Karlsruhe Institute of Technology

Coupling of TRACE and Subchanflow (SCF) based on the Exterior Communication Interface (ECI)

Kanglong Zhang

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Supervisor: Prof. Dr. Robert Stieglitz

Institute for Neutron Physics and Reactor Technology (INR)

Presentation Outline

Coupling of TRACE and Subchanflow (SCF) based on the Exterior Communication Interface (ECI)

- Self-Introduction
- Backgrounds
- Objective Analysis
- Introduction of ECI
- Introduction of the Coupling
- Code Testing
- Summary
- Next steps

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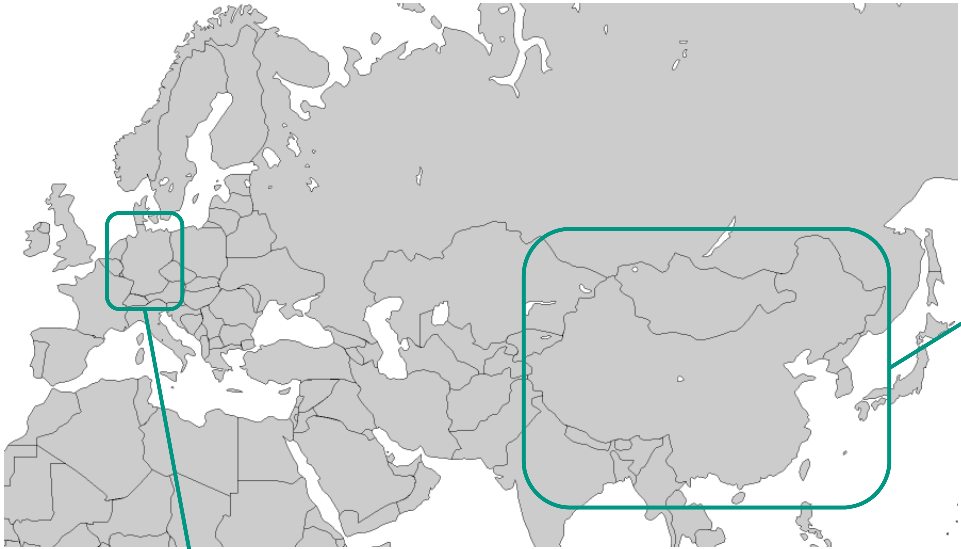
Self-Introduction



- Kanglong Zhang, born in **Shijiazhuang, Heibei Province, China**
- Got the Bachelor´s degree in ***Harbin Institute of Technology (HIT)***, 2008.09-2012.07, Harbin, Heilongjiang Province, China
- Got the Master´s degree in ***University of Science and Technology of China (USTC)***, 2012.09-2015.07, Hefei, Anhui Province, China
- Studying for the doctor´s degree in ***Karlsruhe Institute of Technology (KIT)***, 2015.10-present, Karlsruhe, Baden-Württemberg, Germany

Self-Introduction

Karlsruhe Institute of Technology

Bachelor, _Harbin Institute of Technology (HIT)_, 2008-2012

Major: Nuclear Reactor Technology

Research work: Assist for the development of a reactor simulation code. (MATLAB, 1 paper)

Master, _University of Science and Technology of China (USTC)_, 2012-2015

Major: Nuclear Science and Engineering

Research work: The comceptual design of the control rod assembly for a fast reactor. (Monte Carlo codes and COMSOL, 2 papers)

Self-Introduction

The City of Karlsruhe, Baden-Württemberg, Germany

PhD, *KIT Campus North*, 2015 - now

PhD topic: **Multiscale Thermal Hydraulic** Developments for the Detailed Analysis of the Flow Conditions within the Reactor Pressure Vessel of LWR

Research work: Development and Test of the coupling codes of **System codes, Subchannnel codes and CFD codes**. (Programming, modeling and testing)

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Backgrounds

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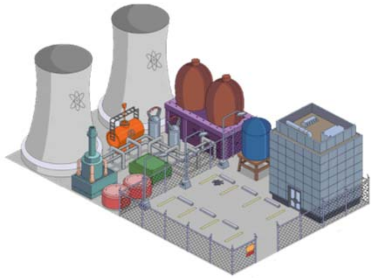
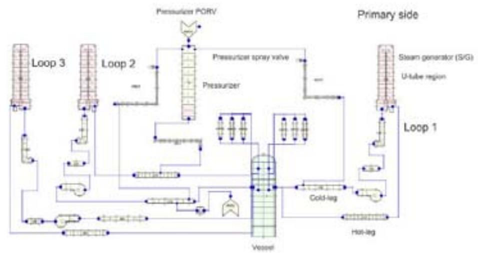
Note: **Simulation tools** play essential roles in Nuclear Insuctry and Research on improving the system **economy** and **safety** and consistent efforts have been made on **development** and **validation** of these tools.

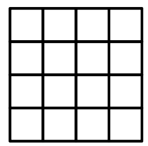


We want to simulate the **dynamic of the whole system** in order to study the **whole system's behaviour** under **normal**, **accident** and some special conditions.

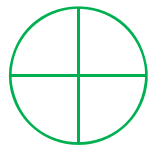


Modeling of the Nuclear Power Plant by a **System Code**

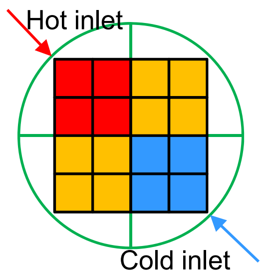
- The basic requirment of the system codes is **speed** so that it could simulate the **whole system dynamic** on a large time scale.
- In order to achieve high speed, system codes usually apply **coarse mesh**.



The real core

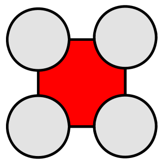


Mesh of the core

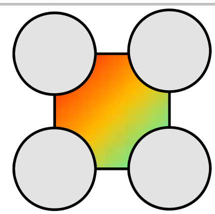


- Resolution of the physical field distribution is **poor.**
- e.g: Important **3D** phenomenons in the core: lateral flow between assemblies and fuel rods are **missing**.

Sometimes, we want to study specially on the **reactor core** and study the physical phenomenon **in detail**.



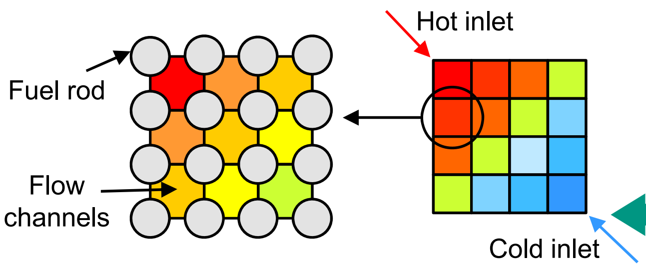
Sometimes, we want to study **specific local problems** on **micro scale** like the turbulance, fuel rod heat tranfer et al.



- **CFD codes** could simulate the turbulance and specific phenomenon **details**.

- However, the physical field is **uniform** within **one channel**.
- Could better simulate the lateral flow between assemblies and fuel rods.
- Fine description of phenomenon occuring in the core.

Physical field predicted by **Subchannel Code**



Backgrounds

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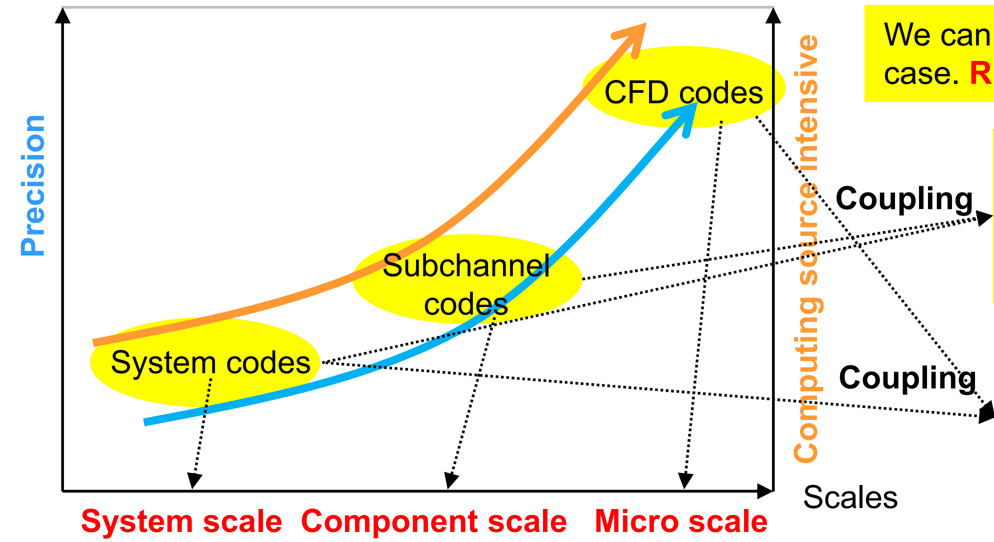
Simulation of the Nuclear Power Plant

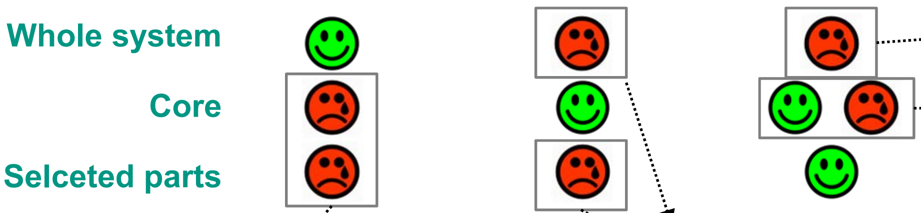
- **System scale**: System codes. RELAP, ALTHELET, TRACE et al.
- **Component scale**: Subchannel codes. COBRA, MARS, Subchanflow et al.
- **Micro scale**: CFD codes. ANSYS CFX, FLUENT, OpenFOAM et al.



