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Multi-Scale Coupling of TRACE and SUBCHANFLOW based on ECI for the Analysis of 3D Phenomena inside the PWR RPV

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Presentation Outline

- Backgrounds
- Objective of the Coupling
- Introduction of ECI
- Implementation of the Coupling
- Code Verification
- Summary

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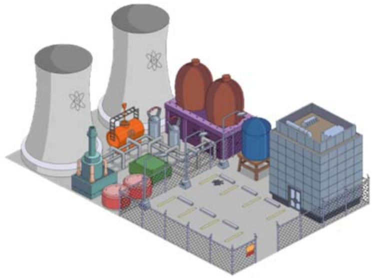
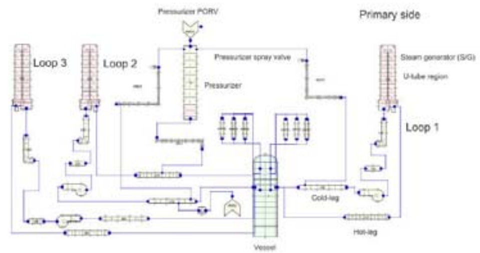
Backgrounds

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.

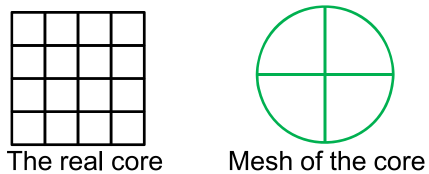


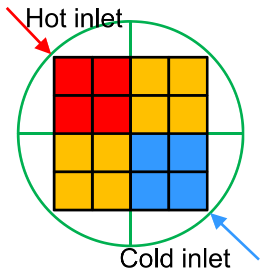
We want to simulate the **dynamic of the whole system** in order to study the **whole system's behaviour** under **normal**, **accident** and some special conditions.



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**.



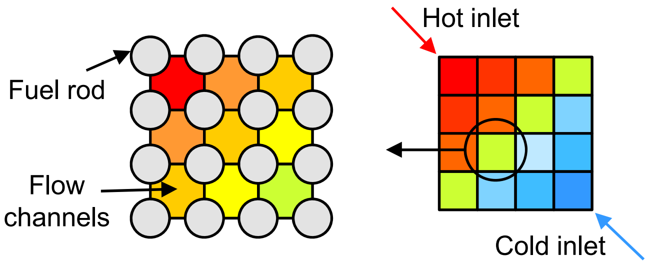


- Resolution of the physical field distribution is **poor.**
- e.g: Important **3D** phenomenons in the core: lateral flow between assemblies and fuel rods are **missing**.

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

- 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**



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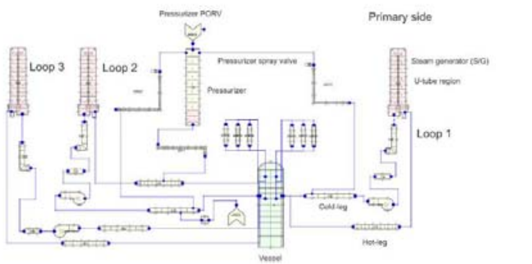
Objective of the Coupling

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**.

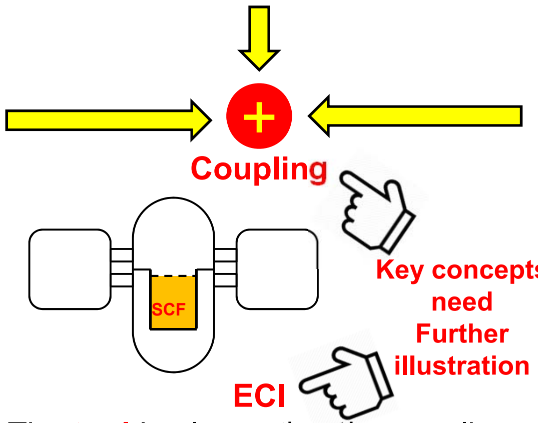
Motivation

TRACE



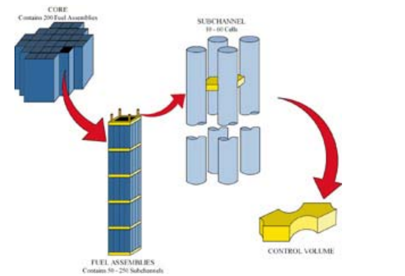
- 1D or 3D coarse mesh TH.
- Could catch the dynamics of the whole system.
- Simulation of the 3D phenomenon in the vessel and core is poor.

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



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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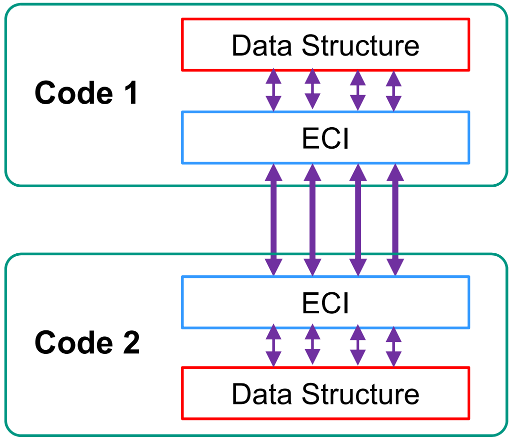
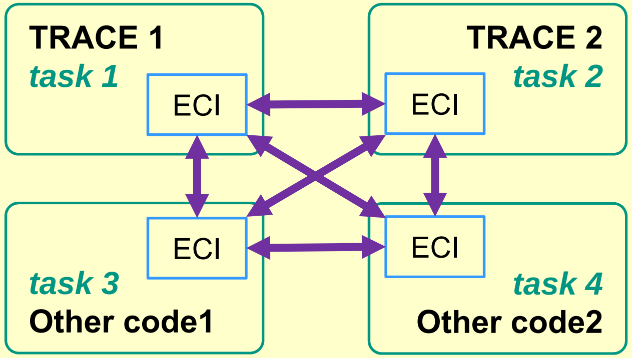
Introduction of ECI

