기 스케일

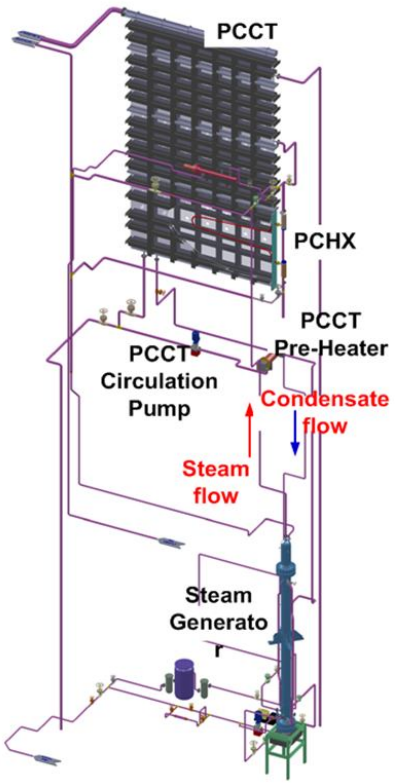
3. CFD 스케일 해석

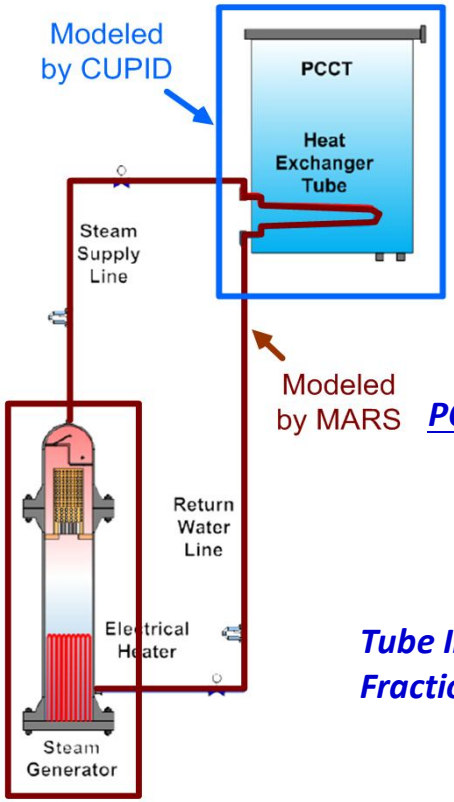
4. **다중스케일 연계 해석**

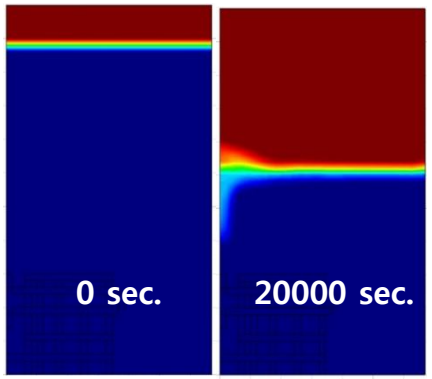
IV. 향후 연구 개발 전략

# CUPID-MARS: APR+ PAFS 해석

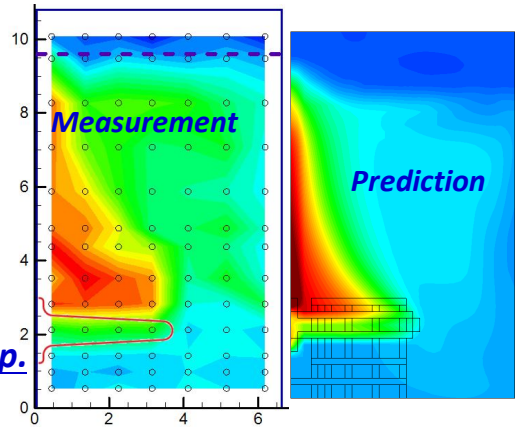
- ***Simultaneous application*** **of** ***component*** **and** ***system*** **scales (*CUPID-MARS* coupling)**
- **Single- and two-phase *natural circulation* in the Passive Containment Cooling Tank (*PCCT*)**
  - ***PASCAL***



