IAEA Technical Meeting on Advanced Technology Fuels

KOREA
ATOMIC
ENERGY
RESEARCH
INSTITUTE

STATUS OF FUEL AND THERMAL HYDRAULIC COUPLED ANALYSIS IN KOREA

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KAERI

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CONTENTS

01

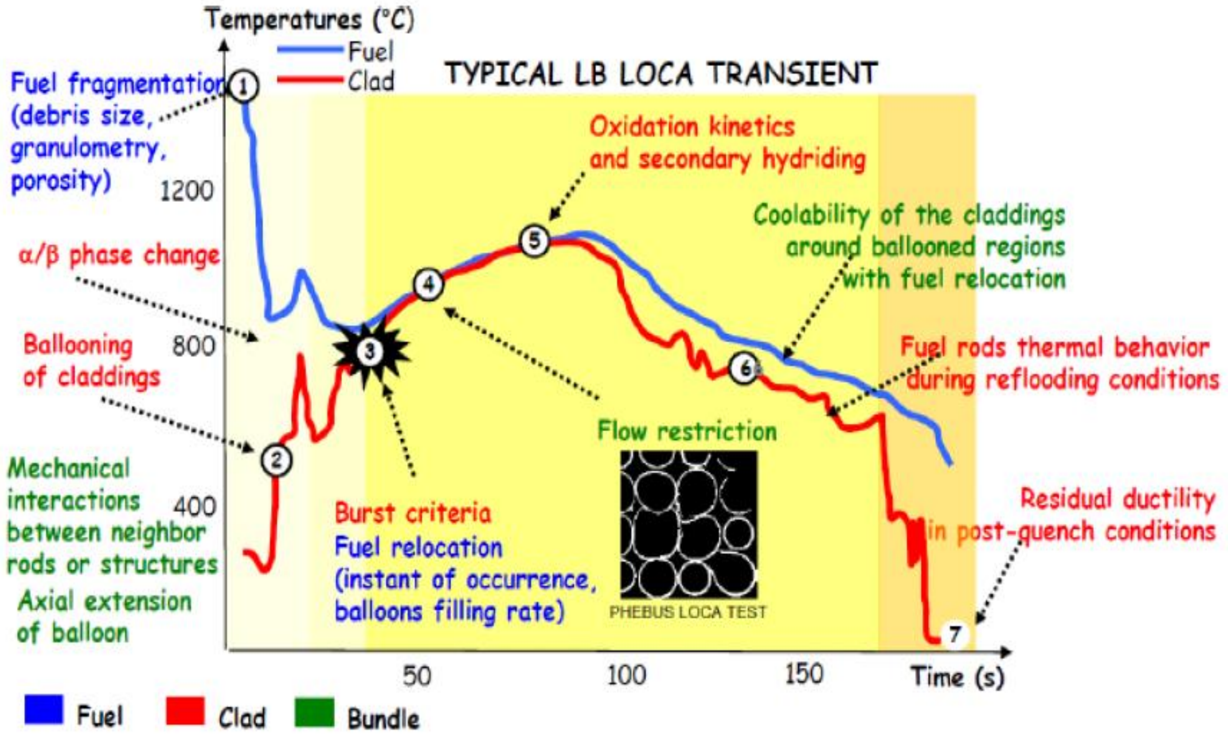
Requirements for multiphysics

- Definition of the adequate scenario for the coupled analysis
  - The fuel behavior should significantly influence the thermal-hydraulic or neutronic response (e.g., fuel ballooning may cause flow channel blockage)
  - Thermal-hydraulic or neutronic feedback should interact with fuel behavior (e.g., the heat transfer coefficient determines the cladding temperature)
  - The results from standalone code calculations can differ considerably from those obtained with coupled code simulations due to the interactive nature of the behaviors (e.g. PCI (not coupled) vs LOCA (coupled))
- The individual coupled codes should be validated and qualified
  - If not, it becomes impossible to identify the source of discrepancies between the coupled code results and experimental data.
- The coupled code needs to be validated against experimental data
  - Even if each individual code has been validated separately, the coupled code must also be validated, since the coupling scheme itself requires verification through experimental data and benchmarking among various codes

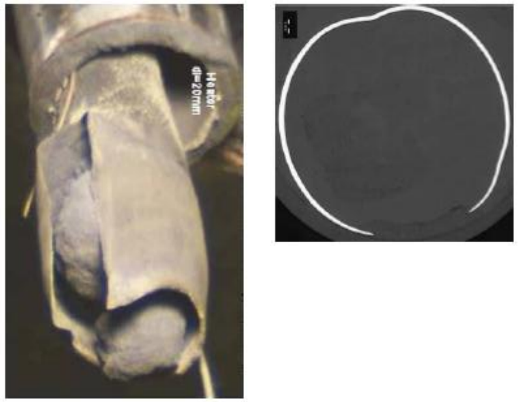
LOss of Coolant Accident scenario

Fuel behaviors affect safety factors during accident conditions

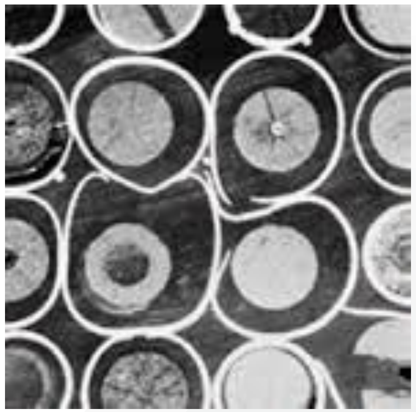
- Fuel initial conditions: material properties degradation, oxide, CRUD etc.
- Accident conditions: Ballooning&burst → flow channel blockage, FFRD → local heat concentration, additional material in coolant etc.



(G.Repetto, IRSN)



Ballooning & Burst
(IFA650.9@HALDEN)

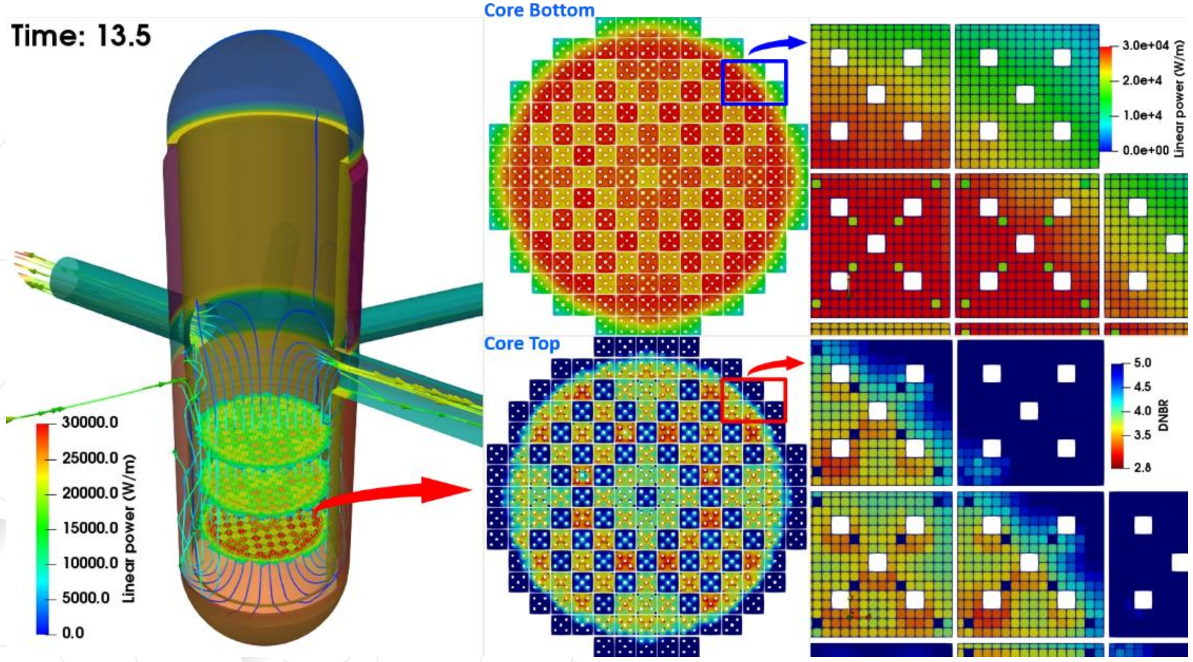


Flow blockage due to Ballooning
(PHEBUS@IRSN)

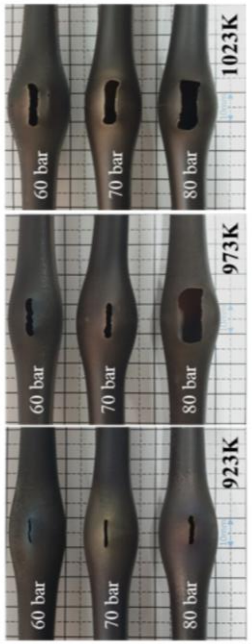
Research approach

Status of Fuel/TH coupled code in KOREA

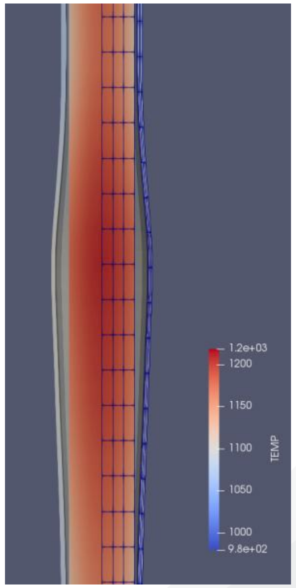
- MARS-KS/FRAPTRAN (FAMILY) : Safety evaluation with fuel behavior (KINS)
- CUPID/FRAPTRAN : Core wide analysis in subchannel and multi rod (KAERI)
- CUPID/MERCURY : Subchannel and multi dimensional fuel analysis (KAERI)
- MARS-KS/MERCURY : Safety analysis evaluation of ATF characteristics (KAERI)



