Evaluation of Applicability and Limitations of Existing Scaling Techniques: Experiences from ROK

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EASI-SMR Workshop on Scaling Issues

Chul-Hwa SONG

KAERI Retired; Prof. Emeritus, UST

chsong@ust.ac.kr
chs7266@gmail.com

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- BEPU: Best-Estimate Plus Uncertainty
- WCR: Water-cooled Reactor
- WC-SMR: Water-cooled SMRs

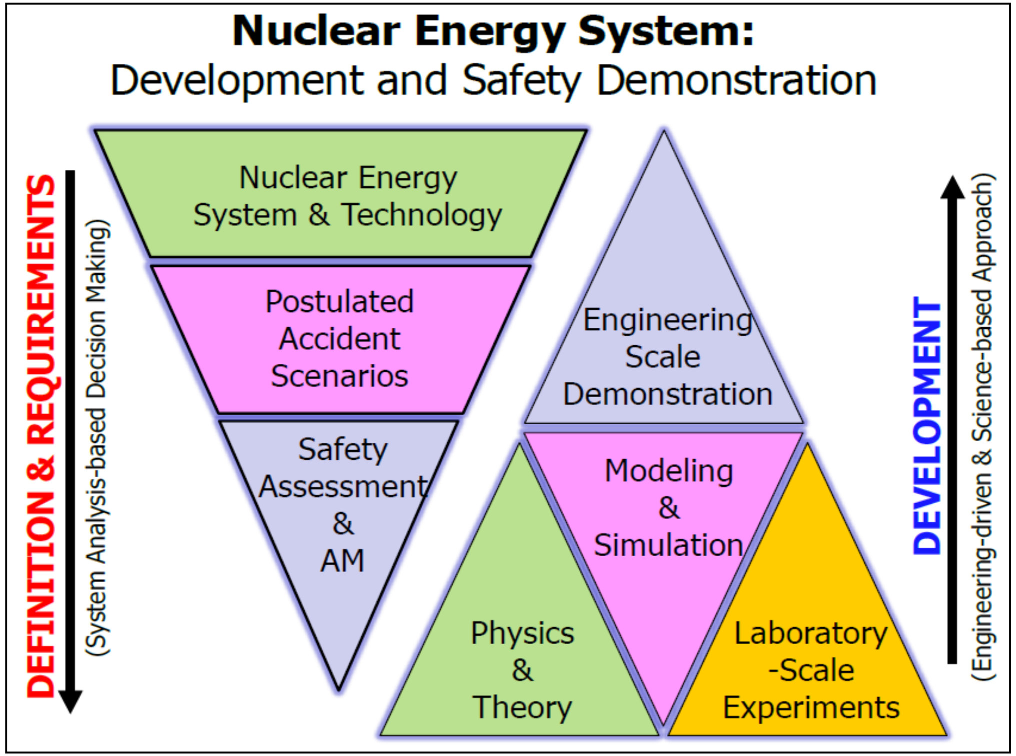
I. Introduction

- Scalability of Validation Data
- Current Status of NRTH Analysis
- EMDAP and Scaling-related Concerns

Nuclear Reactor TH Analysis – Key Features

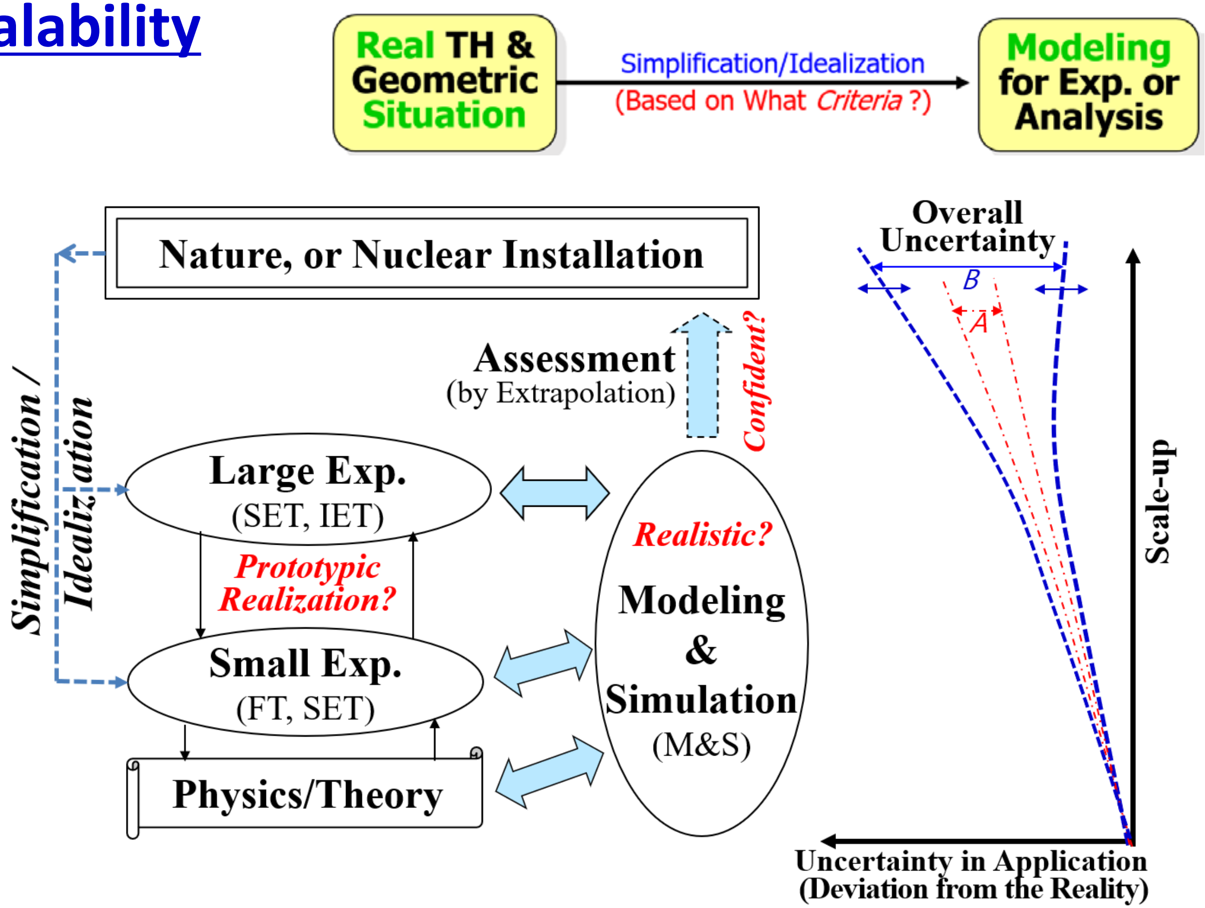
- Issues on Performance and Safety Analyses – Scalability and the Uncertainty

Safety Demonstration



* C.-H. Song @NURETH-15, and ANS2019AM

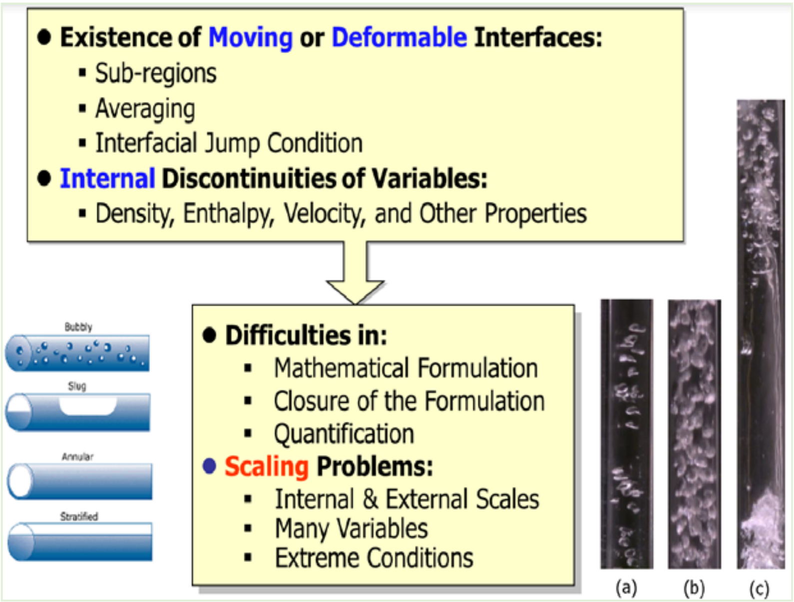
Scalability



* C.-H. Song @FJOH-2018, and @NURETH-21

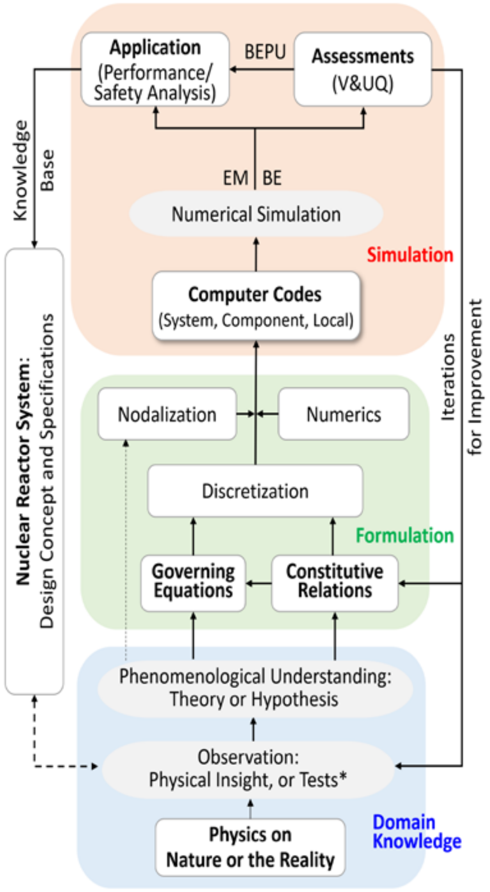
Source of Uncertainties in Two-Phase Flow M&S

- **Complexity of Two-phase Flow with Phase Change**



* C.-H. Song, Lecture in UST/CNU

- **Various Sources of Uncertainties in Each Step**



Characterization of Nuclear Reactor Thermal–Hydraulics Analysis Procedures

Table 1. Sources of uncertainty in nuclear reactor TH analysis

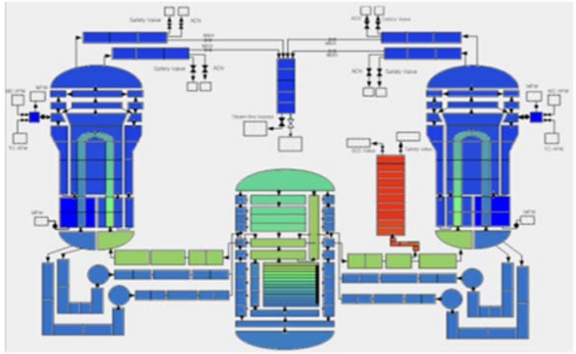
No.	Step	Uncertainty Group	Uncertainty Sources	Relevance* [H/M/L]
1A	Physical Domain Knowledge	Model Uncertainty	Idealization & Simplification	H
			Unmodelled Processes	H
			Closure laws	H
			Correlations	H
1B		Scaling Uncertainty	Non-prototypic Conditions	H
			Scaling Distortions	M
			Experimental Uncertainties	L
2A	Mathematical & Physical Formulation	Model Parameters	Plant configurations	M
			System geometry	H
			Material properties	M
2B		Initial & Boundary Conditions	Initial system condition	M
			Internal energy sources	M
			External heat transfer	H
			Inflow and outflow	H
3A	Numerical Simulation	Numerical Uncertainty	Discretization errors	M
			Convergence	L
			SW defects	L
			Nonlinearity or Chaotic Behavior	L
3B		User Uncertainty	Benchmark & validation gaps	H
			Subjective interpretation	M
			Documentation & training gaps	L

* Relative relevance to the scalability of M&S to a prototypic situation

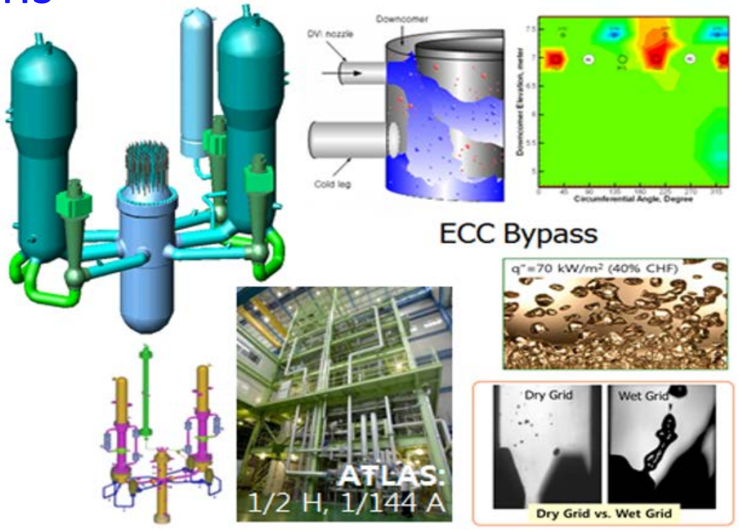
* C.-H. Song et al., NURETH-21

Nuclear Reactor TH Analysis – Current Status

- **Best-Estimate Plus <u>Uncertainty</u> (BEPU) Analysis**
  - B.E. Analysis: Validated against Experimental DB (SETs, IETs)
  - Uncertainty Analysis: to Quantify Uncertainties
- **Relying mostly on <u>System-scale</u> TH (SysTH) Analysis Tools**
  - Adopt mostly 1-D Approach, Relying mostly on Empirical Models
  - Handle mainly Single Physics only: [ex] Pure TH's
  - Provide Information with Limited Spatio-Temporal Resolutions
  - Validated against DB: Good enough, or rather limitedly ?
    - Scalable, Prototypic ? → Generally applicable, Extrapolating to real scale ?
- **<u>Advanced</u> Analysis Tools Developed for WCR Safety: Various Types Being Attempted**
  - LP 1-D Model → Subchannel Model → CFD → CMFD
    - Coupling among Different Codes: MS&MP Analysis
  - Machine Learning Application to WCRs