We can select a proper tool to analysis a special case. **Run it standalone without problem!**

However, sometimes we want simulate the **system dynamic** while at the same time investigate the **details** of what happens in the **core** area.

Sometimes we want simulate the **system dynamic** while at the same time investigate the **micro details** of what happens in a specific part.



The required computer source is **unacceptable**.

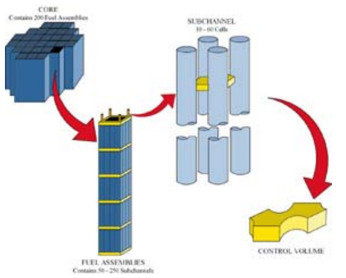
The CFD codes could simulate the core with **porous** model but it is not as **specific** as the **subchannel** codes.

The **precision** is **poor**

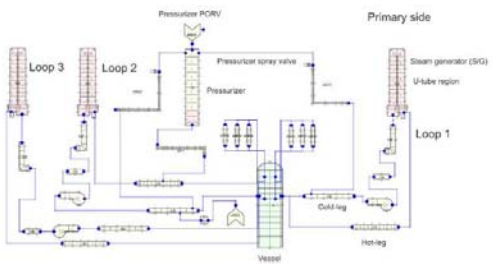
Subchannel codes could **only** simulate the core

Backgrounds

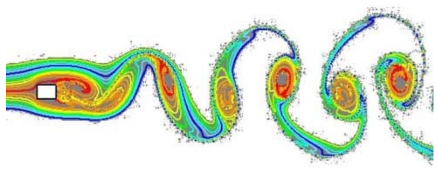
Component scale
Subchannel codes



System scale
System codes



Micro scale
CFD codes

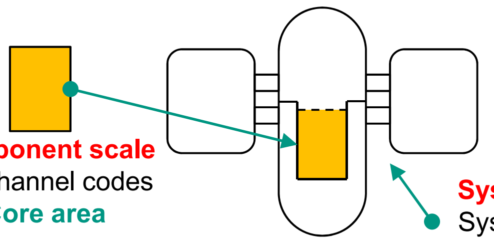


This report!

Coupling
System Dynamic + Core Details
Simulation on system and component scales

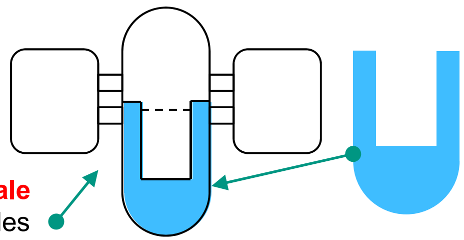
Coupling
System Dynamic + Local Details
Simulation on system and micro scales

Instance



Component scale
Subchannel codes
Core area

System scale
System codes
Whole system



Micro scale
CFD codes
Downcomer and lower plenum

Multi-scale thermal hydraulic analysis of Nuclear Power Plant

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Objective Analysis

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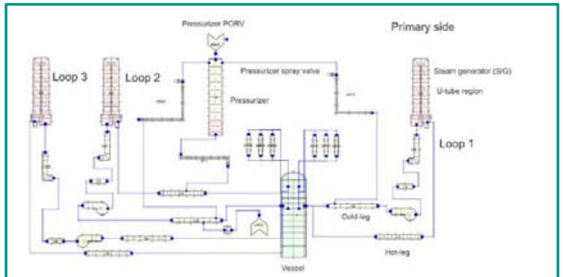
Goal: **Coupling** of **TRACE** and **SUBCHANFLOW (SCF)** based on **Exterior Communication Interface (ECI)**

- **What is TRACE? – System codes/System scale**
  - Full name: **TRAC/RELAP Advanced Computational Engine** which is formerly called **TRAC-M**.
  - Developed by **US NRC** for simulating the **whole system** of light water reactors.
  - Combines the capabilities of NRC four main system codes: **TRAC-P**, **TRAC-B**, **RELAP5** and **RAMONA**.
- **What is Subchanflow (SCF)? – Subchannel codes/Component scale**
  - SCF is a thermal hydraulic **sub-channel** code developed for the simulation of **fuel rod bundles**.
  - Developed by **KIT-INR** for light water and innovative reactor systems.
  - Based on the **COBRA-family**.

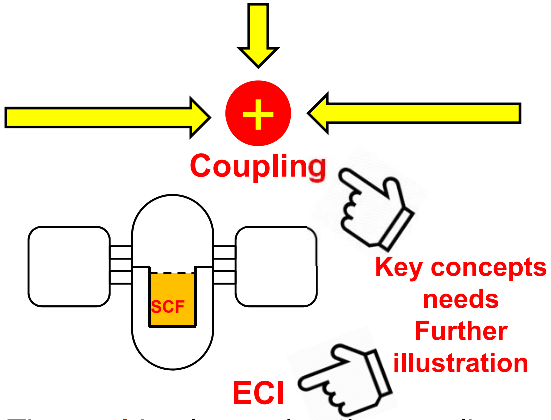
Motivation

We want to enhance the 3D phenomenon simulation capability of system code .

TRACE

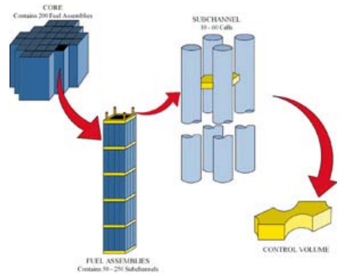


- 1D or 3D coarse mesh TH.
- Could catch the dynamics of the whole system.
- Simulation of the 3D phenomenon in the vessel and core is poor.



The **tool** implementing the coupling

SUBCHANFLOW



- Mesh on component scale.
- Isolated from the system dynamics.
- Simulation of the 3D phenomenon in the core area is good.

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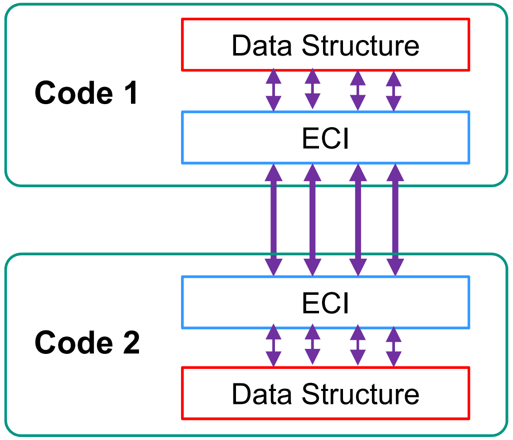
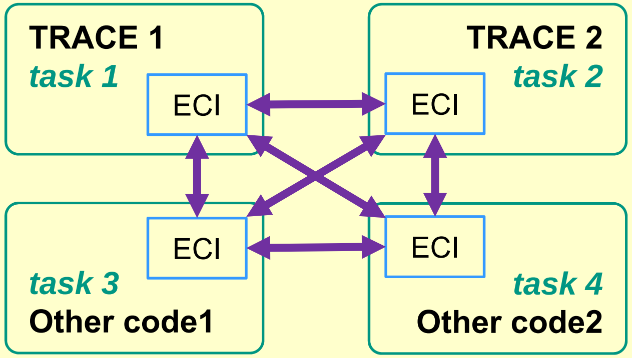
Introduction of ECI

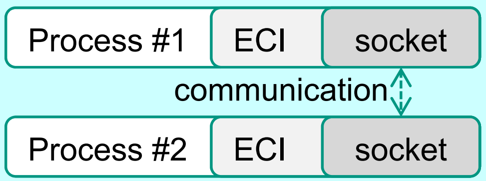


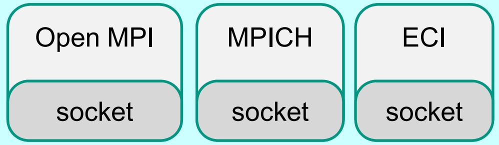
Exterior Communications Interface (ECI)
Developped by **US NRC**, inherently for **TRACE**

- Designed for Codes **Coupling** by generating a **multi-task** system.
- Could run on **distributed** computer systems and run in **parallel** way.
- Closely related to the coupled codes' data structures and each coupled code should has its own **specially designed ECI**.



Severless, all the tasks can communicate directely with each other.

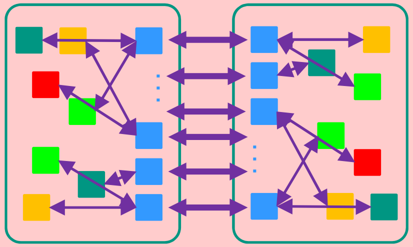


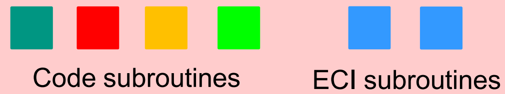


ECI use **socket** for data transfer.

The low level of OpenMPI, MPICH is also the socket.

ECI doesn't use MPI tools, it derectly handle the socket.





ECI is **not an uniform module** for all codes.

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Introduction of the Coupling

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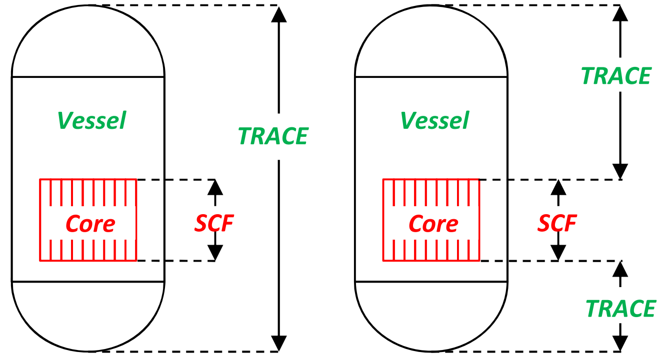
Qestion 1: Since **SCF** is in charge of the **core** area, whether **TRACE** will still **simulate** the core **or** just **ignore** it?