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

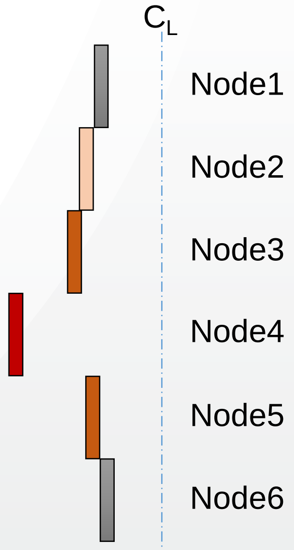


Real world



MultiD approach

VS



1.5D approach

Research approach

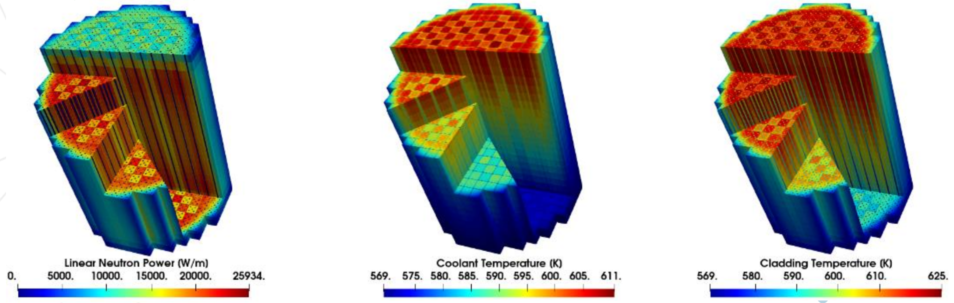
** H.Y.Yoon et al., NURETH-17, 2017.*

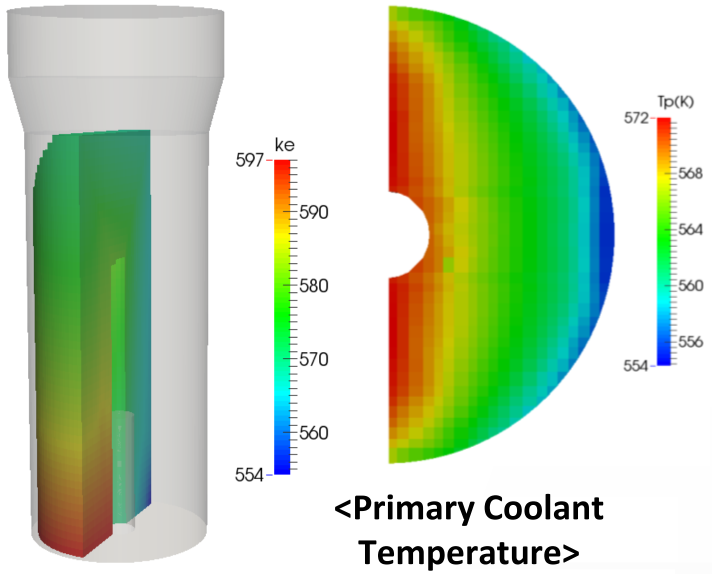
Korea Atomic Energy Research Institute (KAERI)

High-fidelity TH analysis code : CUPID

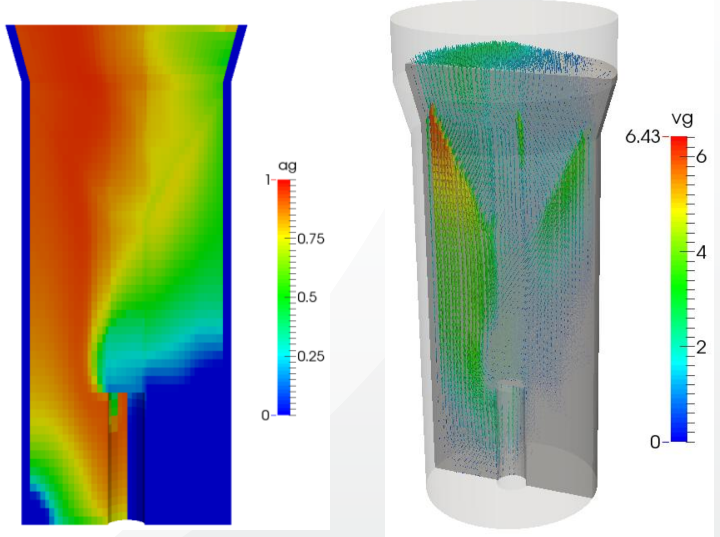
- 3D unstructured FVM incompressible solver
- Two-fluid Three-field approach
- MPI parallel computation and high performance computing using AMG solver
- Component scale to CFD (RANS) Scale
- Multi-scale/multi-physics coupled calculation
- Nuclear power plant module-based solver :Reactor vessel, steam generator, SMR, containment etc.

Neutron Power (N/K Code) | Coolant Temperature (T/H Code) | Clad Temperature (F/P Code)





<Primary Coolant Temperature>

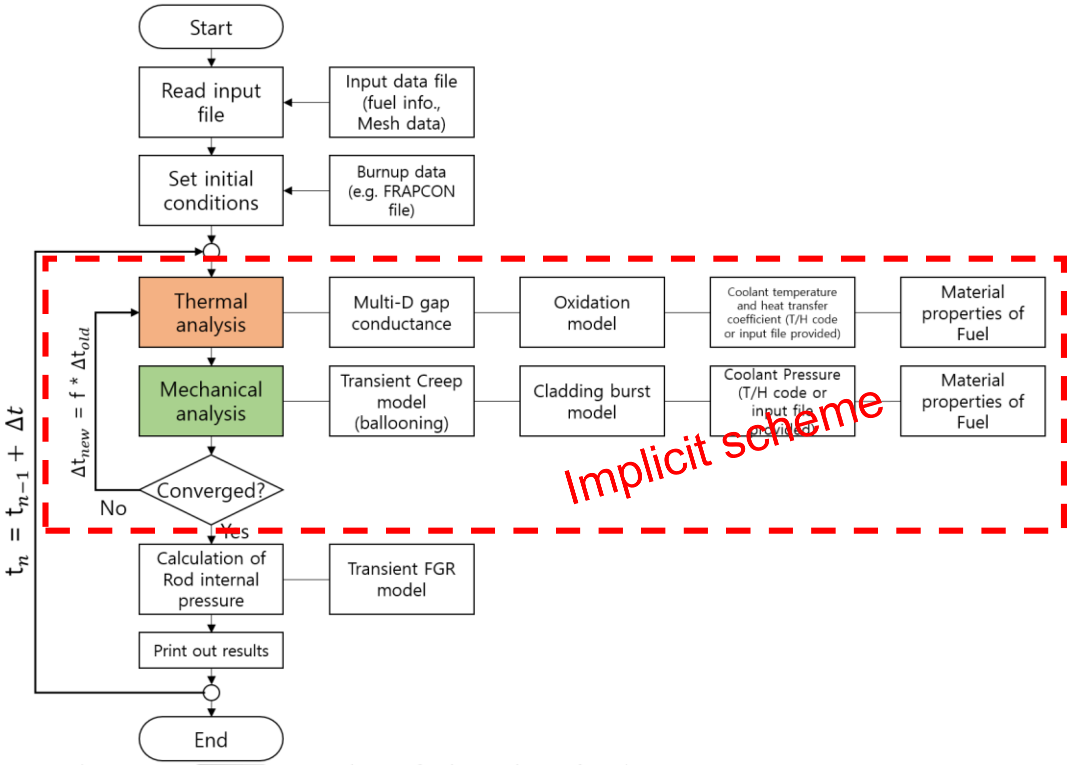


<Secondary Side Void Fraction and Velocity Vectors>

Research approach

Korea Atomic Energy Research Institute (KAERI)

High-fidelity FUEL analysis code : MERCURY



- MERCURY: **M**ulti-dimensional **E**ntire fuel **R**od **C**ode for **U**nderstanding **R**eaction **Y**ield behavior
- Characteristics : Finite element method, multidimensional analysis, parallel processing
- Environment : Intel Visual Fortran XE2019 or upper version
- Input/Output : fuel input file, mesh file, fuel output file, FEM output file (vtk format)

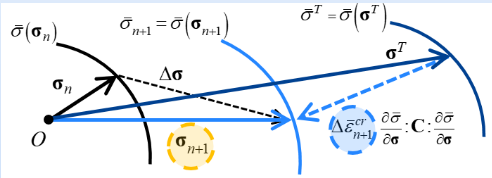
- Transient thermal analysis

$$\rho C_p \dot{T} = \left(k_{ij} T_{,j}\right)_{,i} + f \quad \text{in } \Omega$$

- Nonlinear mechanical analysis

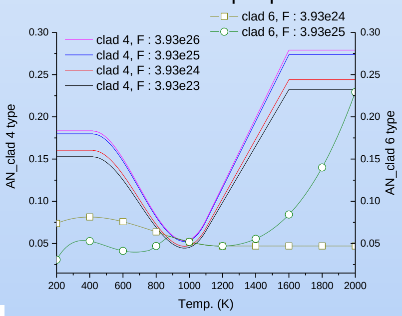
$$\sigma_{ij,j} + \rho b_i = \rho \dot{v}_i \quad \text{in } \Omega$$