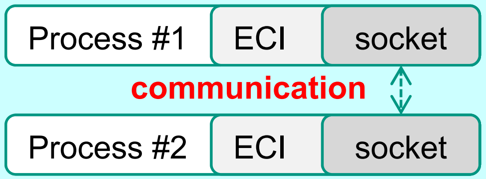


Exterior **C**ommunications **I**nterface (**ECI**)
Developped by **US NRC**, inherently for **TRACE**

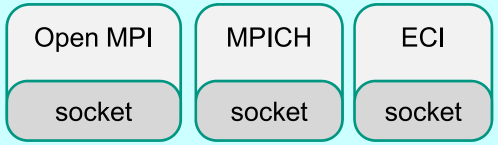
- Designed for Codes **Coupling** by generating a **multi-task** system.
- Could run on **distributed** computer systems and run in **parallel** way.
- Closely related to the coupled codes' data structures and each coupled code should has its own **specially designed ECI**.



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

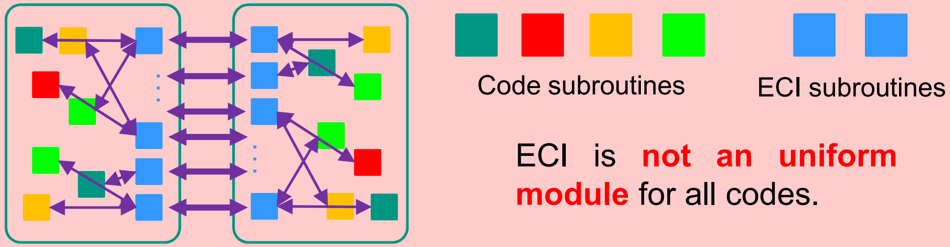


ECI use **socket** for data transfer.



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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Implementation of the Coupling

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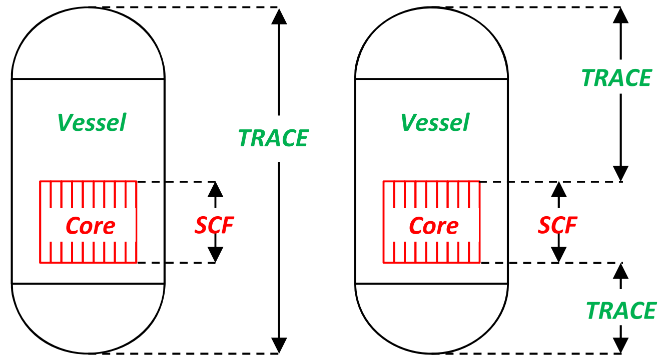
Qestion 1: Since **SCF** is in charge of the **core** area, whether **TRACE** will still **simulate** the core **or** just **ignore** it?

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.



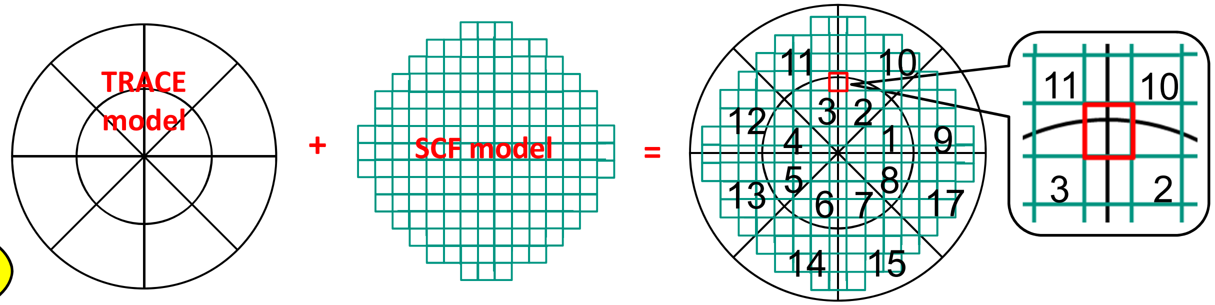
For most cases, the Non-Overlapping shows good robust and the feedback can be introduced to the domains directly through boundary conditions without any further calculation. So the **Non-Overlapping coupling was selected**.

	Overlapping	Non-Overlapping
Advantage	More robust	Logic easy
Short coming	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**).

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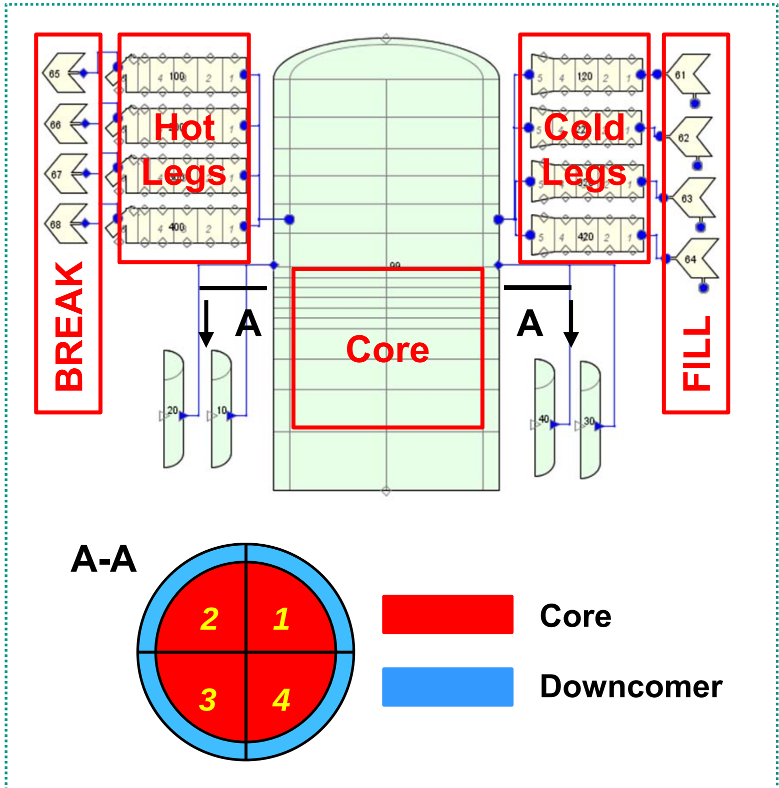
Implementation of the Coupling