System-scale T-H Simulation



EMDAP: Relevance to Scalability

- **EMDAP* (2005, NRC)**
  - A procedure to evaluate adequacy of the applied codes
  - Guidance for continued development of experimental data and analytical tool.
  - Emphasis of Scaling, Similarity, Scalability

- **On the Adequacy of Traditional Strategy:**
  - SysTH code has been utilized to evaluate and assess in EMDAP for providing input for scaling analysis in EMDAP. (Dzodzo)

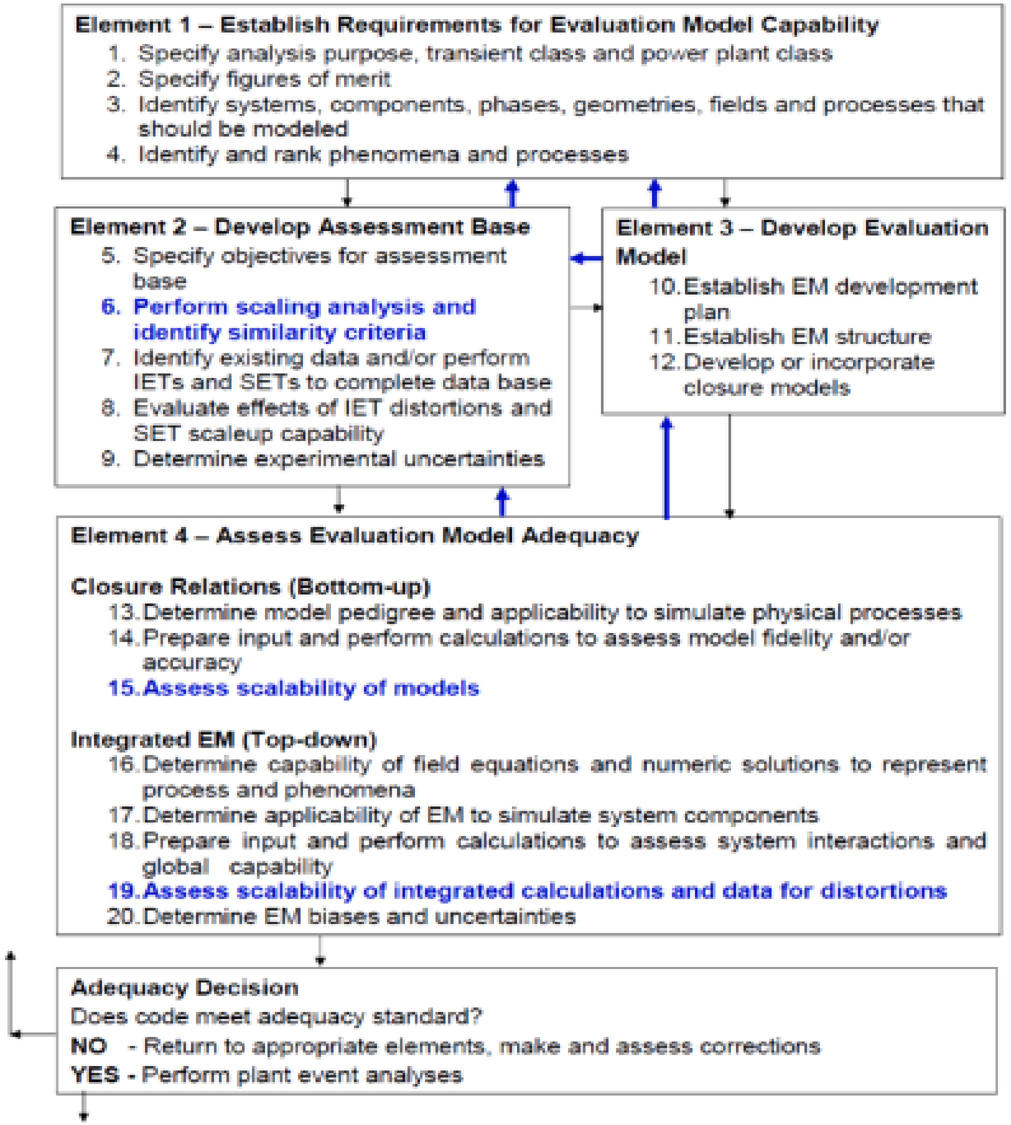


Fig. 4. The Evaluation Model Development and Assessment Process (EMDAP) flow chart.

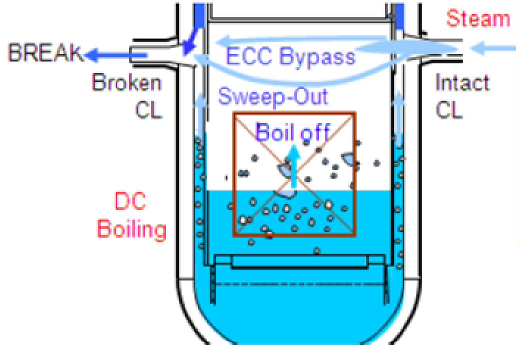
* EMDAP: Reg. Guide 1.203, NRC (2005)

II. Adequacy of Validation Data for WCR TH Safety

- Some Classical TH Issues
- Multi-D TH Phenomena

Classical Pain-taking Issues – Examples*

- **‘Semi-scale’ Tests**
  - USA, early ‘70s
  - IET for LOCA:
    - Height scale: 1/1
    - Area scale: ~1/1600
    - P/T: Prototypic
  - ~90% of ECC bypass observed in the tests
    - Leading to hot discussion on the ECCS effectiveness in ‘70s
      - Induced distrust on ECC
      - Non-disclosed data for a while



ECC Bypass

Mainly Originating from Failing to Reveal or Predict Multi-D Phenomena in RV Downcomer !!

- **‘Downcomer Boiling’ Issue**
  - Common Licensing Issues on PWR
  - LB-LOCA Reflood Phase
    - Higher void fraction estimated and measured previously
      - Leading to smaller hydro-static head in the RV DC
    - Smaller ECC water flowing into the reactor core region previously
    - Higher fuel temperature (PCT) estimated/measured previously
  - Some Penalty Imposed to Many of Operating PWRs until recently

* C.-H. Song (Panel @ANS2019AM)
C.-H. Song et. al. (NURETH-21)

Critical TH Phenomena in LWRs

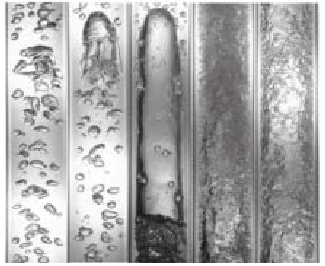
Table 6. Some critical TH phenomena in a typical WCNR

			Geometry		Pressure Effect	Multi-physics	Examples	Ref.
			Multi-D	Scale (D,L)				
ECC	LB-LOCA	ECC Bypass	●	●			RV D/C	
	"	Downcomer Boiling	●	●			RV D/C	
	"	Reflood HT & PCT	●	◐		●	Core, Fuel	
	SB-LOCA	Boil-off HT	◐		●	◐	Core, Fuel	
	SBO	Boil-off HT	◐		●	◐	Core, Fuel	
Mixing	"	TI-SGTR	●	◐	◐	●	HL, SG	
	LOCA	Heterogeneous Flow in Singularities	●	●			IL, HL, SG	
	Long-term cooling	Boiling-induced Pool Mixing	●	◐			PAFS, PRHRS	
	"	Condensation-induced Pool Mixing	●	◐			IRWST, CMT	
Two-Phase Flow Fundamental		Interfacial Area Concentration	◐	●	●		Confined, or Large Channel	
		Interfacial Friction	●	◐	●		"	
		Bubble-to-Slug Flow Regime Transition	●	●	●		"	
		Flashing-induced Instability	◐	●	◐		PRHRS, ADS-4	
		Parallel Channel Instabilities	●	◐	◐			

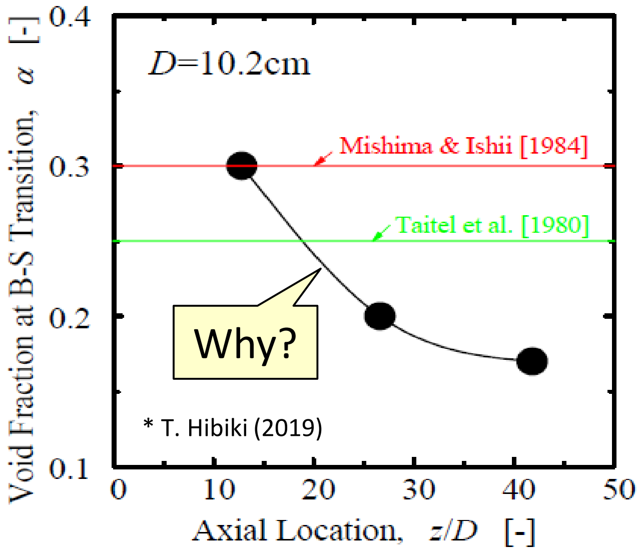
* C.-H. Song et al. (NURETH-21)

System Pressure Effects of Flow Regimes

- **Atmospheric : Most desk-top scale exp.**
- **Pressurized: KAERI (~'90)**
  - Bubble Size Effects on Two-Phase Flow Dynamics → 2-Fluid Modelling ?



(*Interfacial transfer term*) ~ a_i × (*Driving force*)



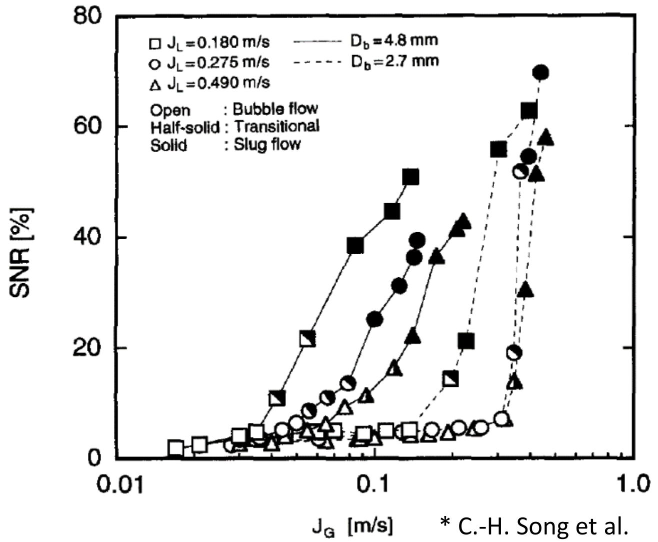
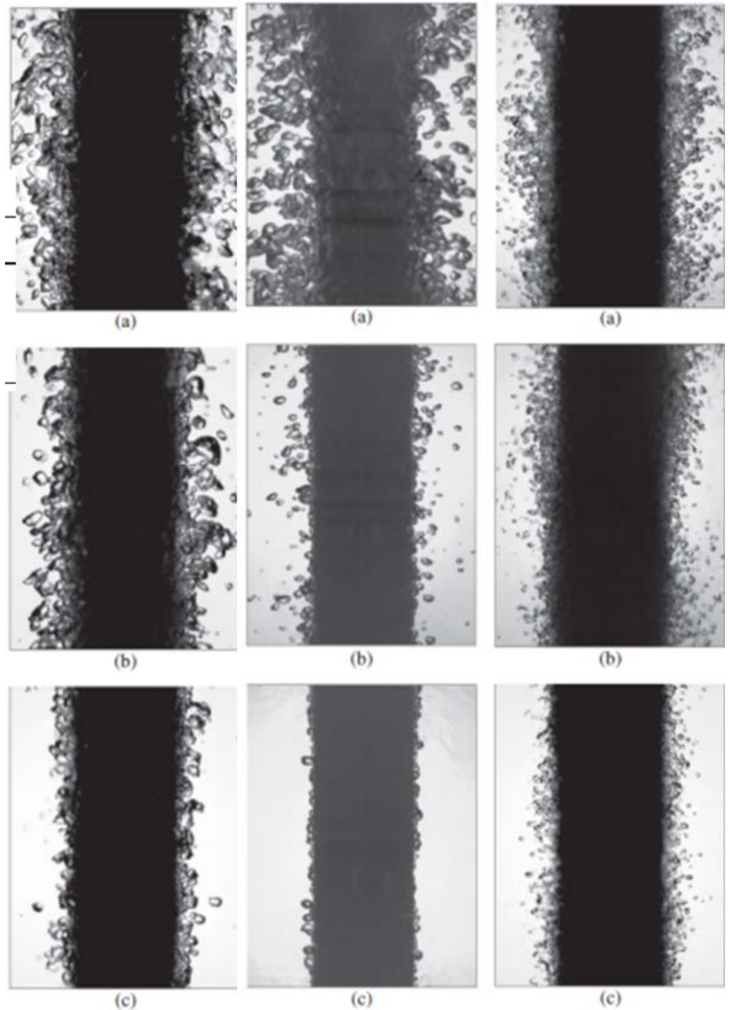


Figure 8. Variation of the signal-to-noise ratio (SNR).



