FROM RESEARCH TO INDUSTRY

QUALIFICATION OF A CFD CODE FOR REACTOR APPLICATIONS

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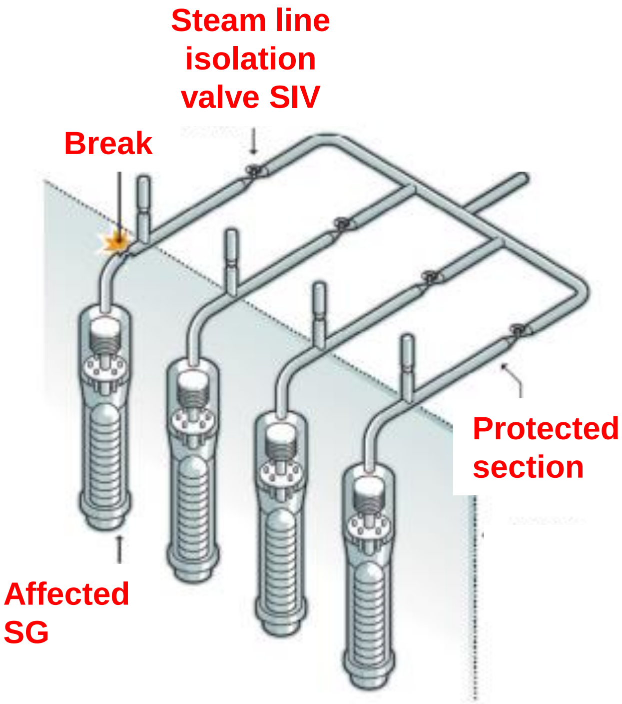
Outline

- Objective: analysis of MSLB accidents
- VVER1000 reactor and the Kozloduy-6 coolant mixing experiments
- PIRT analysis and separate effect validation tests
- The numerical model
- Quantitative analysis of coolant mixing in VVER1000 reactor
- Conclusions and perspectives

Qualification of TrioCFD for simulating MSLB accidents in nuclear reactors

Main Steam Line Break scenario (MSLB)



Break in the main steam-line of a SG

↓

Depressurization of affected SG

↓ Shutdown of the reactor

Isolation of affected SG by closing SIV

↓

Increased cooling of SG secondary side

↓

Transport of cold water in the reactor core

↓ Negative temperature dependency of reactivity

Possible return to criticality

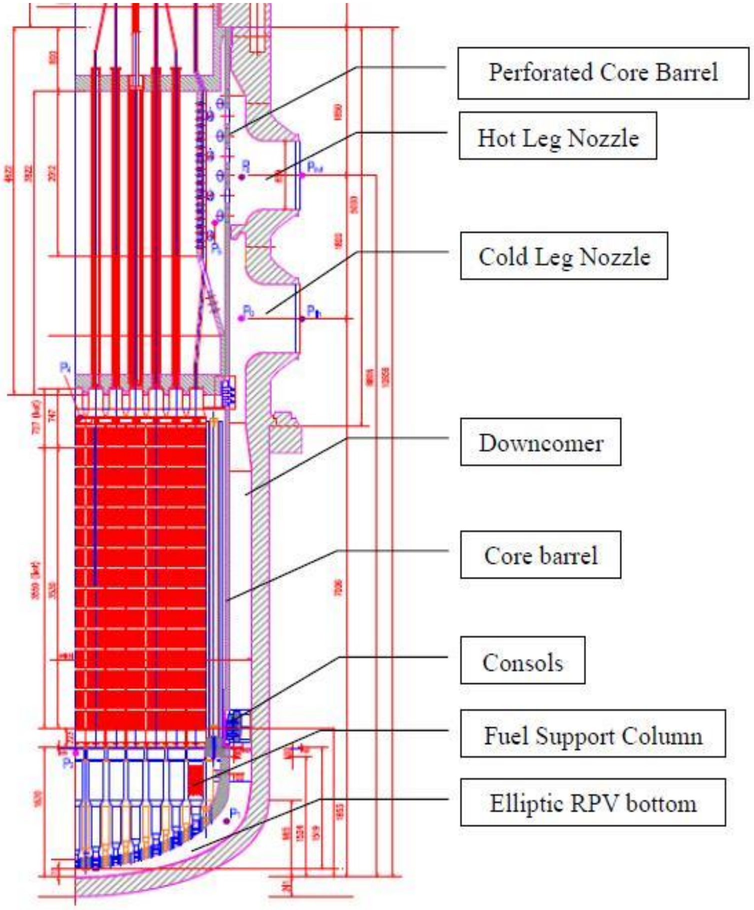
Validation of TrioCFD for fluid mixing in a full scale VVER1000 reactor pressure vessel

- A MSLB accident was simulated by a coolant mixing experiment during the commissioning tests of the unit 6 of the KOZLODUY power plant

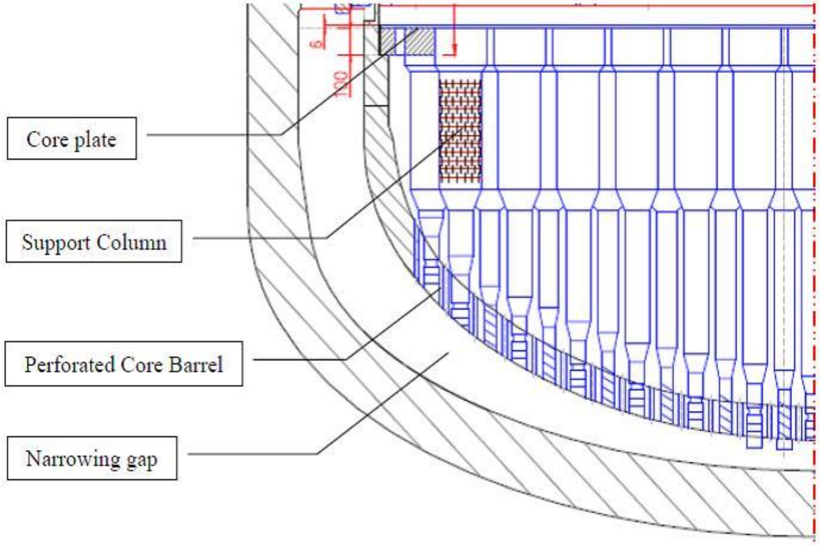
- This coolant mixing experiment was part of an OECD/NEA benchmark of 2003-2006 and CEA has access to the data