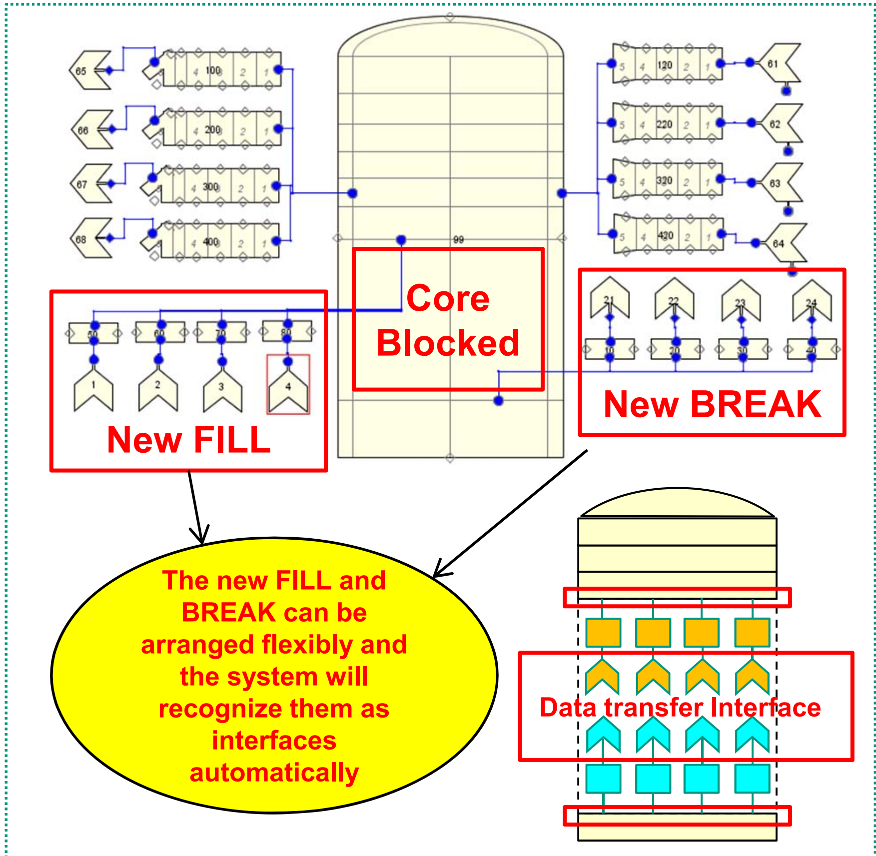
Spatial Coupling – Non-overlapping domains and Area factor weighted

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

Implementation of the Coupling

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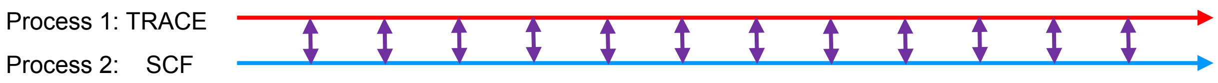
Numerical Coupling – Inter-timestep coupling and Parallel computing



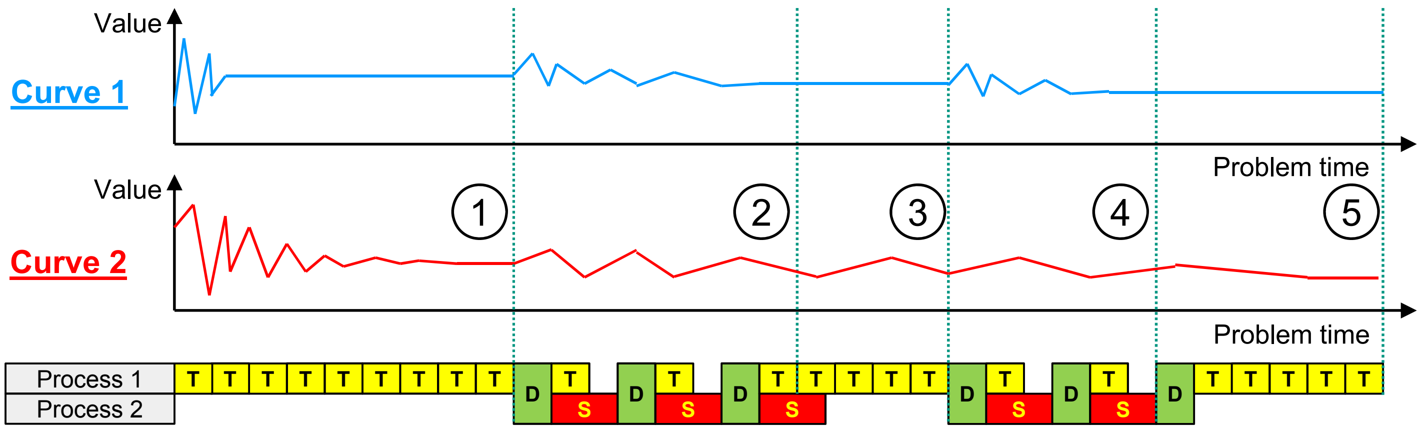
Data transfer between two processes, at the beginning and end of a timestep

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.

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.

