Prospects of Next Generation Safety Analysis Code and Experience of high performance computing

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Bub Dong Chung[1)]

1) Korea Atomic Energy Research Institute, Korea

bdchung@kaeri.re.kr

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- Prospects of next generation safety analysis code
- Experience of high performance computing (or demands)
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- Concluding remarks

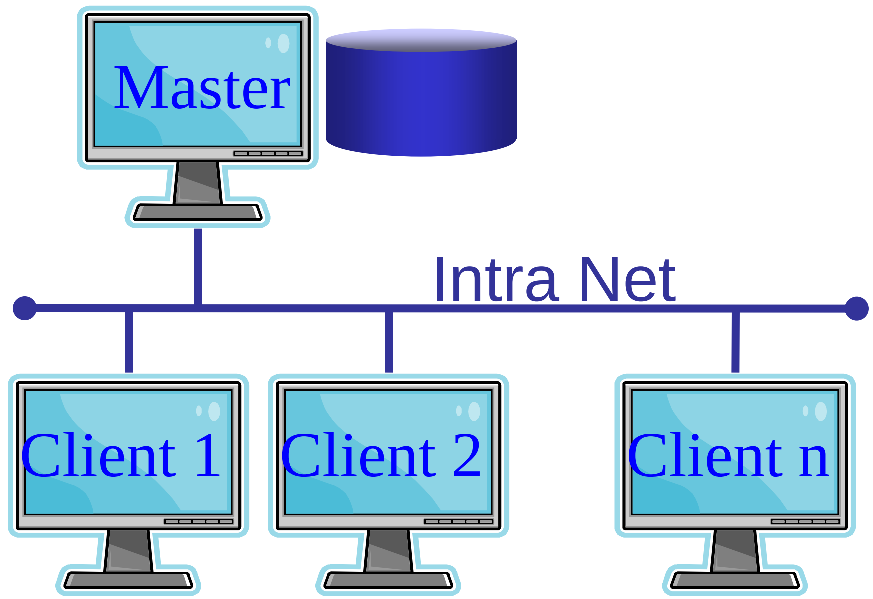
Current Safety Analysis Code in KAERI

- Design Analysis Codes
  - Nuclear design codes (from Monte-Carlo to Diffusion scale)
  - Core TH codes (from RANS to Subchannel scale)
  - Fuel analysis codes (from FEM to in-house 1D scale)
  - Safety analysis code
    - One of key design code for safety system as well as integral system performance
- Current Utilization of Safety Analysis Code
  - Westinghouse Design (PWR) Code (since 1980s)
    - CEFLASH, WFLASH, WCOBRA/TRAC
  - AECL (CANDU) Design code (since 1990s)
    - SOPHT, CATHENA etc
  - Best Estimate Code utilized by Regulatory Body (since 1980s)
    - RELAP5/MOD3, TRACE, COBRA-TF, MARS-KS
  - GEN-IV system TH analysis
    - MARS-LWR(SFR), GAMMA(VHTR)

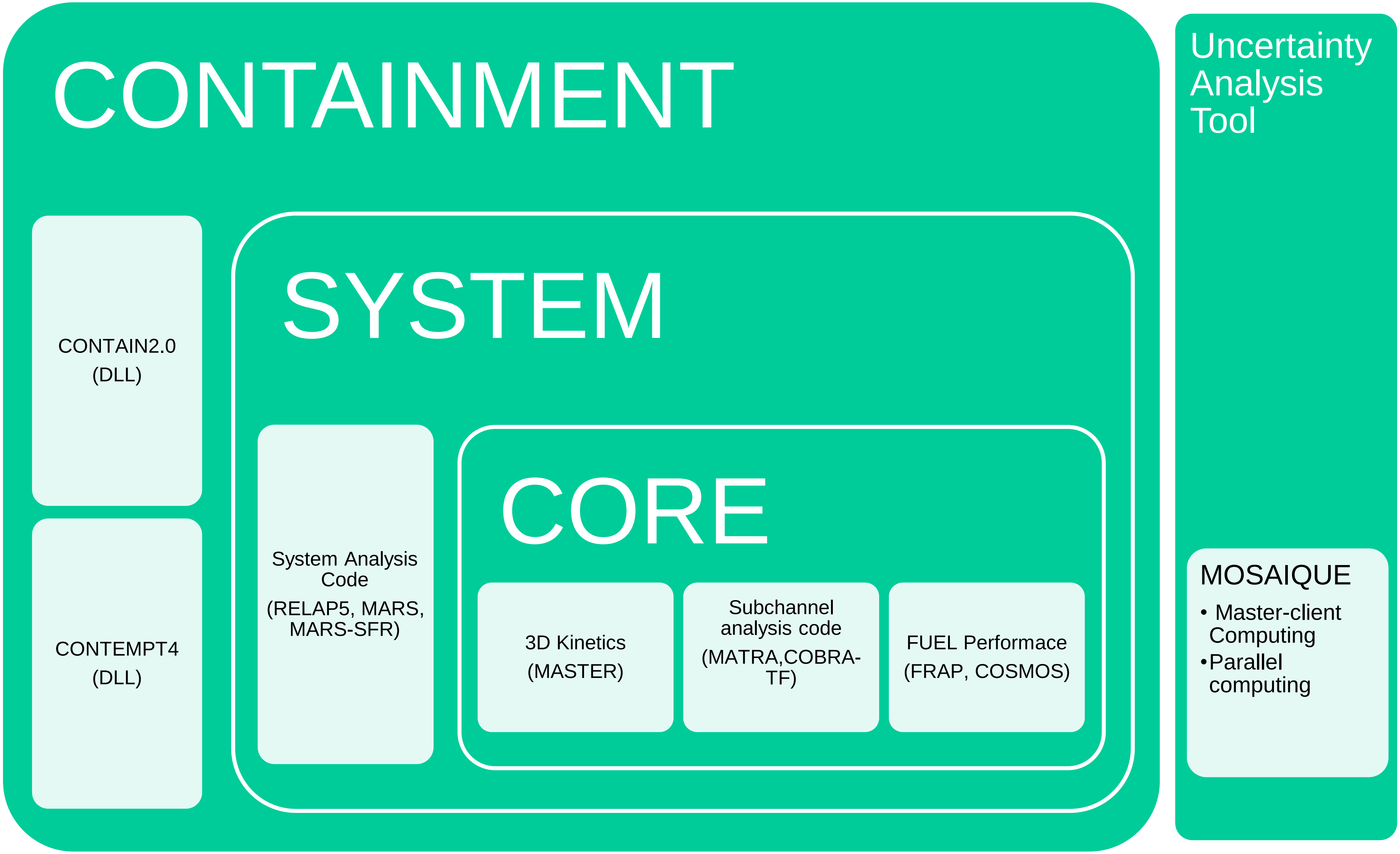
Current Safety Analysis Code in KAERI

- **"MOSAIQUE" is a fully automated software to support the uncertainty and sensitivity analysis of thermal-hydraulic calculations.**
  - **Sampling uncertainty parameters**
  - **Generating the input files for TH system code with uncertainty parameters**
  - **Running a TH code with cluster**
  - **Analyzing the results**