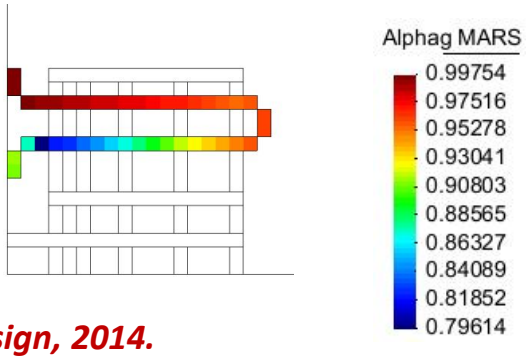




***PCCT Water Level (CUPID)***




***PCCT Liquid Temp. (CUPID)***

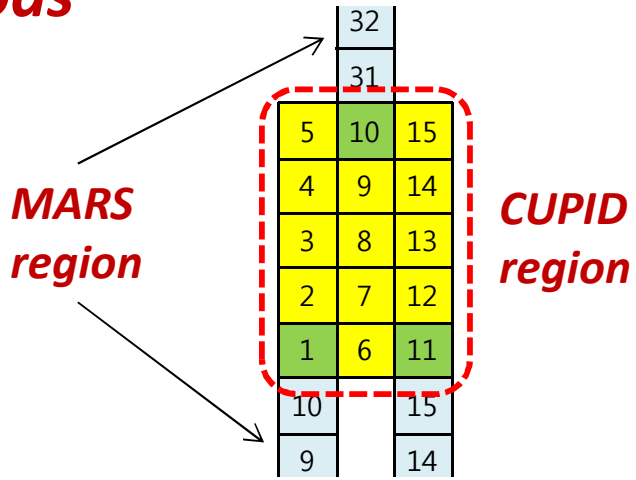


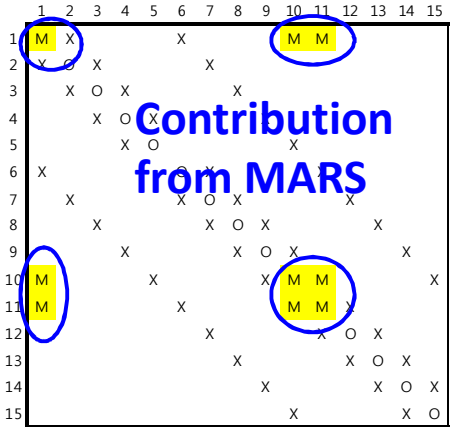

***Tube Inside Void Fraction (MARS)***

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

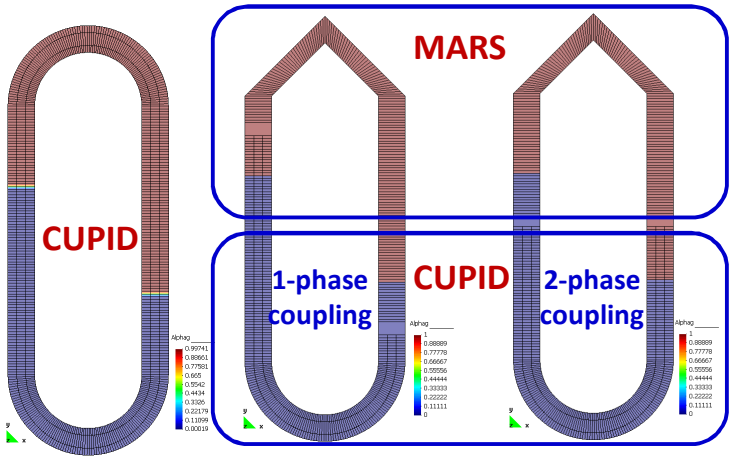
# CUPID-MARS : Flow Field Coupling

- **Provides two different *coupling methods***
  - ***Heat Structure Coupling*** **(Explicit) :**
    **APR+ PAFS simulation (Previous slides)**
  - ***Flow Field Coupling*** **(Implicit)**
    ***Pressure Matrices are Merged***