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Implementation of the Coupling

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Steady State(SS) and Transient

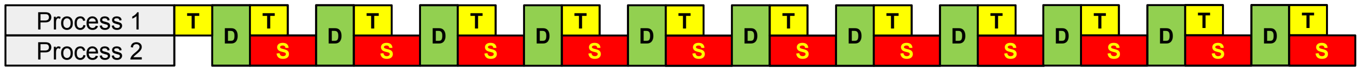
T — TRACE timestep – Transient

S — SCF timestep – Transient

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

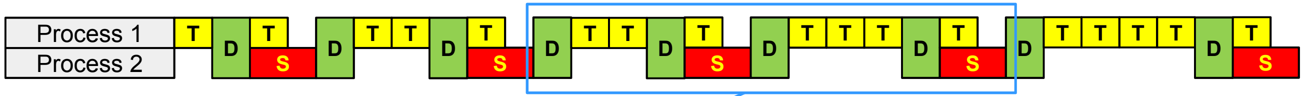
Two modes:

- Step to Step coupling

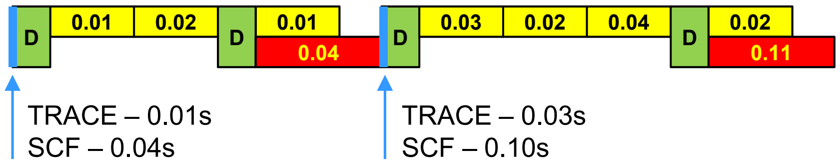


- Data transfer perform **at each timestep**. Timestep of SCF will be transfered to TRACE who will compare and selcet the smaller one as the **globle timestep**, then transfer back to SCF.

- 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 Verification: Specifications of the benchmark

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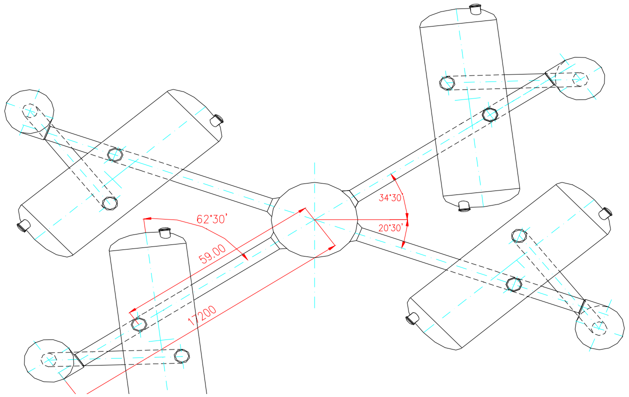
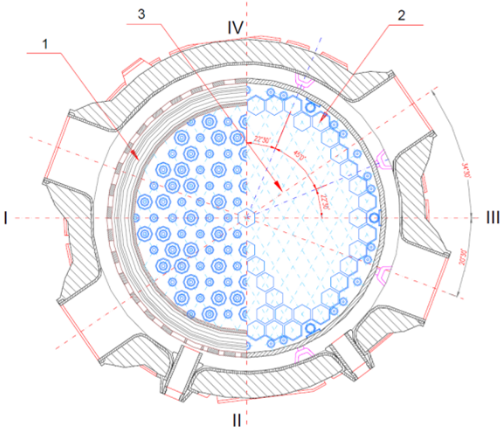
VVER-1000 Coolant Transient Benchmark: Started in **2002**, Sponsored by OECD/NEA, US DOE and CEA. Data from **Kozloduy NPP #6**.

- ***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.

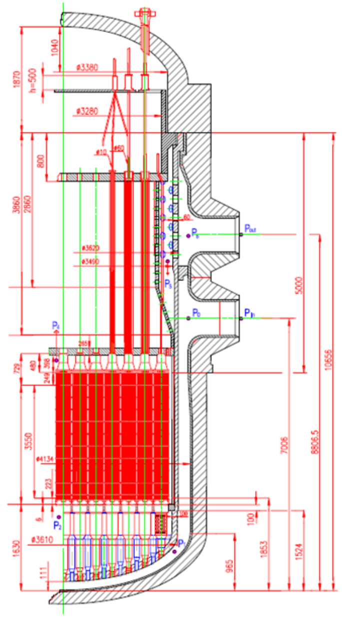
Description of the VVER-1000 RPV:



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 Verification: Specifications of the benchmark

Before the test:

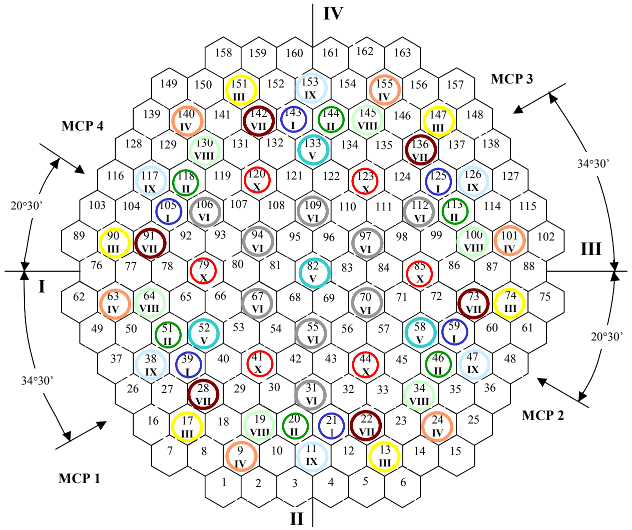
- The power was **281 MW** with all main coolant pumps **running**.
- On the secondary side all steam generators were available.
- The core was at beginning of cycle conditions (**BOC**).
- **Control rod groups**: group #9 and #10: fully inserted; groups #1-#7: fully withdrawn and the regulating rod 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 Verification: Specifications of the benchmark

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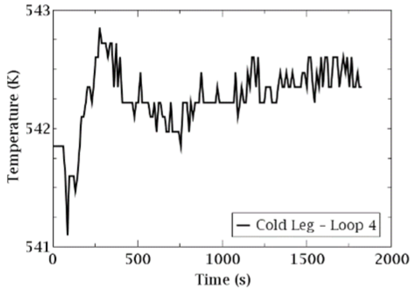
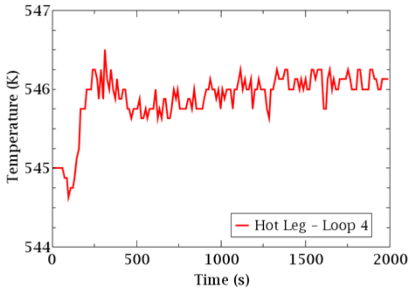
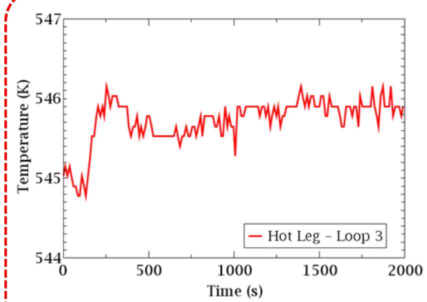
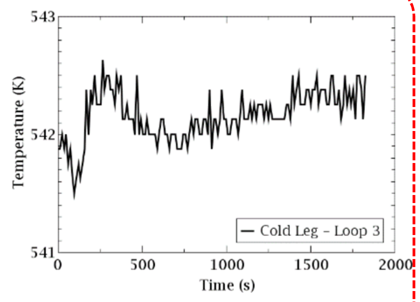