Domain coupling

Two options:

- TRACE simulates the core area – **Overlapping** coupling – feedback from SCF is treated as **additional source** to TRACE.
- TRACE doesn't simulate the core area – **Non-Overlapping** coupling – feedback from SCF is treated as **direct boundary conditions** to TRACE.



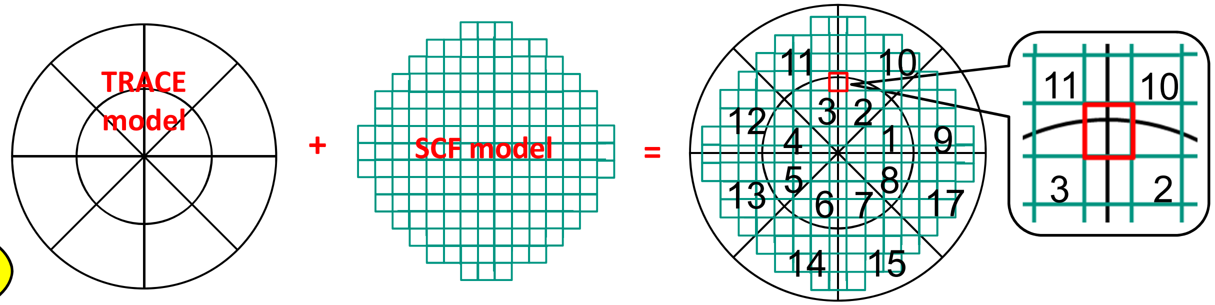
For most cases, the Non-Overlapping shows good robust and the feedback can be introduced to the domains directly through boundary conditions without any further calculation. So the **Non-Overlapping coupling was selected**.

	Overlapping	Non-Overlapping
Good	More robust	Logic easy
Not good	Logic complex	Less robust

Qestion 2: Since the two codes' **mesh differs** from each other at the interface, how to **manage the data transfer**?

Geometry coupling

Spatial coupling



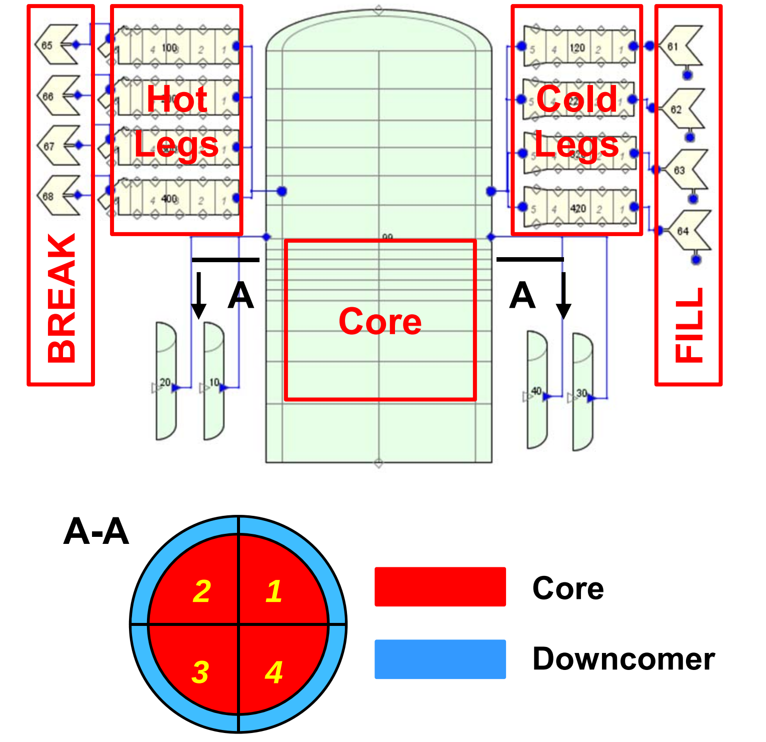
A subroutine was developed to manage the data mapping (**overlapping area weighted**).

Introduction of the Coupling

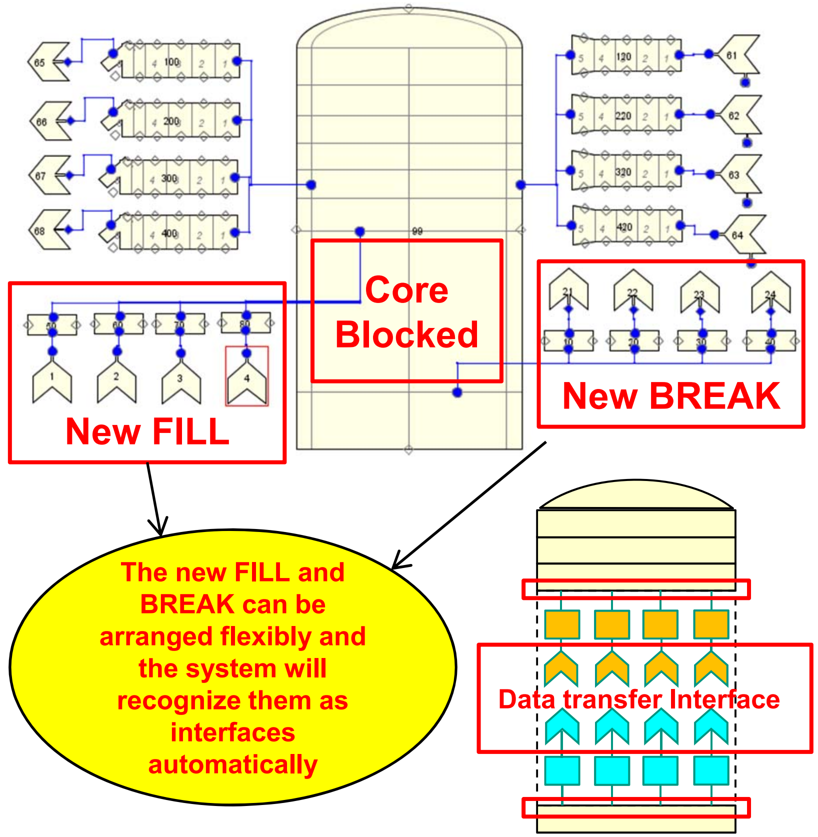
<u>Spatial Coupling</u> – **Non-overlapping domains and Area factor weighted**

Suppose there is a case:

- The VESSEL in TRACE has **four azimuthal sections**, **two radial sections**. The system has four hot legs and four cold legs.
- The SCF model has **nine centrosymmetric channels**.



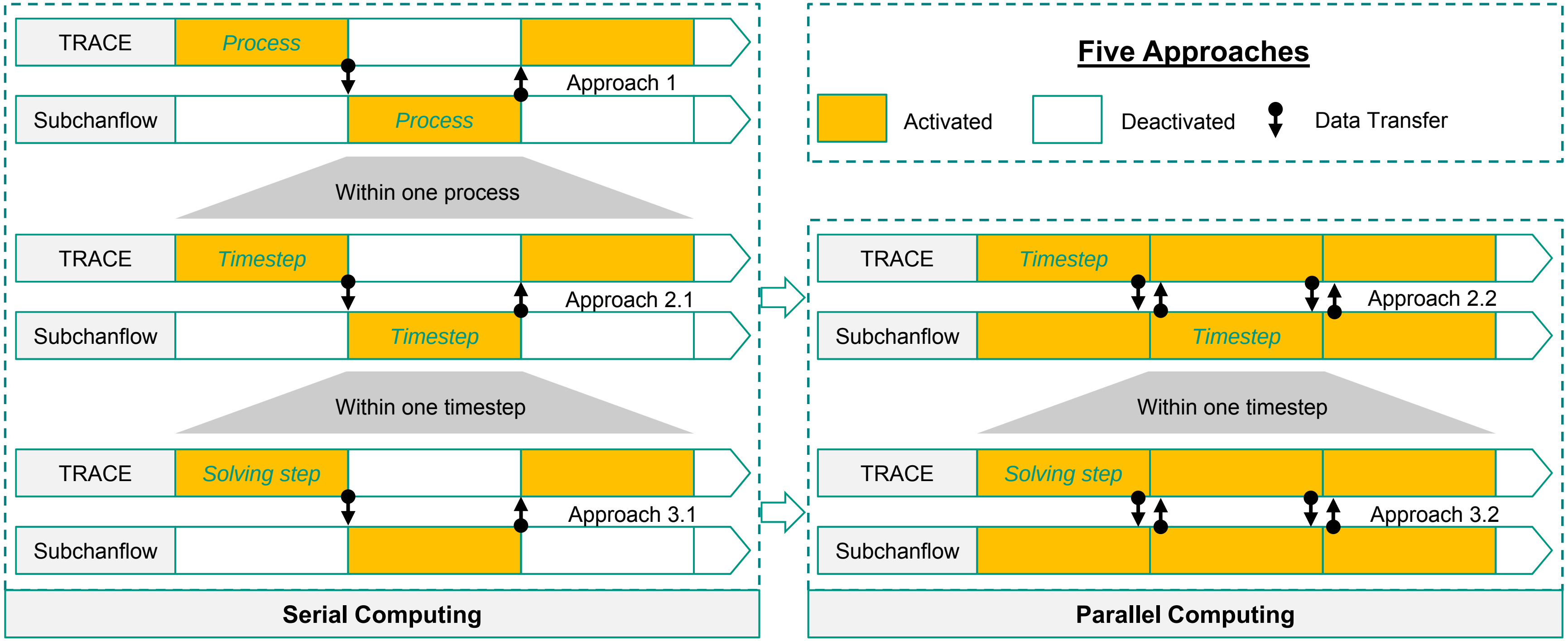
Original TRACE model



TRACE model for the coupling

Introduction of the Coupling

After the illustration of Spatial Coupling, now let's explore the codes' **Numerical Logics**



Approach 1: The most **simple** while the most **unefficient** coupling method.