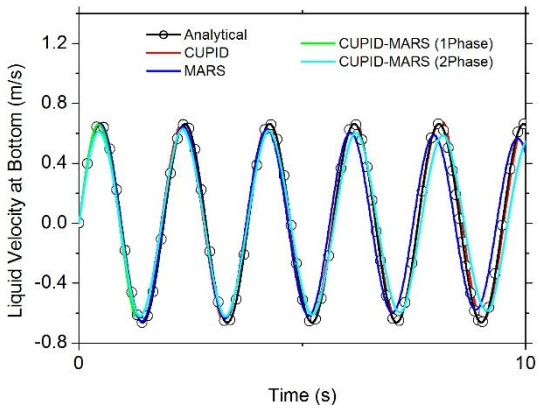



***Pressure matrix of CUPID***




**Verification of implicit coupling**




**** Park et al., ANE, 2013.***

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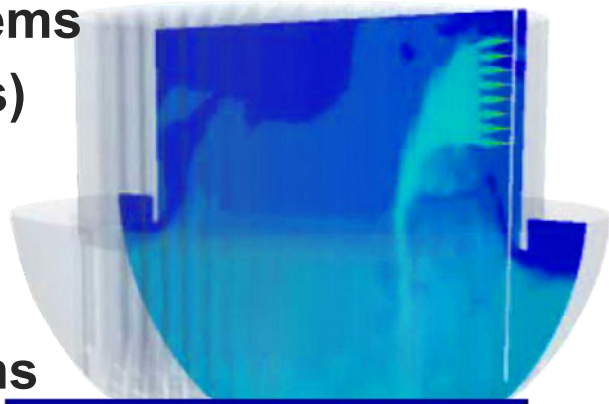
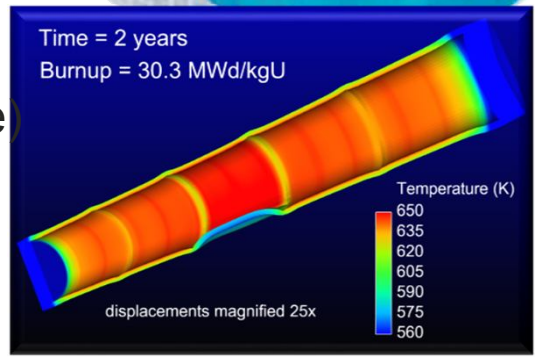
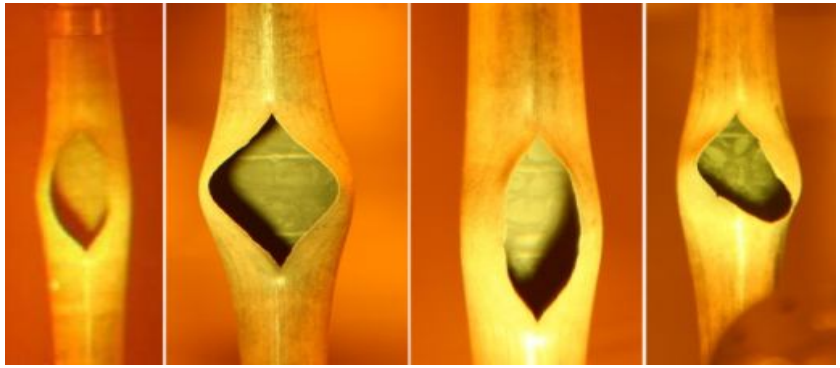
## IV. 향후 연구 개발 전략