<Stress update model>



- Thermo-mechanical analysis
- Burnup dependent material properties
- Multi-D gap conductance
- Oxidation model at high temperature
- Cladding failure model
- Cladding creep model at high temperature
- Oxide and CRUD thermal model

<Fuel material properties>

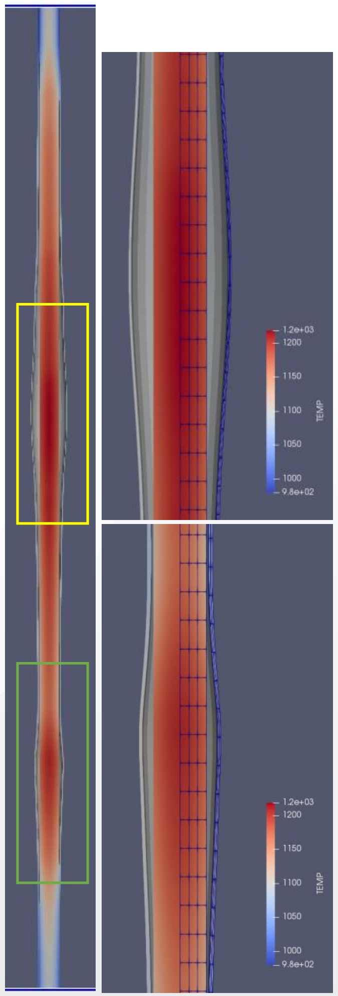


$$\dot{\varepsilon}_{eff} = A_{eff} \exp\left(-\frac{Q}{RT}\right) \sigma_{eff}^{n}$$

Material phase	A_{eff} ($MPa^{-n}s^{-1}$)	n	Q (K)	F/G/H
α phase (T < 1085K)	8736.8	5.89	5321000+24.69 (T-923.15)	0.956 /0.304 /0.24
α + β (1085K < T<1248K)	0.24	2.33	102366	0.5/0.5/0.5
β (1248K < T)	7.9	3.78	141919	0.5/0.5/0.5

HRP IFA650.9 double ballooning simulation

Specimen image



Research approach

Coupling methodology: Conservation of energy between Fuel and Thermal Hydraulic code

$$
\begin{aligned}
q''^{n+1} = {} & h_l^{n+1}\left(T_w^{n}-T_l^{n}\right)+h_{stl}^{n+1}\left(T_w^{n}-T_{st}^{n}\right)+h_d^{n+1}\left(T_w^{n}-T_d\right)+h_{std}^{n+1}\left(T_w^{n}-T_{st}^{n}\right) \\
& +h_g^{n+1}\left(T_w^{n}-T_g^{n}\right)+h_{stg}^{n+1}\left(T_w^{n}-T_{st}^{n}\right)+h_{spg}^{n+1}\left(T_w^{n}-T_{sp}^{n}\right) \\
& +\left(h_l^{n+1}+h_{stl}^{n+1}+h_d^{n+1}+h_{std}^{n+1}+h_g^{n+1}+h_{stg}^{n+1}+h_{spg}^{n+1}\right)\left(T_w^{n+1}-T_w^{n}\right) \\
= {} & q_0''+\sum_k h_k\left(T_w^{n+1}-T_w^{n}\right)
\end{aligned}
$$

Explicit heat flux

Total HTC

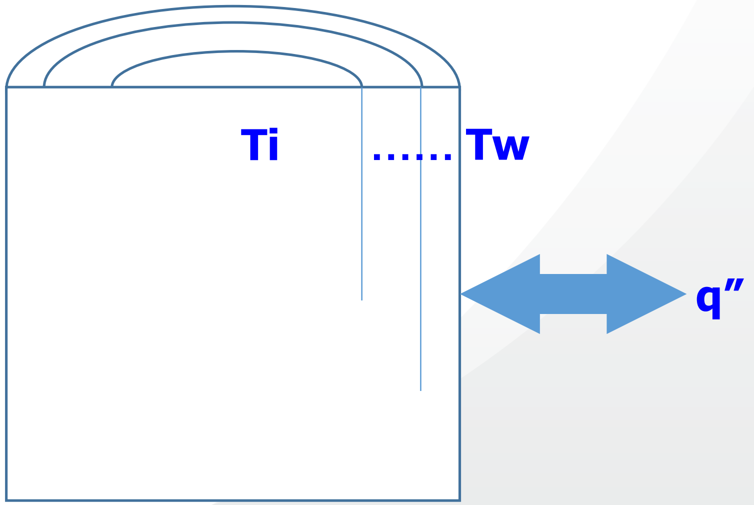
T_f and averaged HTC are not required for coupling.

conduction **convection**

$$
q''^{,n+1} = A T_w^{n+1} + B = q_0'' + h_{total}\left(T_w^{n+1}-T_w^{n}\right)
$$

$$
\therefore T_w^{n+1} = \frac{B + h_{total} T_w^{n} - q_0''}{h_{total} - A}
$$

Major coupling variable



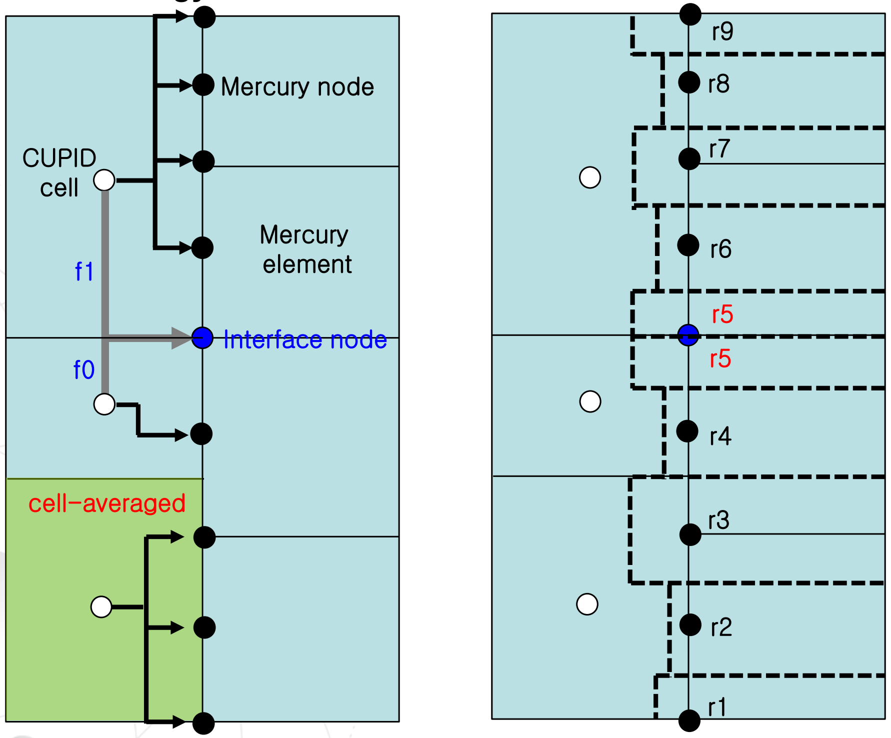
Research approach

Coupling methodology : Space and time

Space Coupling

- Because of the difference in mesh size between the two codes, the coupled variables should be defined based on the conservation of energy.

- Area-weighted wall temperature
- Interpolated wall temperature

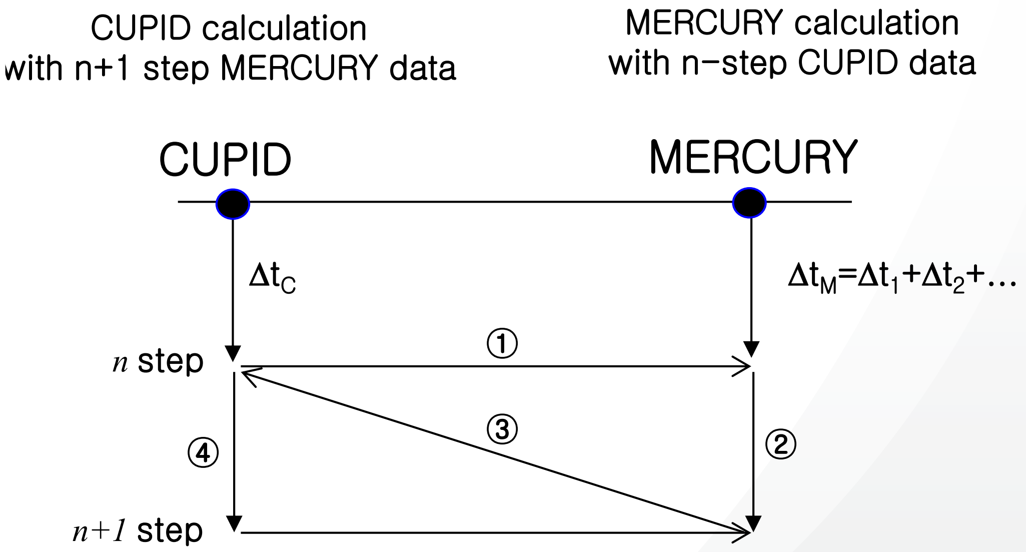


CUPID to MERCURY

MERCURY to CUPID

Time Coupling

- The time-step size of individual code are different
- Considering the characteristics of each code, calling sequence needs to be optimized