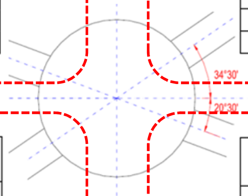


Time, s	Tcl₄, C/ K	dT	Pin, MPa	ρ, kg/m3	dP MCP1 MPa	Q_4 m3/h	G_4 kg/s
0	268.6/541.75		15.97	784.2	0.615	22200	4834
165	268.4/541.55	-0.2	16.12	784.4			
340	269.5/542.65	1.1	15.98	782.5			
920	269.0/542.15	-0.5	15.97	783.2			
1800	269.2/542.35	0.2	15.97	783.0	0.612	22160	4819

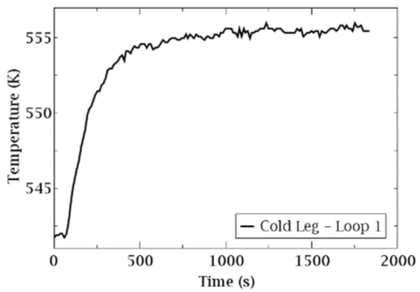


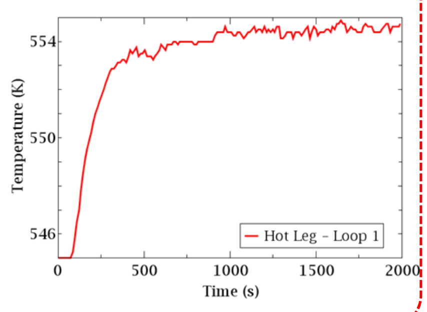


Time, s	T_{cl3}, C/ K	dT	Pin, MPa	ρ, kg/m3	dP MCP1 MPa	Q_3 m3/h	G_3 kg/s
0	268.6/541.75		15.97	784.2	0.606	21500	4682
165	268.3/541.45	-0.3	16.12	784.6			
340	269.4/542.55	1.1	15.98	782.6			
920	268.8/541.95	-0.6	15.97	783.6			
1800	269.0/542.15	0.2	15.97	783.2	0.603	21460	4669

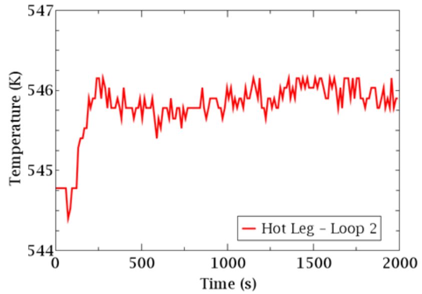


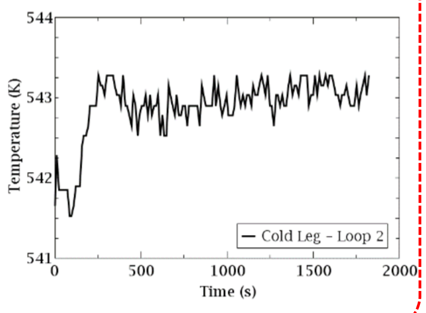
Time, s	T_{cl1}, C/ K	dT	Pin, MPa	ρ, kg/m3	dP MCP1 MPa	Q_1 m3/h	G_1 kg/s
0	268.6/541.75		15.97	784.0	0.620	21750	4737
165	277.6/550.75	9.0	16.12	769.6	0.611	21650	4627
340	281.2/554.35	3.6	15.98	764.2	0.608	21610	4580
920	282.0/555.15	0.8	15.97	761.5	0.607	21600	4569
1800	282.2/555.35	0.2	15.97	761.1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