Available geometrical data

Design of the reactor



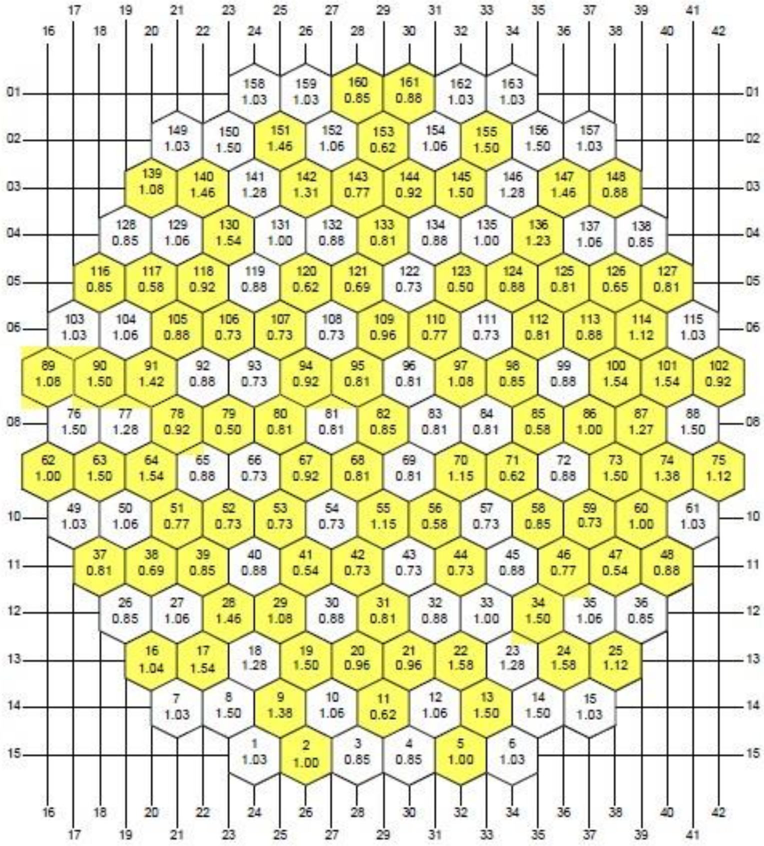
- 4 loops with non-uniform azimuthal distribution of cold leg nozzles (within fabrication tolerance)
- Perforated barrel bottom with1344 flow holes
- Perforated core support columns
- Perforated core barrel in the upper plenum



VVER1000 coolant mixing experiment

- ***Initial state***
    - 4 MCP and 4 SG are in operation
    - Thermal power: 281MW i.e. 9.36% PN
    - Relative temperature rise in the core was calculated from measured cold leg and 95 assembly outlet temperatures
    - Average heat-up over the core: 3.2°C
- ***Transient***
    - Closure of SIV-1 and isolating of SG-1 from feed water
    - Temperature rise in loop n°1: 13.6°C
- ***Final state***
    - Measured core outlet temperature stabilizes about 1800s after closing SIV-1

Measured relative assembly temperature rise in the initial state



Turbulence modelling & boundary conditions

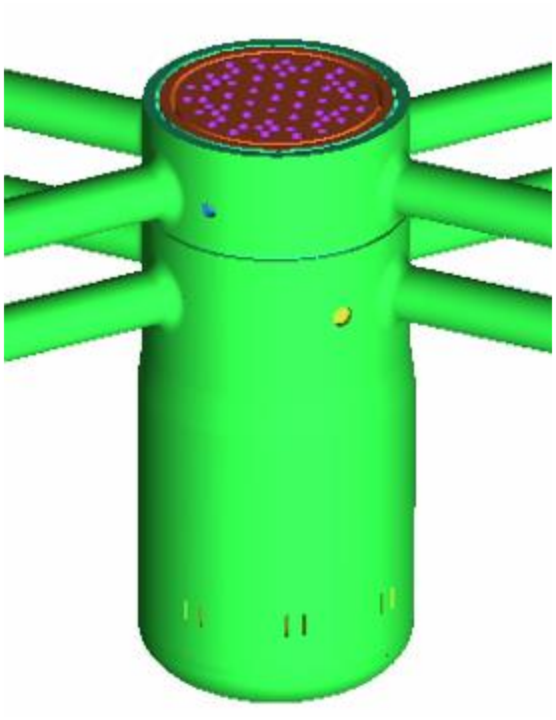
- Boussinesq hypothesis to calculate the Reynolds stresses:

$$-\overline{u_i'u_j'} = \upsilon_T \cdot \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \frac{2}{3} k\delta_{ij}$$