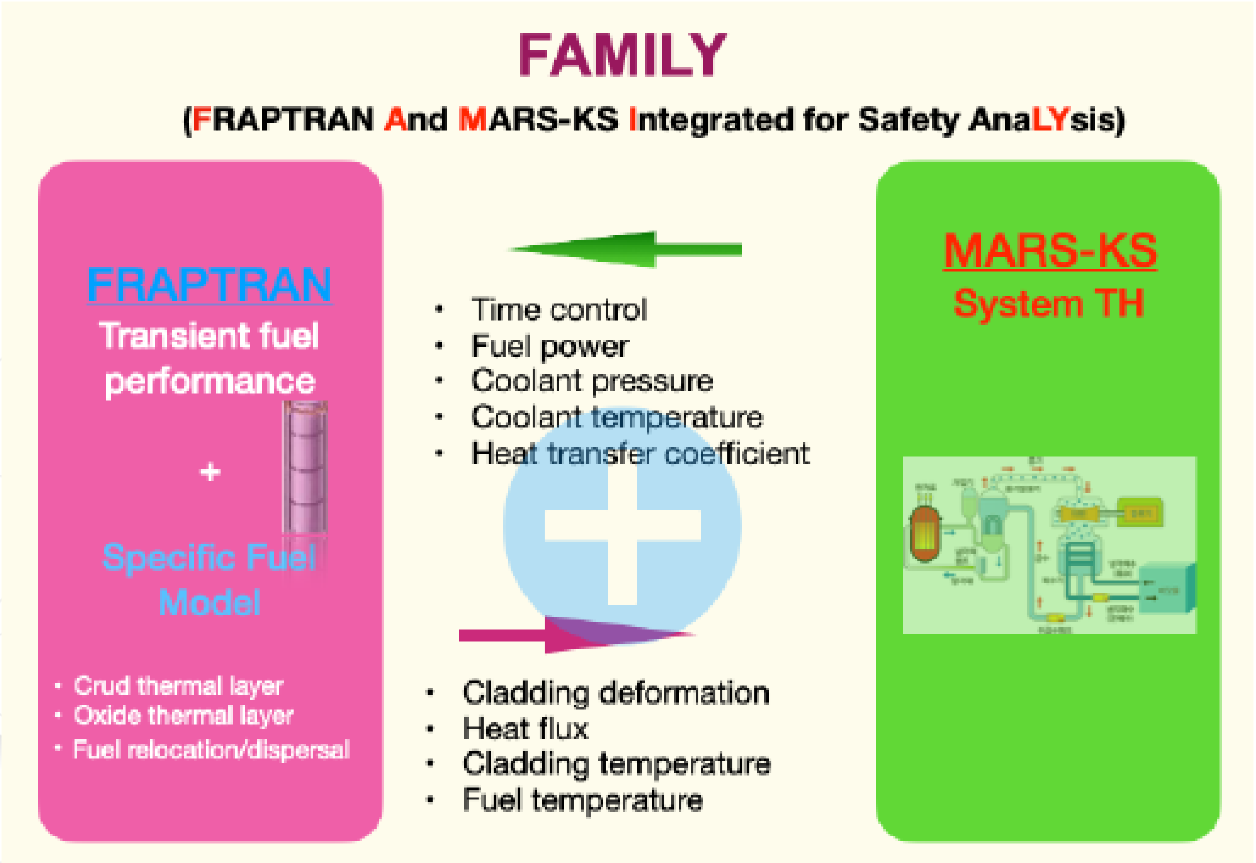
Research status

Korea Atomic Energy Research Institute

** J.S.Lee, 고연소도 핵연료 장전노심 안전성평가 기술교류회, 2022.*

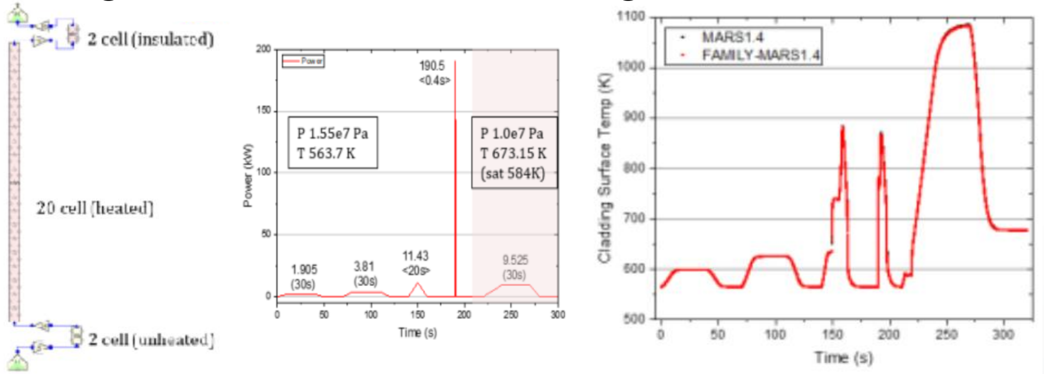
MARS-KS/FRAPTRAN (FAMILY) : Safety analysis + fuel behaviors