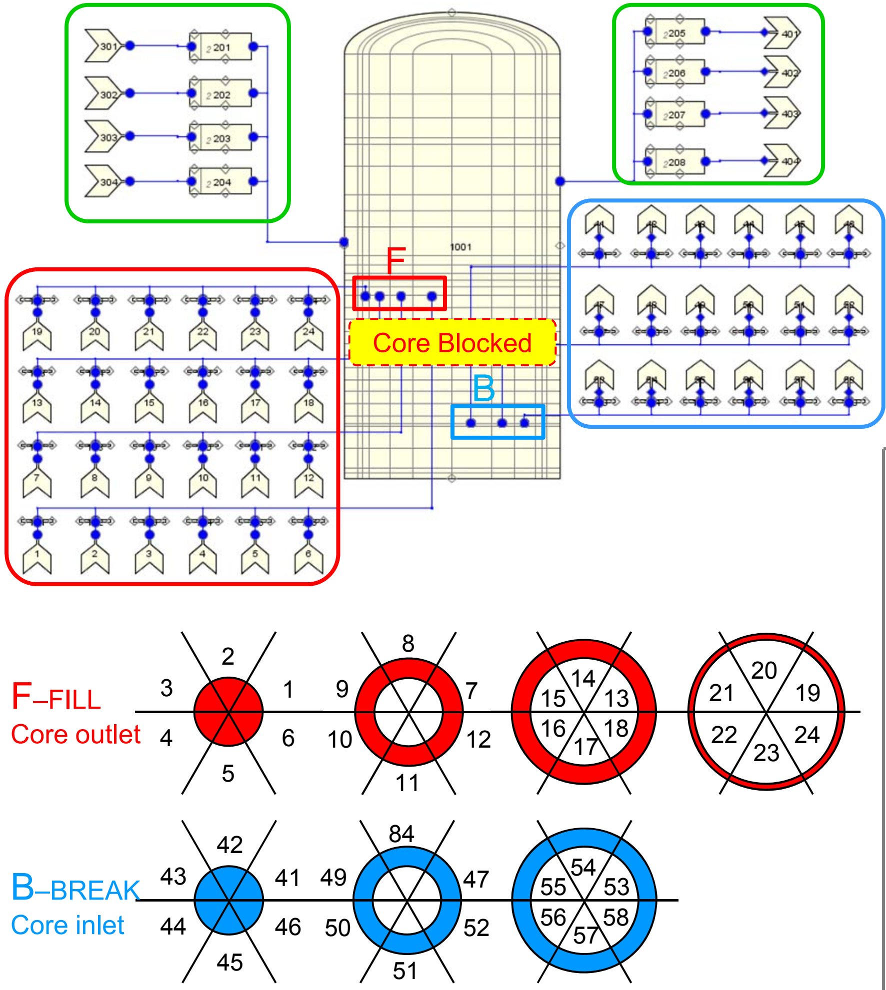


Time, s	T_{cl2}, C/ K	dT	Pin, MPa	ρ, kg/m3	dP MCP1 MPa	Q_2 m3/h	G_2 kg/s
0	268.7/541.85		15.97	784.0	0.609	21670	4718
165	269.3/542.45	0.6	16.12	783.0		21600	4697
340	269.7/542.85	0.4	15.98	782.2		21550	4682
920	269.8/542.95	0.1	15.97	782.0		21540	4678
1800	269.9/543.05	0.1	15.97	781.8	0.609	21530	4676