- **At present, MOSAIQUE supports many system TH codes. Use Client PCs in the Intranet for TH calculations**
  - **Automatically assigns the TH calculations to client PCs**
  - **Independent parallel calculations in client PCs.**
  - **When a client PC completes a TH calculation, it return results to the master PC.**



Current Safety Analysis Code System in KAERI



Prospects of Next Generation Safety Analysis Code

- **Current Safety Analysis Code System**
  - Validated with huge experimental data base (LWR) during last few decades
  - Contributing to solve the operating licensing issue for 3D kinetics coupled problem(CANDU LBLOCA) and 3D TH behavior (UPI PWR)
  - Utilizing for GEN-IV design analysis with some modifications
- **Advanced Simulation versus Next Generation Code**
  - By the definition of GIF task force, advanced model is mechanistic modeling for fundamental phenomena. It is also called “first principle solution”.
  - Example
    - Full core simulation with Monte-Carlo method
    - TH Simulation with DNS (at least LES level)
    - Fuel, material behavior with Molecular Dynamics (at least microstructure level)
  - The depletion calculation with advanced simulation may be possible with supercomputing power, however transient simulation within next few decades is doubtful
  - Focus next generation codes for advanced safety analysis

Prospects of Next Generation Safety Analysis Code

Next Generation Safety Analysis

- May be categorized according to the objectives of the analysis
- In licensing analyses
  - the objective is to provide a high-confidence measure of the safety margins and demonstrate the defense-in-depth design. Uncertainties in the analysis must be quantified to a degree that satisfies a level of confidence set by the regulator.
- In research and development analysis
  - the objective is to gain better understanding of physical phenomena and their interactions relevant to materials and equipment for advanced reactor concepts, expecting the replacement of expensive large validation experiment
- At this moment, the best approach for future safety analysis code may be dual-path programs in KAERI
  - An integrated safety analysis with statistical & PSA tool, aiming uncertainty reduction
  - Code coupling with next generation analysis codes (i.e. Multi-physics), aiming more realistic core behavior and accuracy enhancement,
  - In both areas, high performance computing are needed

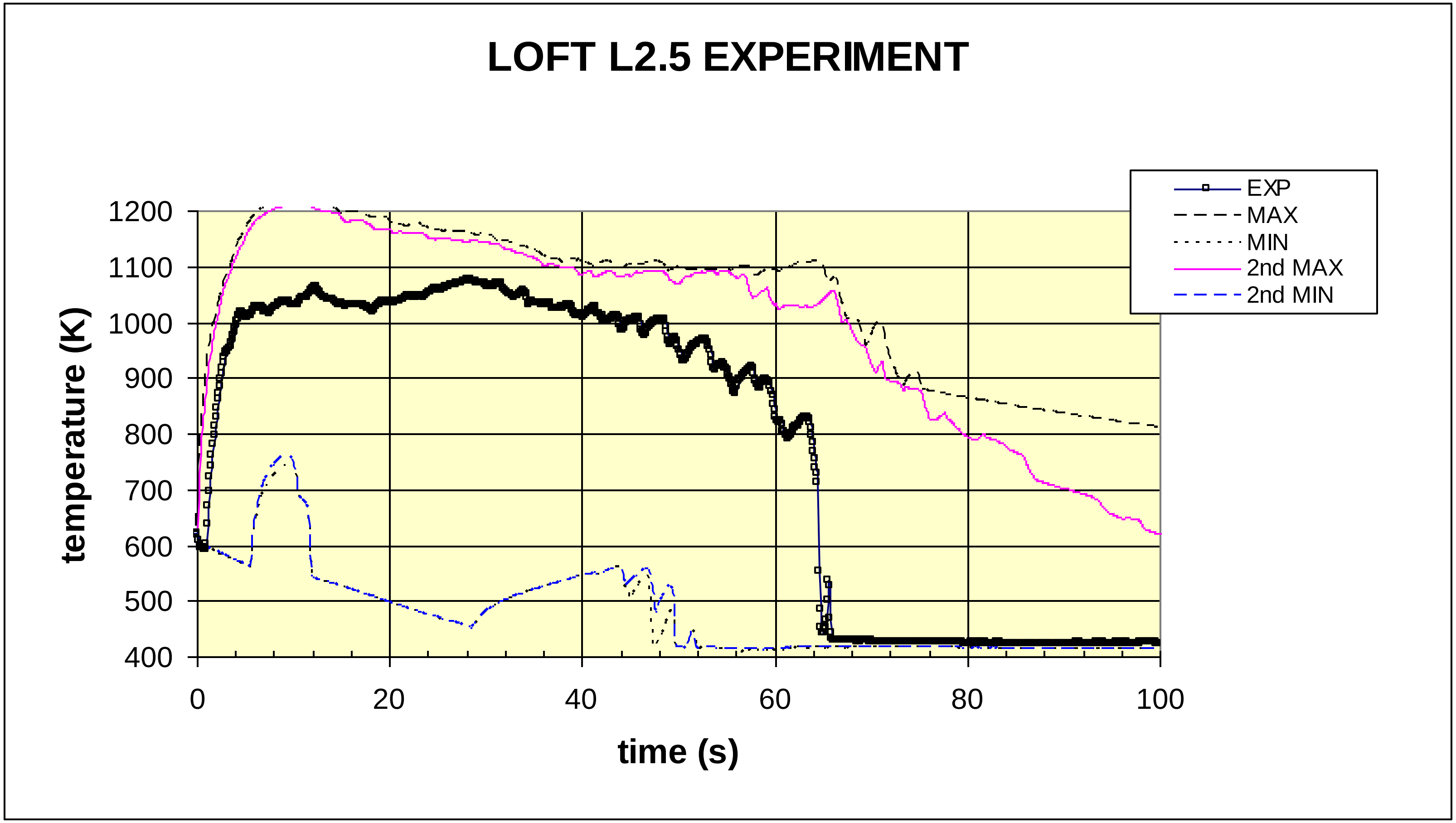
Experience of high performance computing

- **LOFT L2-5 LBLOCA Uncertainty quantification by Monte-Carlo method**
  - Performed by OECD/NEA BEMUSE Program (2007)
  - Code :
    - MARS System analysis code (similar to RELAP5)
    - 2 fluid, multi-dimensional system TH
    - Point kinetics & Simple Fuel model
- **Whole core physic analysis using transport code linked with CFD**
  - Performed by US-ROK collaborative DOE I-NERI project
  - Code System
    - Core Physics: DeCART (3D full core transport) ← McCARD (MC)
    - Core TH: Start-CD (RANS CFD)
    - Fuel : NEPTUNE (FEM)
    - Coupling technique : Data transfer with TCP/IP protocol