- Standard k-ε model to evaluate ν_t:

$$\upsilon_t = C_\mu \frac{k^2}{\varepsilon}$$

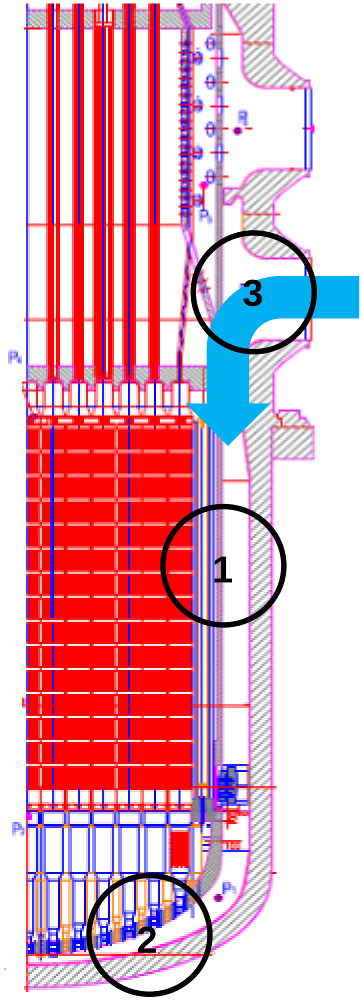
$$\frac{\partial k}{\partial t} + \frac{\partial (U_j k)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\upsilon + \frac{\upsilon_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] - \varepsilon + P \qquad \frac{\partial \varepsilon}{\partial t} + \frac{\partial (U_j \varepsilon)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\upsilon + \frac{\upsilon_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{\varepsilon 1} P \frac{\varepsilon}{k} - C_{\varepsilon 2}\frac{\varepsilon^2}{k} \qquad P = -\overline{u_i'u_j'}\frac{\partial U_i}{\partial x_j}$$



- <u>Boundary conditions</u>
  - Dirichlet conditions at inlets of 4 cold legs
  - Dirichlet conditions at outlets of 3 hot legs
  - Von Neumann condition at one of hot leg outlet
  - Adiabatic walls and logarithmic wall functions at all solid structures

Loop no.	Velocity (m/s)		Temperature (℃)	
	Cold leg	Hot leg	Cold leg	Hot leg
1	10.71	-10.71	282.2	282.2
2	10.69	-10.69	269.9	269.9
3	10.71	-10.71	269.0	269.0
4	10.89	P=0	269.2	dT/dn = 0

PIRT – Physical analysis of the mixing test



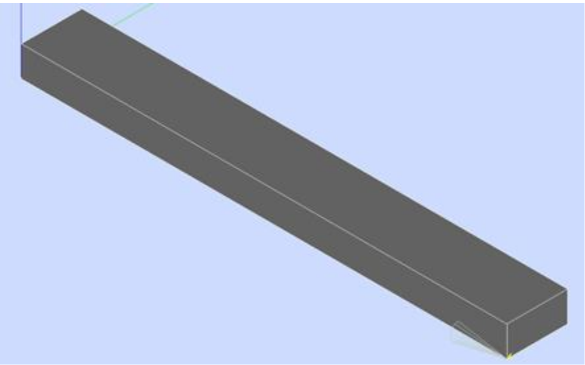
- PIRT (Phenomena Identification and Ranking Table) analysis:
  - To bring into focus dominant physical phenomena
  - To define single effect validation test cases

- For VVER1000 Coolant Mixing Transient:
  - Figure of merit: Pressure drop
  - Dimensionless number: Re number
  - Aimed precision of simulation: 10%

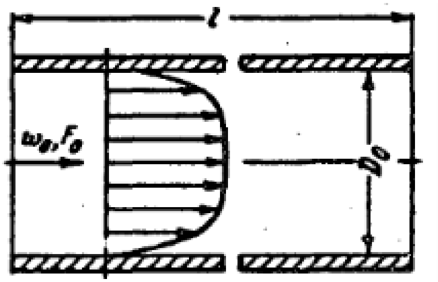
Separate effect test	**Physical phenomena**	**Reynolds Number**
1 – Downcomer	Channel flow	$31.0 \cdot 10^6$
2 – Perforated plates	Flow through orifices	$4.5 \cdot 10^6$
3 – Cold leg nozzles	Baffle impact	$70.0 \cdot 10^6$

Separate effect study – Downcomer

Geometry of channel flow model



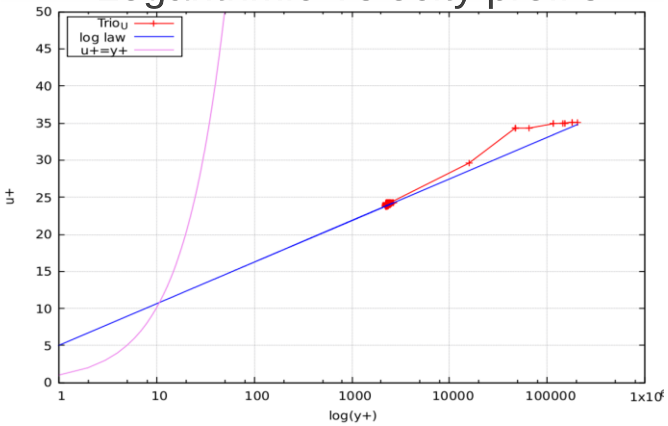
Friction pressure loss in channels (Re>4000):



$$\frac{\Delta P}{(\rho w_0^2/2)} = \frac{l}{D_0 \cdot (1.8\log \mathrm{Re} - 1.64)^2}$$

$$\mathrm{Re} = \frac{w_0 D_0}{\nu}$$

Logarithmic Velocity profile



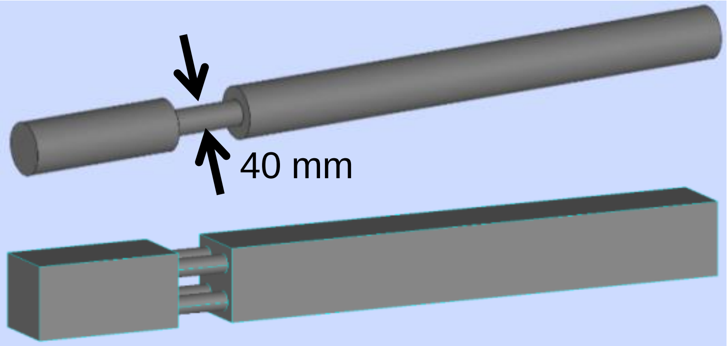
Pressure gradient reference value: 0.370 kPa/m