Approach 3: The most **efficient** and **low-level** coupling method however calls for special **similarity** of the two code´ numerical solution method.

Considering coupling efficiency both with the fact that TRACE and Subchanflow use significantly different numerical methods, **Approach 2** was selected to couple the two codes together. Specially, taking advantage of **ECI**, **Approach 2.2** have been implemented.

Introduction of the Coupling

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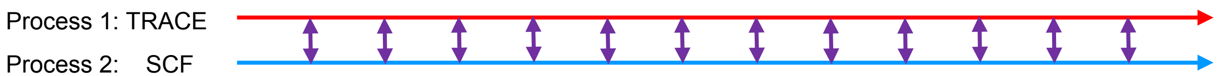
Numerical Coupling – Inter-timestep coupling and Parallel computing



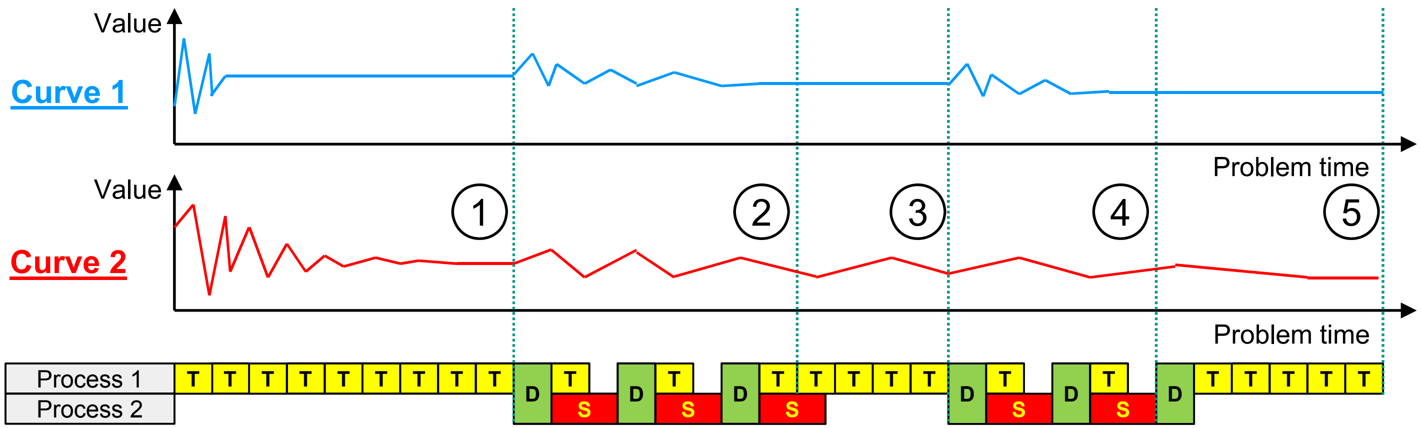
↕ Data transfer between two processes, at the beginning and end of a timestep

Steady State(SS) and Transient

T – TRACE timestep – Steady State

S – SCF timestep – Steady State

D – Data transfer, including massflow, temperature, pressure, timestep and other caculation control data



Curve 1 – variables at the bottom and top of the core, data from TRACE to SCF.

Curve 2 – the global convergence curve of TRACE.

1 – TRACE run standalone and converge the first time. SCF is activated. Reverse the convegence flag from 1 to 0.

2 – Data from TRACE to SCF become stable. SCF is deactivated, TRACE keeps running.

3 – Data from TRACE to SCF has an over-criterion perturbation. SCF is re-activated.

4 – Data from TRACE to SCF become stable again. SCF is deactivated again, TRACE keeps running.

5 – TRACE converge again. This is the end of the whole calculation.

Introduction of the Coupling

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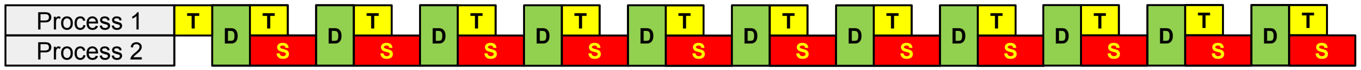
Steady State(SS) and Transient

T — TRACE timestep – Transient   S — SCF timestep – Transient

D — Data transfer, including massflow, temperature, pressure, timestep and other caculation control data

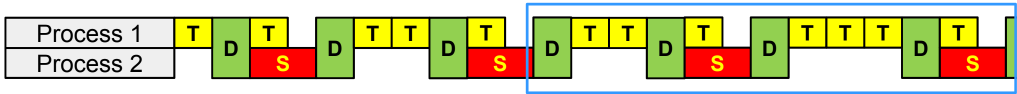
Two modes:

- Step to Step coupling

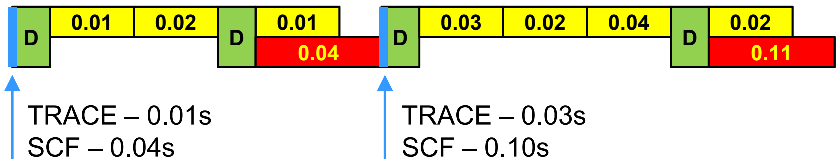


  - Data transfer perform **at each timestep**. Timestep of SCF will be transfered to TRACE who will compare and selcet the smaller one as the **globle timestep**, then transfer back to SCF.

- SCF timestep skipped coupling



  - Under this mode, TRACE is enabled to skip several SCF timesteps.
  - The skipped steps number depends on both TRACE and SCF timestep size.



- The first skip:
  - SCF_**0.04s** = TRACE_**0.01s + 0.02s + 0.01s**
  - The skipped SCF step number is **2**
- The second skip:
  - SCF_**0.11s** = TRACE_**0.03s + 0.02s + 0.04s + 0.01s**
  - The skipped SCF step number is **3**

- The final SCF step will be always be equal or larger than its originally determined size. **0.04 = 0.04, 0.11 > 0.1**

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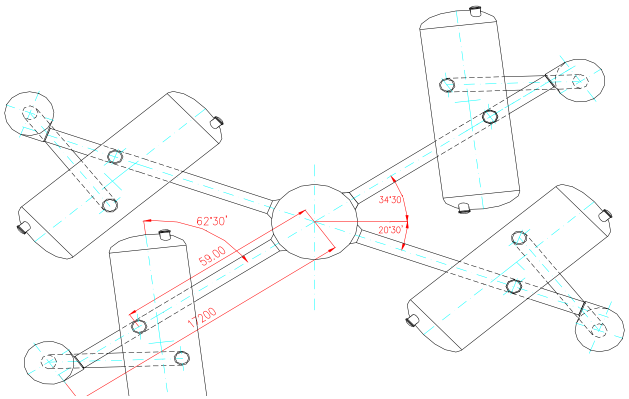
Code Testing: Specifications of the benchmark

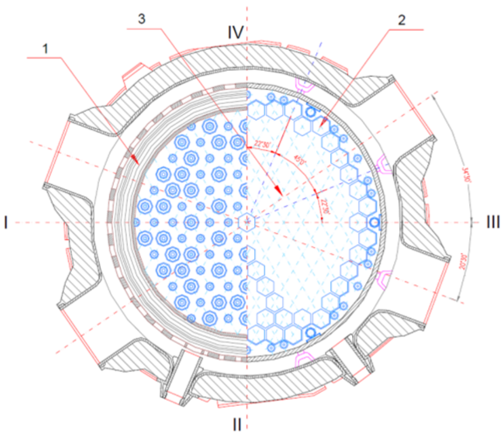
VVER-1000 Coolant Transient Benchmark: Started in **2002**, Sponsored by OECD/NEA, US DOE and CEA. Data from **Kozloduy NPP #6**.

- ***Phase 1, V1000CT-1***: Led by Pennsylvania State University (PSU).
  A main coolant pump (MCP) start-up while three other MCP are in operation.
- ***Phase 2, V1000CT-2***: Led by CEA.
  - ***Exercise 1***: Computation of **Flow Mixing Experiments**. – **Step1: Experiment**; Step 2: Numerical calculation.
  - ***Exercise 2***: Coupled 3D neutronics/vessel thermal hydraulics response.
  - ***Exercise 3***: Best-estimate coupled code plant transient modeling.

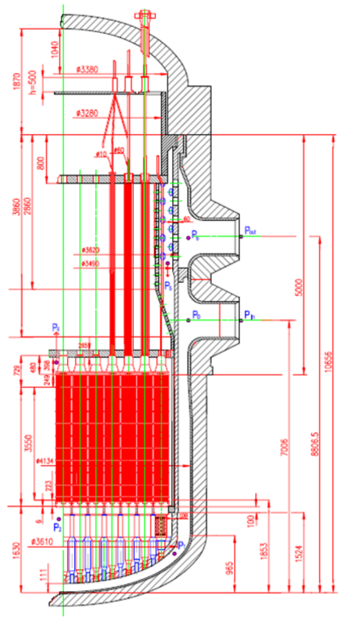
Description of the VVER-1000 RPV:



The plant consists of **four loops**, each one with a horizontal steam generator (SG) and a main coolant pump (MCP).



