HIGH-FIDELITY ANALYSIS OF MTR CORES USING SERPENT2/ SUBCHANFLOW

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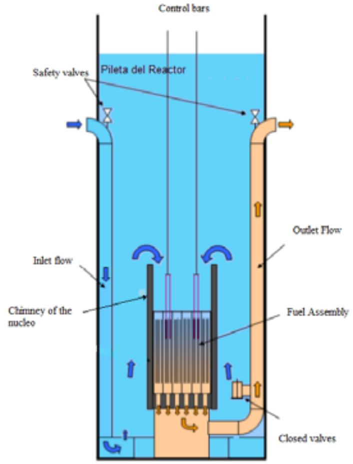
Presentation Outline

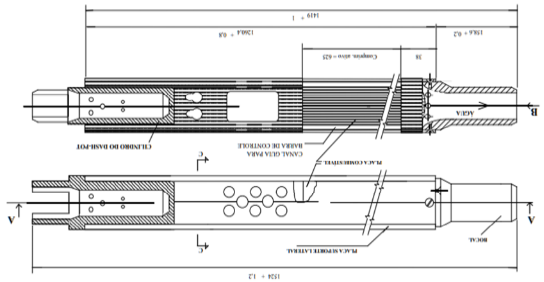
- Motivation
- Numerical tools
- Analysis of a MTR-core
  - Problem description
  - MTR reactor
  - Transient case
- Discussion of results
- Conclusions and Outlook

Motivation (1/2)

- More than 241 MTRs under operation and around 30 MTRs under construction
- Core is characterized by fuel plates and rectangular coolant channels with up/downward flow
- Compact and small cores immersed in a water pool
- Most used analysis methods:
  - 1D dedicated codes or system thermal hydraulic codes
  - Point kinetics and diffusion codes at fuel assembly level
- KIT is developing high-fidelity multi-physics codes like **Serpent2/SubChanFlow** for LWRs
- This work: first-of-the-kind application of high-fidelity tools for detailed simulation of MTR-cores
  - Detailed resolution: Plate /subchannel
  - Local feedbacks between N and TH
  - **Prediction of local safety parameters possible!**



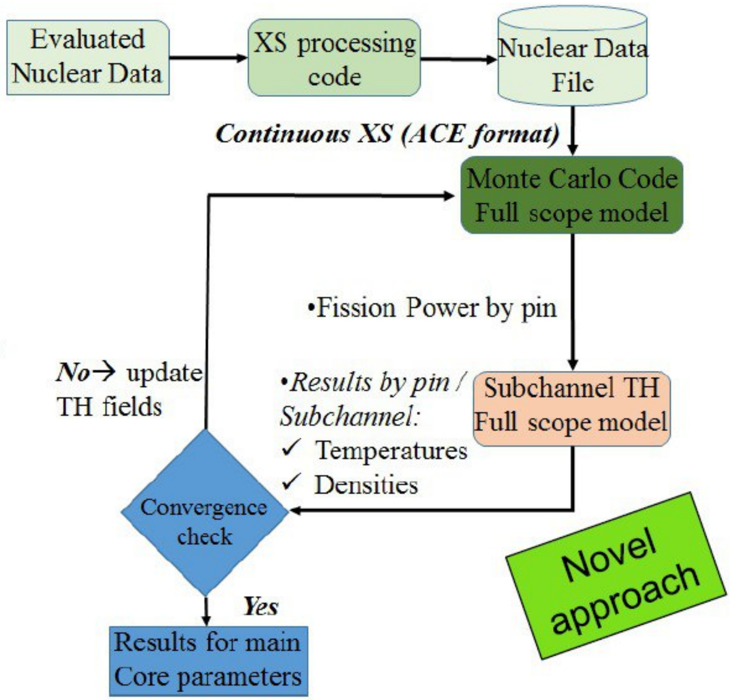
Typical research reactor



Fuel Assemblies

Motivation (2/2): High-fidelity Coupled Tools

- Adaptation of Serpent2/SCF for MTR-cores
  - MC: core resolved at plate level
  - No approximations for neutron transport
  - Heat conduction solver for plate
  - Appropriate heat transfer between plates and subchannels
  - Capability to predict transients