Test-01 **Test-02** **Test-03**

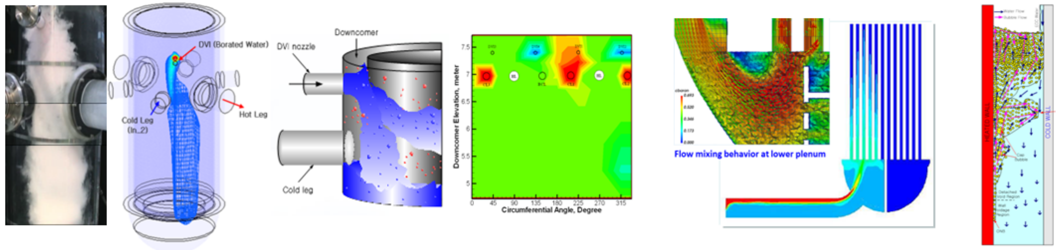
I.C. Chu et al. (2017 NED)

The Change in System Pressure Have Direct and Profound Influences on Most of Bubble Parameters !!

Need of Multi-D Flow Analysis

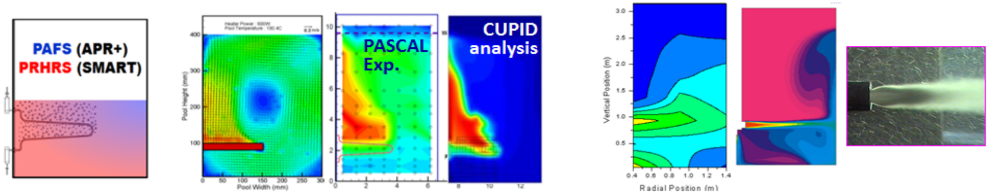
- **Need of Multi-D Analysis: Some Critical Phenomena**
  - Temporal change of a variable comes from both its spatial change and a sink/source:
    - Spatial error and temporal error are co-related.
  - In case of lumped parameter method, momentum can be lost or easily diffused, and local peaks of TH properties are well-diffused.
    - This does Not guarantee a conservatism of an accident progression analysis.

[ex] Multi-D T-H Behavior in RCS:



Boron Dilution ECC Bypass Mixing in LP, HL & SG D/C Boiling

[ex] Passive Safety Concepts:



Mixing in a Pool (1):
Passive Cooling with H/X

Mixing in a Pool (2):
Steam Jet in IRWST

3-D SysTH Codes – Current Status*

	TRACE	CATHARE-2&3	RELAP5/MOD3.3	RELAP5-3D	MARS-KS	SPACE
• **Field Equations**	• 3D model (3 Momentum eq.s for each field)	• 3D model (3 Momentum eq.s for each field)	• 1D Model (with cross-flow model)	• 3D model (2 Momentum eq.s for each field)	• 3D model (2 Momentum eq.s for each field)	• 3D model (3 Momentum eq.s for each field)
• **Geometry**	• Cartesian • Cylindrical	• Cartesian • Cylindrical, Spherical	• N/A	• Cartesian • Cylindrical	• Cartesian • Cylindrical	• Cartesian • Cylindrical
• **Finite difference**	• Staggered	• Staggered • Collocated	• Staggered	• Staggered	• Staggered	• Staggered • Collocated
• **3D convection**	• Fully implemented	• Fully implemented	• Partially implemented with cross flow	• Fully implemented	• Fully implemented	• Fully implemented
• **3D kinetics**	• Coupled	• Coupled	• Coupled	• Built-in	• Coupled	• Coupled
• **Porous media**	• Yes	• Yes	• No	• Yes	• Yes	• Yes
• **Turbulence model**	• None	• k-ε	• N/A	• None	• Prandtl mixing model	• None
• **Flow regime map**	• 1D based	• 1D based	• 1D	• 1D based	• 1D based • Vertical map only • Level gradient term	• 1D based • Vertical map with horizontal stratification
• **Models and Correlation**	• 1D based	• 1D based	• 1D	• 1D based	• 1D based • Use RMS velocity	• 1D based • Use RMS velocity
• **Validation**	• Extensive V&V needed	• Extensive V&V needed	• N/A	• Extensive V&V needed	• Extensive V&V needed	• Extensive V&V needed
• **Numerical scheme**	• Fully-implicit	• Fully-implicit	• Semi-implicit	• Semi-implicit	• Semi-implicit	• Semi-implicit

* C.-H. Song (Lecture @THICKET-5, 2025)

3-D SysTH Codes – Validation Matrix*

- **Validation Matrix for Predicting Multi-D TH Behaviors**

	Code	3D Model	Validation Test Matrix	3D Phenomena Validated	Source
1	MARS-KS (Korea)	Multi-D Module	RPI 2D slab	Two-phase flow regime (air-water)	RPI, USA
			UPTF (7)	ECC bypass in RV downcomer (full-scale)	2D/3D program
			MIDAS	ECC bypass in RV downcomer (1/5 scale)	KAERI
			B&C	Thermal mixing in a IRWST pool	KAERI
			PANDA	Steam injection in a gaseous space	PSI
			LOFT (L2-5)	LB-LOCA	INL
		COBRA-TF Module	GE 9-rods	Subchannel flow in core channel	GE
			CREARE	ECC bypass in RV downcomer	Creare, USA
2	SPACE (Korea)	3D Component	RPI 2D slab	Two-phase flow regime (air-water)	RPI, USA
			MIDAS	ECC bypass in RV downcomer (1/5 scale)	KAERI
			DYNAS	Flow pattern in a slab (air-water)	KAERI
			UPTF (7)	ECC bypass	2D/3D program
			(PRIUS, METERO)	Cross-flow btwn FA's	KAERI-CEA
3	ATHLET (Germany)	3D Flow Model	ROCOM	Flow mixing in RV downcomer & cold leg	HZDR
			UPTF (6,7,Z3, TRAM)	ECC mixing; CCFL in RV downcomer	2D/3D program
			ATLAS (ISP-50, OECD)	Overall 3D phenomena in RV (SBLOCA)	KAERI
			TALL-3D (Pb-Bi)	Forced-to-natural convection in metal pool	KTH
			INKA (NOKO, PCFS)	Passive cooling (pool & core) in BWR	Framatome/AREVA
4	CATHARE (France)	3D Vessel Model	PIERO	Voiding in lower plenum (blowdown phase)	CEA
			UPTF (6,7,10c)	LB-LOCA refill; CCFL at upper tie plate	2D/3D program
			DOBO	Downcomer boiling in reflood phase	KAERI
			PERICLES-2D	Reflood heat transfer; Core boil-off	CEA
			LOFT (L2-5,LP2-6)	LB-LOCA	INL
			ROSA/LSTF (7)	IB-LOCA (13%)	JAEA

- **Additional V&V Efforts Required.**
- **Strong Needs of V&UQ Data on Multi-D Phenomena**

* Song (2021), C. Herer et al. (2023), NEA (2024), Song et al. (2025)

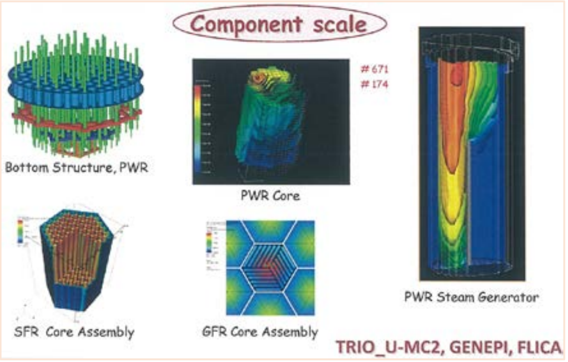
Some Efforts on Finer-scale TH Analysis

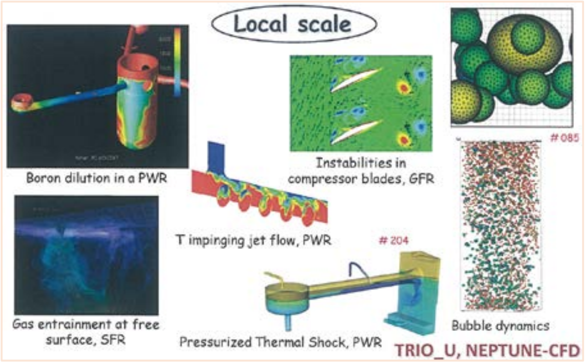
- **Extension of CFD/CMFD Codes to NRS Problems**
  - WGAMA/WG-3 (Chaired by D. Bestion): NEA ('05~'14), Bestion ('10)
  - **NEPTUNE-CFD** Code (EdF and CEA, '01~)
    - Euro. FP's: NURESIM ('05~) → NURISP ('09~) → NURESAFE ('12~'15)
  - **CUPID** Code (KAERI, '07~): CUPID-RV, CUPID-SG, MS&MP analysis
- **Multi-scale (MS) Approach**
  - SysTH Codes Coupled with Finer Scales: Component-scale or CFD
    - France: CATHARE + NEPTUNE-CFD + …
    - Korea: MARS + CUPID + …

System

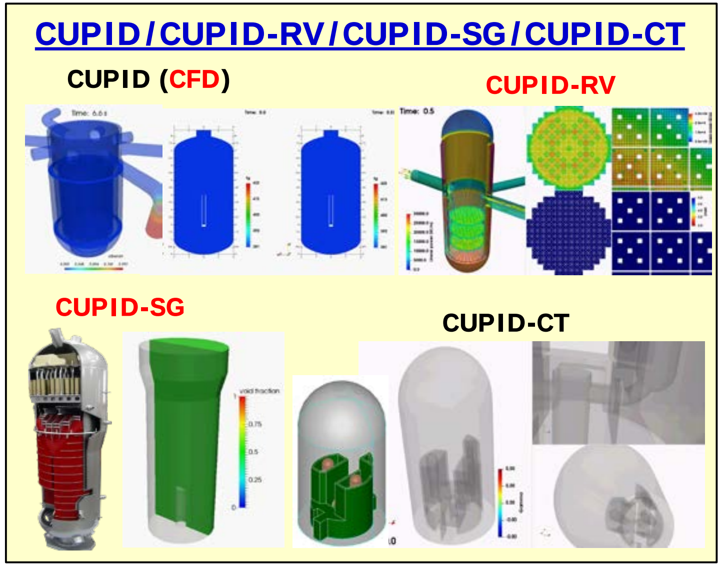
Component

CFD





Figures: D. Bestion and A. Guelfi (2005)

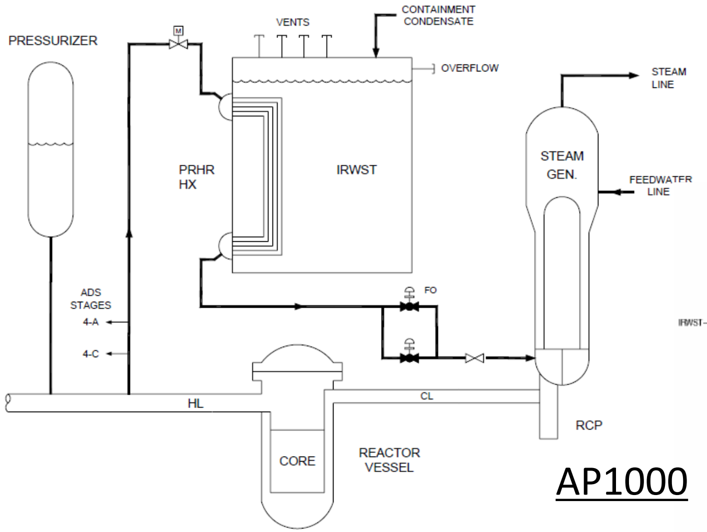


III. Potential TH Issues on WC-SMRs Modelling and Simulation

- TH Safety Concerns for WC-SMRs M&S
- EASI-SMR Experimental Program

TH Considerations for WC-SMRs Safety

- **Safety Issues of Large LWRs**
  - Non-uniform TH behaviors in core and the RV
  - Discontinuity of flow in geometric singularities in the RCS
  - Interaction of TH behaviors between the RV space and the connected systems
- **New Concerns on WC-SMRs Safety:** [ex]
  - Core flow distribution
    - Non-uniform in flow and concentration
  - CHF: Low flow, highly skewed power profile
  - Natural circulation (N/C)
    - Flow instabilities
  - Passive safety systems
    - Natural or mixed convection heat transfer
    - Coupled with non-uniform flow behaviors in a pool
  - Flow discontinuity in geometric singularities within RV or at its boundary: Affect N/C



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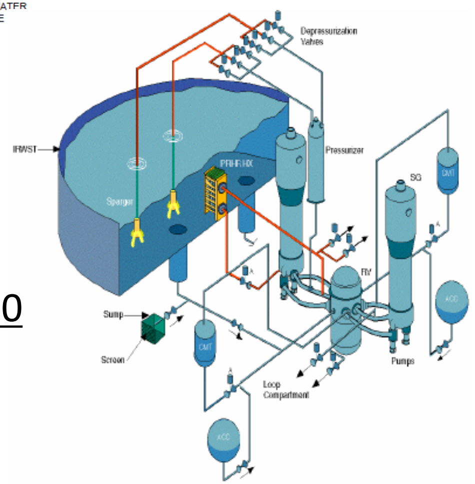
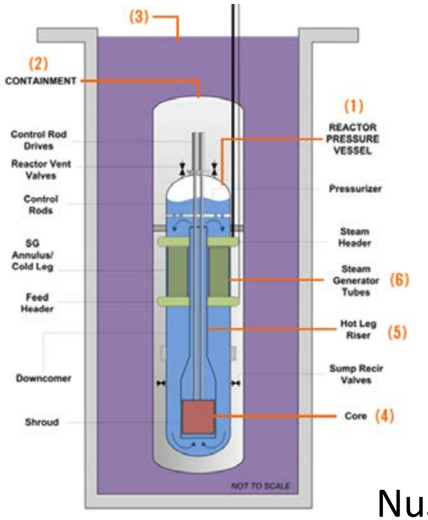