The loops are **not symmetrically arranged**. There are 163 hexagonal fuel assemblies(FA) and 48 reflector assemblies (RA) in the core.



An elliptical cone with many perforations and 163 support columns exist in the lower plenum.

Code Testing: Specifications of the benchmark

Before the test:

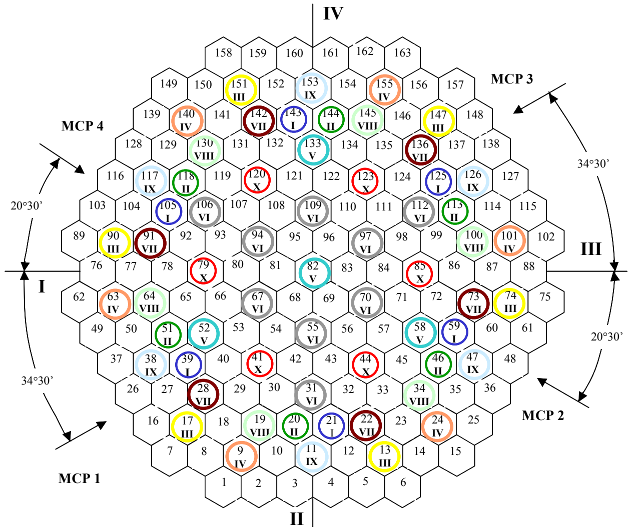
- The power was **281 MW** with all main coolant pumps **running**.
- On the secondary side all steam generators were available.
- The core was at beginning of cycle conditions (**BOC**).
- **Control rod groups**: group #9 and #10: fully inserted; groups #1-#7: fully withdrawn and the regulating rod group #8 was about 84% withdrawn from the bottom of the core.
- The main steam header pressure amounts **5.07 MPa**.
- The main operational parameters are summarized in **Table 1**.

Table.1 Main parameters of the loops before test

Parameter	Initial State	Accuracy
Thermal power, MW	281	± 60
Pressure above core, MPa	15,593	± 0,3
Pressure drop over RPV, MPa	0,418	± 0,043
Coolant temperature at core inlet #1, K	541,75	± 1,5
Coolant temperature at core inlet #2, K	541,85	± 1,5
Coolant temperature at core inlet #3, K	541,75	± 1,5
Coolant temperature at core inlet #4, K	541,75	± 1,5
Coolant temperature at core outlet #1, K	545	± 2,0
Coolant temperature at core outlet #2, K	545	± 2,0
Coolant temperature at core outlet #3, K	544,9	± 2,0
Coolant temperature at core outlet #4, K	545	± 2,0
Mass flow rate of loop #1, kg/s	4737	± 110
Mass flow rate of loop #2, kg/s	4718	± 110
Mass flow rate of loop #3, kg/s	4682	± 110
Mass flow rate of loop #1, kg/s	4834	± 110

The test phase:

- Isolation of the steam generator of **loop-1** and isolation of the steam generator from feed water.
- Primary coolant **temperature** of loop-1 **increase** up to about 14 °C.
- **Coolant mixing** occurred first of all in the **downcomer** region.
- Coolant mixing occurred in the **lower plenum**, **core** and **upper plenum**.
- Temperature of the unaffected loops increased.
- The test lasted for **1800s**. At that time the power increased up to 286 MW.
- The coolant temperature at the **cold/hot legs** was measured.
- Coolant temperature at some **fuel assembly outlet** was measured.



Control rod groups of the core

Code Testing: Specifications of the benchmark

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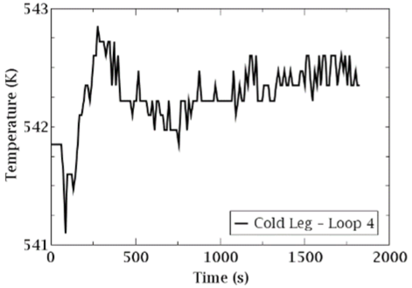
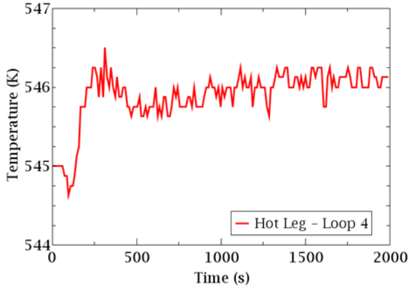
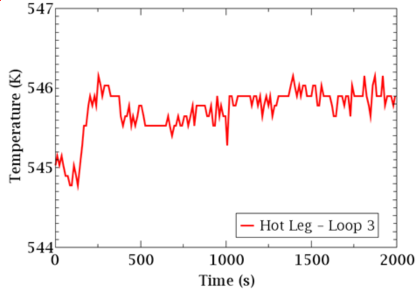
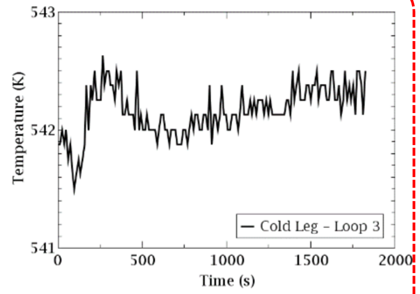


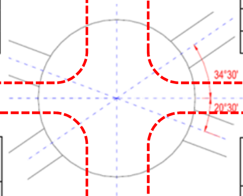


Time, s	T_{cl4}, C/ K	dT	P_{in}, MPa	ρ, kg/m3	dP MCP1 MPa	Q_4 m3/h	G_4 kg/s
0	268.6/541.75		15.97	784.2	0.615	22200	4834
165	268.4/541.55	-0.2	16.12	784.4			
340	269.5/542.65	1.1	15.98	782.5			
920	269.0/542.15	-0.5	15.97	783.2			
1800	269.2/542.35	0.2	15.97	783.0	0.612	22160	4819

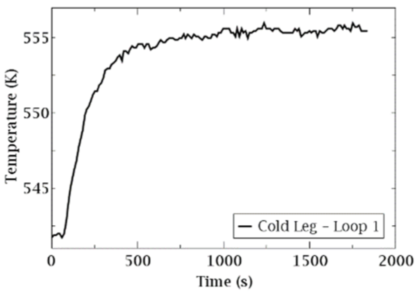


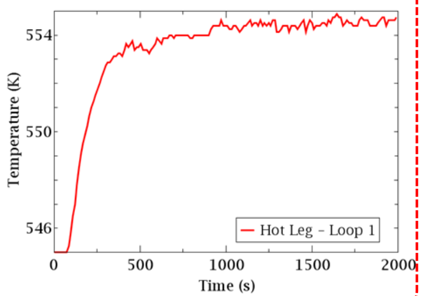


Time, s	T_{cl3}, C/ K	dT	P_{in}, MPa	ρ, kg/m3	dP MCP1 MPa	Q_3 m3/h	G_3 kg/s
0	268.6/541.75		15.97	784.2	0.606	21500	4682
165	268.3/541.45	-0.3	16.12	784.6			
340	269.4/542.55	1.1	15.98	782.6			
920	268.8/541.95	-0.6	15.97	783.6			
1800	269.0/542.15	0.2	15.97	783.2	0.603	21460	4669

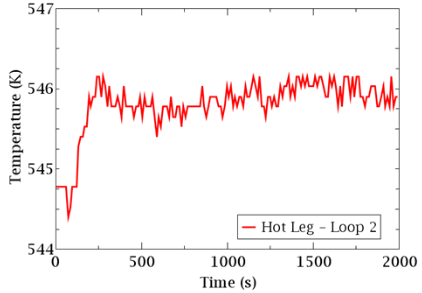


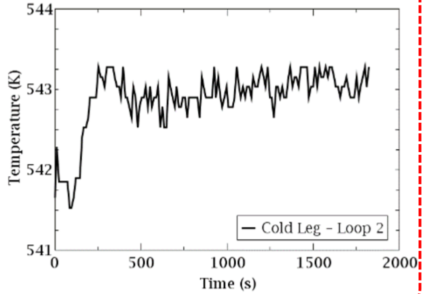
Time, s	T_{cl1}, C/ K	dT	P_{in}, MPa	ρ, kg/m3	dP MCP1 MPa	Q_1 m3/h	G_1 kg/s
0	268.6/541.75		15.97	784.0	0.620	21750	4737
165	277.6/550.75	9.0	16.12	769.6	0.611	21650	4627
340	281.2/554.35	3.6	15.98	764.2	0.608	21610	4580
920	282.0/555.15	0.8	15.97	761.5	0.607	21600	4569
1800	282.2/555.35	0.2	15.97	761.1	0.607	21600	4566