Grid size (mm)	**y+**	**Pressure gradient (kPa/m)**	**Relative error (%)**
7	3772	0.336	7.69
3	1563	0.320	12.08
1	509	0.368	1.09

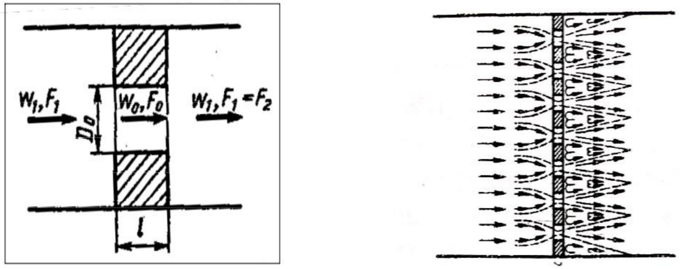
- Consequence for the reactor scale calculation:
  - A maximum error of 10% is intended
  - A y^+ value of 1000 is the target for the mesh refinement in tubes and channels

Separate effect study – Perforated plates

Geometry of 1 orifice- and 4 orifice model



Pressure drop coefficient for orifices:



$$\frac{\Delta P}{\rho w_1^2/2} = \left[0.5\left(1-\frac{F_0}{F_1}\right)^{0.75} + \tau\left(1-\frac{F_0}{F_1}\right)^{1.375} + \left(1-\frac{F_0}{F_1}\right)^{2} + \lambda\frac{l}{D_h}\right]\left(\frac{F_0}{F_1}\right)^2$$

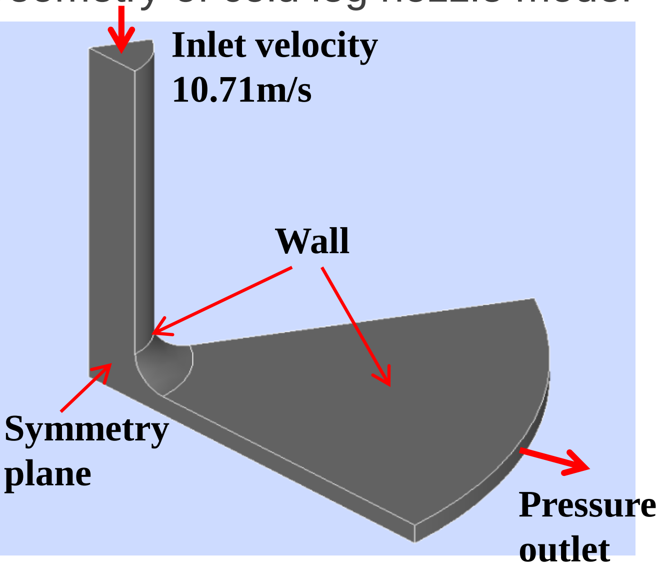
Reference value: 80.798 kPa (one orifice) and 91.16 kPa (four orifices)

Mesh size of orifice (mm)	**Pressure loss (kPa) of one orifice model**	**Relative error (%)**	**Pressure loss (kPa) of four orifice model**	**Relative error (%)**
8	135,2	67.33	-	-
6	114,5	41.71	-	-
5	103,4	27.9	-	-
4	89,43	10.62	101,1	10.9
3	83,95	3.9	96,56	5.9

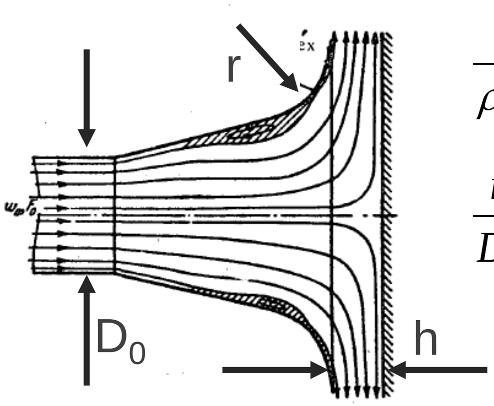
- Consequence for the reactor scale calculation:
  - A maximum error of 10% is intended
  - The orifices should be meshed with mesh sizes of at least 4mm

Separate effect study – Cold leg nozzle

Geometry of cold leg nozzle model



Pressure drop coefficient of the baffle impact:



$$\frac{\Delta P}{\rho w_0^2/2} = f\left(\frac{h}{D_0}, \frac{r}{D_0}\right)$$

$$\frac{r}{D_0} = 0.3 \qquad \frac{h}{D_0} = 0.2$$

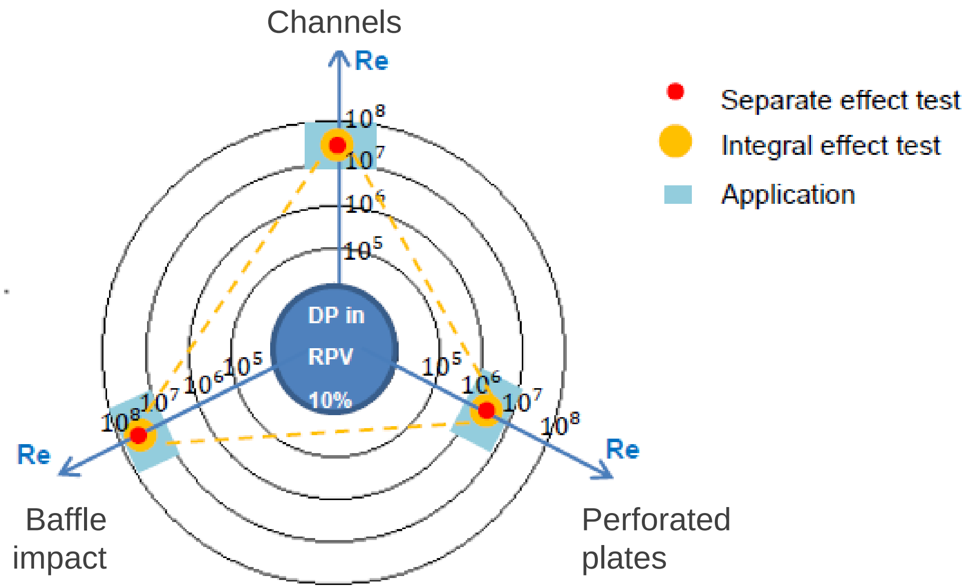
Reference value: 21.58 kPa

Mesh size (mm)	Pressure loss (kPa)	Relative error (%)
20 pure tetra	9.676	50.50
12 pure tetra	8.988	58.35
10 tetra with prism layers	8.748	59.46

- Consequence for the reactor scale calculation:
  - Non-isotropic turbulence is not correctly calculated by k-ε model
  - Errors are expected for the flow in the cold leg nozzles

Definition of the validation domain

Validation domain of separate effect studies, VVER1000 coolant mixing experiment and further reactor applications



Separate Effect studies -> PIRT
Integral Effect study -> VVER1000 experiment
Applications -> MSLB scenario

Strengths of the approach:

- Each separate effect test covers one important physical phenomenon of the application domain,
- One integral test covers all the dominant physical phenomena of the application domain,
- The Re numbers of separate effect studies and integral test are consistent with the application domain.

Weaknesses of the approach:

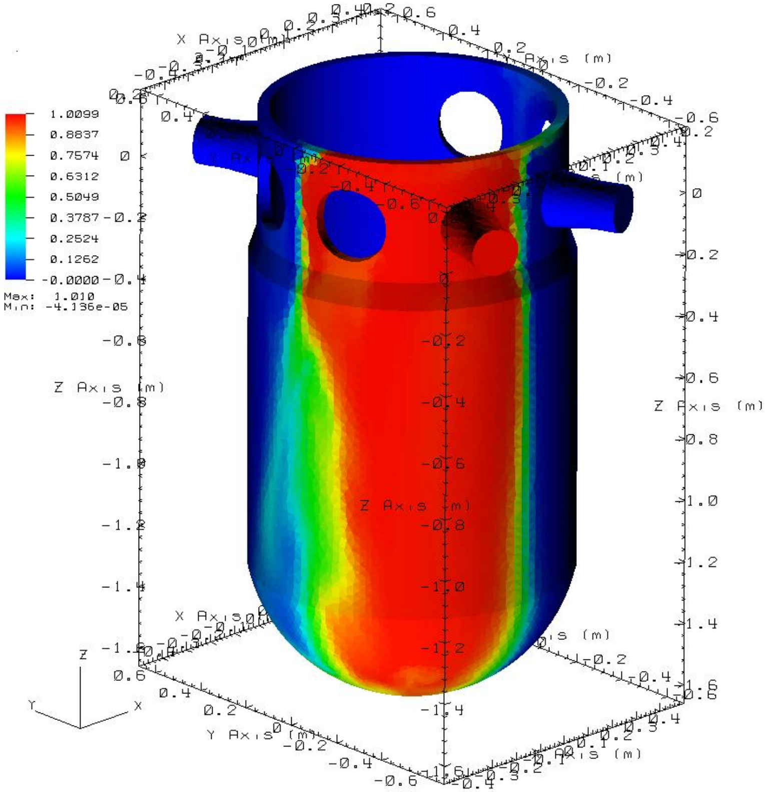
- More separate test cases are needed to validate other phenomena than ΔP,
- More integral tests are needed coupling two or three physical phenomena.

Extension of the validation domain

Realized integral tests oriented to other physical phenomena than ΔP

ROCOM test facility

1:5 scale primary circuit of a KONVOI reactor



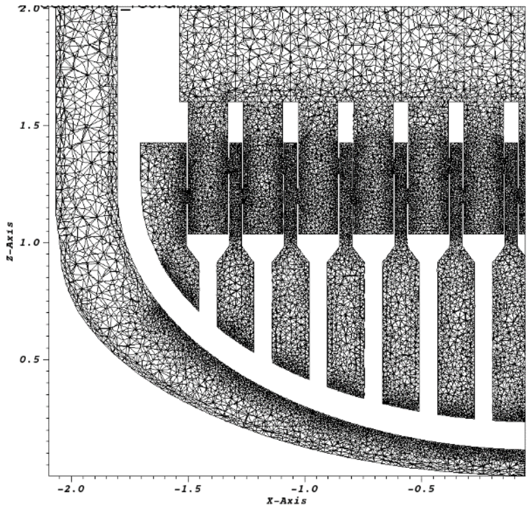
<u>Main inconvenience:</u>

It is not possible to respect the reactor scale Reynolds Number in small scale experiments.