# Plans for CASL Phase 2 (2016~2020)

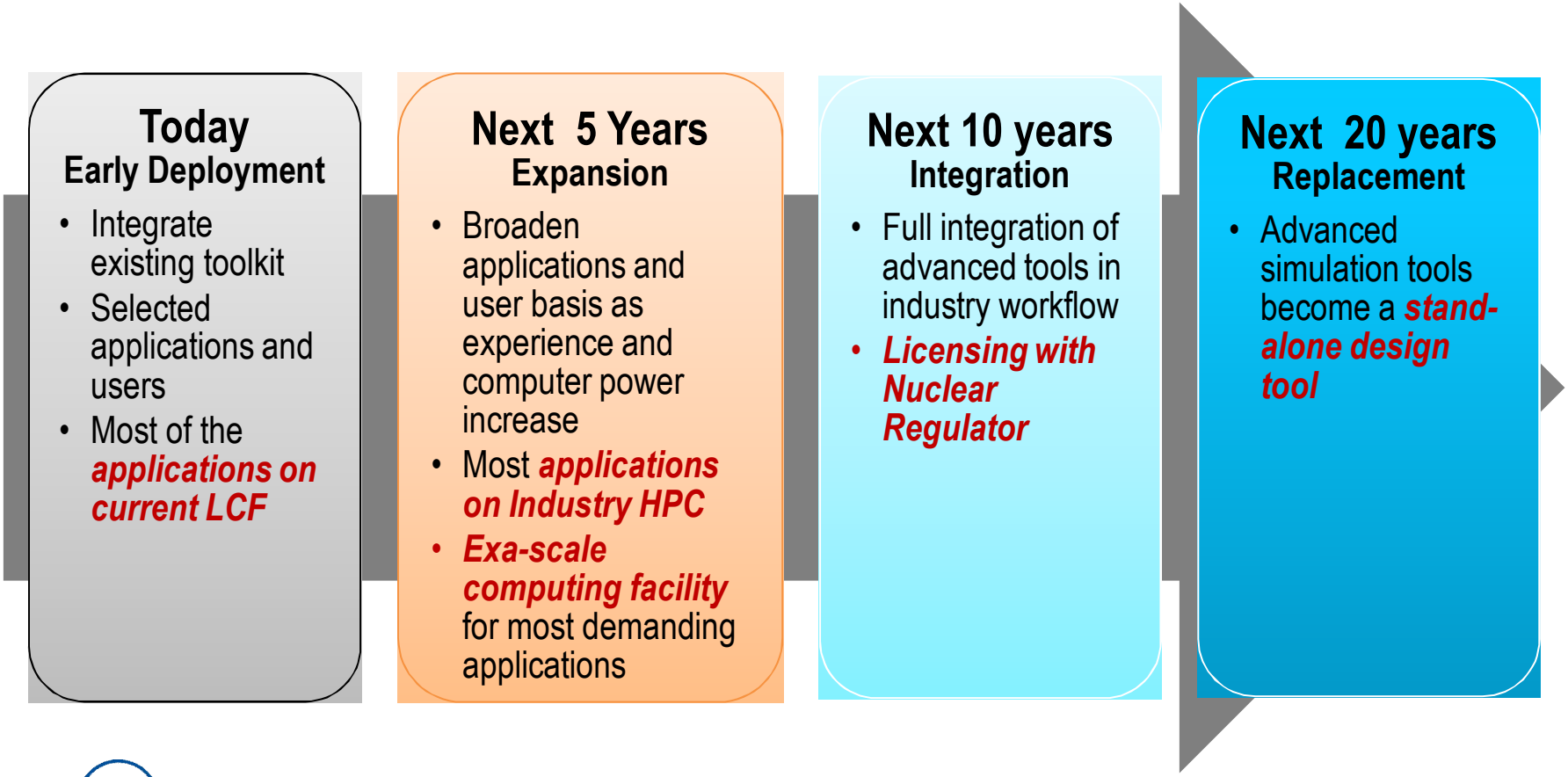
- ***Expand capabilities*** **for PWR Challenge Problems**
- **Extend and apply capabilities to SMRs (iPWRs)**
  - Natural circulation
  - DNB in low-flow conditions
  - CRUD for long-cycle operations
- **Extend capabilities to BWR challenge problems**
  - Thermal-hydraulic flow regimes
  - Core simulation (sub regions and potentially full core)
  - Fuel performance – PCI, cladding integrity
  - Convective and solute flows and mixing
- ***Continued releases*** **and deployment to potential end users**