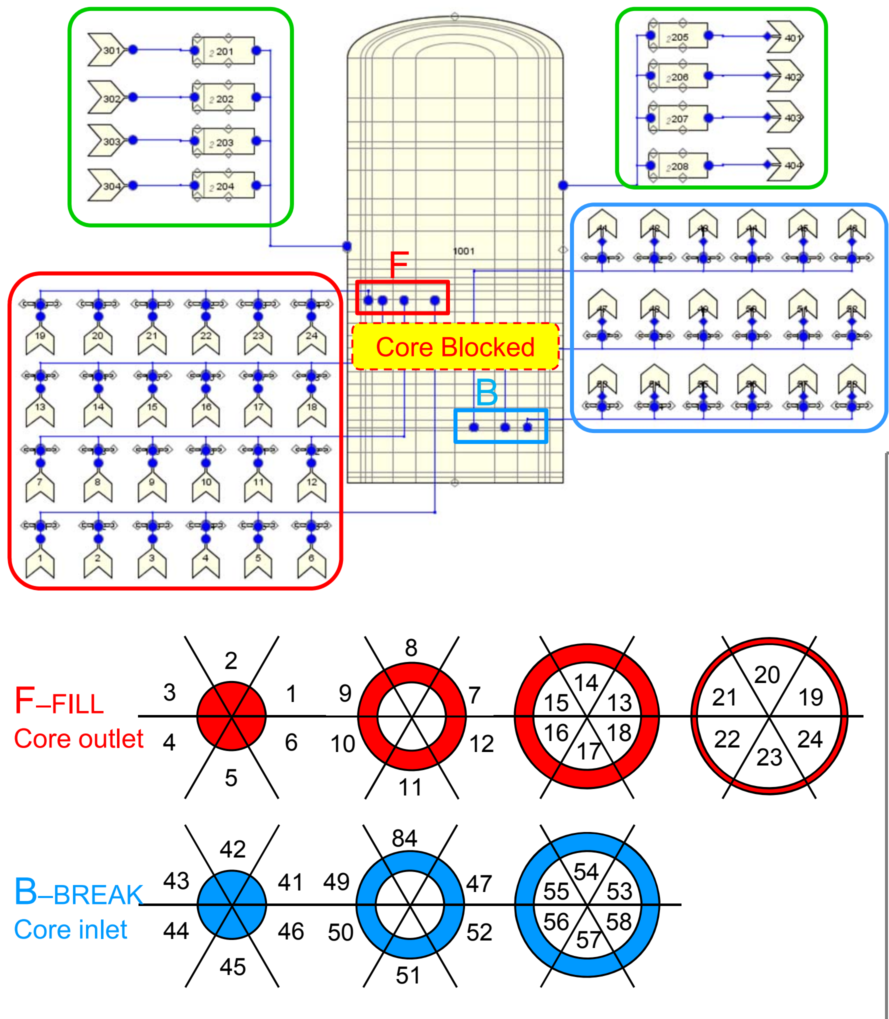


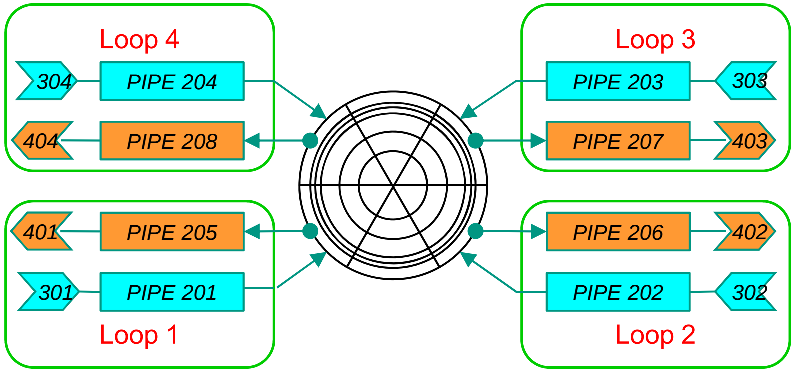
Time, s	T_{cl2}, C/ K	dT	P_{in}, MPa	ρ, kg/m3	dP MCP1 MPa	Q_2 m3/h	G_2 kg/s
0	268.7/541.85		15.97	784.0	0.609	21670	4718
165	269.3/542.45	0.6	16.12	783.0		21600	4697
340	269.7/542.85	0.4	15.98	782.2		21550	4682
920	269.8/542.95	0.1	15.97	782.0		21540	4678
1800	269.9/543.05	0.1	15.97	781.8	0.609	21530	4676



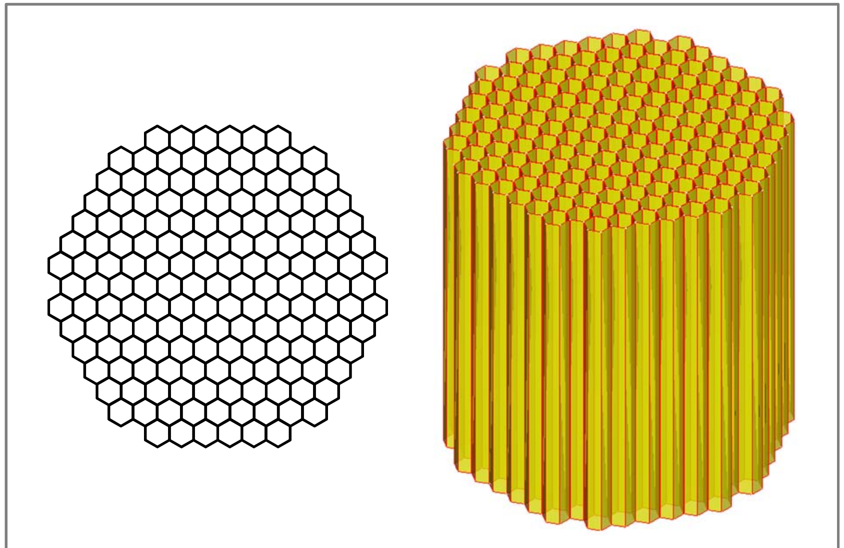


Code Testing: TRACE/SCF-ECI model





TRACE model – TRACE V5.1051



SCF model – Subchanflow3.3

Code Testing: Results (1/5)