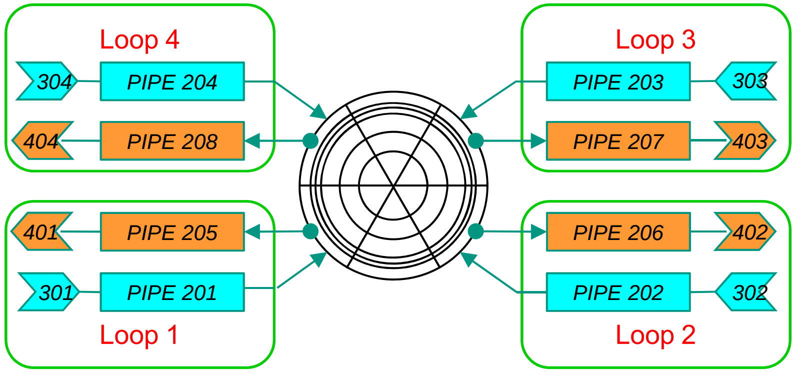


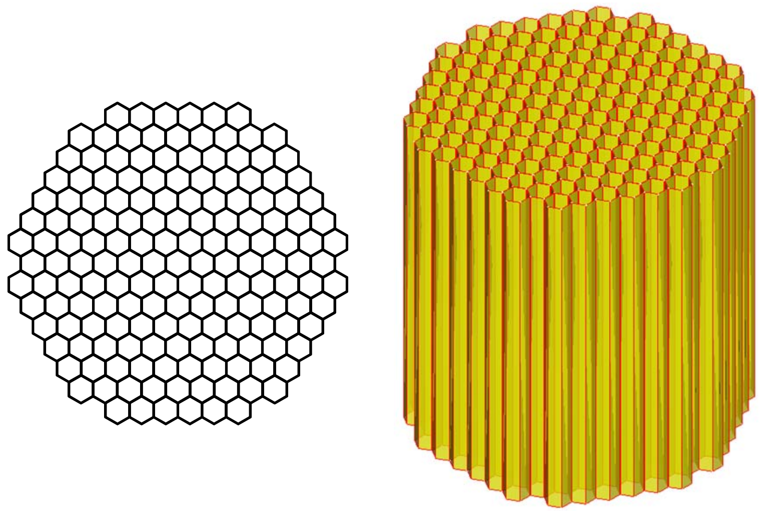


Code Verification: TRACE/SCF-ECI model



TRACE model – TRACE V5.1051





SCF model – Subchanflow3.3

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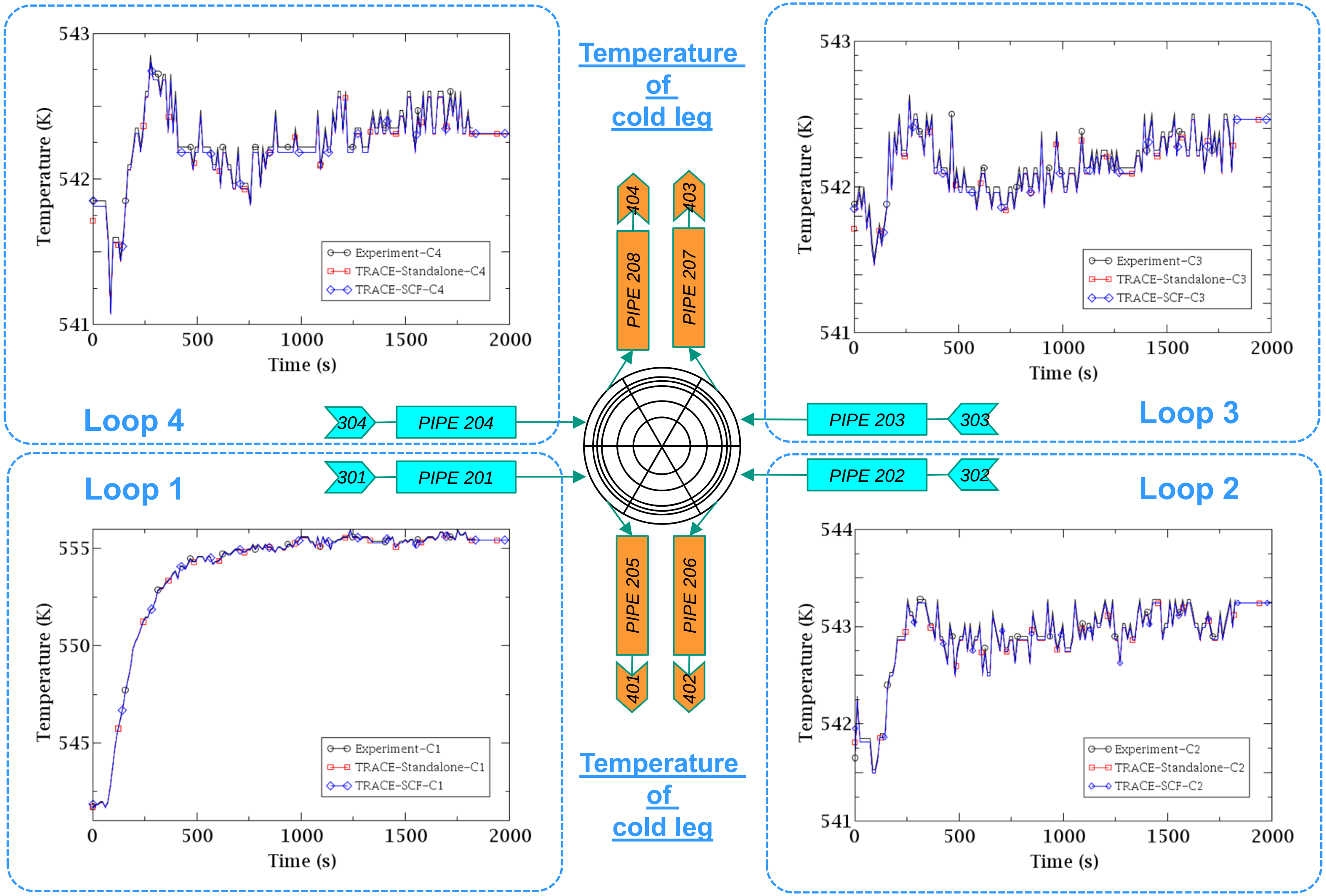
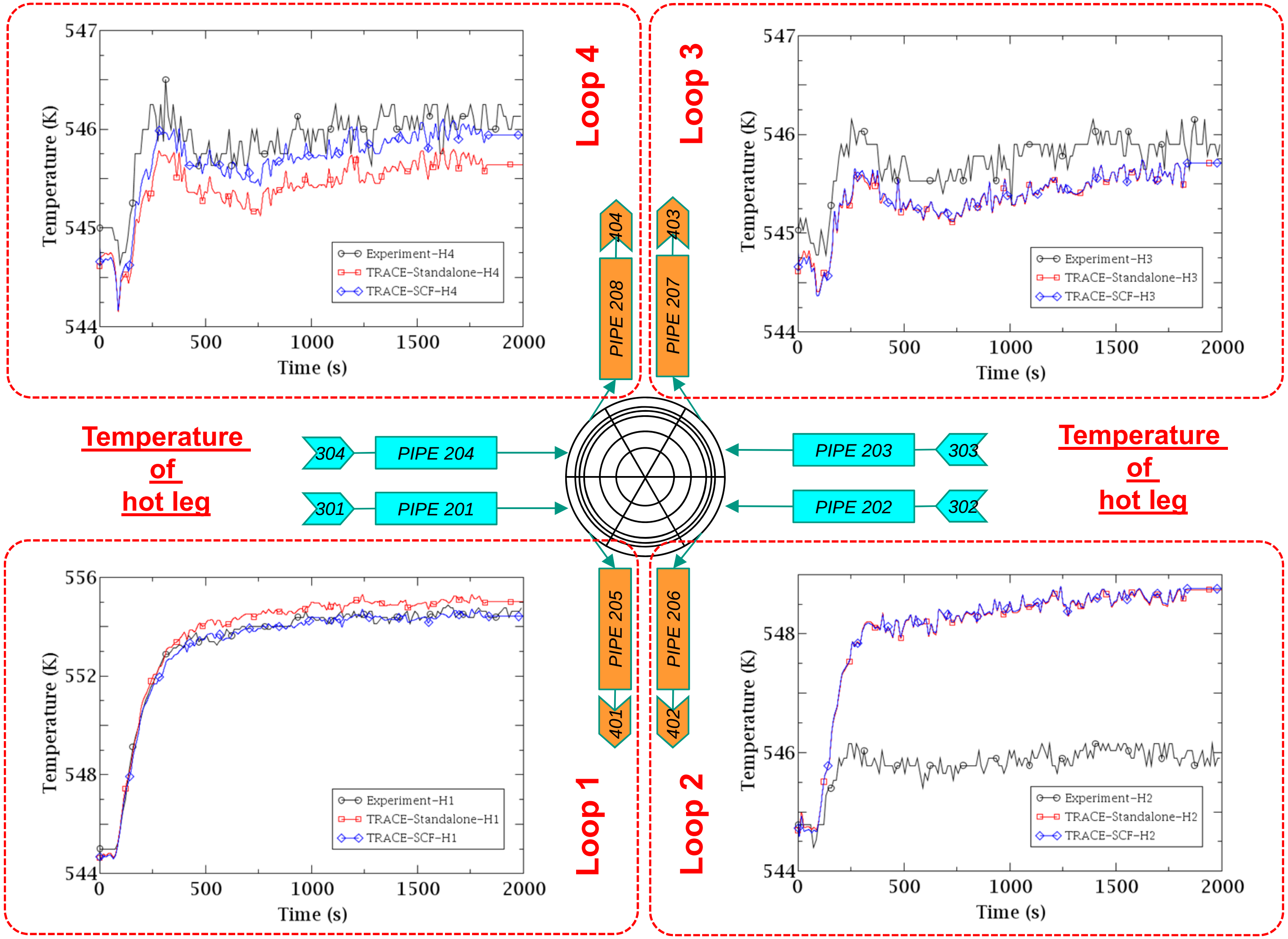
Code Verification: Results (1/4)



Code Verification: Results (2/4)



Code Verification: Results (3/4)