NuScale

EASI-SMR Experimental Program – Summary*

	Test	TH Phenomena of Consideration	Remarks
1	COSAC	• In-tube (Single or multi): Condensation, Gravitational drain flow • On-tube: Liquid convection and boiling-induced heat removal	Vertical SACO tubes; Pool-side flow pattern
2	FHEASIK	• Natural convection in annulus (Gap reduced; Ra # scaled) • Condensation/evaporation in containment • Thermal stratification in a pool	Annulus gap (1/3) Aspect ratio preserved Semi-IET (Press. Preserved)
3	GRADAC	• DCC; Steam pressurization (~40 bar); Sparger optimization • Thermal stratification in liquid; Thermal absorption by wall	Similar to CMT/H-SIT; L/D ~ 1/2.5; CFD
4	ELSMOR-II	• Two-phase N/C; HT at plate HX and SACO tubes; NCG effect; • Thermal stratification in a SACO pool	Semi-IET (SBO, LOCA); 1/1 H, 1/50 P/V;
5	IVR-LOOP	• Pool boiling (CHF) tests; Surface inclination angles • Thermosyphon tests with deflector gaps (50/100 mm W)	1/1 H; 1/95 W (15 cm)
6	PANDA	• Natural convection at CS wall (high Ra #); NCG effect in CS; • Thermal strat. inside CS and pool; Nonuniform circulation in pool	CS (0.5m D, 5.6m H) in pool (4m D, 8m H)
7	PRECISE	• SACO tube: Condensation, Film thickness; Flow directions (up/down) • Cooling jacket design (4mm gap) for X-ray application; NCG effects	Hi-resolution film measurements by X-ray
8	ALCINA	• N/C instabilities; NCG; 2-phase flow regimes (HT, DP)	SACO; WMS
9	ECRINS	• Mini-channel condensation; NCG; Cooling jacket (Shell side)	

* Based on the EASI-SMR D2.1 (Definition of Test & Design Components, 2025)

IV. KAERI’s Experience on WCRs Modelling and Simulation

Key TH Phenomena in Advanced WCRs

Table 2. Major TH phenomena in new design features of ALWRs

Rx Type	Phenomena	Boiling	Condensation	Multi-D TH phenomena	Remarks
APR1400	DVI	Vertical annulus	DCC in annulus	ECC bypass in annulus	RV downcomer
	IRWST	-	DCC on spargers	Thermal stratification; 1-phase natural convection	with SDVS
	CFS	RV outer wall	DCC	2-phase natural circulation	IVR-ERVC
APR+	DVI	Similar to APR1400	←	←	Reduced bypass
	PAFS HX	On-tubes of HX	In-tubes of HX (horizontal)	-	PAFS
	PCCT	-	DCC	Thermal stratification; 2-phase natural convection	PAFS
	IRWST	Similar to APR1400	←	←	
	CFS	Similar to APR1400	←	←	IVR-ERVC
iPOWER	DVI	Similar to APR1400	←	←	Reduced bypass
	HSIT	-	DCC on free surface	Thermal stratification; 1-phase natural convection	
	PAFS HX	On-tubes of HX	In-tubes of HX (horizontal)	-	PAFS
	PCCS HX	Flashing in tubes	On-tube of HX (vertical)	Parallel-channel instability	PCCS
	PCCT	Similar to APR+	←	←	PCCS & PAFS
	IRWST	Similar to APR+	←	←	
SMART	DVI	-	DCC in upper annulus	ECC bypass in annulus	@ UDC
	PRHR HX	On-tube of HX (vertical)	In-tube of HX (vertical)	Thermal stratification; 2-phase natural convection	PRHRS & ECT
	CMT	-	DCC on free surface	Thermal stratification; 1-phase natural convection	PSIS
	PCCS	On-tube of HX (vertical)	In-tube of HX; Instability; Non-condensable gas	Thermal stratification; 1/2-phase natural convection	CPRSS HX (CHX) with ECT
	IRWST	-	DCC on spargers; Chugging	Thermal stratification; 1-phase natural convection	with ADS
	CFS	Similar to APR1400	←	←	IVR-ERVC

* C.-H. Song et al. (2021, NED)

Multi-D Phenomena - Examples

Table 4. Typical multi-dimensional TH phenomena in a RCS of PWR

	Location	Scenario	Technical Issue	Multi-D TH Phenomena	Relevance to Safety	Maturity
1	D/C	MSLB	Boron dilution	Inhomo. mixing, Temperature gradient	PTS (1-phase), DNBR	M
		FLB+LOOP	Over-cooling	Asymm. cool-down, Inhomog. mixing	PTS (1-phase), Re-criticality	M
		LB-LOCA	ECC bypass	Interaction of ECC water & steam	ECC delivery, PCT, Inlet subcooling	L
		"	D/C boiling	Wall HT, Subcooled boiling, Recirculation	Reflood rate, PCT, Hydrostatic head	L
		SB-LOCA	Pressurized shock	Inhomogeneous mixing, RV cooling	PTS (2-phase), SI mode	M
2	Core	MSLB/FLB	Return-to-power	Inhomog. power & temperature	DNBR, Fuel failure, Re-criticality	M
		LB-LOCA	Reflood HT	Heterogenous de-entrainment from UP	PCT, Reflood rate, Ballooning, FFRD	L
		"	Crossflow btwn FA's	Non-uniform power, Diverging effect	PCT, Uncovered upper core cooling	L
		IB-LOCA	Crossflow btwn FA's	Non-uniform power, Chimney effect	PCT, Uncovered upper core cooling	L
		"	Upper core cooling	3D power, Heterog. water fall from HL	Top quench., Reflux condensing	L
		SB-LOCA	Eccentric core cool.	Inhomog. in D/C, Thermal stratif. in UH	Heterog. clad temp. distribution	M
		LOCA	Above-core THs	Radial profile of velo./temp. in UP & HL	Core exit temp., HJTC location	L
3	HL	IS-LOCA	Containment bypass	Counter-current steam flow in HL	TI-SGTR, Steam superheating	M
		NO	Power-flow control	Inhomogeneity of power/velo./temp.	Power-to-flow imbalance	M
4	IL	LOCA	LSC time	Asymm. pressure build-up in RCS loops	Core uncovery, Quench front, LSC	L
5	SG	LOCA	Heat removal capa.	Inhomog. temp. & phases in inlet plena	Non-uniform in-tubes flow	L
		LOCA	CCF in tubes	Counter-current flow among tubes	2ry heat removal capacity	M
		MSLB/FLB	Cooldown rate	Asymm. cooldown, N/C interruption	EOP, Proper cooldown rate,	M
		DEC	TI-SGTR	Counter-current steam flow among tubes	Steam superheat, 2ry heat removal	M

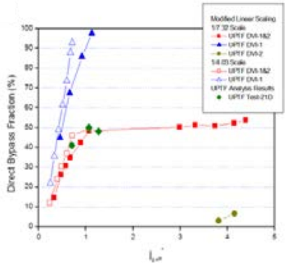
* D/C: RV downcomer, DNBR: DNB ratio, ECC: Emergency core cooling, FFRD: Fuel fragmentation/relocation/dislocation, HL: Hot leg, HT: Heat transfer, IL: Intermediate leg, LOOP: Loss–of-offsite power, LSC: Loop seal clearing, N/C: Natural circulation, NO: Normal operation, PCT: Peak clad temperature, PTS: Pressurized thermal shock, RV: Reactor vessel, SG: Steam generator, TI-SGTR: Thermally-induced SGTR, UP: Upper plenum, UH: Upper head

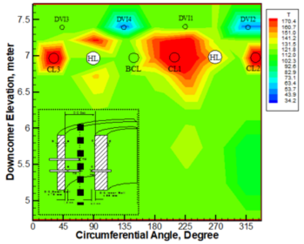
* C.-H. Song et al. (NURETH-21)

Example: Multi-D Phenomena in DC

❑ Case of LB-LOCA Reflood Phase: [ex] APR1400

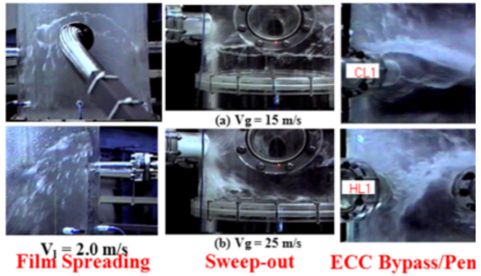
$$j_k^* = \alpha_k u_k \left[\frac{\rho_k}{(\rho_f - \rho_g) g D} \right]^{1/2}$$





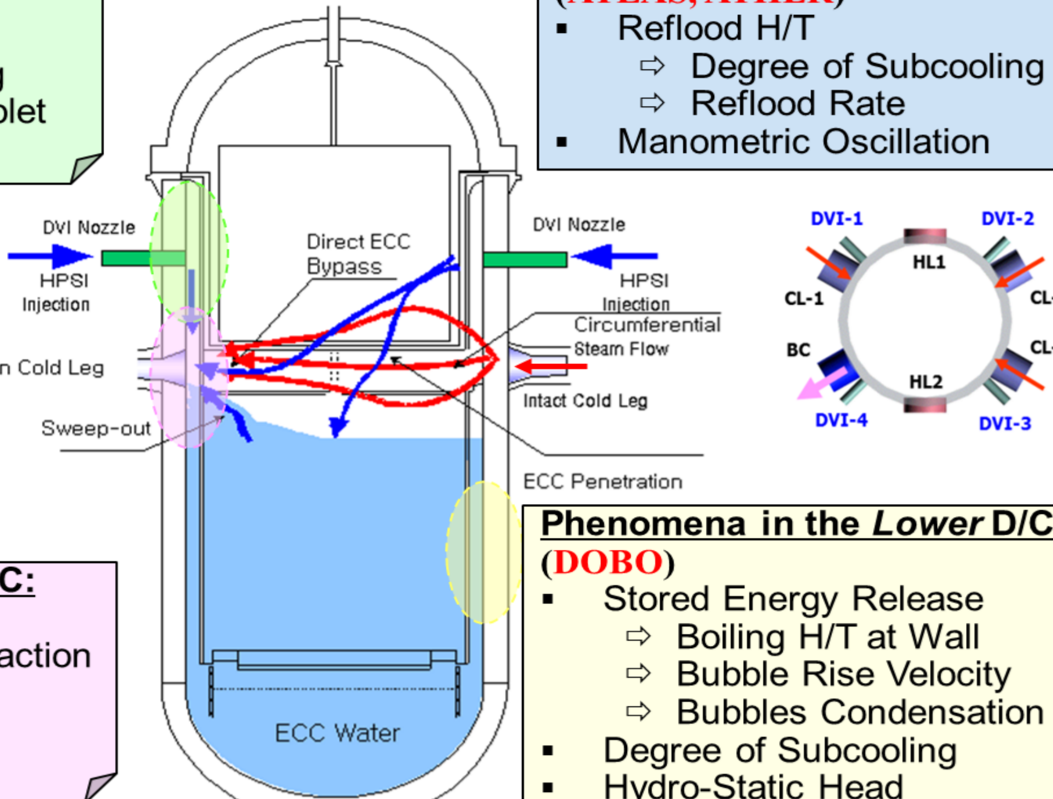
Phenomena in the *Upper* D/C:
(MIDAS, DIVA, LFS)

- Water Jet Impingement
  - ⇨ Liquid Film Spreading
  - ⇨ Entrained Liquid Droplet
- H/T: Steam Condensation



Phenomena in the *Middle* D/C:
(MIDAS, DIVA)

- Multi-D Steam-Water Interaction
  - ⇨ Direct ECC Bypass
  - ⇨ Sweep-out
- ECC Penetration

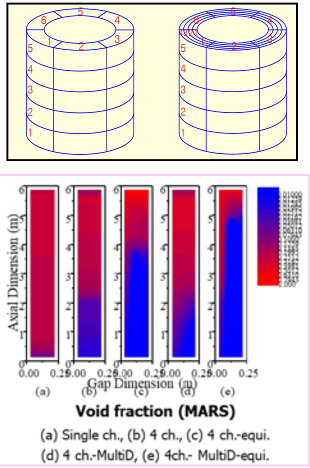


D/C-Core *Interaction*:
(ATLAS, ATHER)

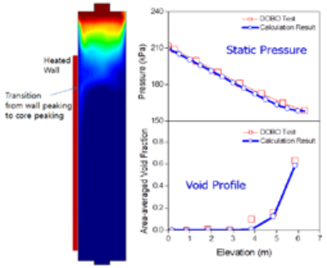
- Reflood H/T
  - ⇨ Degree of Subcooling
  - ⇨ Reflood Rate
- Manometric Oscillation

Phenomena in the *Lower* D/C:
(DOBO)

- Stored Energy Release
  - ⇨ Boiling H/T at Wall
  - ⇨ Bubble Rise Velocity
  - ⇨ Bubbles Condensation
- Degree of Subcooling
- Hydro-Static Head



Void fraction (MARS)
(a) Single ch., (b) 4 ch., (c) 4 ch.-equi.
(d) 4 ch.-MultiD, (e) 4ch.- MultiD-equi.