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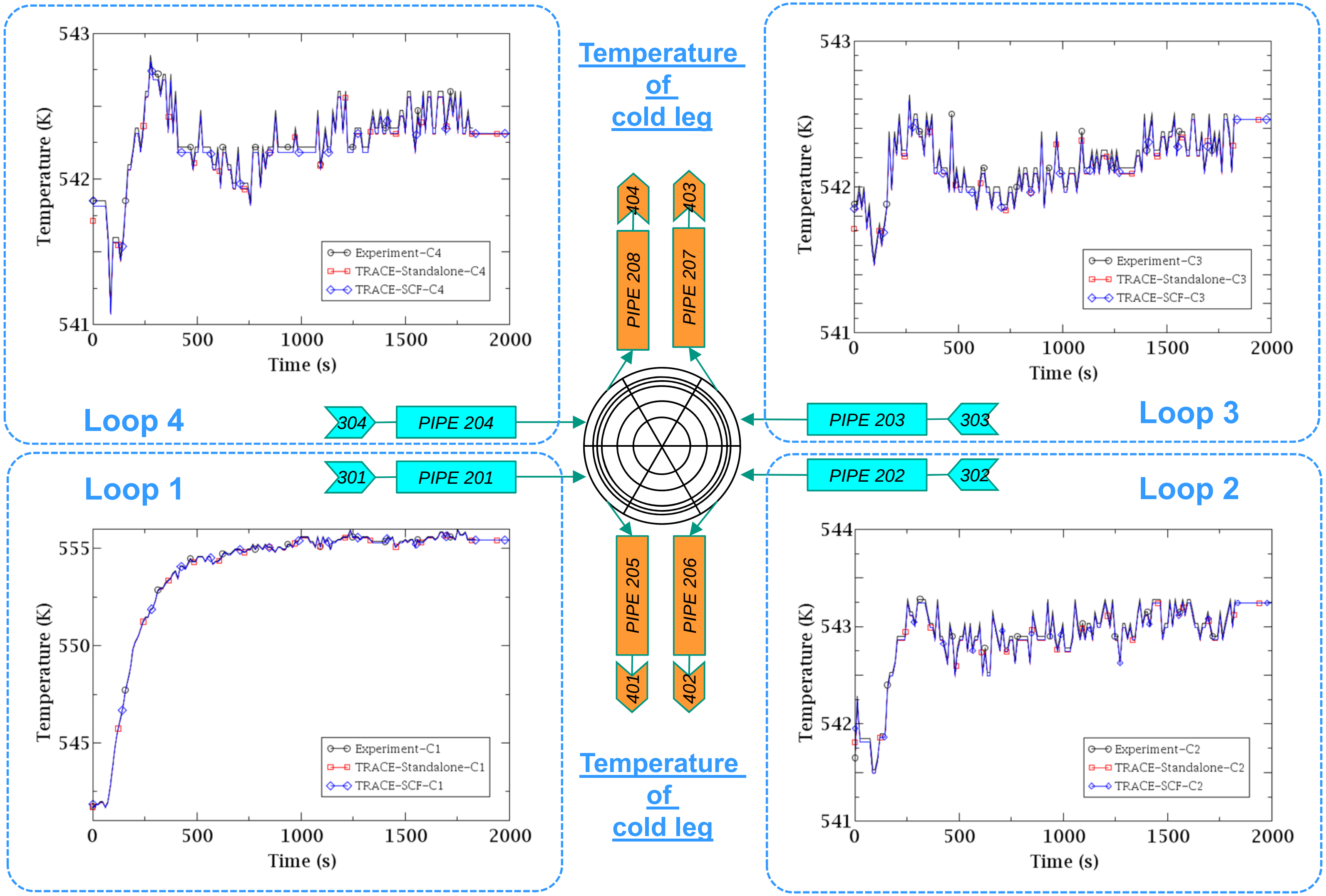
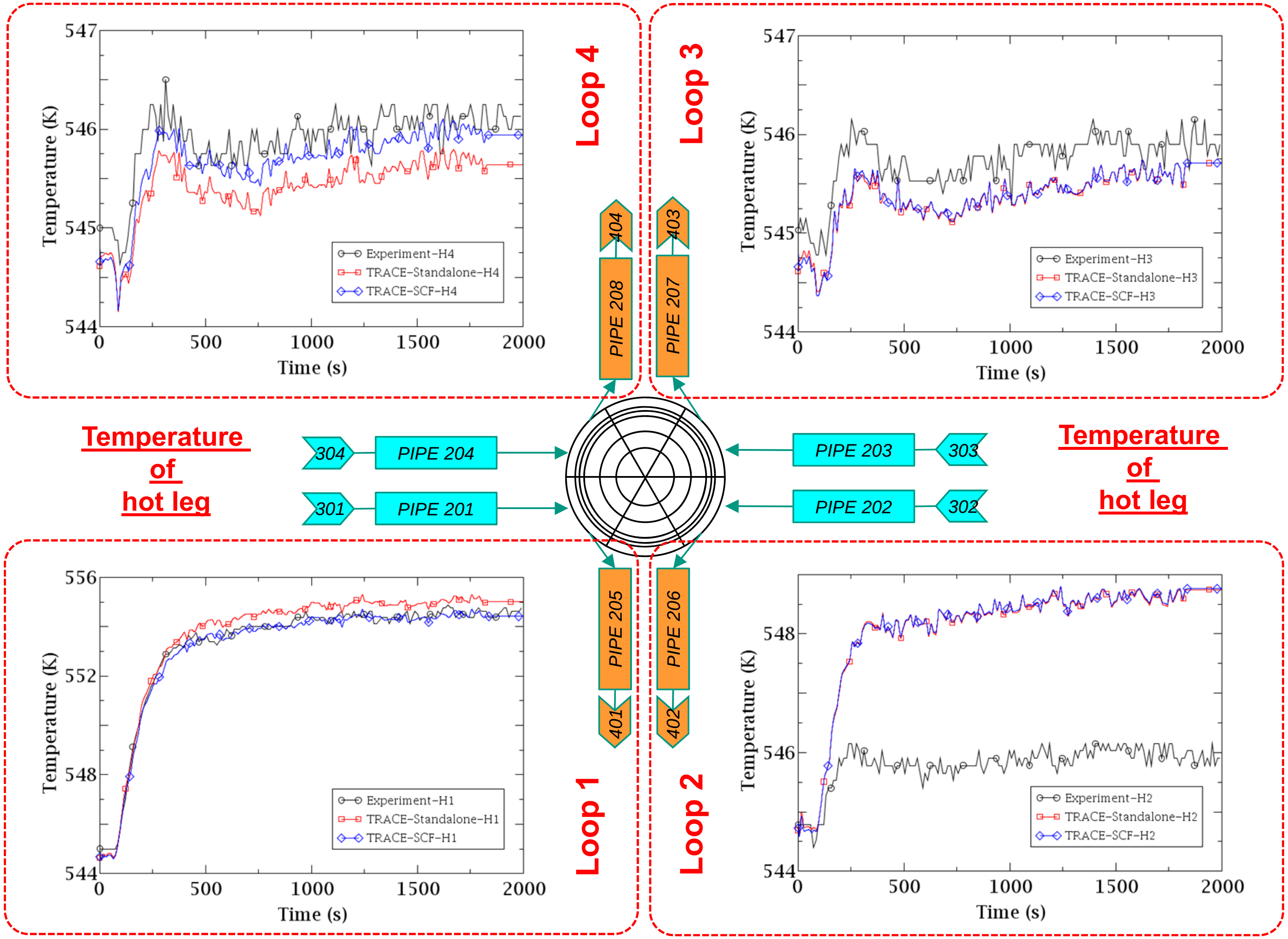
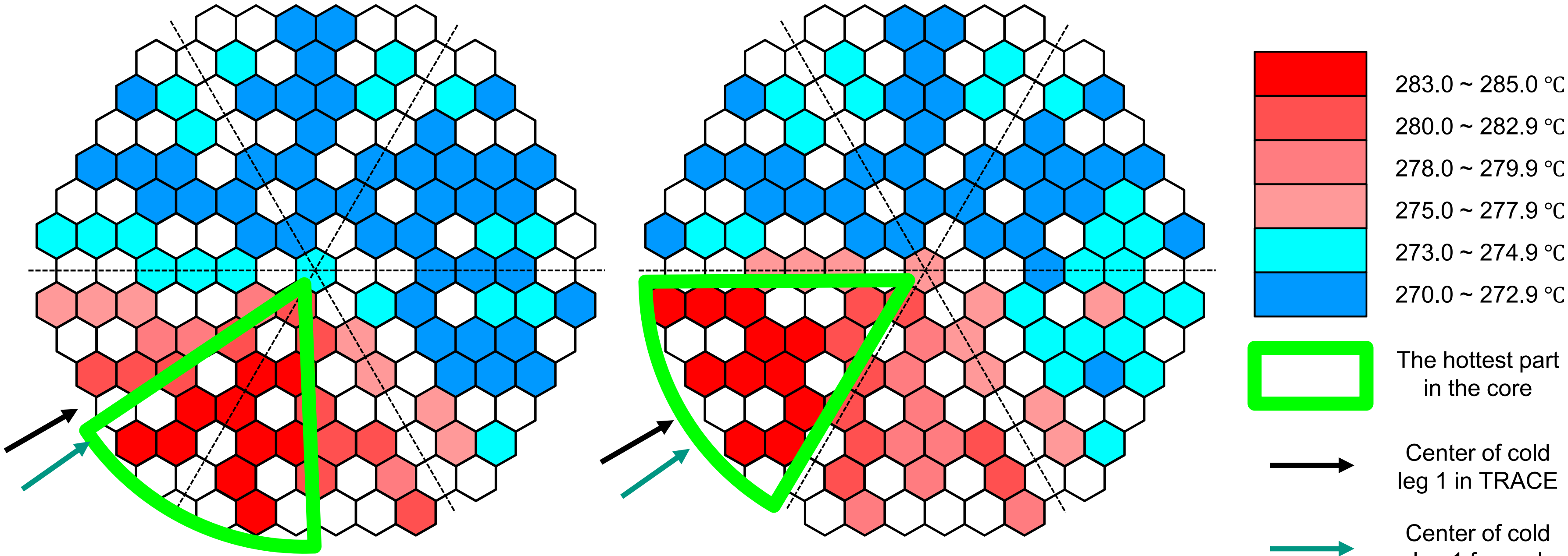


Code Testing: Results (2/5)



Code Testing: Results (3/5)

- The coupled code gives a notable **improvement** on predicting the temperature distribution **at hot legs** than TRACE standalone.

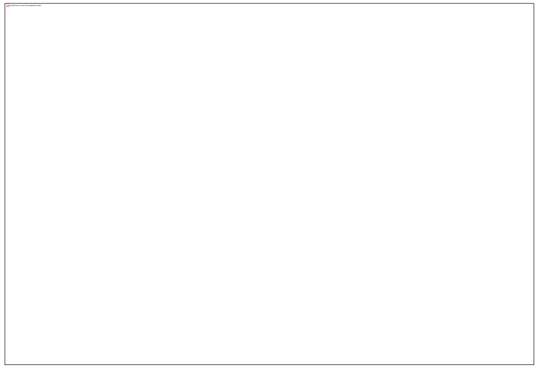


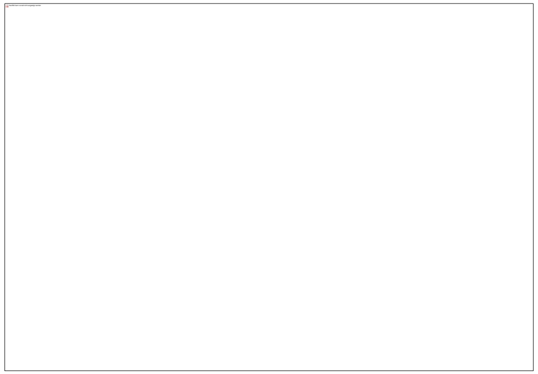
Temperature distribution - Experiment

Temperature distribution – TRACE:SCF

- The center of hottest channels **shifts** an counter clock-wise angle than the centerline of cold leg 1 in experiment while there is no such phenomenon observed in the simulation. Possible reasons could be:
  - The **cross flow** in the core is strong while the core model of SCF is just **assembly wise** which may loss some cross flow.
  - The **coolant mixing** is considerate in the **downcomer** and **lower plenum** of the vessel while TRACE couldn't properly simulate the mixing.
  - The inlets and outlets of the vessel are arranged by a **swirl** according to the horizontal axis.
- The replacement of TRACE by the **CFD codes** at the **downcomer** and the **vessel lower plenum** may improve the core temperature distribution prediction.

Code Testing: Results (4/5)





- The result under **timestep skipped** mode with a SCF timestep of **0.5s** is the same with the result of a typical step to step coupling.
- The result under **timestep skipped** mode with a SCF timestep of **1.0s** is also the same with the result of a typical step to step coupling.
- The **timestep skipped** mode of the coupling codes behaves just **as good as** the **step to step** mode.
- The SCF timestep seems has **no significant effect** on the final results.
  - Or to be more precise, the **cases which were tested** just share the **same results**.
  - However, there could be **difference** between the two modes when the SCF timestep is set **too big**, which could lead to the **lost of real transient details**.