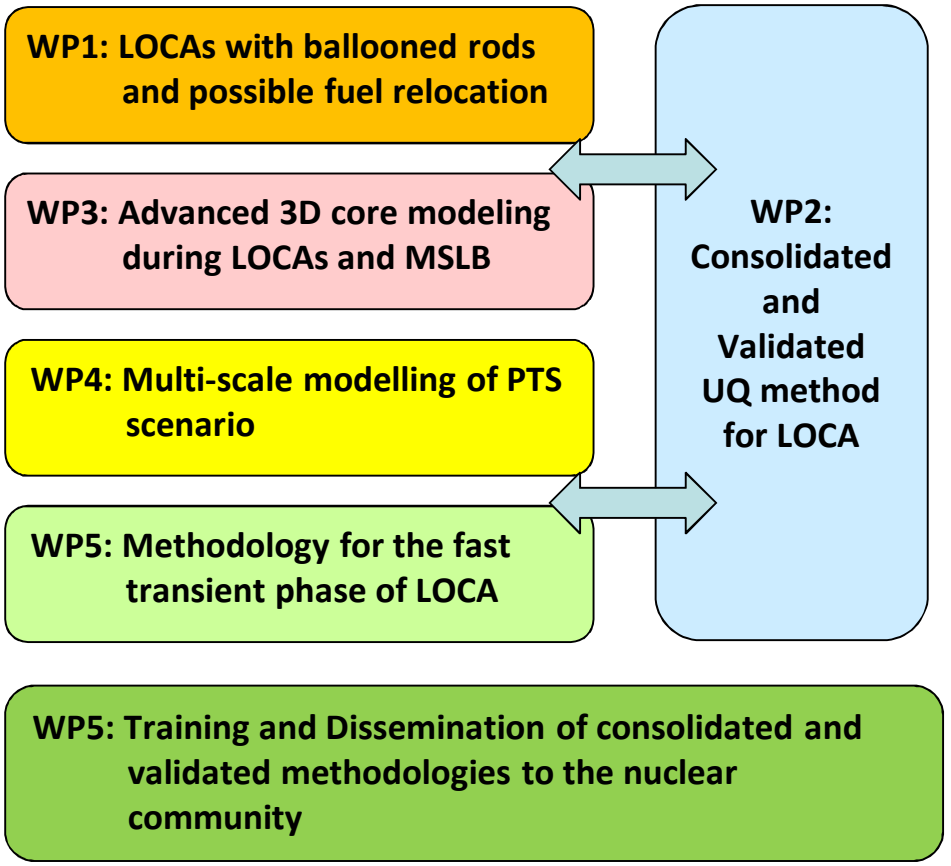
# Path Envisioned for Advanced Simulation Tools (CASL)




Westinghouse

# SOCRATES (EU NURESIM 차기 프로젝트)

- 3 year project
- 3* 10 MY
- 4.2 M€ (3.5 M€ requested to EU)
- 10 partners
- CEA coordinator
- Submitted Oct. 5th
- Possible kickoff in Sept. 2017
- Collation with KAERI



# 다중 스케일 열수력 해석기술 개발 전략

## ❒ 안전해석

- *기기스케일* 원자로 3차원해석
  - ✓ 원자로심, 강수부, Lower/Upper Plenum
  - ✓ *격자 수 100만개 내외*
  - ✓ 계통연계를 통한 *3차원 LOCA 해석*
- 기기스케일 격납건물 해석

## ❒ 성능해석

- *기기+CFD 스케일* 원자로 해석
  - ✓ *가상원자로* 적용
  - ✓ 봉 단위 해석
  - ✓ 단상 및 sub-cooled 비등
  - ✓ *격자 수 1억개 내외*