World-wide Uncertainty Propagation Method for LOCA

- **USNRC methods : CSAU method**
  - **Response surface construction using sensitivity analysis**
  - **Monte-carlo calculation with response surface(> 50,000), Find pdf**
- **GRS, IPSN, K-REM(KEPCO), ASTRUM(W) methods:**
  - **identify and combine input uncertainties, using subjective pdfs.**
  - **Monte-Carlo calculation with direct calculation**
  - **Find 95%/95% tolerance limit value or curve (by limited number of calculation according to non-parametric statistics; Wilks' formula)**
- **Number of code calculations can be determined by Wilks' formula**
  - **Number of code runs n**
    - **upper statistical tolerance limit (one-sided): $1 - \alpha^n > \beta$**
    - **α is desired probability percentile,**
    - **β is confidence level**
  - **One sided 95% probability, 95% confidence limit require 59 calculations (non-parametric statistics)**
  - **If Wilks' formula at the second order, 93 sample set is needed**

95%/95% Tolerance limit of PCT

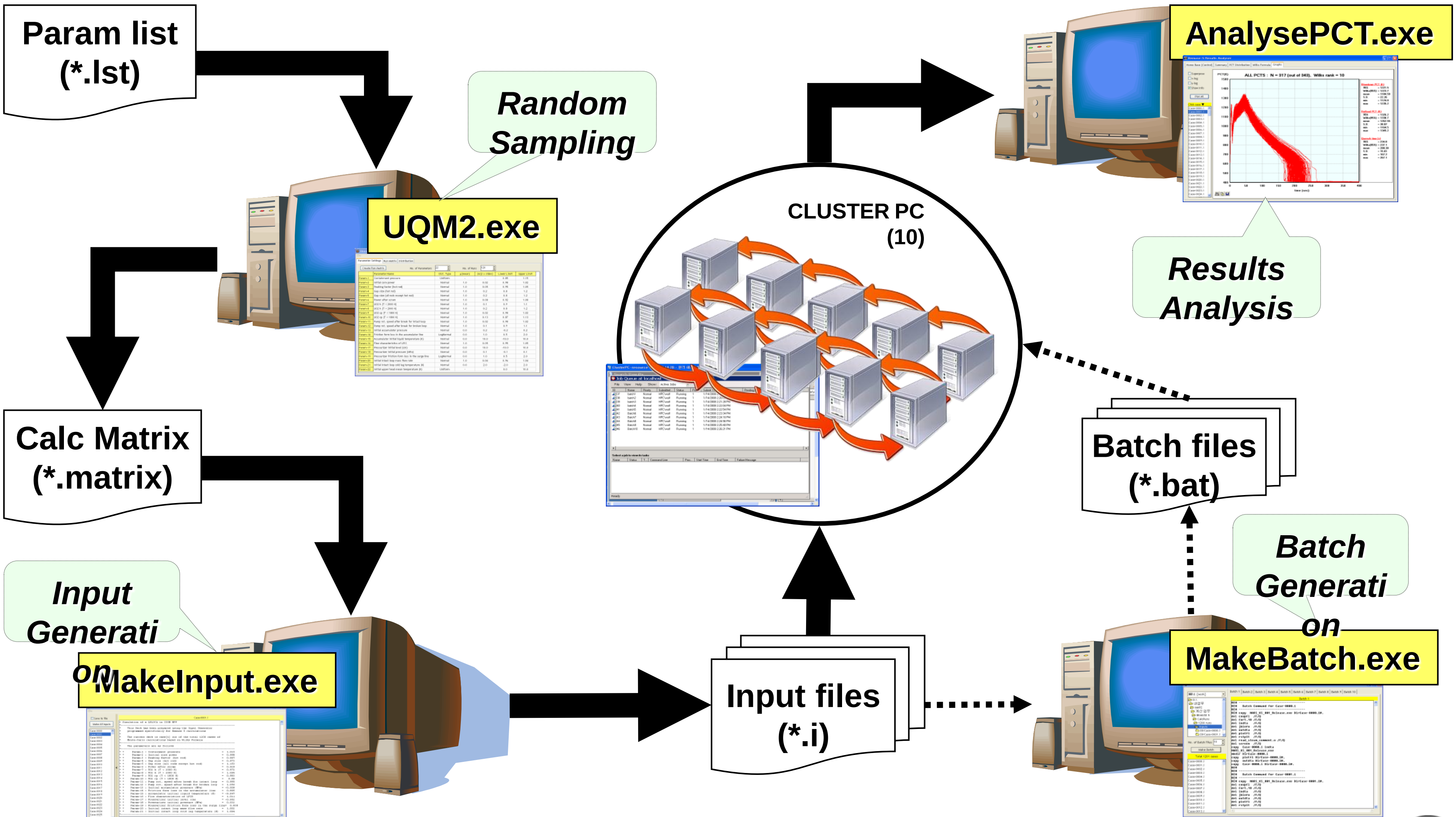


Full Monte-Carlo Calculation

- **Motivation to compare with the results from full Monte-Carlo method**
  - **Approach based on Wilks' formula is an ad-hoc approach with a limited computing power**
  - **Need to find the statistical fluctuation of small sampling (~ 100 runs) effects for non-parametric statistical method**
  - **Full Monte-Carlo approach, more than 10,000 runs are needed**

Full Monte-Carlo Calculation

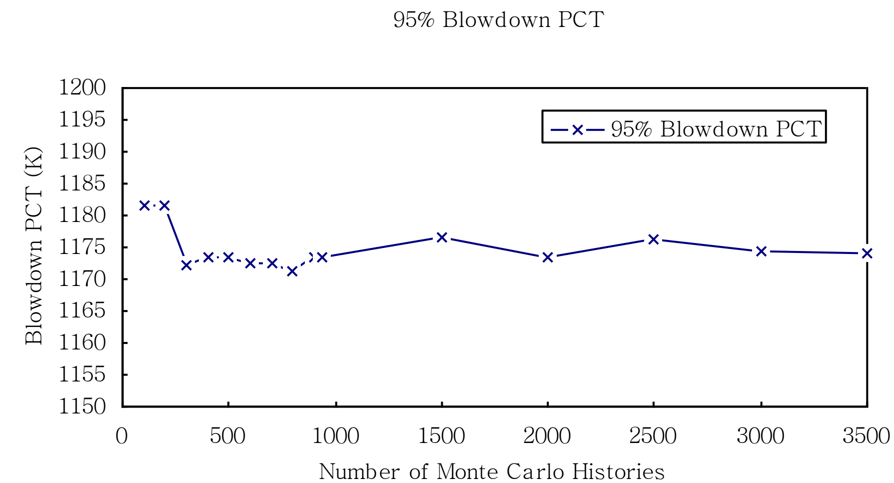
This semi-auto process has been now replaced with "MOSAIQUE", which is a fully automated software