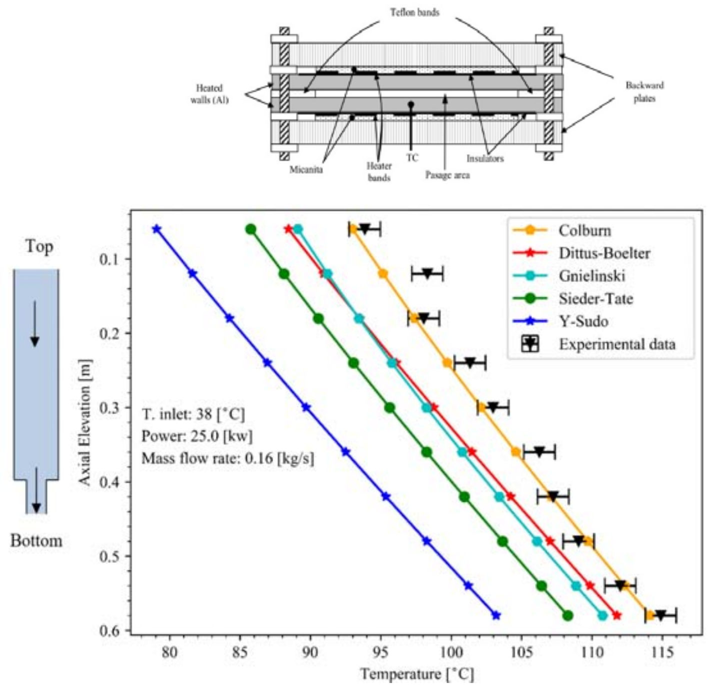


Novel approach: Serpent2/Subchanflow* for LWRs

* D. Ferraro et al. "Serpent/SUBCHANFLOW pin-by-pin coupled transient calculations for a PWR minicore" Annals of Nuclear Energy, 137:107090, 2020.

Numerical tools (1/2)

- SubChanFlow extension of MTR-cores:
  - Dedicated correlations for rectangular narrow channels
  - New module of heat conduction for plates
  - Modifications for downward flow
  - Validation using relevant experiments (RA-6 facility)
- Serpent2/SCF:
  - Updated internal coupling developed in H2020 McSAFE project
  - Dynamic capability validate for LWR using SPERT REA E tests
  - Applied to a PWR REA analysis

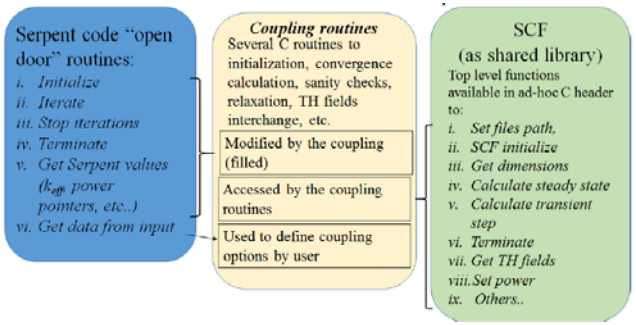


Extension of SCF *

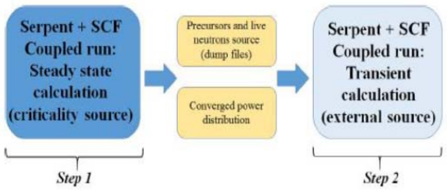
*Almachi, J. C., Sánchez-Espinoza, V., & Imke, U. (2021). Extension and validation of the SubChanFlow code for the thermo-hydraulic analysis of MTR cores with plate-type fuel assemblies. Nuclear Engineering and Design.