- As a first work, modified FRAPTRAN source code was embedded in MARS-KS



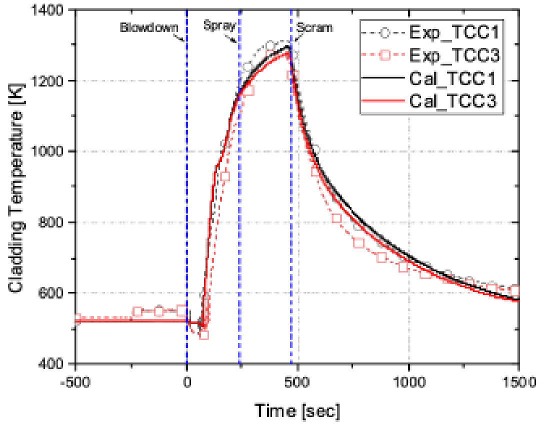
Verification

Single heat structure and single flow channel

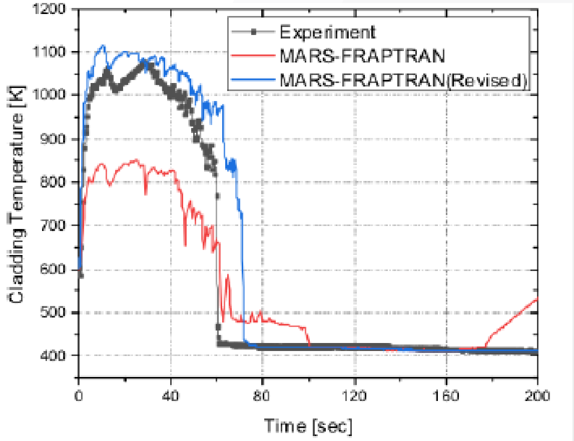


Validation

HRP IFA650.5



LOFT L2-5



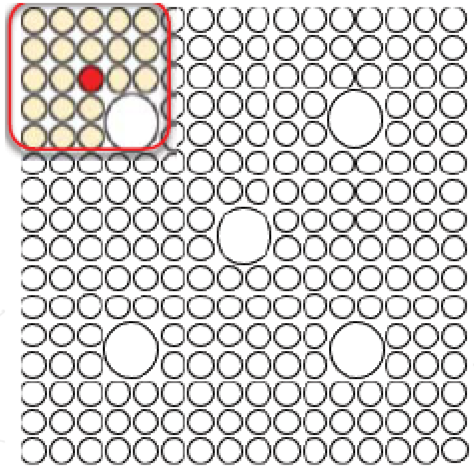
Research status

Korea Atomic Energy Research Institute

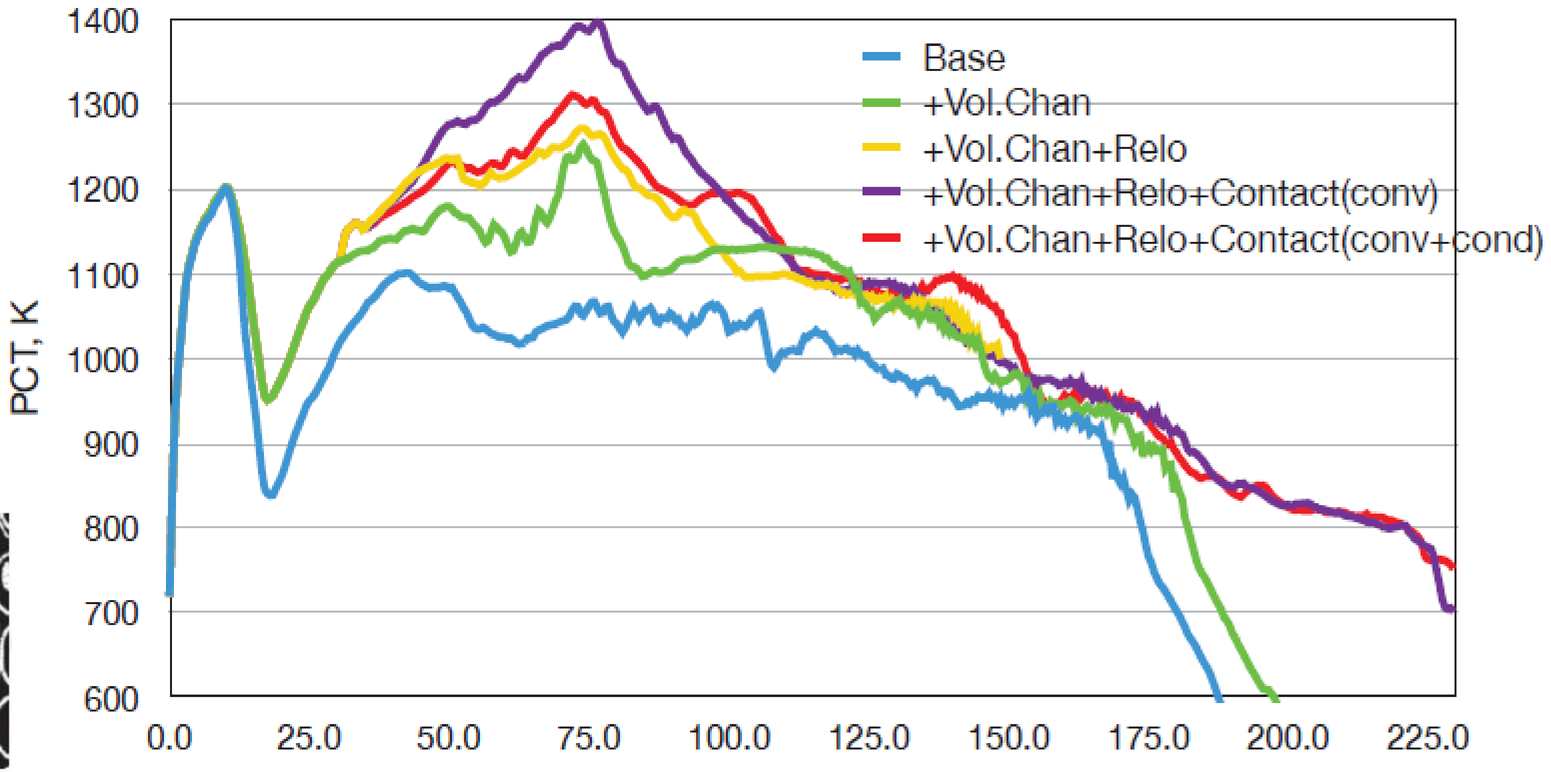
** J.S.Lee, NuSTEP meeting, 2024.*

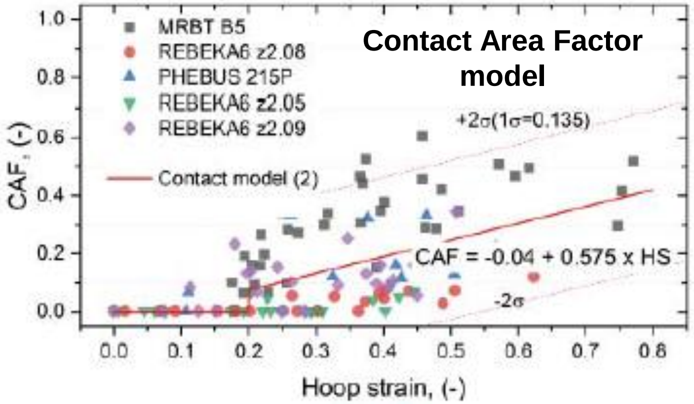
MARS-KS/FRAPTRAN (FAMILY) : Safety analysis + fuel behaviors

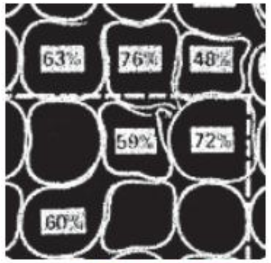
- Fuel safety issues evaluated taken into account relocation (QT), rod contact, flow blockage (volume change), subchannel analysis, UA/UQ etc.



Hot pin
30 MWd/kgU
5X5 array
T/H MultiD
(subchannel)







ORNL MRBT

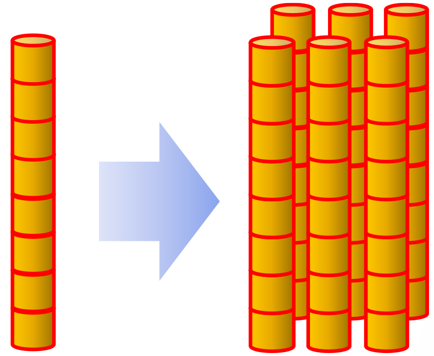
CUPID/FRAPTRAN : Subchannel + Multiple rods

Extension to multiple fuel rod conditions

- Extend coupling variables for multi-rods
- F/P code modification(array)

Parallel for pin-wise full core simulation

- Partitioned 2-D plane and Extrusion



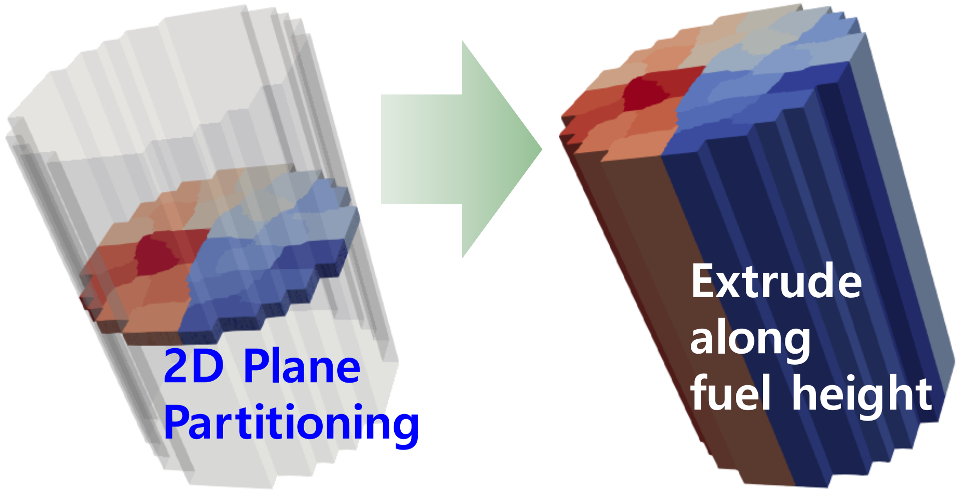
Single fuel
a(1:nz)

Multi fuels
a(1:nz,1:Nrod)

Weakly coupled pressure solver

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

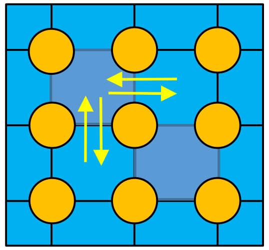
Repeat single fuel performance analysis

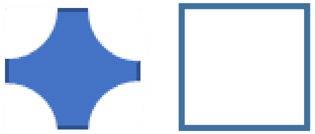


MPI domain decomposition

Research status

CUPID/FRAPTRAN : Subchannel + Multiple rods





Real Subchannel geometry

CUPID computing cell with
- subchannel type
- Porosity
- Hydraulic diameter
- Gap distance
- cell-to-cell pitch

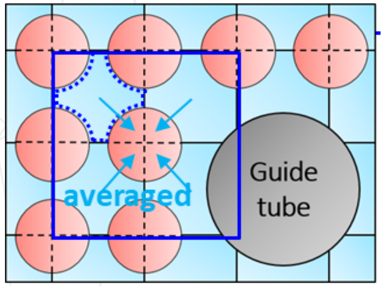
➔ Geometric input

Multiple fuel rods

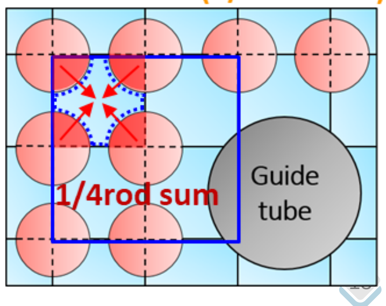
- **Subchannel TH mesh** (CUPID-FRAP)
- **Physical model in subchannel resolution**
  - Pressure drop
  - Turbulent mixing
  - Spacer grid

Information between TH subchannel and fuel rod

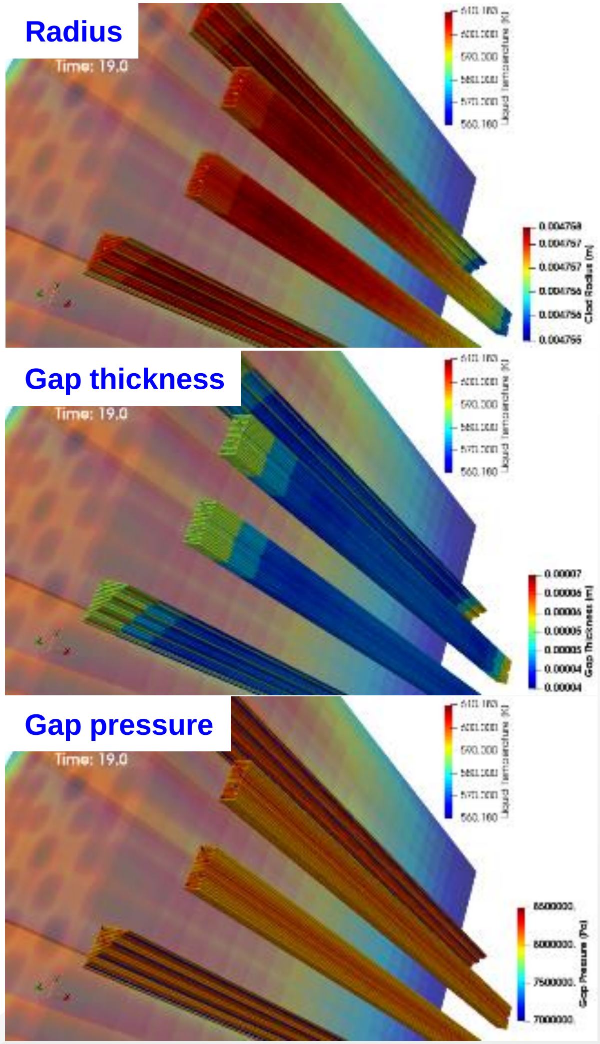
TH transfer (averaged)