Code Testing: Results (5/5)

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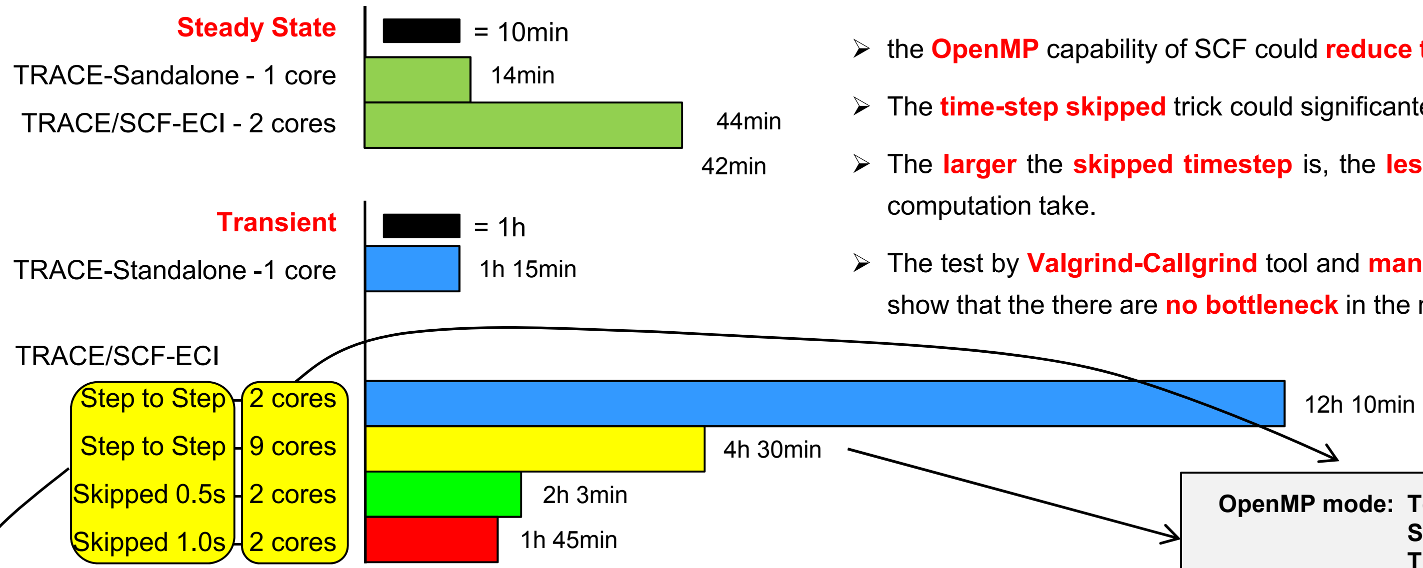
Analyze of the Computing time.

Operating System and version:	Debian GNU/Linux 8
Software title and version:	TRACE V5.1051 and Subchanflow 3.3
Hardware information:	Processor – 48 Intel(R) Xeon(R) CPU E5-2697 v2 @ 2.70GHz, Installed memory (RAM) – 378 GB, System type – 64 bit

Data from three sources are compared: **TRACE-Standalone**, **TRACE/SCF-ECI**

- the **OpenMP** capability of SCF could **reduce the elapsed time**.
- The **time-step skipped** trick could significantely **save CPU time**.
- The **larger** the **skipped timestep** is, the **less elapsed time** will the computation take.
- The test by **Valgrind-Callgrind** tool and **manually** CPU time analyze show that the there are **no bottleneck** in the new added codes.



Step to Step:	**TRACE and SCF run one by one, step by step.**
Skipped 0.5s:	**SCF steps could be skipped, the minimum SCF timestep is 0.5s.**
Skipped 1.0s:	**SCF steos could be skipped, the minimum SCF timestep is 1.0s.**

OpenMP mode:	**Total – 9 cores** **SCF – 8 cores** **TRACE – 1 core**
Normal mode:	**Total – 2 cores** **SCF – 1 core** **TRACE – 1 core**

Presentation Outline

Coupling of TRACE and Subchanflow (SCF) based on the Exterior Communication Interface (ECI)

- **Self-Introduction**
- **Objective Analysis**
- **Introduction of ECI**
- **Introduction of the Coupling**
- **Code Testing**
- ***Summary***
- **Next steps**

Summary

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Goal: **Coupling** of **TRACE** and **SCF** based on **ECI**

- **Coupling**
  - Spatial coupling
    - Computational domain — *Non-overlapping*
    - Geometrical — *Area factor weighted*
  - Numerical coupling — *Inter-timestep Parallel*
    - **Steady State(SS):** Only the SCF SS function is called. TRACE controls SCF‘s running.
    - **Transient:** Two modes: step to step and SCF timestep skipped coupling.
- **TRACE**: System code. Simulate on system scale. Developed by US NRC
- **SCF**: *Subchannel code. Simulate on component scale. Developed by KIT INR*
- **ECI**: Developed by US NRC. The tool implementing the coupling. Generate multi-task system. Use socket and run in parallel way. Closely related to code‘s structure. Specific for specific code.

TEST: with a Coolant Mixing Experiment performed on VVER-1000

- Comparison of Temperature distribution at coldlegs and hotlegs: **Experiment**, **TRACE-Standalone** and **TRACE/SCF-ECI**
  - Notable improvement was observed in the TRACE/SCF-ECI result compared with TRACE standalone.
- Analysis of Temperature distribution at fuel assembly outlet: **Experiment**, **TRACE/SCF-ECI**
  - There are obvious difference between the results.
  - Improving ways could be: let CFD simulate the flow in downcomer and lower plenum, more TRACE azimuthal sections.
- Comparison of the Temperature distribution at hotlegs: **Couple-Step_to_Step**, **Couple-Skip_0.5**, **Couple-Skip_1.0**
  - The results are almost the same, which indicates that the timestep skipped mode work well just as a typical coupling.
- Comparison of the computing time: **Couple-ECI- (Step_to_Step, OpenMP_SCF, Skip_0.5, Skip_1.0)**
  - OpenMP capability of SCF could reduce the computing time.
  - The timestep skipped mode could significantely reduce the computing time.

Presentation Outline

Coupling of TRACE and Subchanflow (SCF)
based on the Exterior Communication Interface (ECI)

- Self-Introduction
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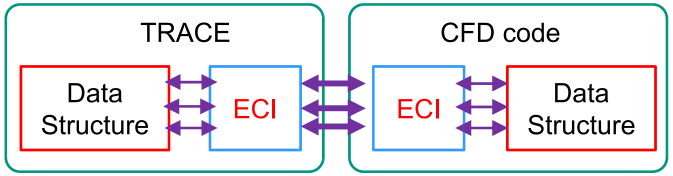
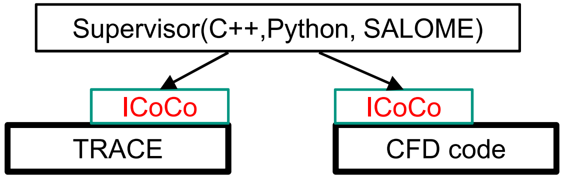
- Summary
- *Next steps*

Next Steps

➢ **Prepare** for the **coupling** of **TRACE** with **CFD** code.

- Investigate the **ICoCo** (Interface for Code Coupling) and compare it with **ECI**, select the most proper tool for the System/CFD coupling.





- **Select** the proper CFD code for the coupling.

Commercial codes …

Open source codes …

➢ **Implement** the coupling of TRACE and the selected CFD code.

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Thanks for your attention.

Introduction of The Coupling: Modification to the input files

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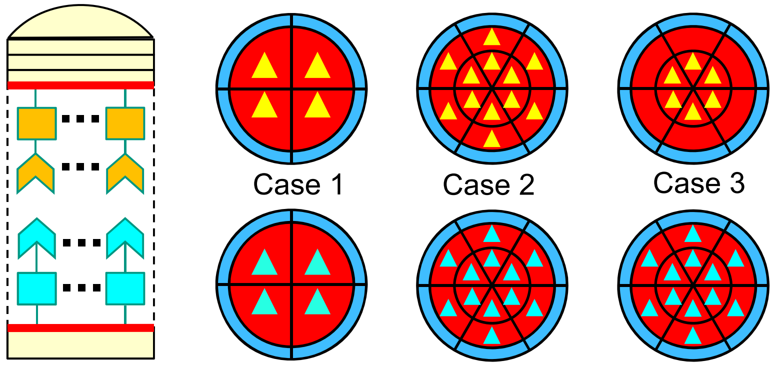
SCF input.txt: Four new input parameters.

- **radial_n_f**: number of the radial rings of FILL in TRACE.
- **radial_n_b**: number of the radial rings of BREAK in TRACE.
- **angular_n**: number of TRACE anzimuthal sections.

Core

Downcomer

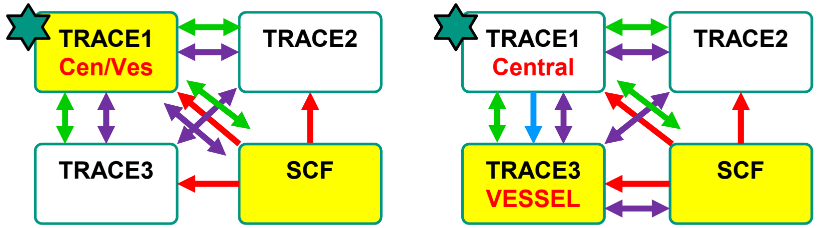


- **compnum**: component number of VESSEL in TRACE.

taskList: The taskname of SCF must be “SCF”

- The file contains all the tasks information:

Taskname	Program name
Hostname	Working directory



1 - Send the VESSEL component number to all TRACE tasks;
2 - Central task fix SCF task number based on taskList;
3 – Central task send SCF task number to task having VESSEL;
4 – Numerical data transfer;
5 – Calculation control data from central task.

TRACE tracin: Two new input parameters.

- **j_skip**: 0-TRACE will run a step to step coupling with SCF
  1-TRACE is enabled to skip several SCF steps.
- **bound_l**: its value is used as the boundary to identify the data transfer interfaces between TRACE and SCF.

FILL From 1 to bound_l

BREAK From bound_l+1 to 2* bound_l

Treated as Interfaces

bound_l=3 FILL 1 FILL 2 FILL 3 FILL 11 FILL 12 BREAK 5 BREAK 6 BREAK 7 BREAK 15