Numerical tools (2/2): Internal Coupling

- Internal approach:
  - Maintainability + user friendly
- Master-slave approach
  - Keep original capabilities of involved codes
  - Additional coupling routines
  - One single executable
- Application:
  - Criticality
  - Burnup
  - transients
- Coupled transient simulation:
  - First do criticality source mode calculation (to predict the source distribution)
  - Next, do a external source calculation



Internal coupled



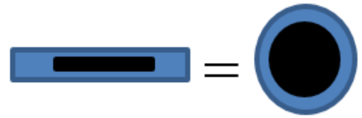
Transient two-step approach for coupled calculation*

* D. Ferraro et al. "Serpent/SUBCHANFLOW pin-by-pin coupled transient calculations for a PWR minicore" Annals of Nuclear Energy, 137:107090, 2020.

Verification and Validation of tools for MTR-Cores

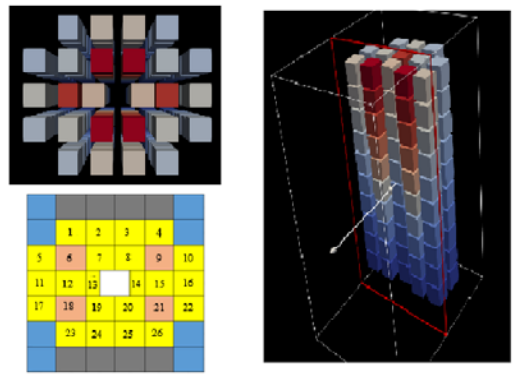
- The IAEA 10 MW Reactor Benchmark
  - Well defined benchmark
  - All data provided
  - Results of different kind of codes available for code-to-code comparisons
  - Public available

- Limitations of former analysis
  - Use of plate equivalents
  - Heuristics methods used
  - Coupled 1D TH and simplified neutronics (PK, Diffusion)
  - Coupled and stand alone simulations:
    - Averaging description of the fuel assemblies
    - No resolution of the plates and rectangular coolant channels



$$Perimeter_{plate} = \pi D_{equivalent}$$

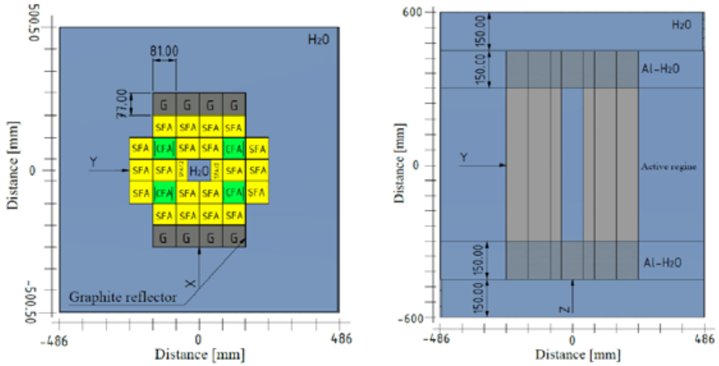
Equivalent plate calculation



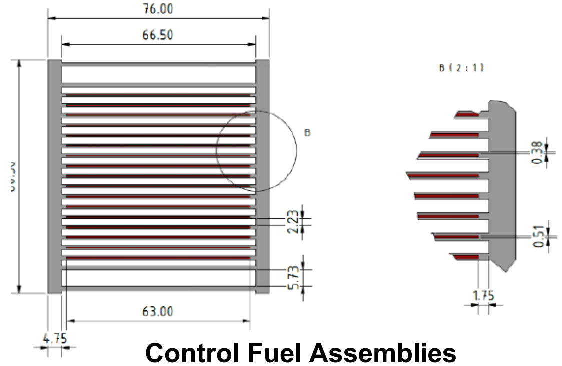
IAEA 10 MW benchmark: Analysis with low order methods at FA-Level

IAEA 10 MW Reactor Benchmark: Specifications

- Data (geometry, initial conditions, materials) taken from TECDOC-233 and TECDOC-643
- Core configuration:
  - 21 Standard Fuel Assemblies (SFA) with 23 plates
  - 4 Control Fuel Assemblies (CFA) with 17 plates
  - The core is reflected by graphite on two opposite sides
- The CFA have a special region for the absorber plate
  - B4C was used