PW transfer (1/4rod sum)



Analysis for SLB scenario



Research status

CUPID/MERCURY : Subchannel + Multi-dimensional Fuel

CUPID

Subchannel scale thermal-hydraulic analysis code
+
Complicated two-fluid model
+
Entire rod or assembly analysis under accident condition

Full 3D code
MPI parallelization

CUPID → MERCURY:
Linear power [mW/mm]
Coolant temperature [K]
Convective coefficient [W/m^2-K]
Coolant pressure [MPa]
Time increment [sec]

Space and Time coupling scheme introduced for the coupling

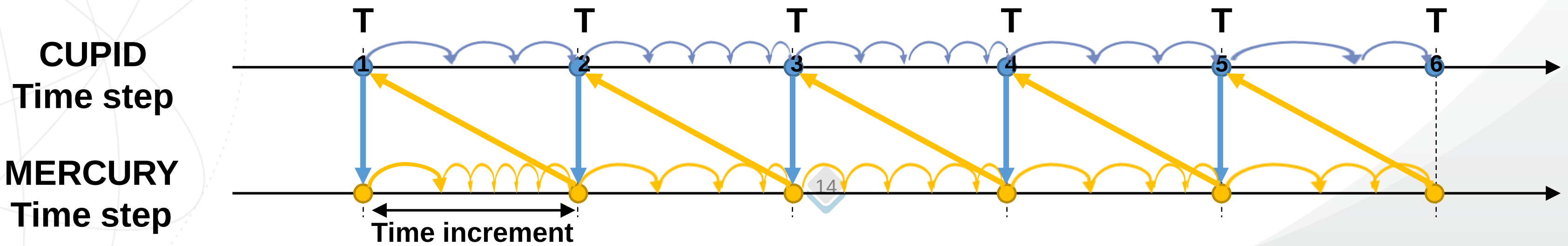
MERCURY → CUPID:
Heat flux [W/m^2]
Cladding diameter [m]
Cladding surface temperature [K]

MERCURY

Fuel performance code based on the FEM for the multi dimensional analysis
+
Fuel models
+
Base irradiation data

Axisymmetric code (r-z dir.)
OpenMP parallelization

Analysis time synchronize between two codes



Research status

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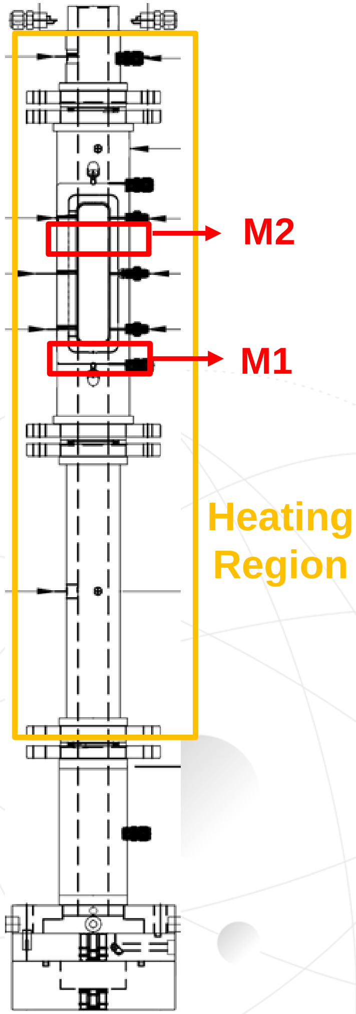
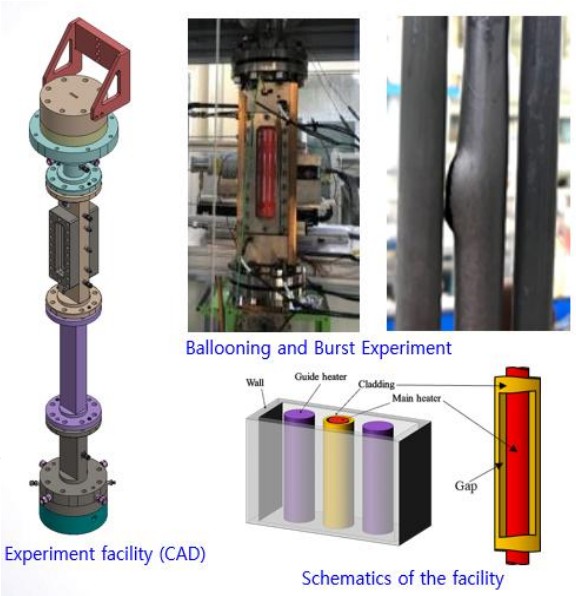
CUPID/MERCURY : Subchannel + Multi-dimensional Fuel





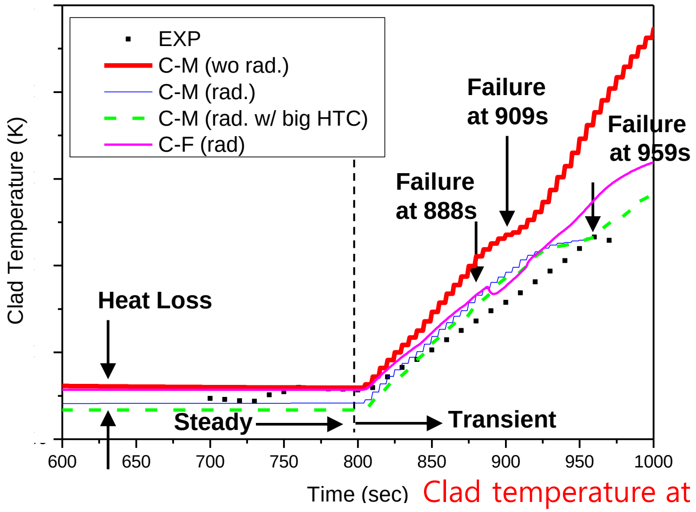
Ballooning and Burst Experiment

Experiment facility (CAD)

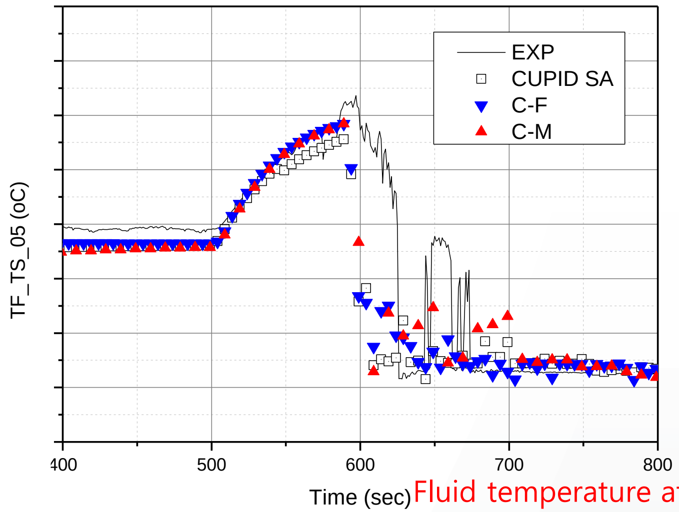
Schematics of the facility

<ICARUS* experiment result>

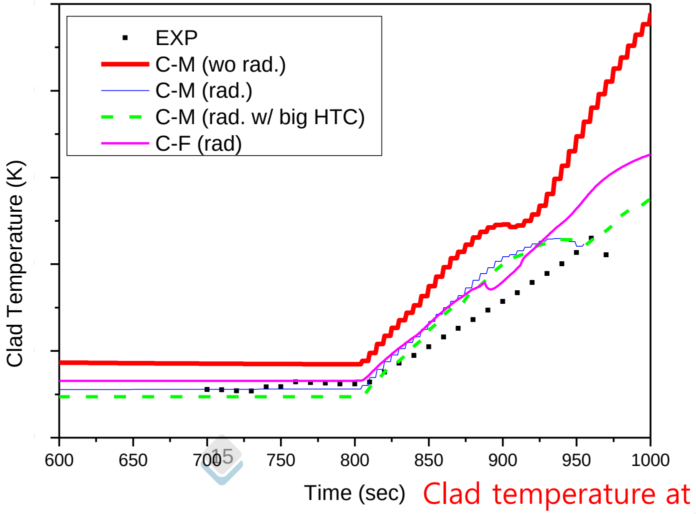
*ICARUS(Integrated and Coupled Analysis of Reflood Using fuel Simulator)



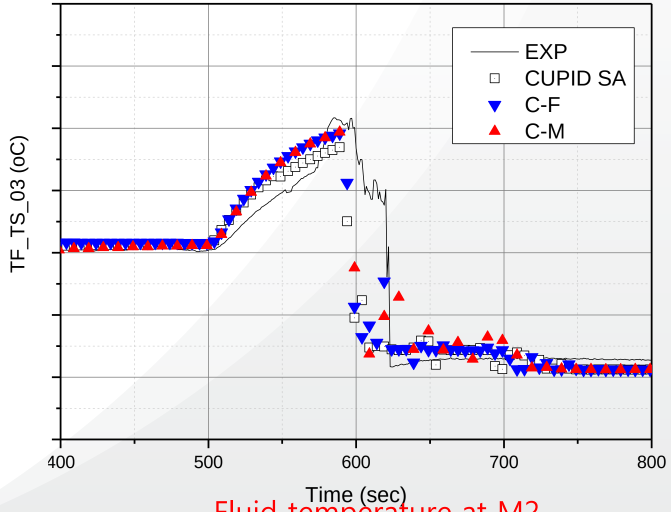
Clad temperature at M1



Fluid temperature at M1



Clad temperature at M2



Fluid temperature at M2

Research status

- J. Hong et al., Measurement of local mechanical properties for Cr-coated accident tolerant fuel cladding, Journal of Nuclear Materials 579 (2023) 154407.