(c) CUPID vs. DOBO: Void & Press.

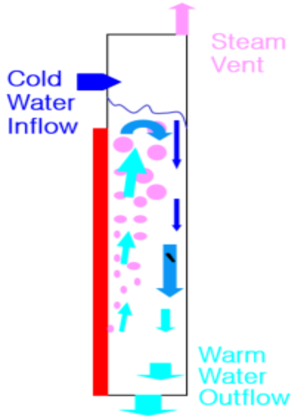
KAERI Korea Atomic Energy Research Institute

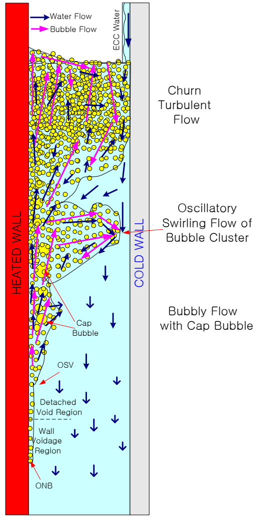
* Source: C.-H. Song et al., KAERI (2007 NET)

Proper Treatment of Multi-D Effect and the High Thermal Non-equilibrium in a RV Downcomer Is Important for Accurately Predicting the PCT !!

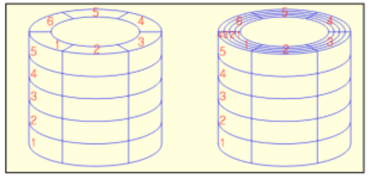
DOBO Tests and Analyses ('03~'09)*

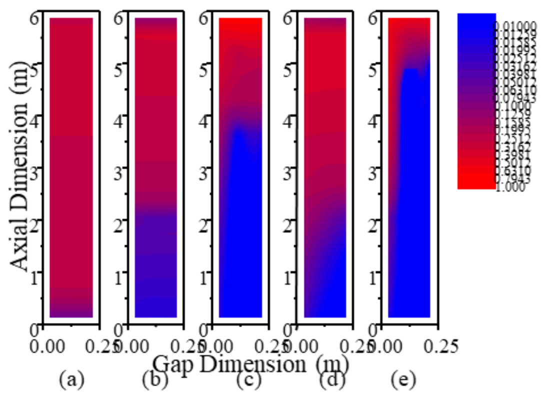
- **Measurements: at DOBO**
  - Full-size gap width (~25 cm)
  - At 5 elevations with 2-D traverse
    - 5-sensor void probe
    - Bi-directional flow tube





- **Analyses: RELAP, MARS, CUPID**
  - MARS Analysis: Multi-Nodes
    - Different from a 1-D Pipe Model
    - Higher inlet subcooling
    - No late reheating in reflood phase
  - CUPID Analysis
    - Realistic





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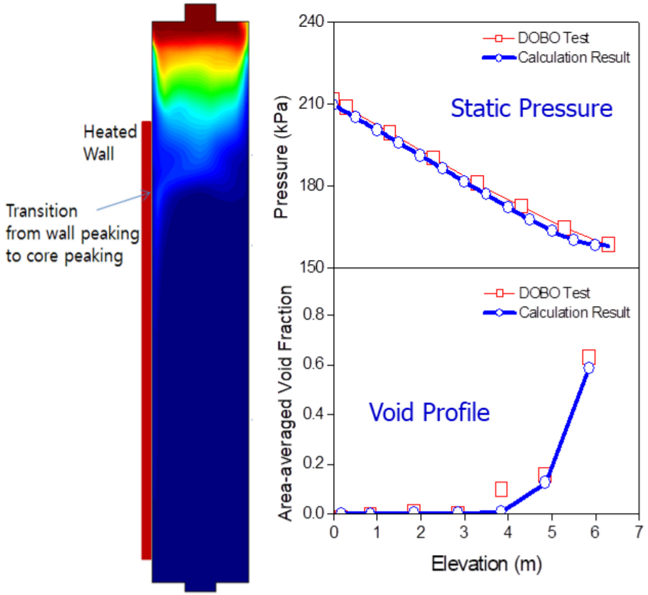
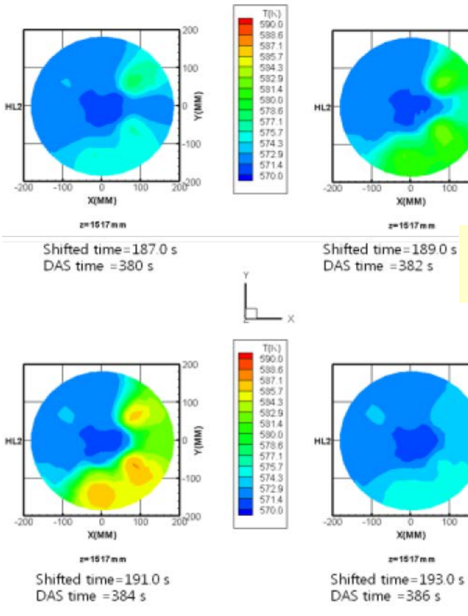


(c) CUPID vs. DOBO: Void & Press.

* C.-H. Song (2006, NTHAS-5),
B.J. Yun et al. (2008 NED),
Euh et al. (2008 NT),
H.Y. Yoon et al. (2014 NET),
NEA (2024) sec. 5.1.9

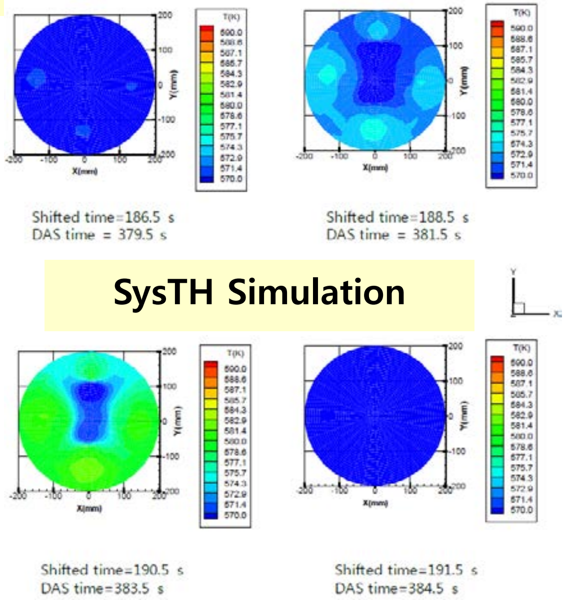
Non-uniformity in a Core – ATLAS

- **ATLAS: SB-LOCA**
  - Non-uniform PCT
  - ATLAS vs MARS simulation



ATLAS

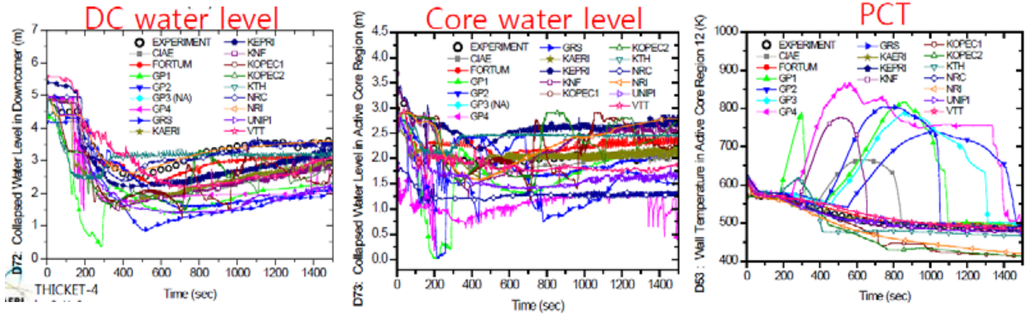
1/2 H, 1/144 A
(2006~)

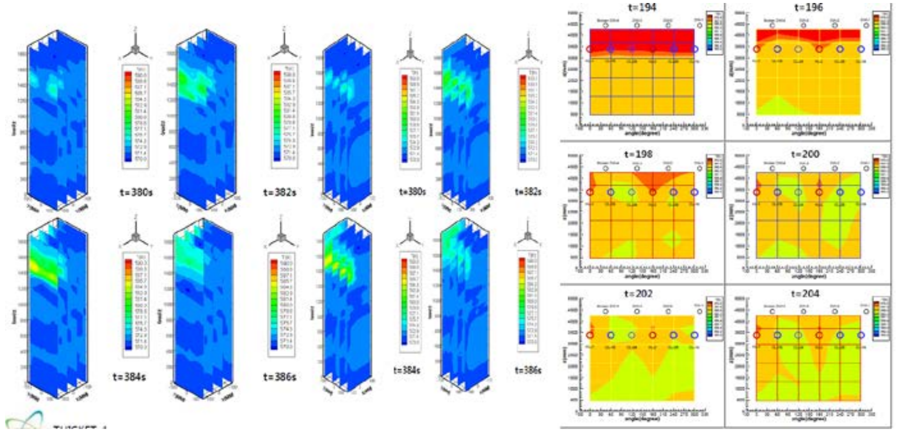


SysTH Simulation

* ATLAS Team (KAERI),
* C.-H. Song (2016 @THICKET-4)

- **ATLAS: ISP-50**
  - DVI Line Break (50%) Scenario
    - Multi-D nature in Core and DC
    - Asymmetric LSC between loops

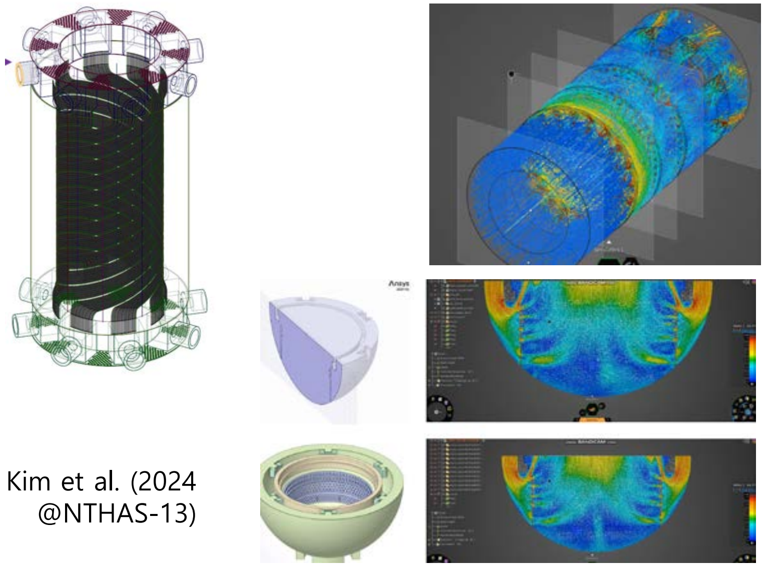




* NEA/CSNI/R(2012)6 ; C.-H. Song (2016 @THICKET-4)

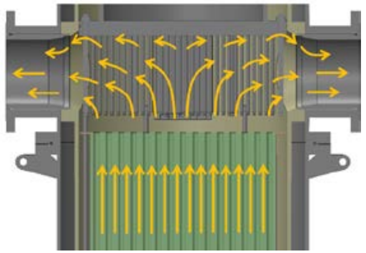
3-D Flow in Core Inlet, UP and HL Regions

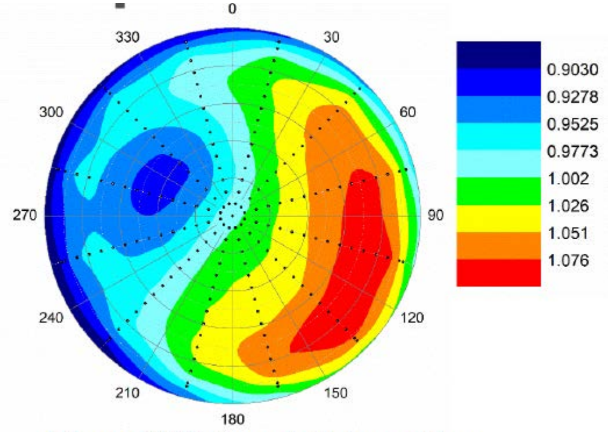
- **Multi-D Flow in Core Inlet**
  - ACOP Tests: APR1000, APR+, i-SMR, …
  - Linear scaling with Eu # Preserved
    - Geometric, Kinematic, Dynamic Similarity
  - FA simulators: Pre-calibrated



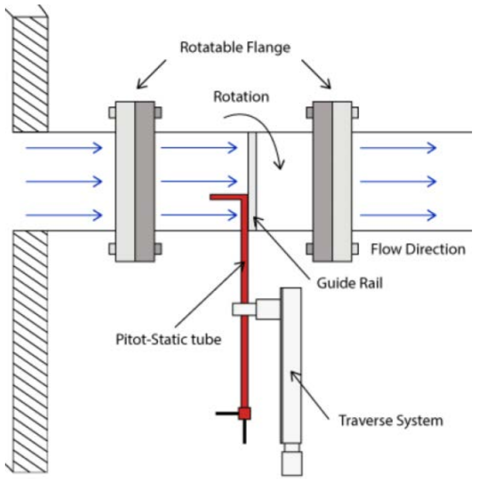
* K.H. Kim et al. (2024 @NTHAS-13)