Radial and axial scheme of the MTR core*



Control Fuel Assemblies

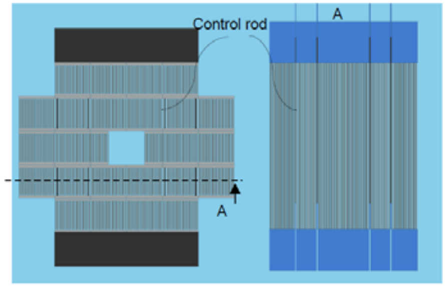
Material fuel HEU	Enrichment 93 wt. % ^{235}U $280g\,^{235}U$ per fuel element 21 wt. % of uranium in the $UAl_x - Al$
Total power	10 MW
Coolant temperature inlet	311 K
Pressure at top of the core	1.7 bar
Coolant mass flow rate (downward)	1000 m³/h

Benchmark MTR 10 MW specifications

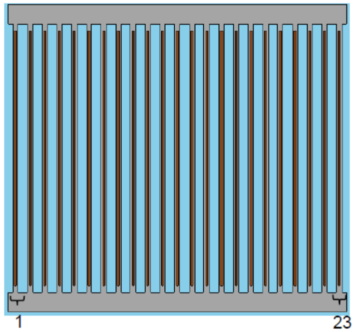
* IAEA-TECDOC-233. (1980). INTERNATIONAL ATOMIC ENERGY AGENCY, Research Reactor Core Conversion from the Use of Highly Enriched Uranium Fuels

Serpent2/SubChanFlow Model of the IAEA 10 MW Core (1/2)

- Serpent model
  - Detailed model 3D model resolved at plate-by-plate level
  - IFC type 22 used for the data transfer between N and TH
  - Nuclear data library ENDF/B-VII
  - 20 inactive and 200 active cycles
  - 150,000 particles for the criticality calculation
  - The dynamic Serpent 2 calculations:
    - 150,000 particle populations as external source
    - 100 time binning
  - Vacuum boundary conditions



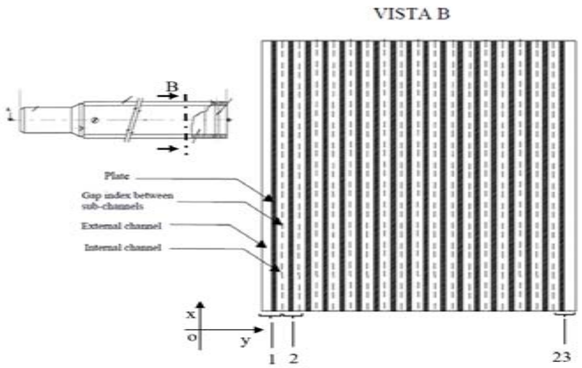
Serpent 2: axial and radial core discretization



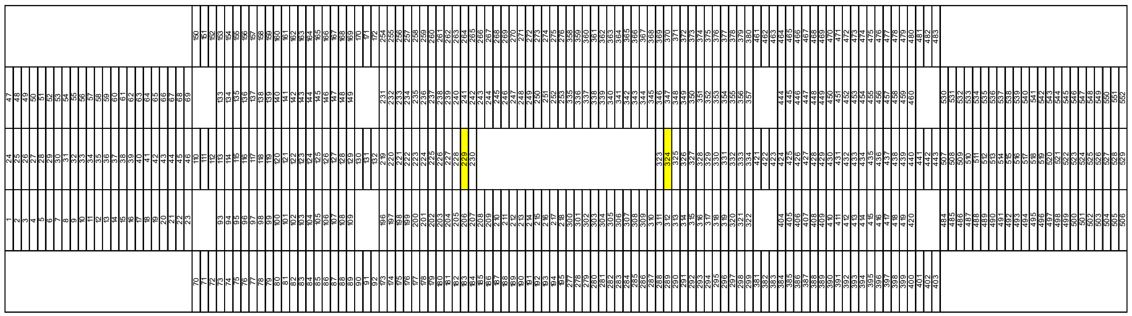
Radial SFA discretization

Serpent2/SubChanFlow Model of the IAEA 10 MW Core (2/2)