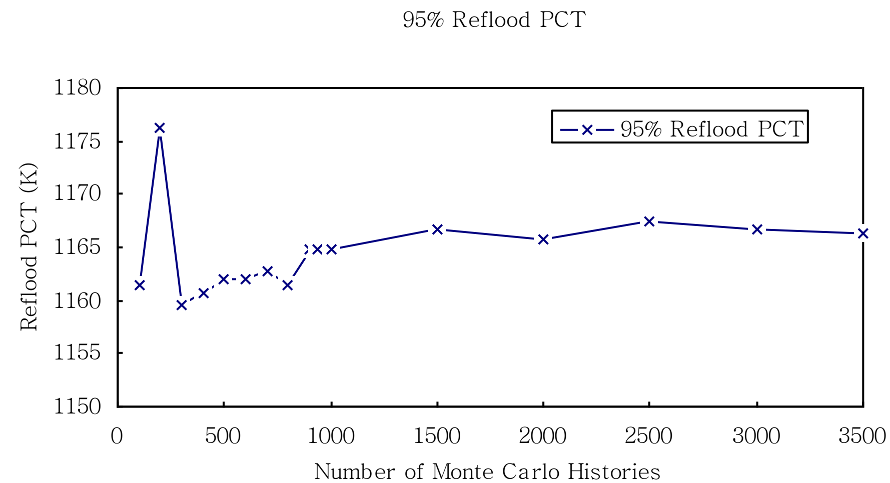


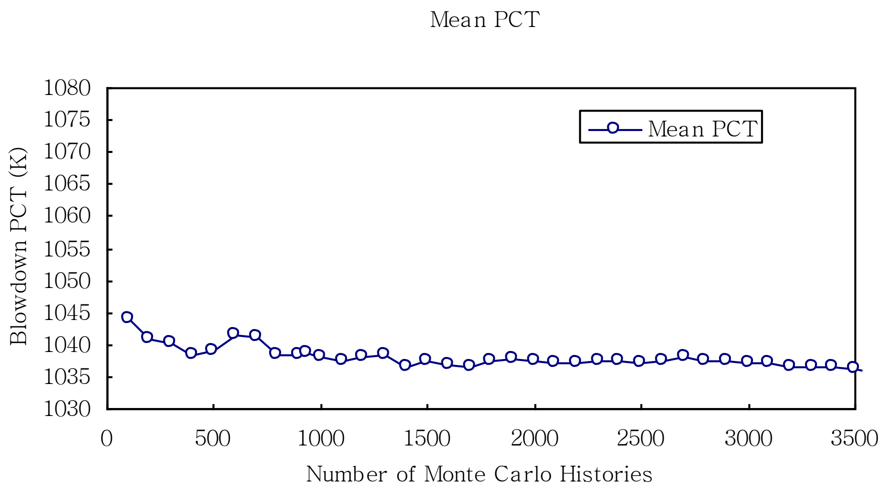
Full Monte-Carlo Calculation

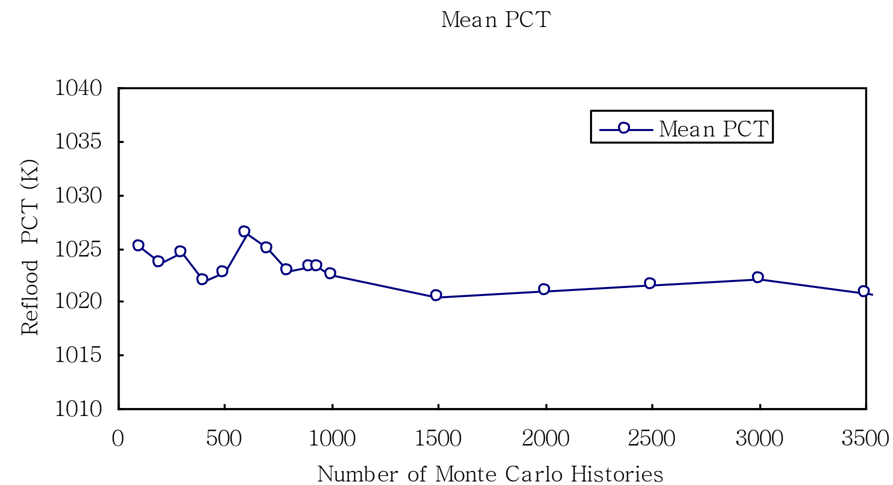
- **CPU times**
  - 3.0 GHZ CPU with Window XP
  - Estimated computing time for scheduled 10,000 runs
    - 100 days on single core
    - 10 days on 10 nodes PC cluster
  - When 4,000 calculations were obtained, terminate calculations intentionally
- **Selection of results**
  - Failure rate ~ 7%
  - Calculation failures were not systematic, but random.
  - May be from code deficiencies at low P and flow condition, after the completion of core quench
  - Discard the failure cases
  - 3,500 success runs were used for statistical treatments