- **Multi-D Flow Behaviors in the UP/HL**
  - ACOP Tests: 4 pumps
  - FA simulators:
    - Pre-calibrated





4-Pump 100% flow rate Balanced flow



* Y.H. Kim et al. (2025 @WORTH-11)

Multi-D Phenomena in a Large Space

Table 5. Typical multi-dimensional TH phenomena in large spaces of WCNR

	Space	Location	Reactor	Tech. Issue	Multi-D Phenomena	Relevance to Safety	Maturity
1	Water pool with bubbling	HX's submerged in pool	APR+	Passive aux. FW supply	Macro-scale circulation; Temperature distribution; Tube bundle effect	Heat removal capacity, Circulation pattern, Water level, Grace period	M
			AP1000, SMART, i-SMR	Passive RHR functioning	Macro-scale circulation; Temperture distribution; Tube bundle effect	Heat removal capa., Circulation pattern, Water level, Local hot spot, Grace period	M
			BWRs	IC Functioning	Macro-scale circulation; Temp. distribution; Tube bundle effect	Heat removal capa., Water level, Local hot spot, Grace period	M
2	Water pool with DCC	Spargers submerged in pool	AP1000, EPR, APR1400, APR+, SMART	IRWST as heat sink	Jets-induced macro-scale circulation; Chugging	DCC, Condensing regimes and efficiency, Local hot spot; Hydrodynamic loads onto structures	L
			PWRs	RDT rupture	Condensation in closed tank	Reactor depressurize., Rupture time	M
			AP1000, SMART	CMT behavior	DCC; Thermal stratification at phasic interfaces; NC gas effect	Condensation regimes and efficiency,	M
			BWRs	PSP as heat sink	DCC; Plumes-induced circulation; Non-uniform thermal mixing;	Rx depressurization; Chugging; Condensation effic.; Local hot spot	M
3	Contain-ment	Spray into air space	PWRs, BWRs	Depressuriz., Scrubbing	Thermal stratification; Steam concentration; Spray distribution; Inhomog. NC gas concentration	Pressurization, Release to environ.; Scrubbing efficiency; Condensation heat removal at wall	M
		HX in air space	AP1000, i-SMR	Passive RHRs, Passive CCS	Condensation on multiple tubes; NC gas effect; NC gas stratificat.	Heat removal capacity; Wall condensation heat removal	M
		Depressur. Valve	SMART, i-SMR	Automatic depressuriza.	Steam impingement; Liquid film	Wall heat transfer; Heat removal by condensation	L
		Recirculat. Valve	i-SMR	Passive safety injection	Flow disturbance by bubbles; Chugging	Core water level; Change in flow direction	L
		Pool scrubber	BWRs, AP1000, APR1400	Scrubbing efficiency	Plumes-induced circulation; NC gas effect; Bubble behaviors	Scrubbing efficiency	L
4	SF pool	Submerged HX	All	Decay heat removal	Macro-scale circulation; Local vorticies,	Heat removal capa., Water level, Pool temp. distribution	M

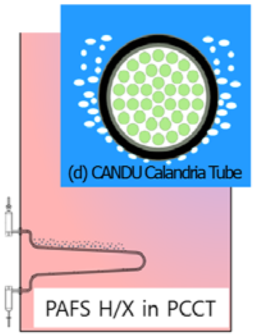
* CCS: Containment cooling system, CMT: Core makeup tank, DCC: Direct contact condensation, FW: Feedwater, HX: Heat exchanger, IC: Isolation condenser, NC: Non-condensable, PSP: Pressure suppression pool, RDT: Reactor drain tank, RHR: Residual heat removal, SF: Spent fuel

* C.-H. Song et al. (NURETH-21)

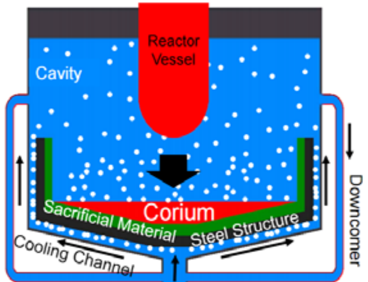
Pool Boiling in Inclined Surfaces

- **Boiling on the Surface of Inclined Surfaces**

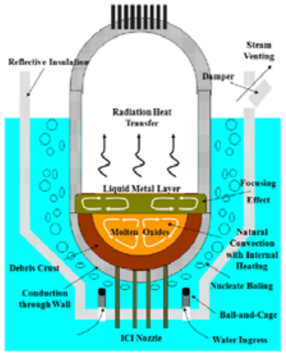
  [Ex] Passive Condenser, IVR by ERVC, Core Catcher, …



(a) PAFS in APR+

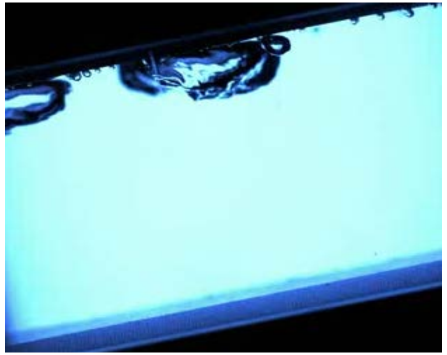


(b) Core Catcher in APWR



(c) IVR-ERVC in APWR

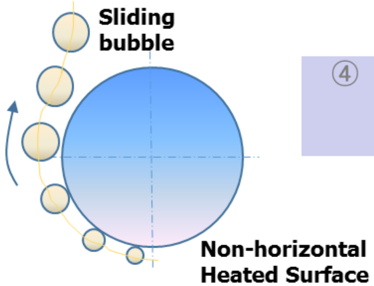
* H.K. Cho, SNU (2017)

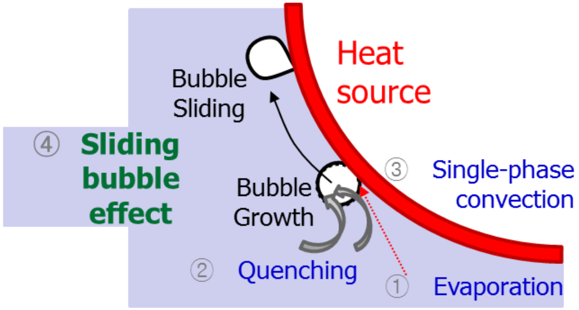


* B.J. Yun, PNU (2017)

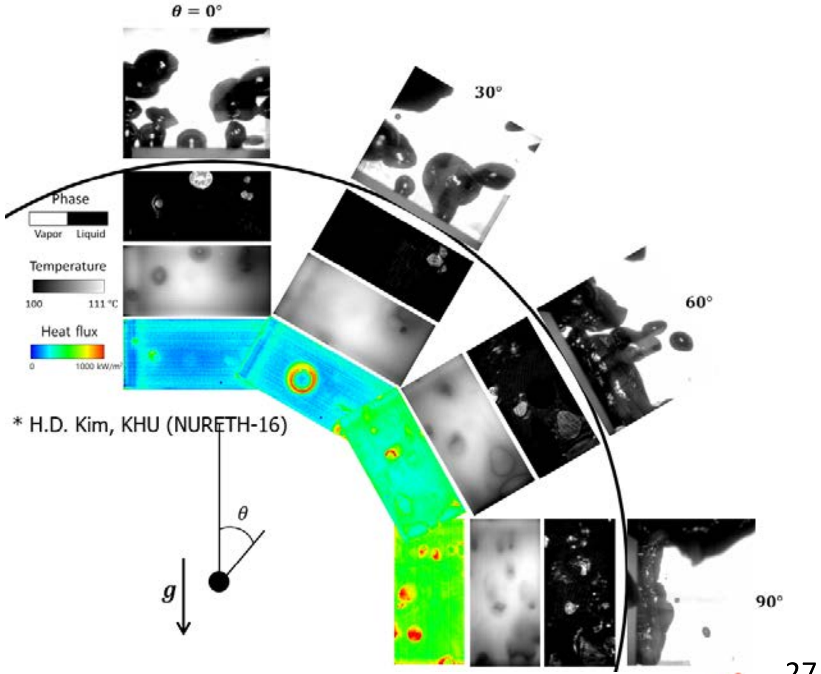
- **Effect of Surface Inclination on the Boiling:**
  - Wall heat partitioning effects (3 terms)

    + Sliding effect





* H.K. Cho et al., SNU

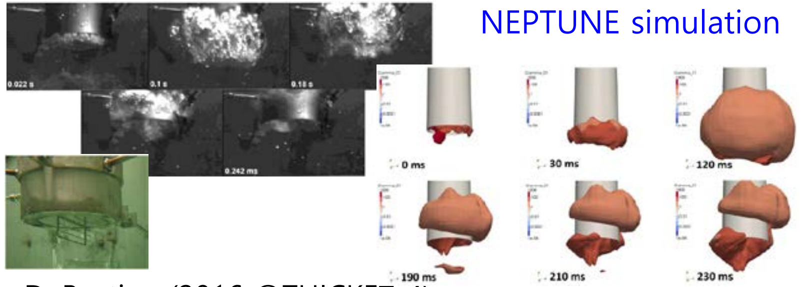


* H.D. Kim, KHU (NURETH-16)

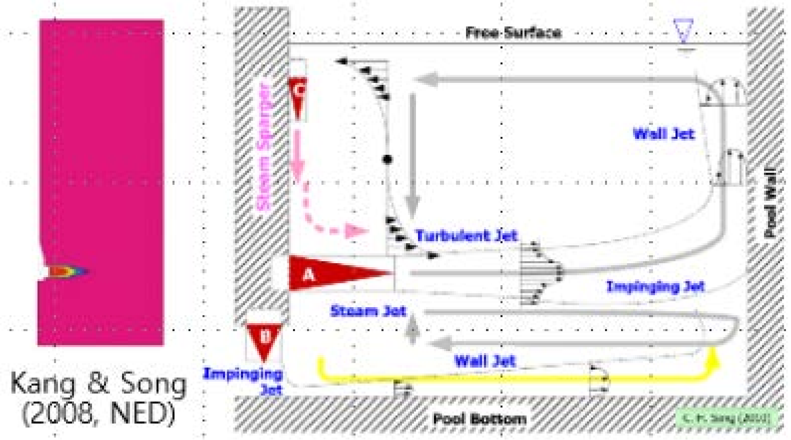
Multi-D Phenomena in a Large Volume: Ex.

- **Steam Discharge in a Pool***
  - Steam Plume: PSP in BWR
  - Steam Jet: in Adv. PWR
    - IRWST (e.g., APR1400, AP1000, …)
    - CMT, …

NEPTUNE simulation

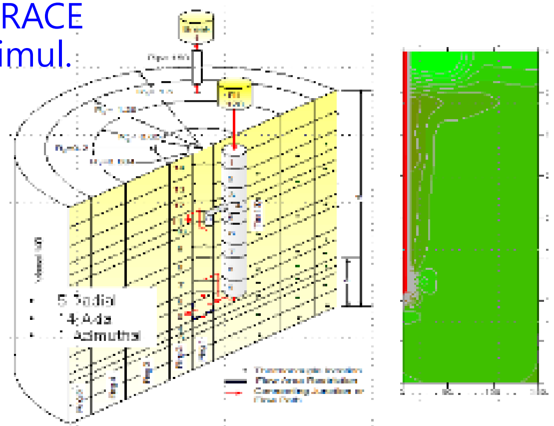


D. Bestion (2016 @THICKET-4)



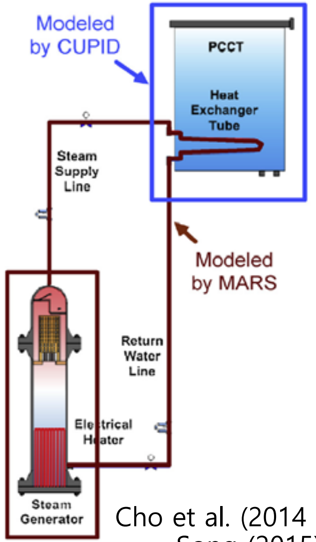
Kang & Song (2008, NED)

TRACE simul.

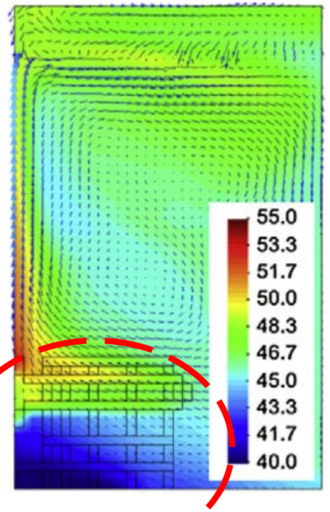


Y.S. Bang et al. (ANS2005WM)

- **Bubbling-induced Mixing in a Pool**
  - Passively operating sys.: [ex]
    - PAFS with PCCT (APR+)
  - SFP, …



Cho et al. (2014 NED), Song (2015)



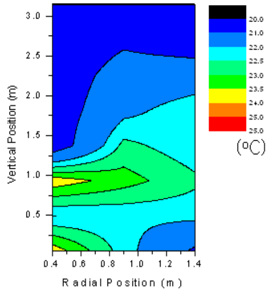
(d) Liquid temperature (°C) and velocity vector

Strong Needs of Validation Data and further V&V Efforts on Multi-D Phenomena !!