- SubChanFlow model
  - The detailed core plate-centered
  - 20 axial nodes (channels & plates)
  - Plate is subdivided radially in 3 and 2 cells for the fuel meat and cladding
  - Correlations:
    - friction factors: Blasius
    - heat transfer: Colburn
- Remapping external file containing the information about axial al radial nodes of 552 plates and channels



radial plate-centered discretization

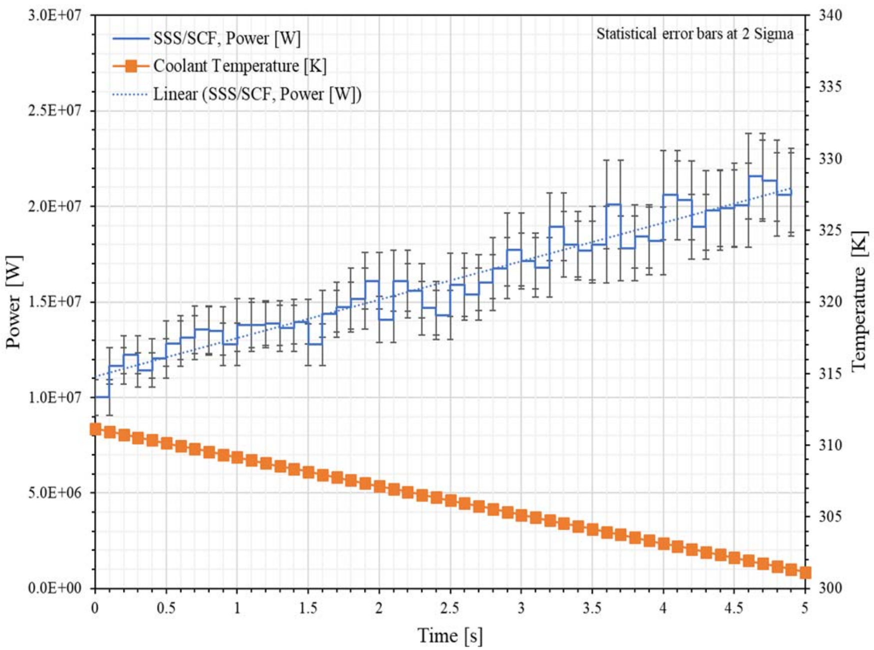


Numbering of the plates and coolant channels for the radial mapping between Serpent2/SubChanFlow

IAEA 10 MW: Academic transient scenario

- **Goal:**
  - Check how the power increase due to increased moderation in the core
  - Test capability of the coupled code
- **Initial event:**
  - Reactor is under critical conditions
  - Four CR-plates inserted at 9.315 cm measured from the lowest point of the fuel plates
  - Decrease of the inlet coolant temperature from 311 K to 301 K within 5 s
- **Simulation environment:**
  - Hybrid parallel computation using MPI and OpenMP (Linux cluster with 48 cores)
  - 4 MPI processes with 12 OpenMP threads
- **CPU-time:**
  - 36.4 h