Full Monte-Carlo Calculation



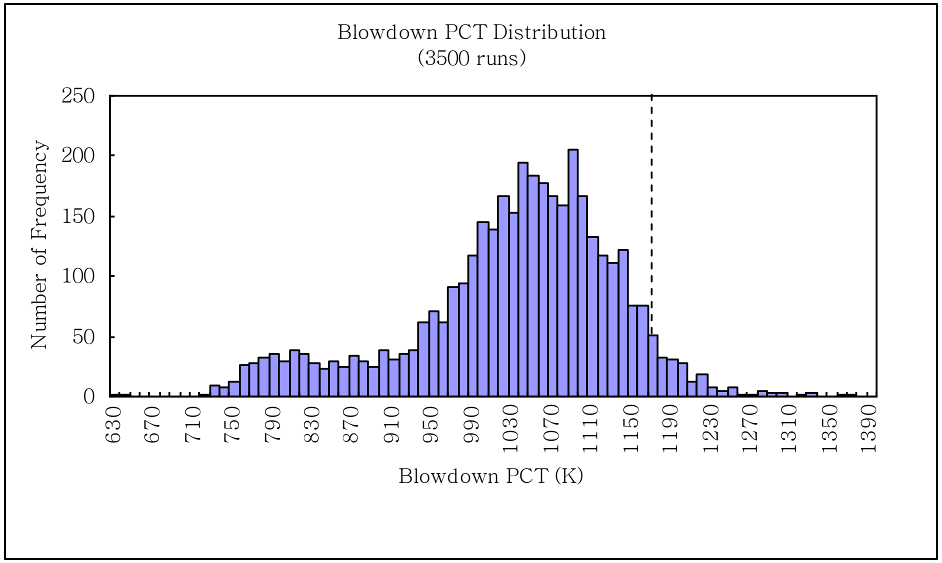


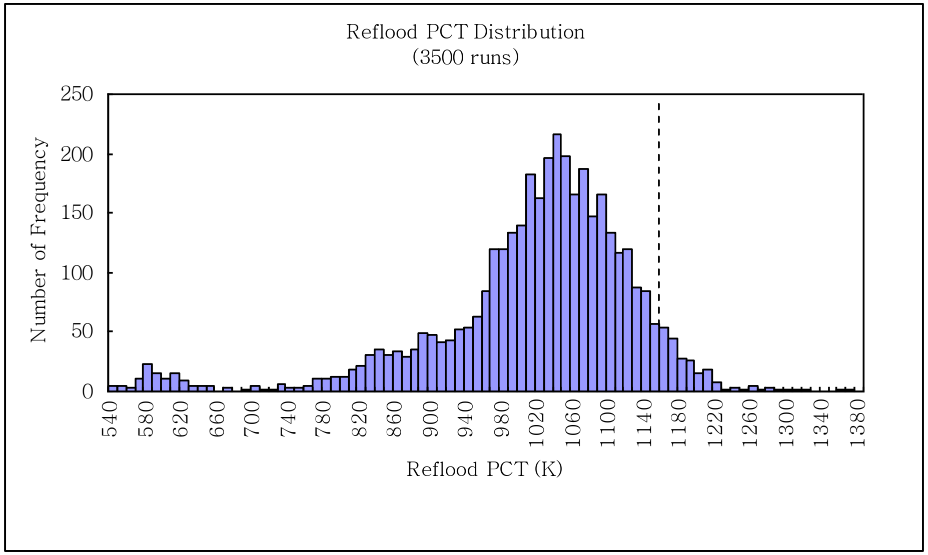




Full Monte-Carlo Calculation (PCT Distributions)

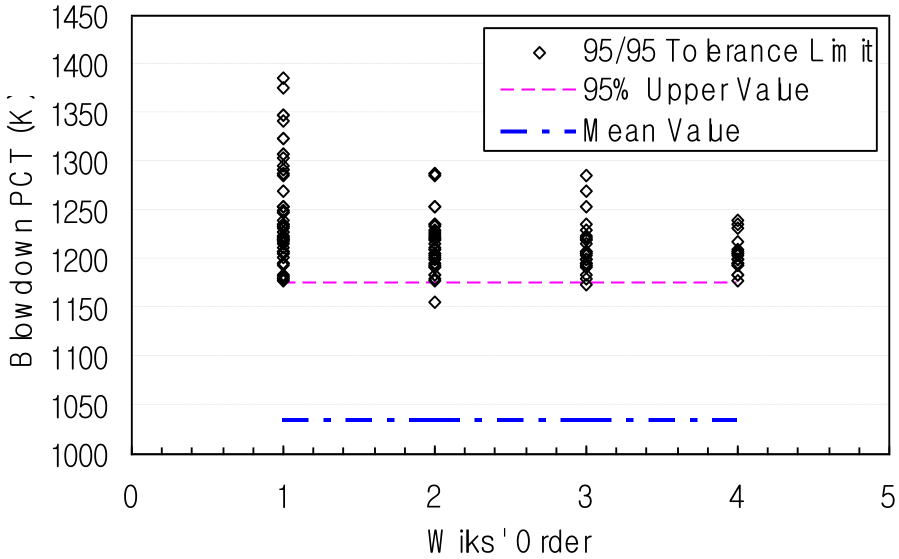
- **Histogram**
  - **Use success 3,500 PCT data**
- **Blowdown PCT**
  - **Two peaks**
    - **Blowdown CHF bifurcation**
- **Reflood PCT**
  - **Two peak**
    - **Rewet bifurcation just after blowdown**
- **Bifucation phenomena is difficult to capture using response surface method and others**

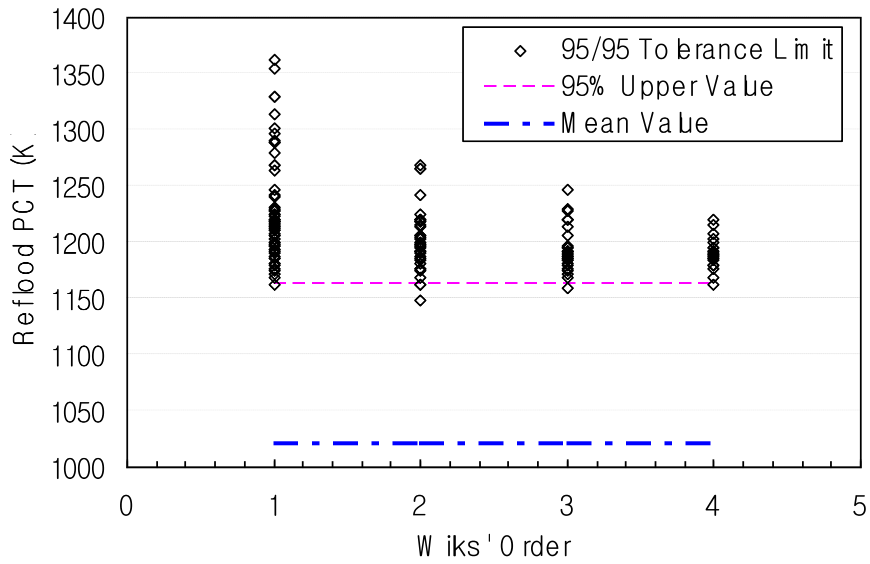




Comparison with Tolerance Limits based on Wilks' Formula

- Tolerance limit value is higher than the 95% limit value by 95% confidence level, it means there is a risk of 5% under-prediction
- Statistical variance can reduce significantly with increasing Wilks' order, but still too high to quantify the safety margin (license margin)