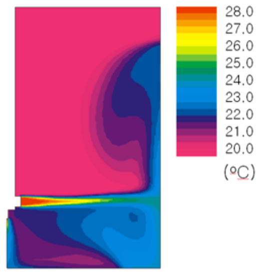
* Song (Lecture @IHTC-14, 2010)

Pool Mixing – Tests and Analysis

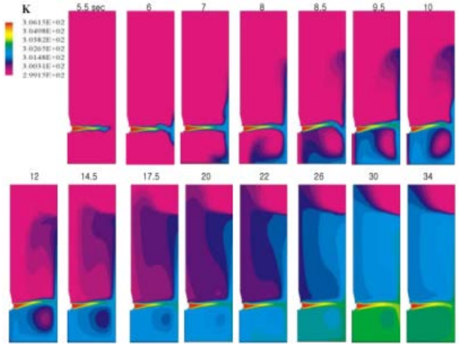
- **Basic Flow Processes (B&C Test)**
  Steam Jet/Plume → Turbulent Mixing
  - Steam Jet :
    - Vapor Core: Forced Jets or Buoyant Plumes
    - 2-ϕ Mixing Regions
  - Turbulent Jet
  - Impinging Jet and Wall Jet
  - Global Circulation
- **Applicability of SysTH Cdes to Predicting Thermal Mixing in IRWST**
  - Local temperature in IRWST can be changed by interfacial condensation and flow fields induced by the condensing steam jet
  - Requires 3-D two-phase transient calculation.



Temperature Distribution at t=10sec (100bar, 20°C)



CFX Calculation Result at t=10sec (100bar, 20°C)



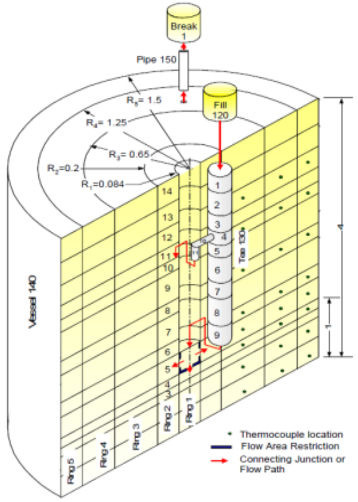
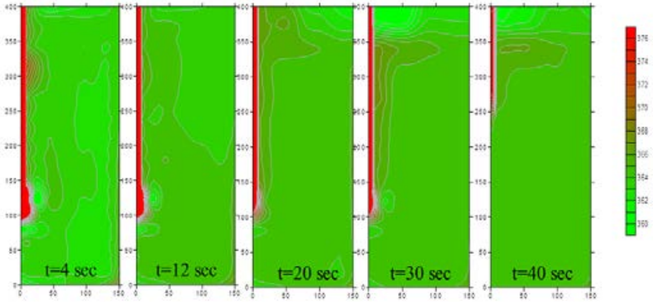


Fig. 1. TRACE model of the experiment

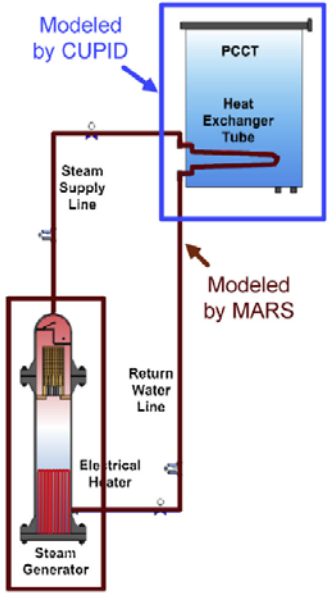


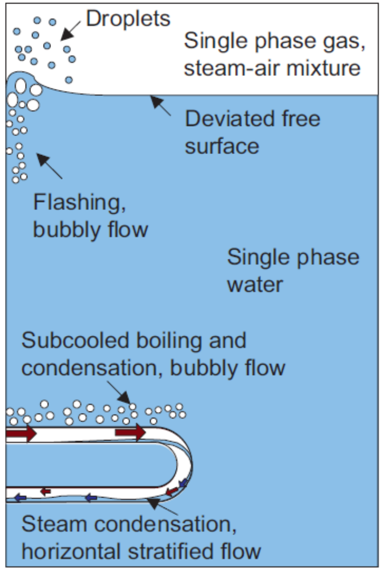
* Y.S. Bang et al. (2005 ANS)

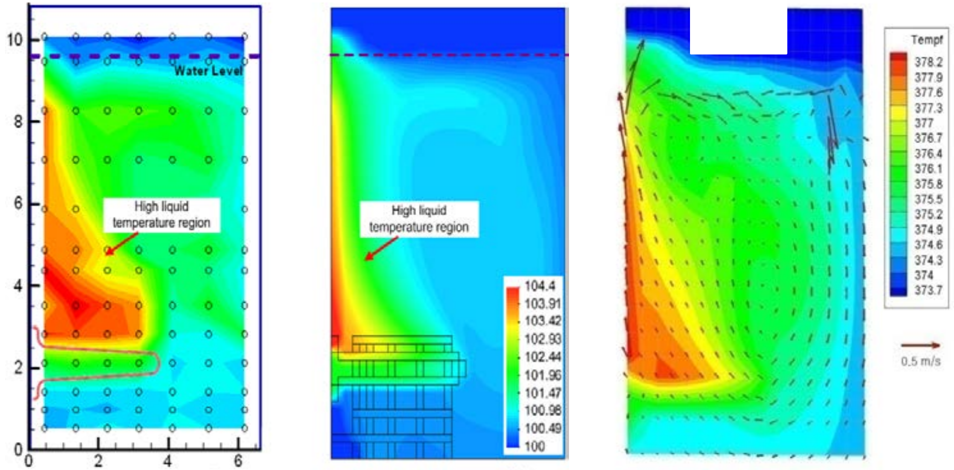
* C.-H. Song, NEA/CSNI Report (2010)

Boiling-Induced Mixing – Test and Analysis

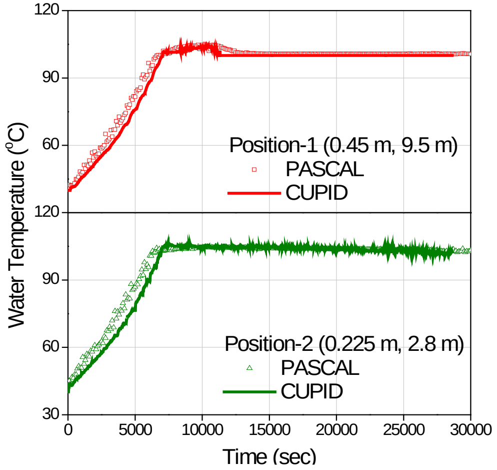
- **Thermal Mixing in a Passive Cooler, PAFS/PCCT**
  - Bubbles-induced Circulation in a Tank is so Important.
  - Limitation of Predicting Multi-D Phenomena by SysTH Codes
    - Weak for natural convection in a bulk volume







(a) PASCAL Test (b) CUPID Calcul. (c) MARS Calcul.

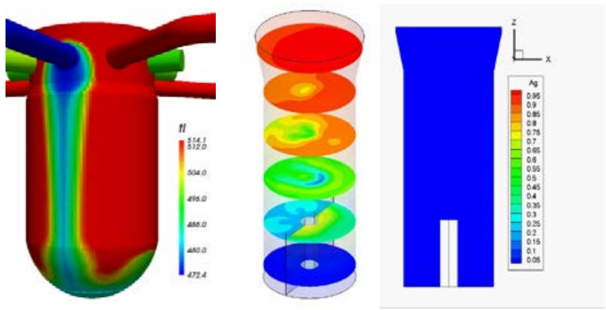


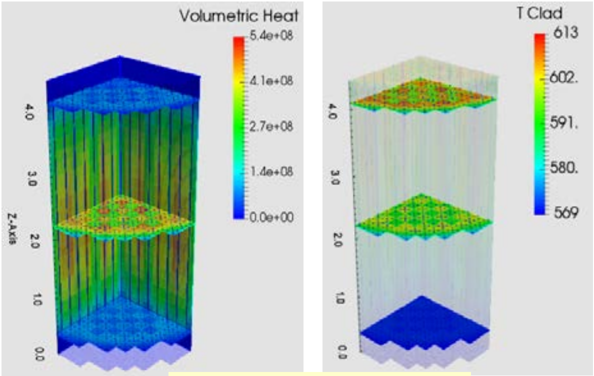
(d) PASCAL vs. CUPID

* H.K. Cho et al., SNU/KAERI (2014 NED); S. Kim, KAERI (2018)

CUPID Code for MS&MP Analysis

- **Steady-state and Transient Analyses of 1-ϕ/2-ϕ Flows in Nuclear Reactor System**
  - Component scale, or
  - CFD-scale





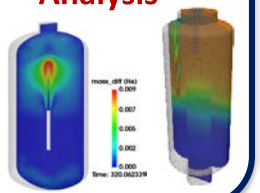
(CUPID/DeCART)

2017~2021 3D Safety Analysis using CUPID

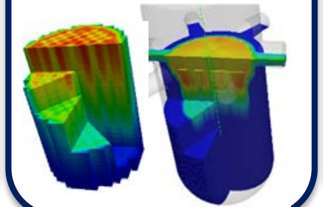
2012~2016 Development of CUPID

2007~2011 High-resolution Numerical Method

High-fidelity Containment Analysis



3D TH Analysis for Reactor Core



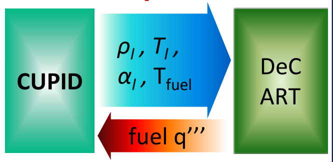
Coupling of TH and Fuel Structure Codes
- 3D TH and 2D Fuel Structure Codes
- Coupled simulation of fuel deformation

CUPID Users Group

KAERI — User Agreement / CUPID V/V — University

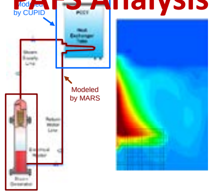
KAERI — User Contract / Technical Support — Industry

CUPID/DeCART



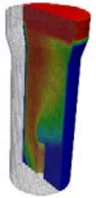
Pin wise kinetics code coupling

PAFS Analysis



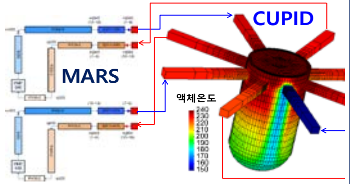
Application to passive system

CUPID -SG



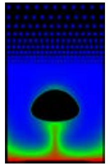
Component Analysis

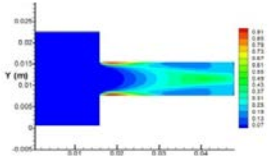
CUPID/MARS



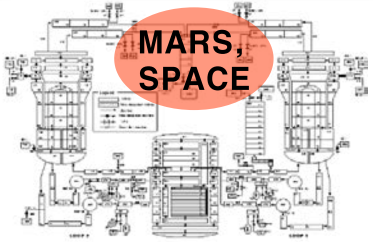
Multi-scale TH

DNS





Setup Numerical Method
- 3D *2-fluid 3-field*
- *Implicit* scheme
- *Unstructured* FVM
- Verifications

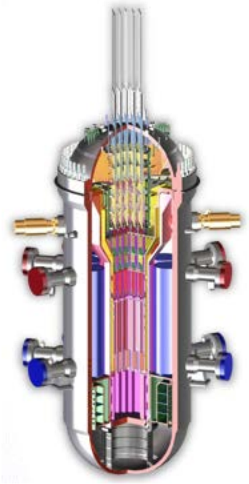


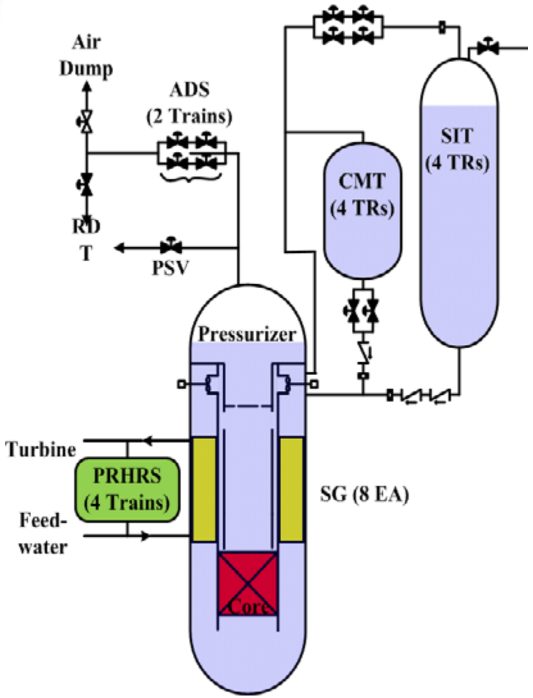
Meso-scale | Component-scale | System-scale | Scale (m)

… 10^{-3} | 10^{-2} | 10^{-1} | 10^{0}

SMART – Experimental Program

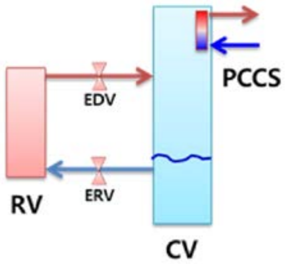
- **Developed by KAERI**
  - SDA in 2012.
- **Passive Design Features**
  - Passive RHRS
    - 4 Trains
    - Emergency Cooldown Tank (ECT) and Makeup Tank (MT)
  - Passive SIS
    - 4 CMTs, 4 SITs
    - PBLs : from RCP discharge to CMTs & SITs
  - ADS: 2 stages (ADV-1 & -2)
  - PCCS
    - Containment Pressure and Radioactivity Suppression System (CPRSS)