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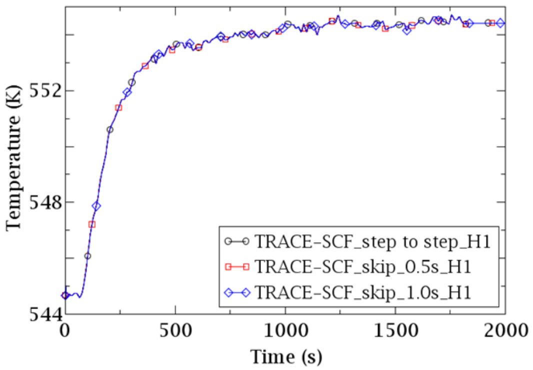
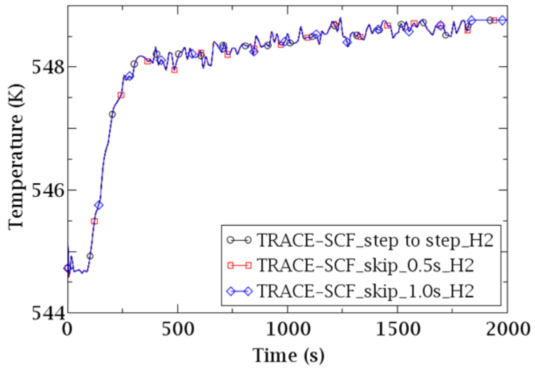
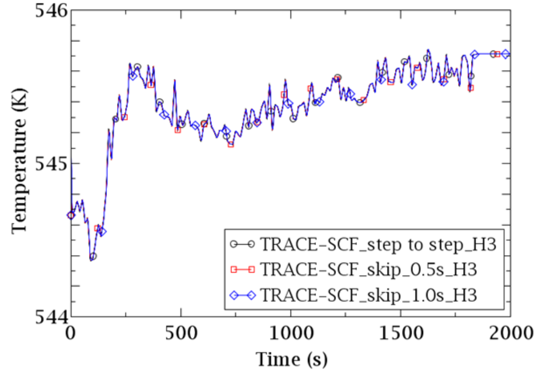
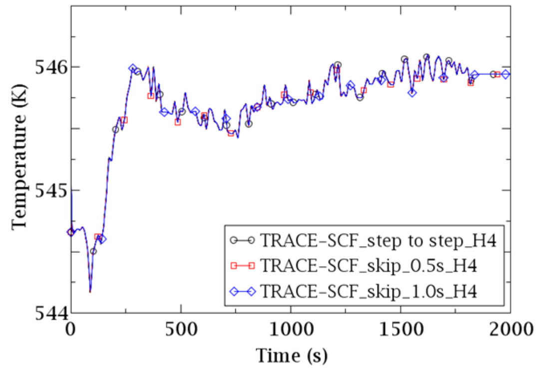






- The result under **timestep skipped** mode with a SCF timestep of **0.5s** is the same with the result of a typical step to step coupling.
- The result under **timestep skipped** mode with a SCF timestep of **1.0s** is also the same with the result of a typical step to step coupling.
- The **timestep 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 (4/4)

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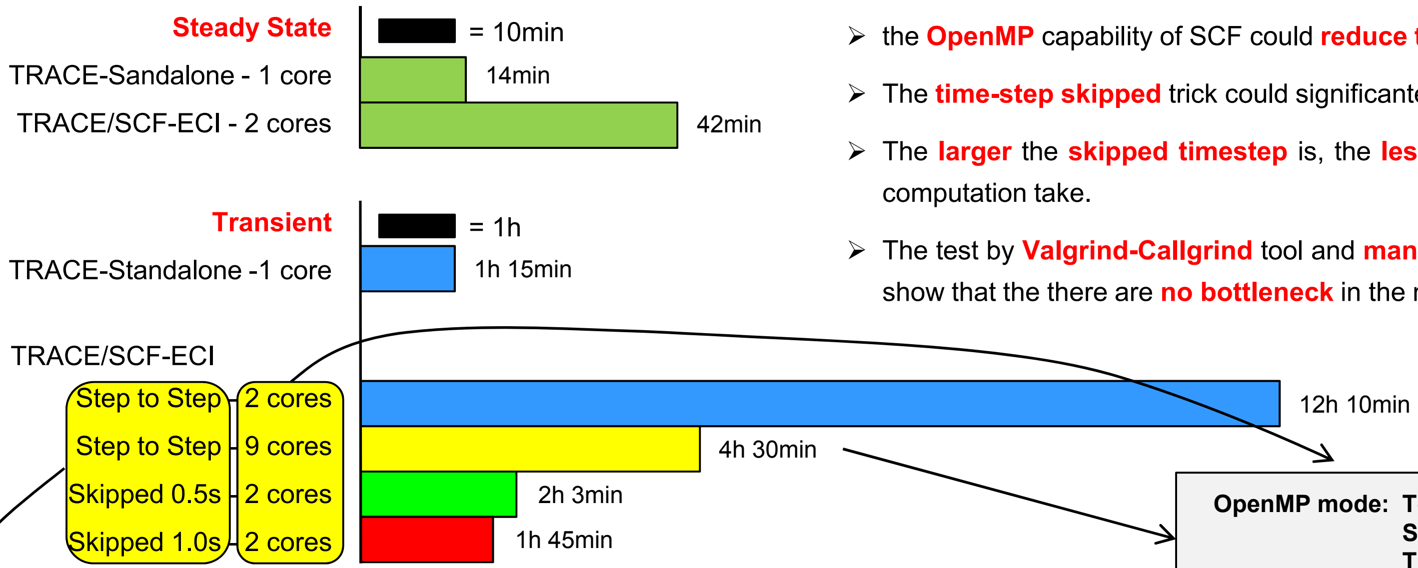
Analyze of the Computing time.

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.

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

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.**

Presentation Outline

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- Backgrounds
- Objective of the Coupling
- Introduction of ECI
- Implementation of the Coupling
- Code Verification
- ***Summary***

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.
- 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.

Thanks for your attention.

Summary

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