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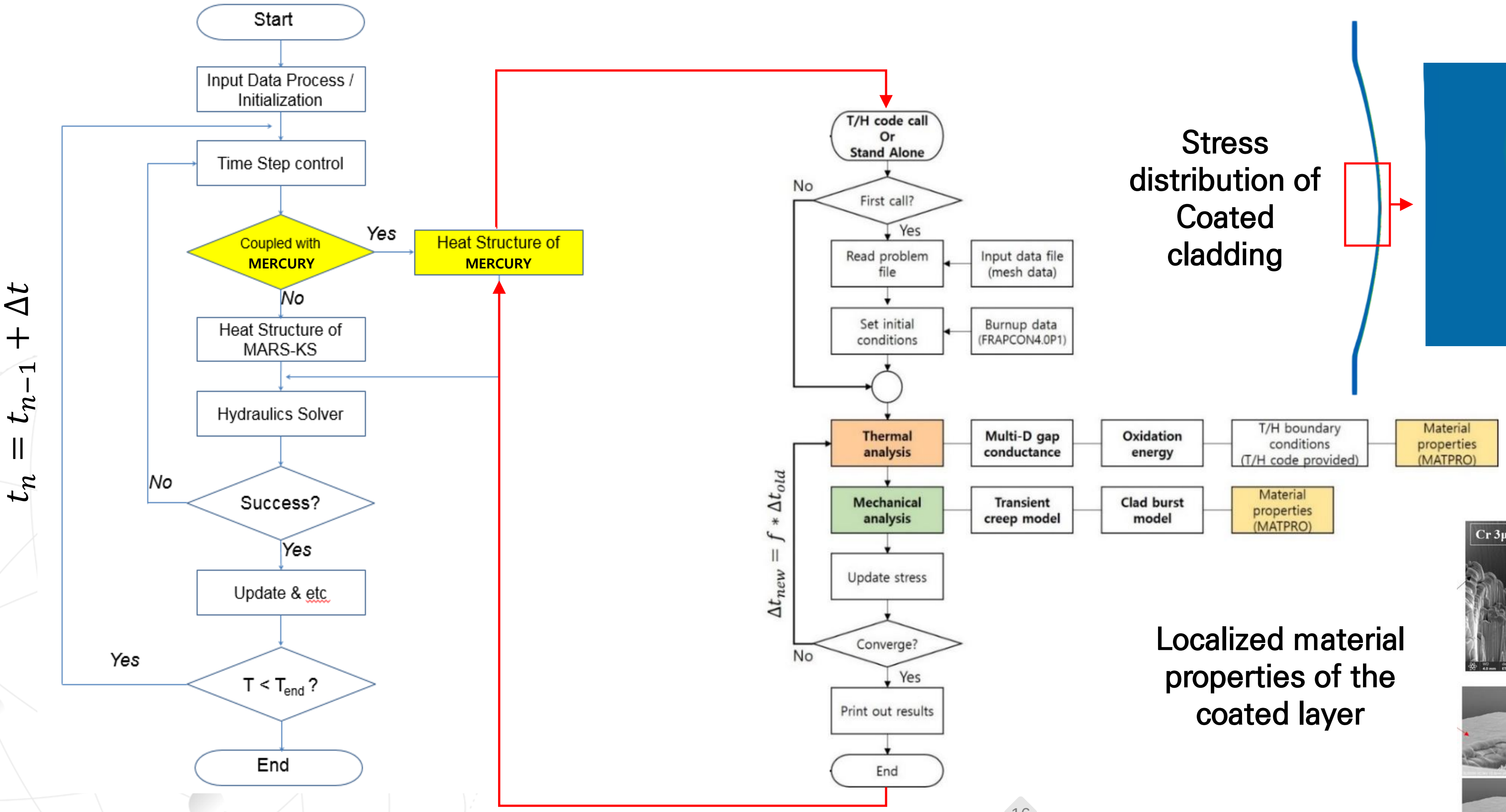
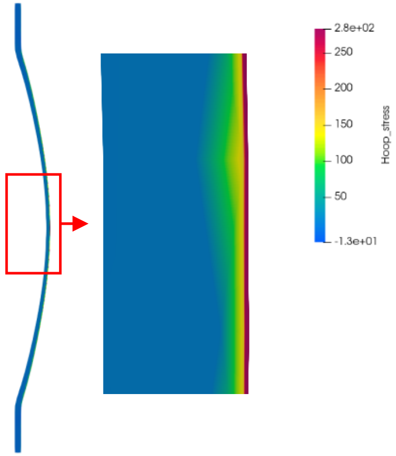
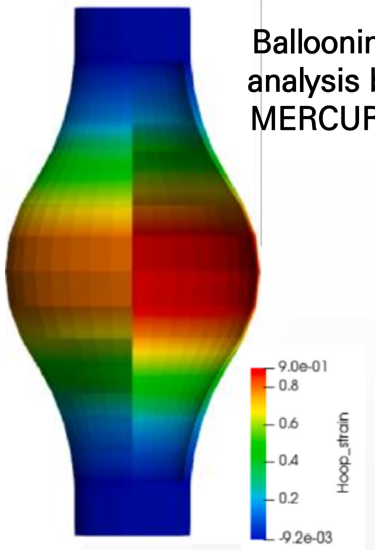
MARS-KS/MERCURY : Safety analysis + ATF characteristics



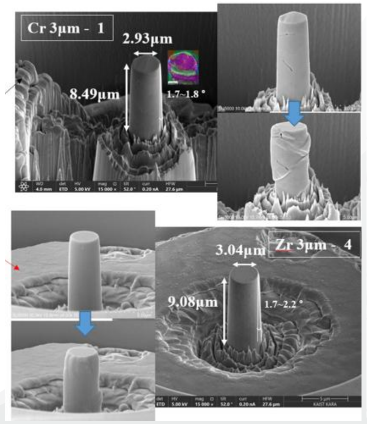
Stress distribution of Coated cladding

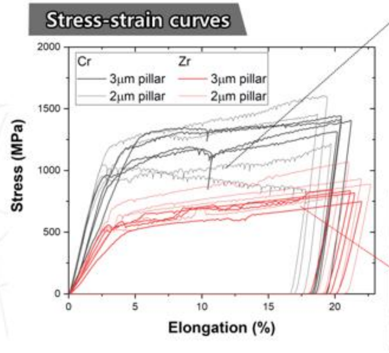


Ballooning analysis by MERCURY



Localized material properties of the coated layer





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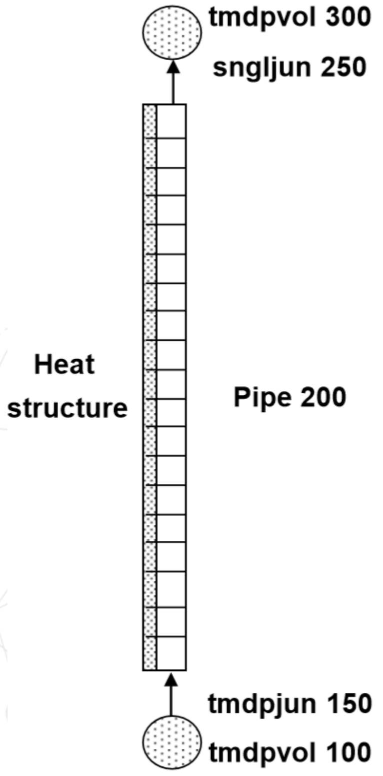
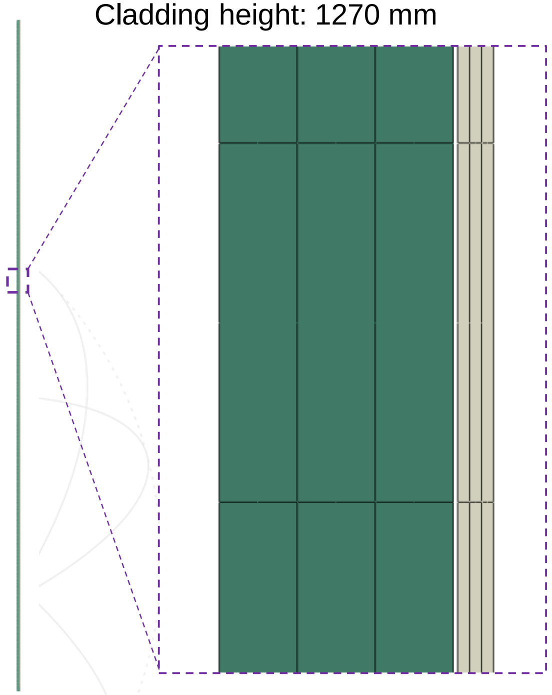
MARS-KS/MERCURY : Safety analysis + ATF characteristics

Single heat structure and Single flow channel problem for the verification of the coupled code