World's Unique and Largest Full Scope Accident Simulation
- 1:1 Height, 1/49 Volume

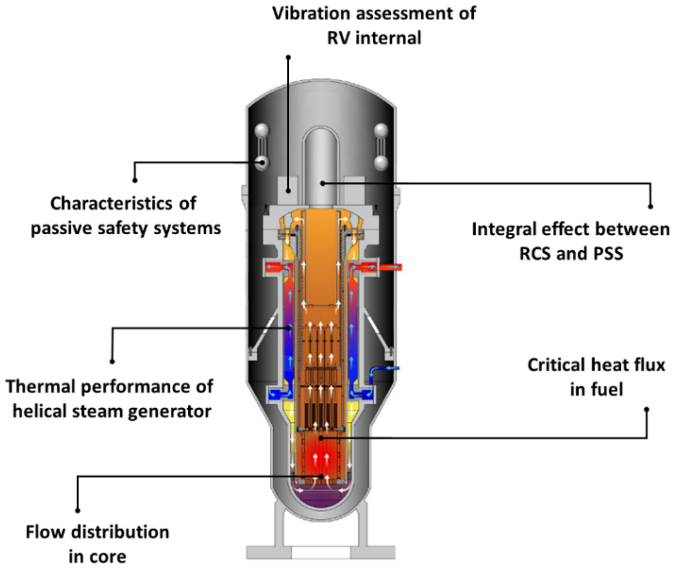
i-SMR – Technical Features

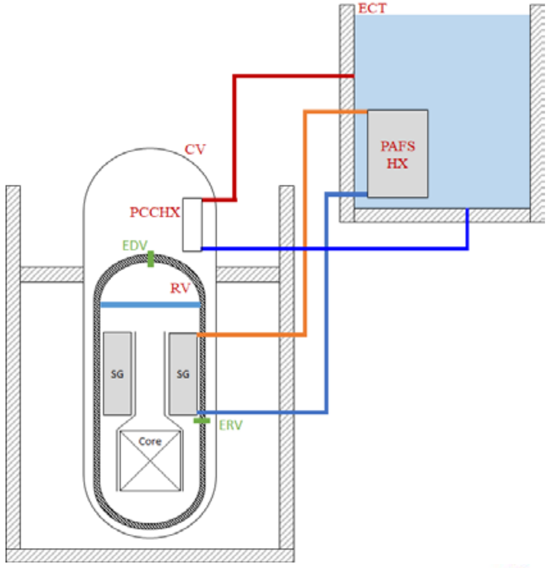


- **SDA: Targeted by 2028**
  - 1st module installed by 2033
- **IET: Constructed by 2026**
  - 1st test run: early '27

Nominal net output	680 MWe
# reactor units	4
Safety systems	PAFS, PECCS, PCCS
Thermal power	520 MWth
Gross electric output	170 MWe
SG #	Helical coiled (Mono.)
Steam cycle	Rankine-subcritical
RCS pressure	15 MPa
RCP #	4
RCP type	Vertical canned motor
Fuel	UO2 (5 % enrich.)
FA's in Core	69
Reactivity Control	In-vessel CEDM (No soluble boron)
Refueling intervals	24 months

- **Major TH Phenomena:**
  - PCCS : Condensation HT with nearly pure steam onto the outer wall of vertical HX tubes
  - PECCS : Natural circulation using EDV and ERV (recirculation by hydraulic head)
  - PAFS : well-validated in APR+ and SMART
  - CV: Internal flow



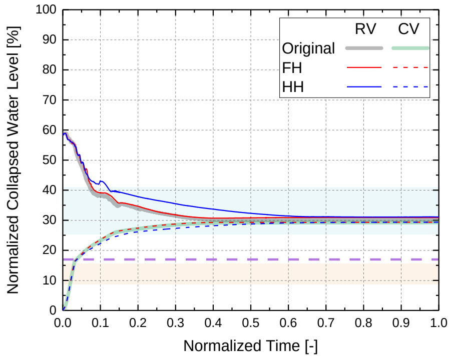


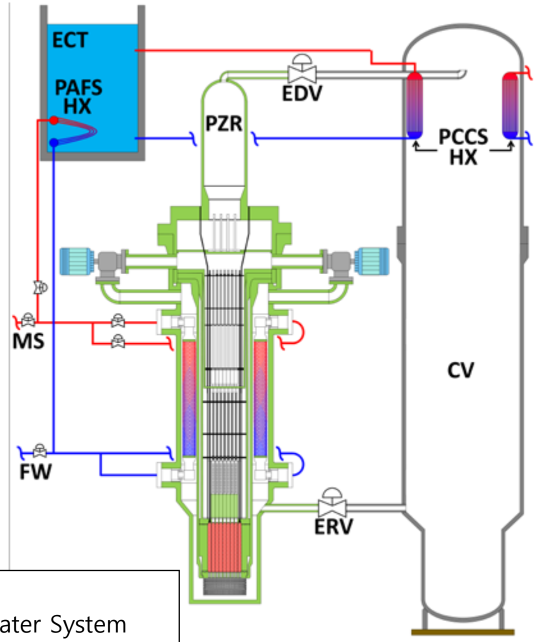
* Ref. : JH Yang et al. (NURETH-21)

i-SMR – Experimental Program

Integral Effect Test

- Ratio: 1/2 H, 1/49 A
- Monobloc HCSG
- Separated RCPs and CV
- 2ry Sys. and PAFS: 4 trains
- PCCS and ECT: 2 trains
  - Combined PAFS-PCCS effects
- EDV/ERV : 2 / 2
  - Separated break line and recirculation line in ERV



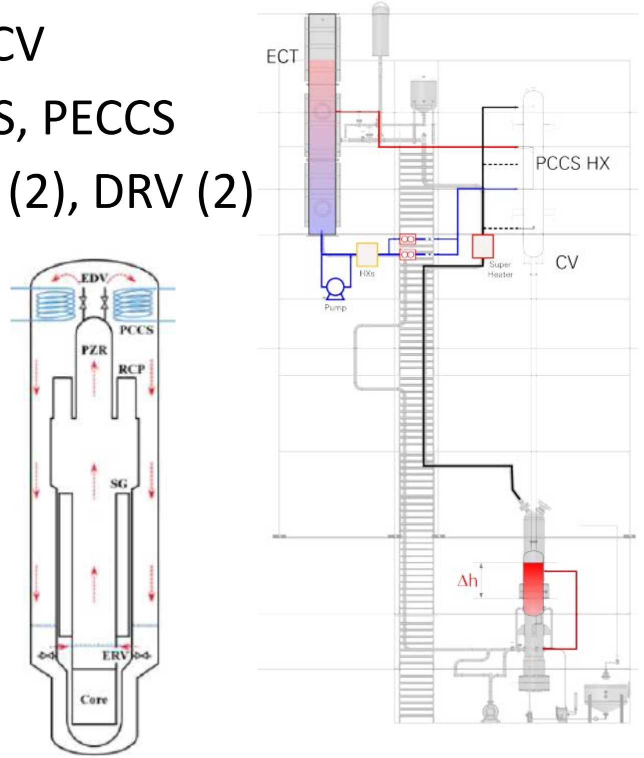


* Ref. : J.H. Yang et al. (KNS 2024 Autumn)

- PECCS: Passive ECCS.
- PAFS: Passive Aux. Feedwater System
- EDV: Emergency Depressurization Valve
- ERV: Emergency Recirculation Valve

Separate Effect Test

- Full Height
  - 1/1 H, 1/84 A
- Components
  - RV, CV
  - PCCS, PECCS
  - EDV (2), DRV (2)

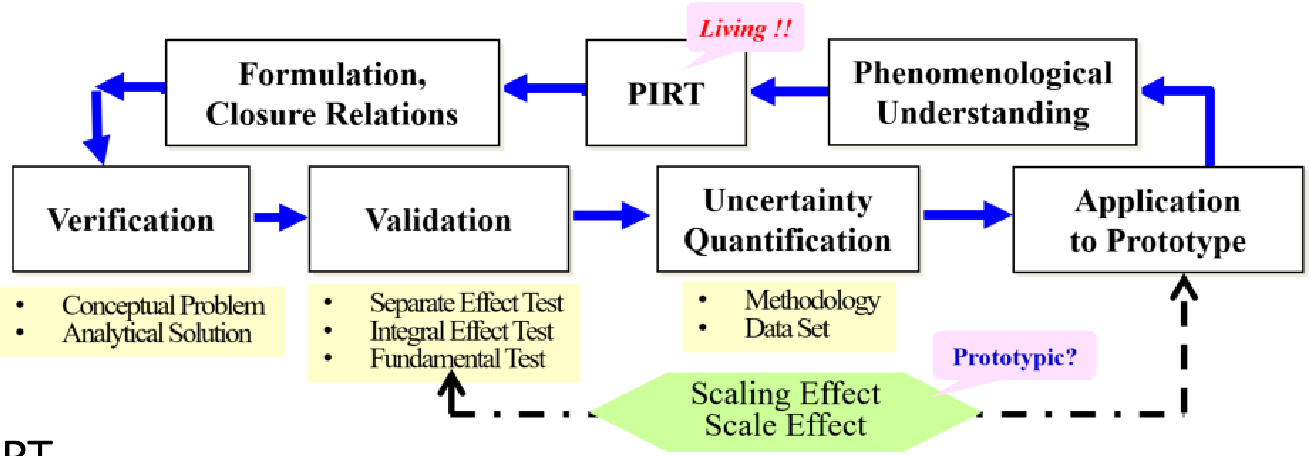


* Ref. : J.H. Yang et al. (NTHAS-13, 2024)

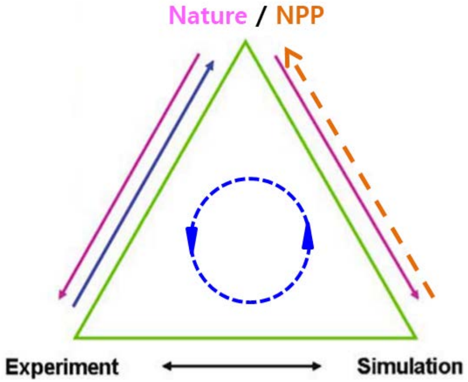
V. Summary

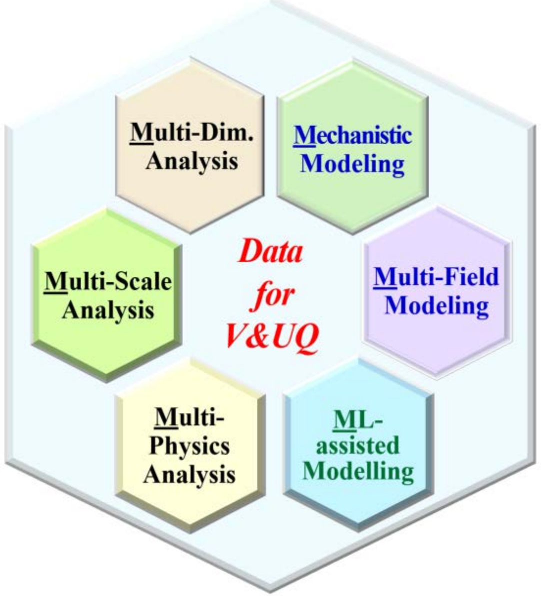
Advanced Modelling and Simulation

- **Improved Physical Understanding of Key TH Phenomena**
  - Developing ADFs for enhancing reactor safety: e.g., WC-SMRs
- **Need to Revisit Existing PIRTs***



  - Living PIRT
    - Continued Efforts on Improved Understanding of Relevant Physical Phenomena Should be Made before Scaling Analysis.
- **Leading to New Efforts of Developing:**
  - Improved Modelling: Finer scale, Multi-D, Inter-disciplinary, …
  - Advanced M&S Technologies: HPC environments, ML techniques, …





6 M's approach for advanced safety analysis*

* C.-H. Song (2018), C.-H. Song et al. (NURETH-21)

Concluding Remarks

- **Scaling Methods and Relevant Scoping Analysis Have to be carefully Selected to Ensure that Our System of Interest properly Reveals:**
  - Multi-D T-H Phenomena in a Large Space, and
  - Singularities in Flow Junctions.

- **Careful Validation of Existing Codes Are Required for Multi-D TH phenomena, especially to Appear in Large Components and/or New Design Features.**
  - Need to be Validated under Prototypic TH Conditions with Realistic Geometric Conditions.

- **Passive Safety Systems**
  - How to Demonstrate the Performance and Safety Contributions under Prototypic Conditions?

Some References

- C.-H. Song et al. (2025), “Scalability of Validation Data for the Safety Evaluation of Water-cooled Nuclear Reactors”, Presented at NURETH-21 and Invited for Submittal to *Nucl. Eng. & Technol*.
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- C.-H. Song et al. (2021), “Progress in Light Water Reactor Thermal-Hydraulics Research in Korea,” *Nucl. Eng. & Des.* 372.
- C.-H. Song (2018), “Challenging Experiments for Validating Advanced Two-Phase Flow Analysis Codes,” Invited Lecture, *FJOH-2018 Summer School on Nuclear Reactors*, Aix-en-Provence, France.
- C.-H. Song (2016), “Some Issues and Challenges in Advanced Thermal-Hydraulic Safety Research,” *Nucl. Technol.* 196.
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- H.Y. Yoon et al. (2014), “Recent Improvements in the CUPID Code for a Multi-dimensional Two-phase Flow Analysis of Nuclear Reactor Components,” *Nucl. Eng. & Technol.* 46.