- Re reactor 1.000.000
- Re experiment 50.000

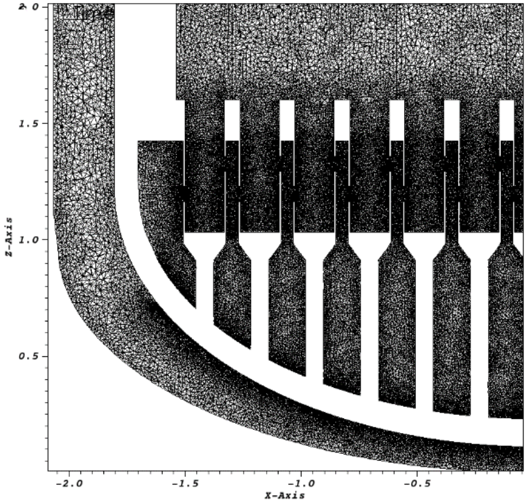
Tetra meshing of the flow domain

50 million meshes (ICEM)

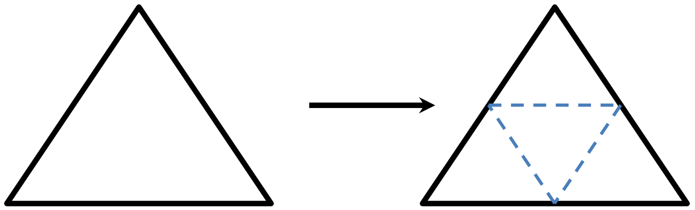


- Explicit modelling of important structures:
  - perforated plate,
  - core support columns,
  - upper plenum (guide tubes, perforated walls)

350 million meshes (TrioCFD)



- Isotropic refinement by TrioCFD
  - 1 tetrahedral element is cut into 8 new ones



- CPU on TGCC CURIE:
  - 50 million meshes
    1024 processor cores
    36h execution time
  - 350 million meshes
    9984 processor cores
    72h execution time

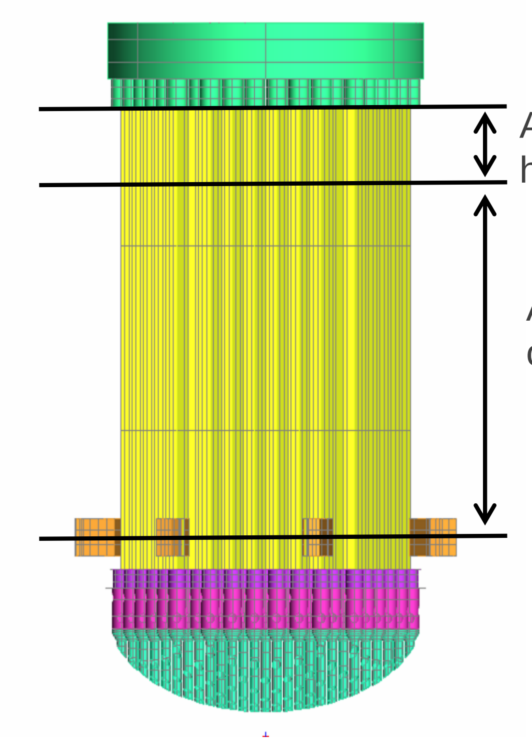
Modelling of the reactor core (active part)

- Volume porosity: $\phi = \frac{V_{fluid}}{V_{total}} \approx 0.54$
- Thermal source:
  - Constant normalized core power distribution
  - Proportional to the relative temperature rise in the initial state
- Additional flow resistance for tube bundles:

$$\vec{\nabla} P_{TB} = -\rho \cdot C_{fa} \frac{\left|\vec{u}_a\right|}{2 \cdot D_h} \vec{u}_a - \rho \cdot C_{ft} \frac{\left|\vec{u}_t\right|}{2 \cdot D_e} \vec{u}_t$$

$C_f = a \mathrm{Re}^{-b}$ with $\mathrm{Re} = \frac{UD}{\nu}$

Direction	a	b	U	D
Axial	0.316	0.25	$\lvert\vec{u_a}\rvert$	D_h
Transverse	4.03	0.27	$\lvert\vec{u_t}\rvert$	D_e