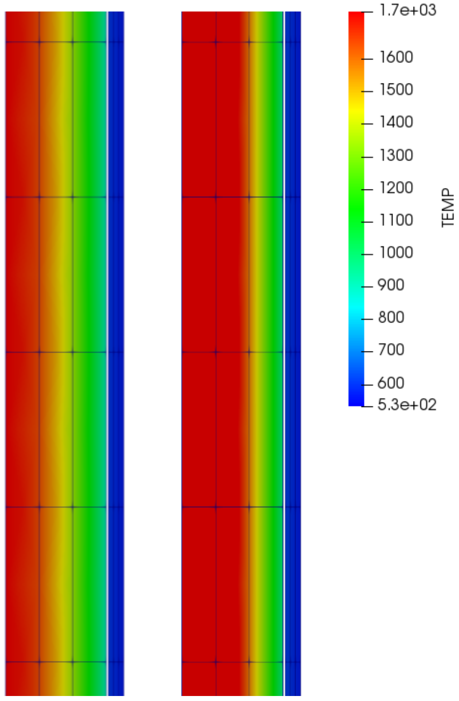
MARS-KS model

Pellet width: 4.134 mm
Gap thickness: 0.078 mm
Cladding height: 1270 mm



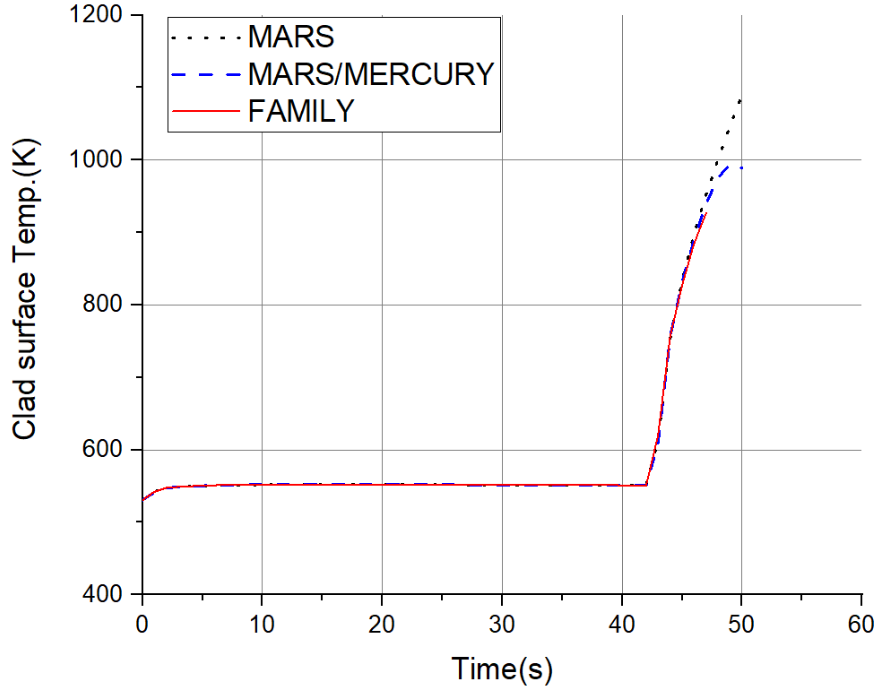
MERCURY model

Calculation result of MERCURY



t=1.09s t=45s

- **The coupled code predicts a lower surface temperature than the standalone MARS calculation due to fuel ballooning, which reduces the surface heat flux.**
- **The MARS/FRAPTRAN calculation was terminated because of numerical instability.**



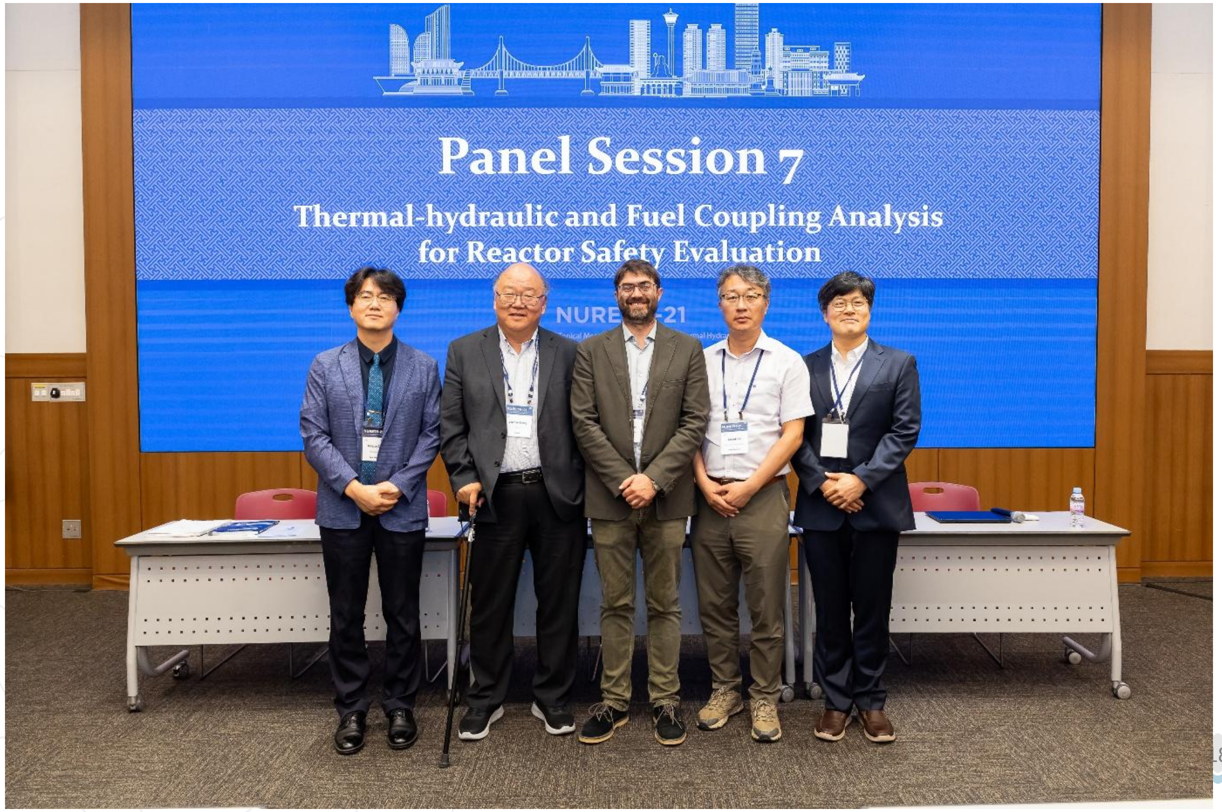
NURETH21 panel discussion on the issue

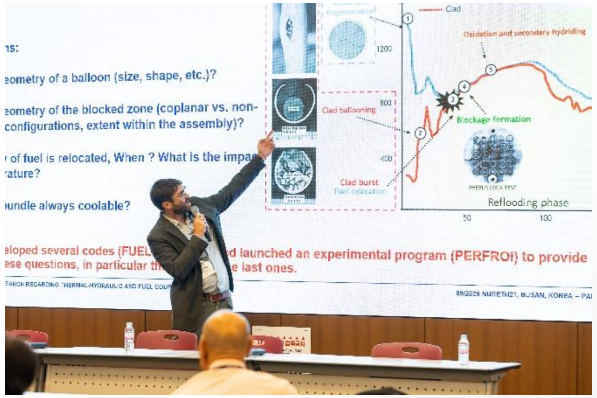
Korea Atomic Energy Research Institute

Panel session regarding Fuel/TH coupled analysis

5 speakers are invited to discuss the issue on the coupled analysis based on the panel's presentation

- Jinzhao Zhang(Tractebel), Pierre Ruyer(ASNR), Tongsoo Choi(KNF), Joosuk Lee(KINS), Hyochan Kim(KAERI)





NURETH21 panel discussion on the issue

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Need and challenges of coupling for reactor safety analysis

- **T/H and FP coupling is important for Best estimate simulation of interdependent fuel and T/H phenomena:**
  - Ballooning and burst, fuel fragmentation, relocation and dispersal (FFRD), reduced flow due to blockage, increased heating due to ballooning and relocation.
  - Improve accuracy by capturing feedback between fuel and coolant during certain specific accident scenarios (DBA, DEC)

Regulatory perspective

- **It is necessary to evaluate reactor safety because the coupling effect may influence the safety criteria**

Industry perspective

- **Partially fuel behaviors can be considered in the T/H code, Not coupling code**

Research institute perspective

- **To investigate the realistic fuel and thermal-hydraulic (T/H) behavior under accident conditions, studies on T/H and fuel performance (FP) coupling are ongoing, including validation against experimental data**

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Possible contribution of TH/Fuel coupled code for IAEA CRP regarding fuel safety evaluation

Safety evaluation of ATF fuel

- Based on single-effect tests (in-pile and out-of-pile) conducted with fabricated ATF, various models for ATF fuel will be incorporated into the fuel performance code
- Considering the developed ATF models, the coupled code can be used to evaluate the safety contribution of ATF under specific accident scenarios.

⇒ ATF models and accident scenarios should be clearly defined prior to the safety evaluation

Code benchmark for IET experiment (e.g. QUENCH, CODEX, DEGREE etc.)

- Integral Effect Tests (IET) with fuel bundles can be used for code benchmarking among participants for code validation and inter-code comparison.

⇒ The IET dataset for validation should be discussed in advance, and at least three organizations should participate in the benchmarking to ensure a meaningful comparison

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THANK YOU FOR YOUR ATTENTION

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