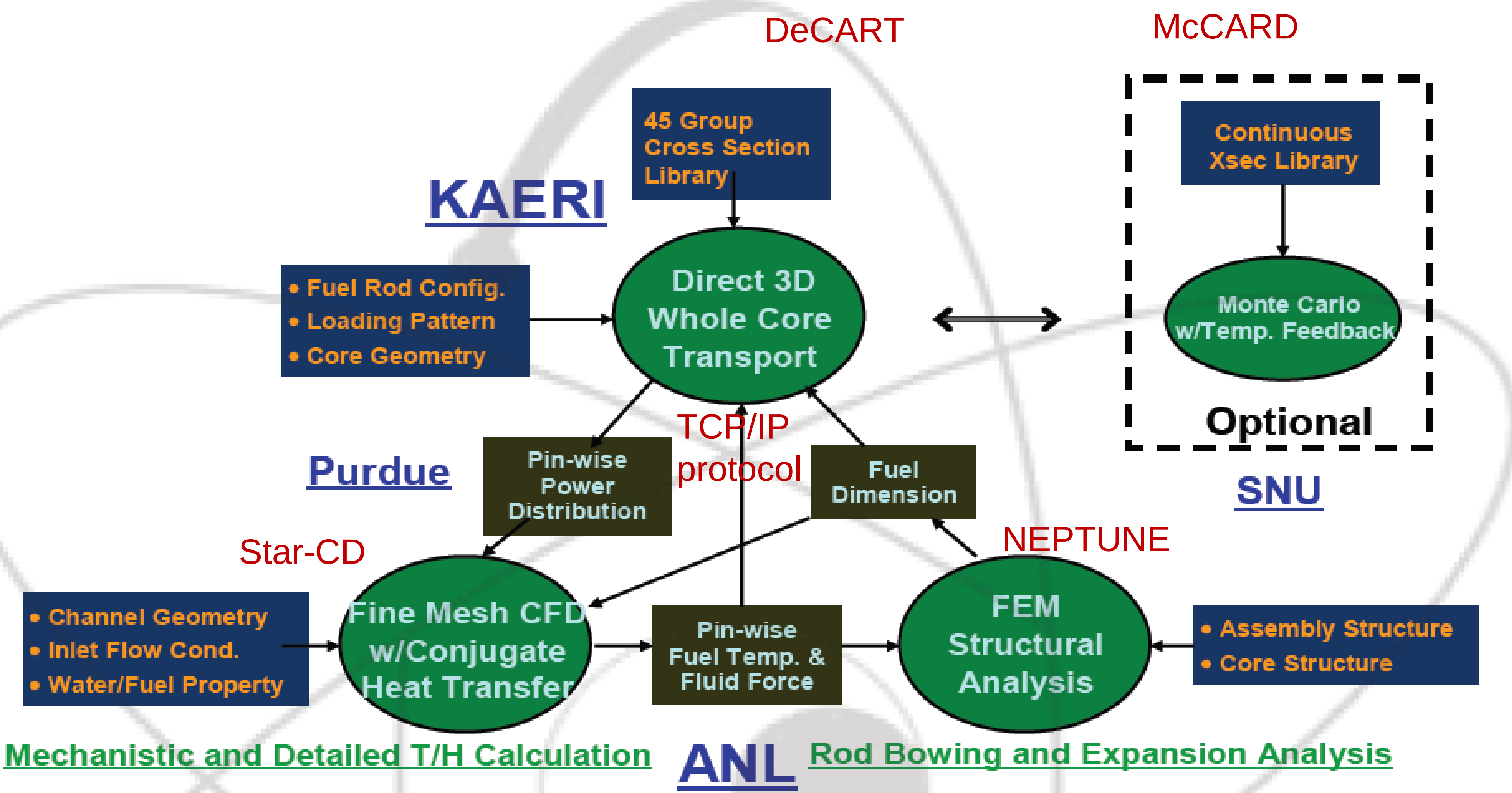


Lessons

- **Results**
  - **The uncertainty method using non-parametric statistics , i.e. Wilks' formula, is an ad-hoc approach with a limited computing power**
  - **It may be useful for auditing evaluation of existing design**
  - **However, full Monte-Carlo method is needed to quantify the design safety (license) margin**
- **Need of High Performance Computer**
  - **1 week computing time was required for LOFT LBLOCA (50 sec transients) using 10 core machine**
  - **For practical BEPU LOCA application to PWR full scale**
    - **< 1 day calculation speed may be necessary to get LOCA full spectrum analysis**
    - **numbers of core ~ 10core x10(500sec)x10(1day)=1,000 core**
  - **For SBLOCA, longer time is needed (> 3000 sec)**
    - **~ 10,000 core is needed**
  - **To support risk informed regulation**
    - **Huge numbers of scenarios according PSA event tree**

Experience of US-ROK collaborative DOE I-NERI project

- **Whole core physic analysis using transport code linked with CFD**



DeCART: Deterministic Core Analysis based on Ray Tracing
McCARD: Monte-Carlo Code for Advanced Reactor Design and Analysis

- Whole core calculations have been performed successfully for a small PWR.
- The neutronic model included nearly 5 million neutronic zones, while the CFD RANS model included 73 million cells.
- Calculations were performed on the Jazz LINUX Cluster at ANL, using 57 of the available 350 processors.
- Results were obtained in several hours, demonstrating the feasibility of running whole core calculations on currently available parallel computer systems.

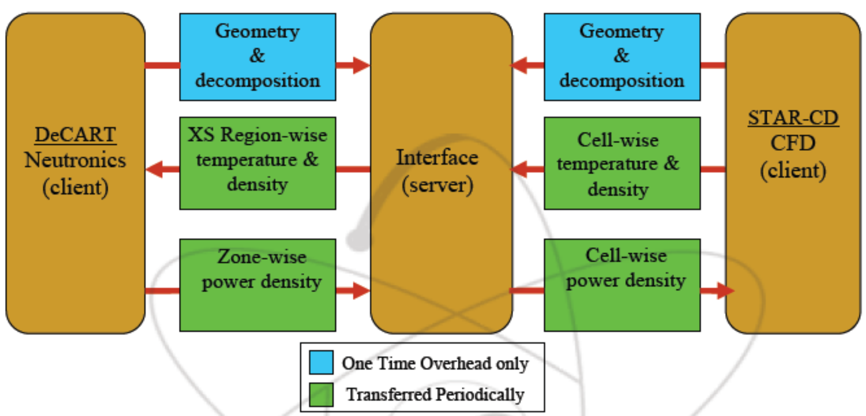
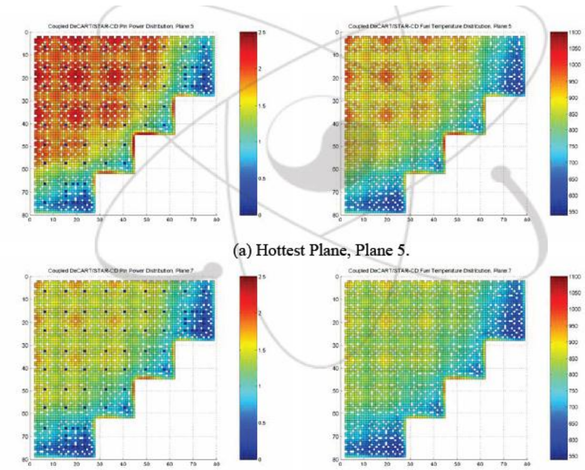


Fig. 3.3.2. Schematic of the DeCART/STAR-CD Coupling Scheme.



(a) Hottest Plane, Plane 5.

(b) Mid-plane, Plane 7.

Fig. 4.1.11. Pin power (left) and average fuel temperature (right) for the core mid-plane and the plane with the highest power. (The scale is from 0 to 2.5 for pin power and from 550K to 1100K for fuel temperature).