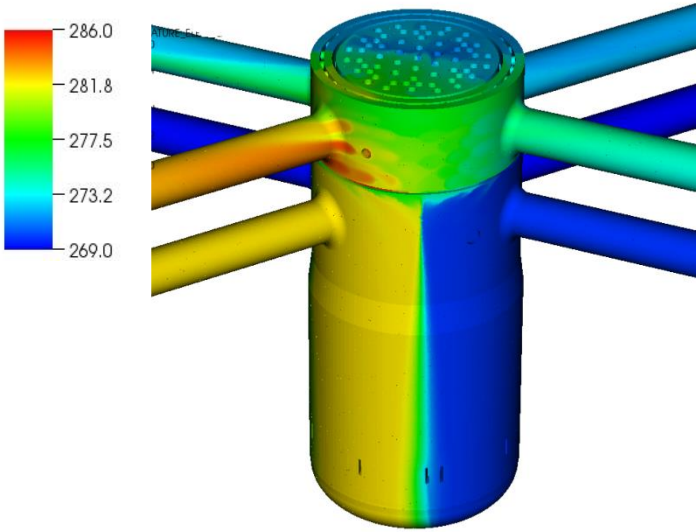


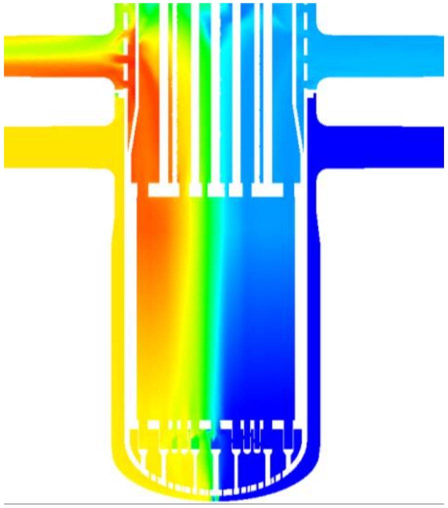
Assembly heads

Active core

Temperature distribution in the reactor

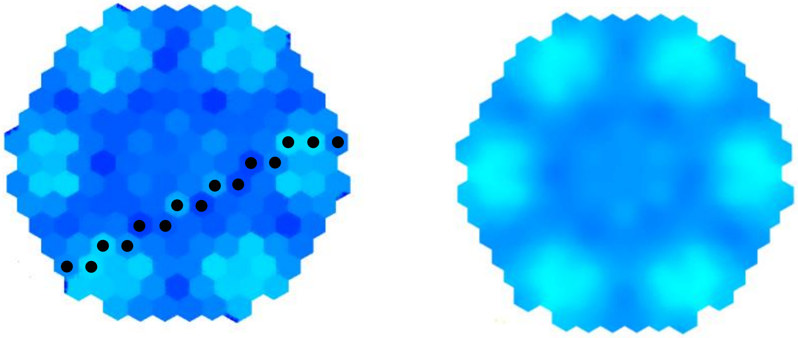
Temperature distribution of the RPV

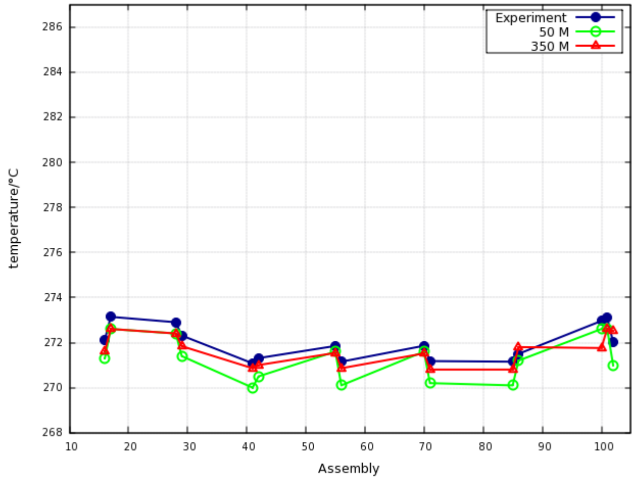




Core outlet before closing of SIV-1

Experiment TrioCFD

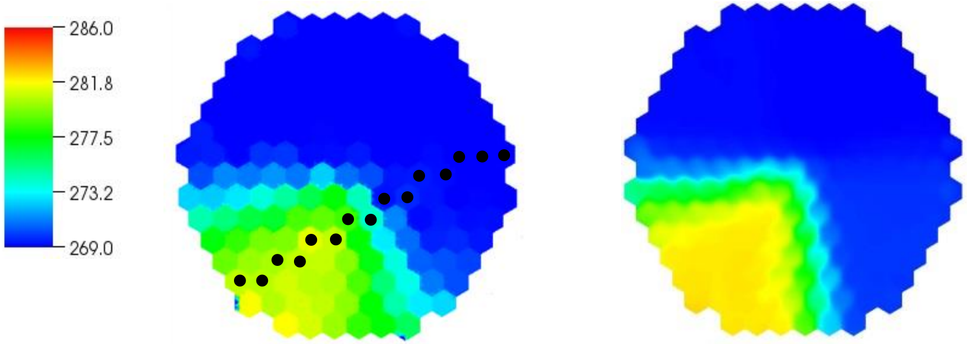


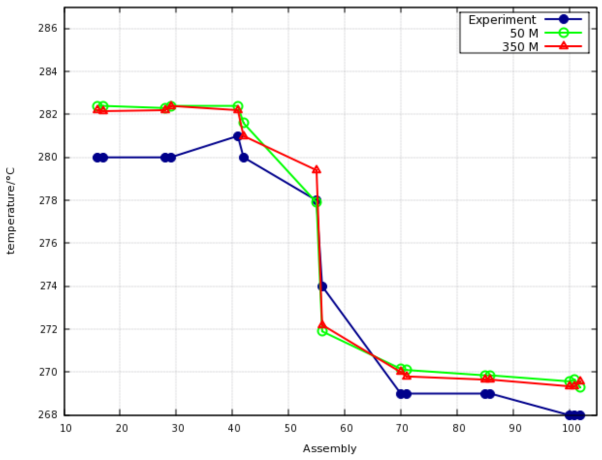


- Clear distinction of the region affected by cold leg n° 1,
- The temperature at the core outlet before the closure of SIV-1 is very well predicted.