Serpent2/SubChanFlow: Global results

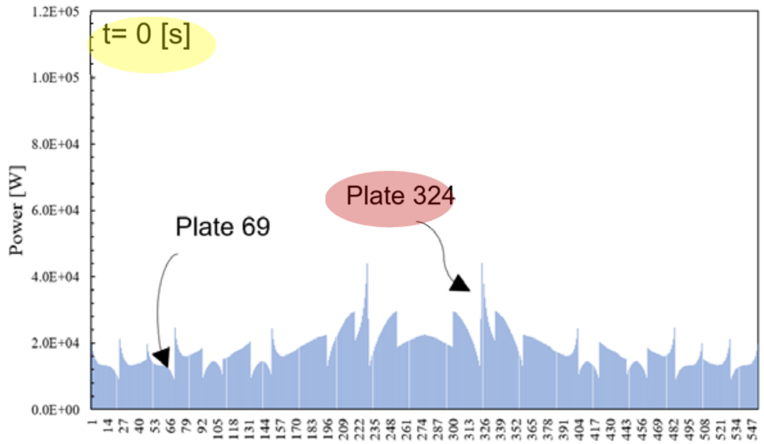


Evolution of the core power and inlet coolant temperature during the transient

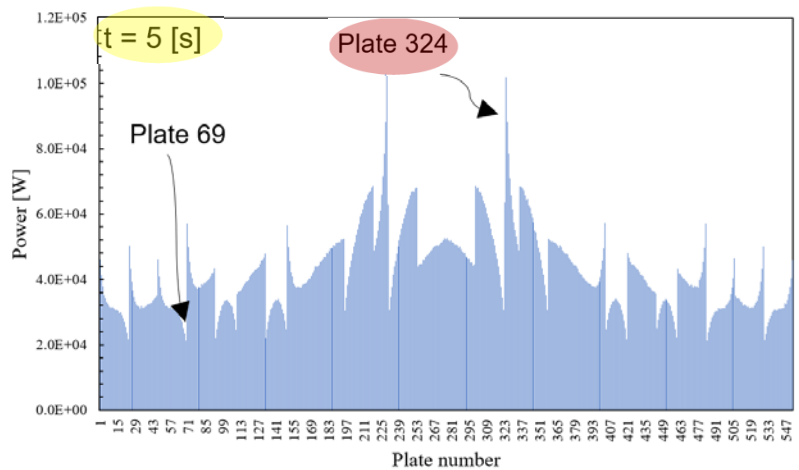
- The power increases linearly reaching the highest value of 20 MW after 5 s
  - Driven by coolant density increase
  - Increase neutron moderation
  - Increase fissions
  - Increase of power
- Statistical uncertainty is 2 sigma

Serpent2/SubChanFlow: Local Results (1/3)

- Radial power distribution t=0 s and t=5 s



Identification of the plate with the highest and lowest power

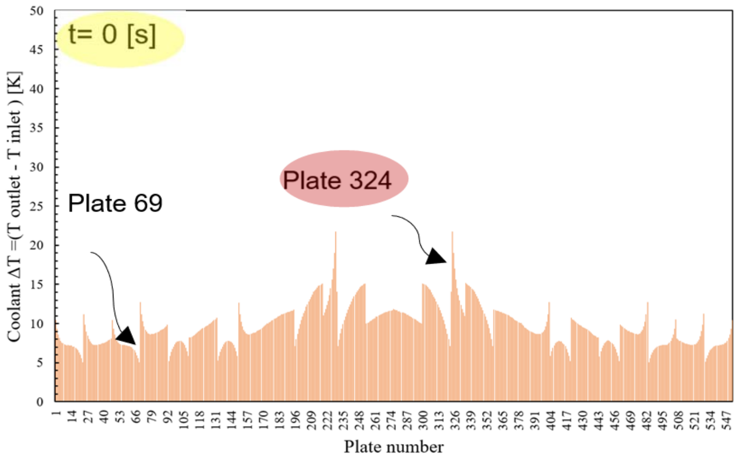


Identification of the plate with the highest and lowest power

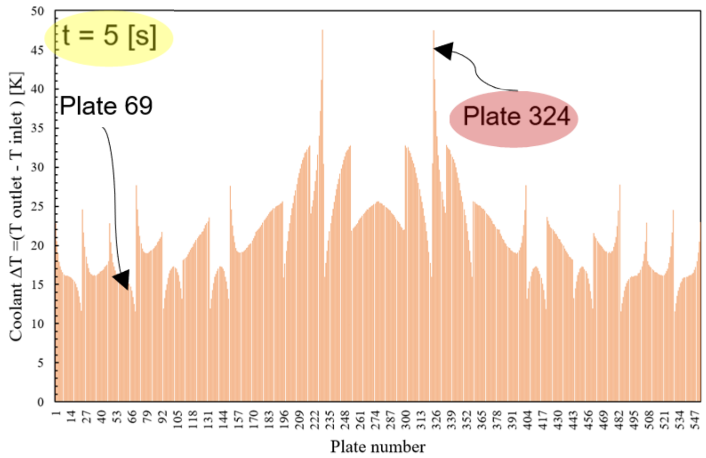
- Main observations:
  - Plate power predicted at 0 and 5 seconds
  - Location of the hottest plate is the number 324, (center left)
  - Location of coldest plate is the number 69, upper left side in CFA