Lessons

- **Need of HPC**
  - Transient Application of Coupled System
    - Core : 3D Transport – CFD RANS(+ Subchannel) – Fuel (1D/3D)
    - System : Conventional System Code (RELAP5, MARS, etc)
  - Considering a typical core have 50,000 fuel rods and 50,000 subchannels. May need >10,000 core
  - Expected improvement area of safety analysis
    - AOO : More accurate DNB margin calculation based on full core pin-power and subchannel behavior
    - RIA : More detailed pin-wise power coupled with TH and fuel behavior, direct evaluation of fuel failure rate
    - SLB : More detailed thermal mixing and re-critical evaluation
    - Radiological Consequences : Accurate source term with pin-wise evaluation
  - Uncertainty quantification of high fidelity model for engineering purpose
    - Brute force MC method may be not possible
    - Combination of perturbation and MC method

Concluding remarks

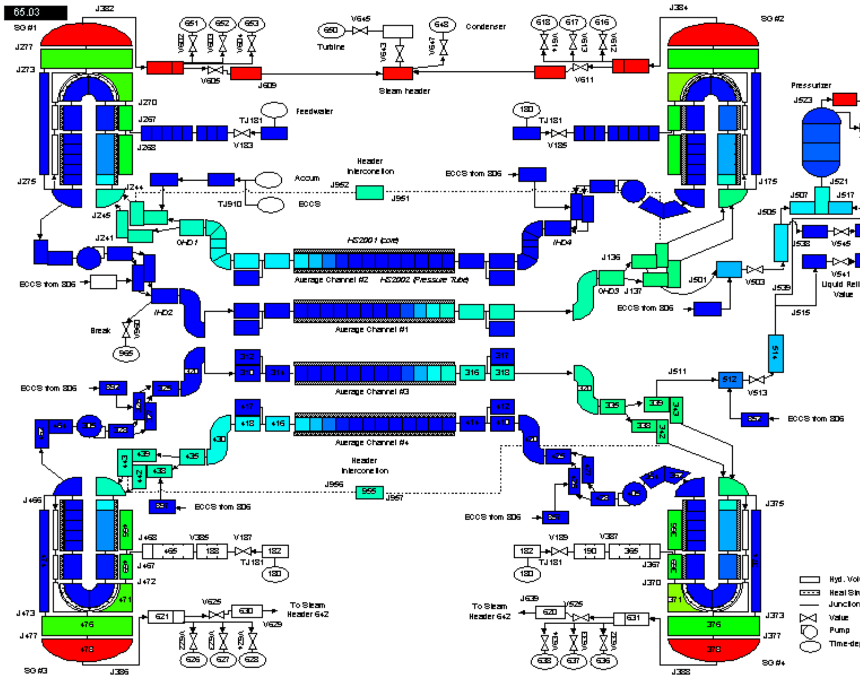
- At this moment
  - dual-path programs for future safety analysis code system are considering in KAERI
- Integrated safety analysis with uncertainty quantification tools
  - Demonstrate the defense-in-depth design and reduce uncertainty
  - Utilizing HPC
    - Enable full spectrum analysis of DBA with UQ
    - Support risk informed regulation
      - Safety margin quantification for licensing analysis require huge number of calculations
- Code coupling with next generation analysis tools (i.e. Multi-physics)
  - More realistic full core behavior and accuracy enhancement based on high fidelity models which is now available
    - 3D transport neutronics code (few million nodes)
    - RANS scale TH or subchannel code (few million nodes)
    - 3D FEM or in-house 1D fuel performance code (few million nodes)
    - Conventional system TH code (few hundred nodes)

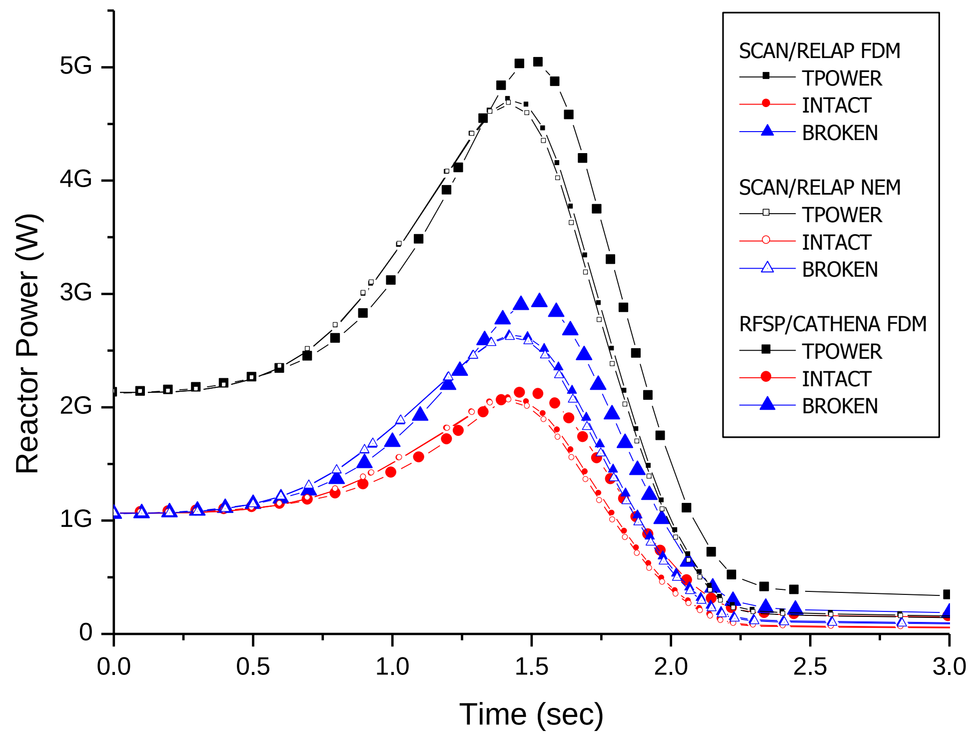
APPENDIX

Examples of Calculation Result

Application for CANDU (PHWR) LBLOCA

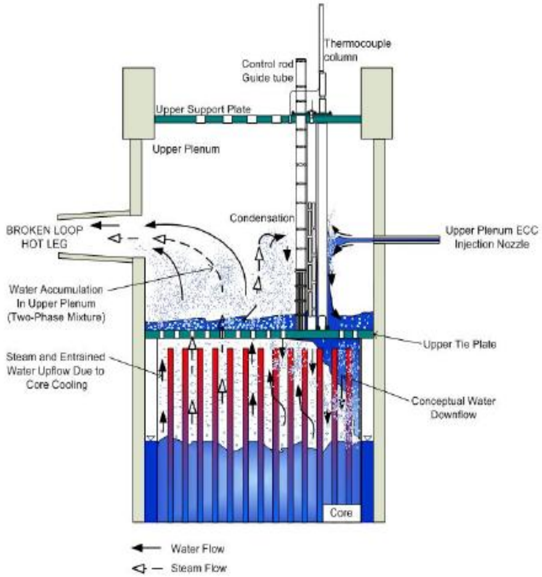
- Safety issue during licensing for Wolsong #1 reoperation
- Power peak during LBLOCA due to positive moderator coefficient
- Coupled analysis with 3D kinetics is utilizing for auditing calculation

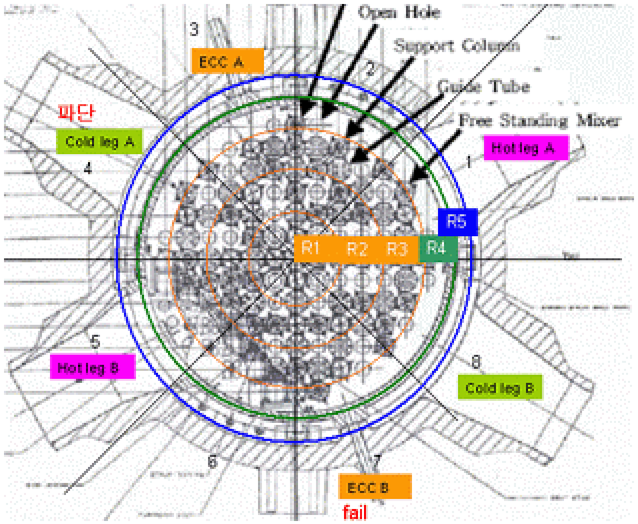


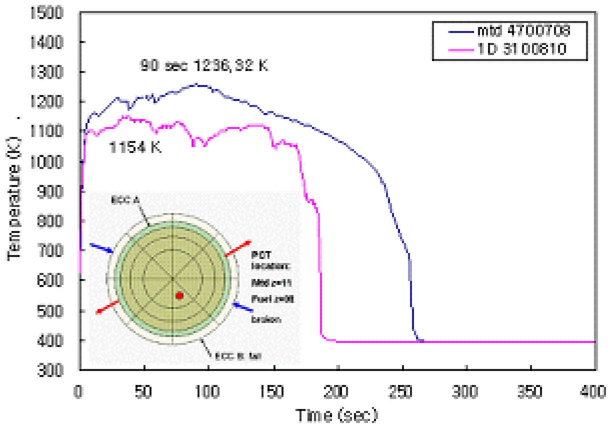


Kori Unit 1 UPI LBLOCA Audit Calculation

- Safety issue during licensing for Kori #1 Life extension
- Multidimensional behaviour during LBLOCA reflood phase
- Full 3D analysis show the non-conservatism of 1D calculation
- BE+Uncertainty still below safety limit



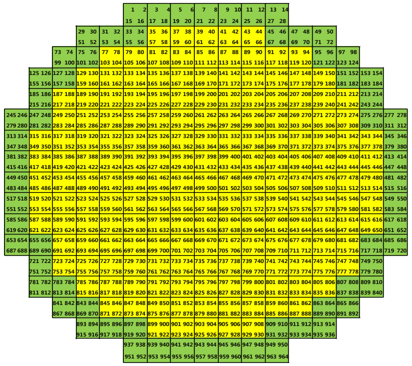




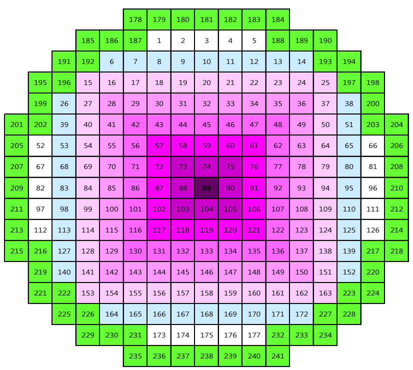
Application for Detailed Core TH Behavior

25 Finger Control Element Assemble Drop Accident

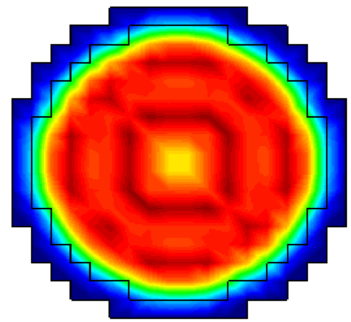
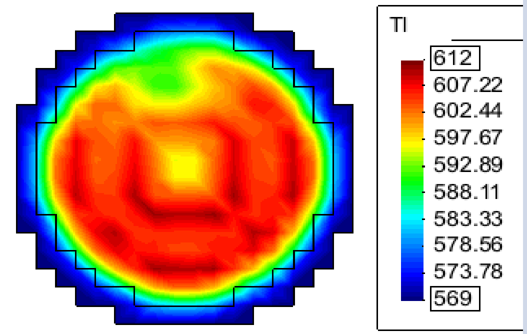
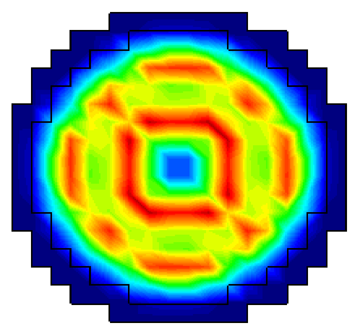
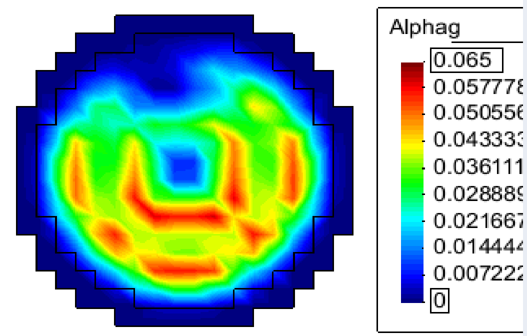
- **CUPID-MASTER(3D Kinetics) Coupled Calculation**



MASTER mesh, 962x26



CUPID mesh, 241x16

	Steady State	After 25 Finger CEA Drop
Distribution core exit temperature		
Distribution of Exit Core Void Fraction		

Possible Software for the Multi-Scale Multi-Physics Analysis

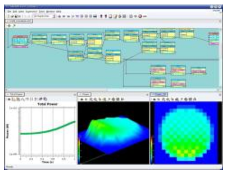
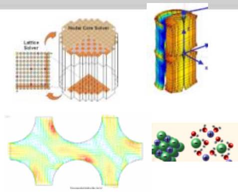
Project \ Software	Thermal Hydraulics				Neutronics		
	System	Macro	Meso (DNS)	Commercial CFD	Diffusion	Transport	Monte Carlo
KAERI	MARS (SPACE)	MATRA CUPID (Developing)	-	TBD (Start-CD)	MASTER	DeCART	McCARD (SNU)

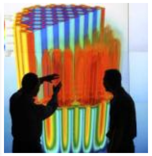
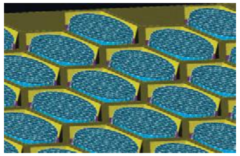
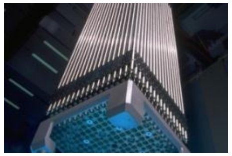
Project \ Software	Fuel Performance	Structural Mechanics	Chemistry	Uncertainty Quantification	Multi-physics Multi-mesh Integrator
KAERI	COSMOS (developing)	TBD (NEPTUNE)	-	MOSAIQUE	-

Long term prospect (KAERI)

Short term	Mid-term	Long term
Establish Base tech and coupling tech.	AMS with personal Supercomp cluster	Application NPP Utilize New Design

Integrated Analysis Platform	Realization of Advance M&S	Application of VR
• Coupling Tech. • Nuclear & Mat. DB • Core Physics • Core TH • Fuel Performance • Water-chemistry	• Structure Coupling • Material Science • Base DB Extension • Parallel Compute • Utilize personal GPU supercomp.	• Uncertainty Quant • App. for Design • App. for SA • Utilize world-class supercomp.

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