Serpent2/SubChanFlow: Local Results (2/3)

- Radial heat-up distribution (t=0 s and t=5 s): Channel hotter and colder identification



Identification of the channel with the highest and lowest coolant heat-up

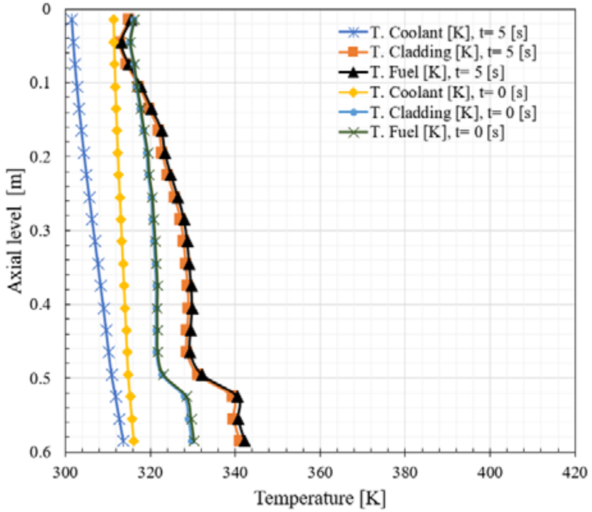


Identification of the channel with the highest and lowest coolant heat-up

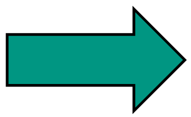
- Main observations:
  - Location of the **highest** coolant heat-up is the channel number 324, (center left)
  - Location of **lowest** coolant heat-up is the channel 69, upper left side in CFA

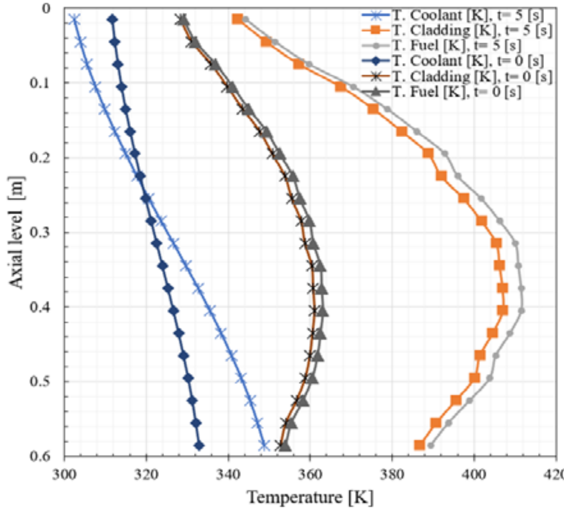
Serpent2/SubChanFlow: Local Results (3/3)

- **Local safety parameters: coolant, cladding, and fuel axial temperatures at time 0 and 5 s**



Axial distribution of Tc, Tc, Tf for the coldest plate at 0 and 5 s





Axial distribution of Tc, Tc, Tf for the hottest plate at 0 and 5 s

- Main observations:
  - Maximal value of **T cladding** change from **340 K** to **408 K**; and the location change from 0.58 to 0.4 m from the top
  - Maximal **T fuel** change from **342** K (cold) to **412** K (hot); the location change from o.58 to 0.4 m from the top
  - The hottest plate 342 is very close to the absorber plate

Conclusions and Outlook

- The multi-physic high fidelity code Serpent2/SCF (KIT version) was the FIRST TIME applied to analyze the MTR-core at very detailed level (plate/subchannel)
- This kinds of codes pave the way for:
  - Very detailed simulations to predict **LOCAL SAFETY** parameters in a direct way contrary to the low-order approaches (FA-level, 1D TH)
  - Simulation of academic transient conditions of MTR-cores with Monte Carlo coupled with subchannel thermal hydraulics is demonstrated (novel simulations)
- The next steps at KIT:
  - Validate the Serpent2/SubChanFlow using SPERT-IV REA test performed with MTR-fuels
  - Application of the coupled code for licensing issues of MTR-reactors under operation and for new licensing issues MTR-reactors to be build

Acknowledgment

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