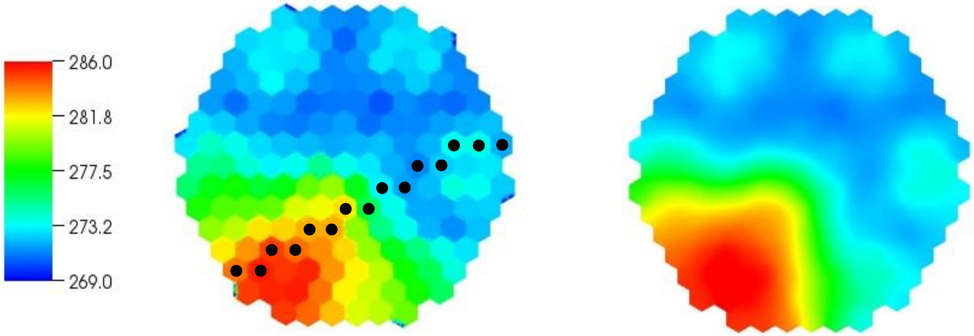
Temperature distribution in the reactor

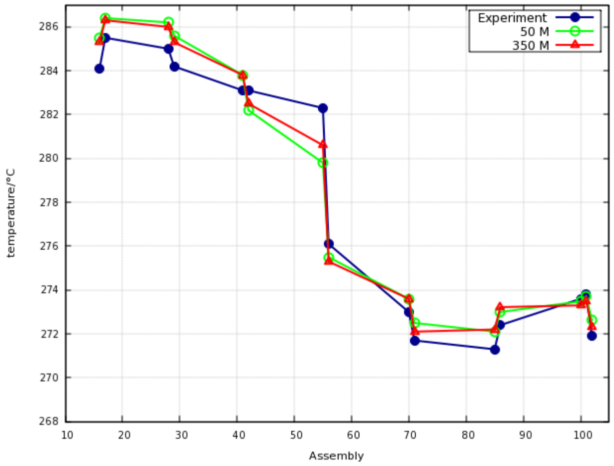
Core inlet after closing SIV-1


Experiment
TrioCFD



Core outlet after closing SIV-1

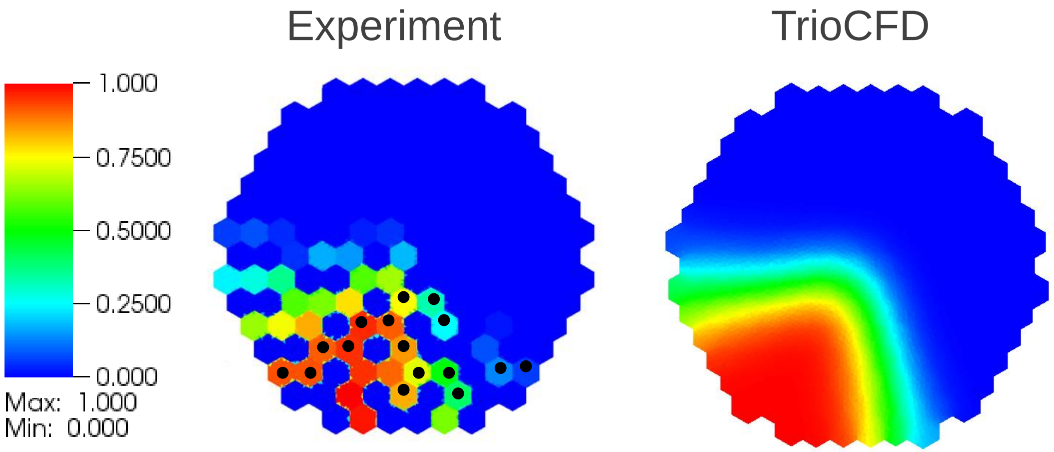




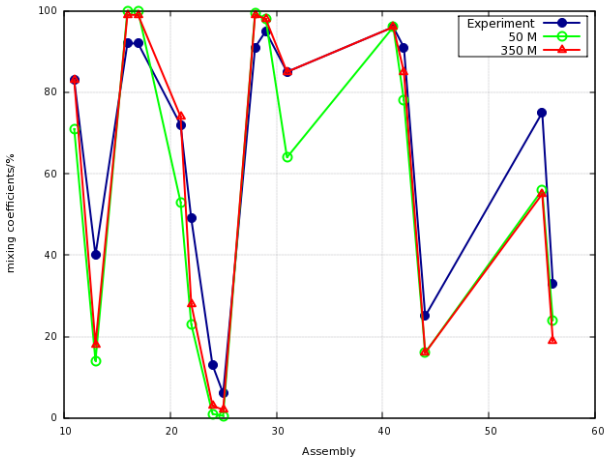
- Good representation of the temperature at core outlet (error globally < 1°C)
- Slight overestimation of the temperature maximum at core inlet (error < 2°C)
- Doubs on the estimation of the experimental core inlet temperature

Mixing coefficients

Loop-to-assembly mixing coefficients at core outlet for cold leg n° 1


Experiment TrioCFD

Mixing coefficient in %



- Loop-to-assembly mixing coefficients are globally well predicted

Loop-to-loop mixing coefficients from cold leg i to hot leg j:

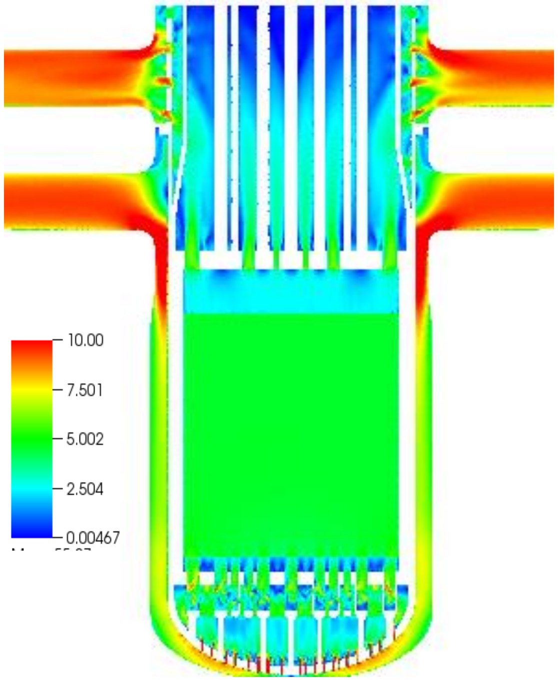
$$K_{ij} = \frac{flow\ from\ loop\ i\ to\ j}{total\ flow\ in\ loop\ j}$$

Kij	Experiment	Calculation
K12	0.12	0.1183
K21	0.10	0.09852
K41	0.16	0.1572
K32	0.14	0.1391

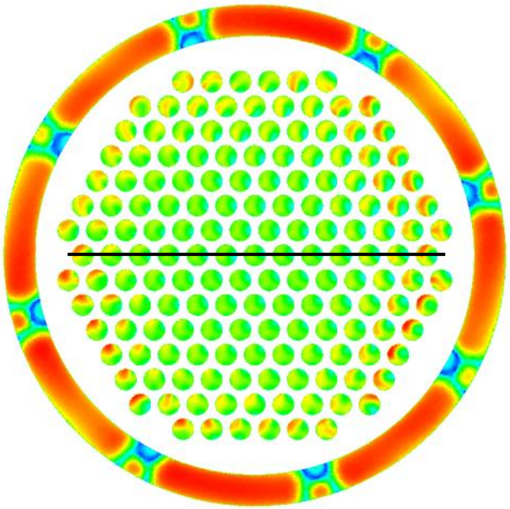
- Loop-to-loop mixing coefficients are very well predicted

Velocity distribution

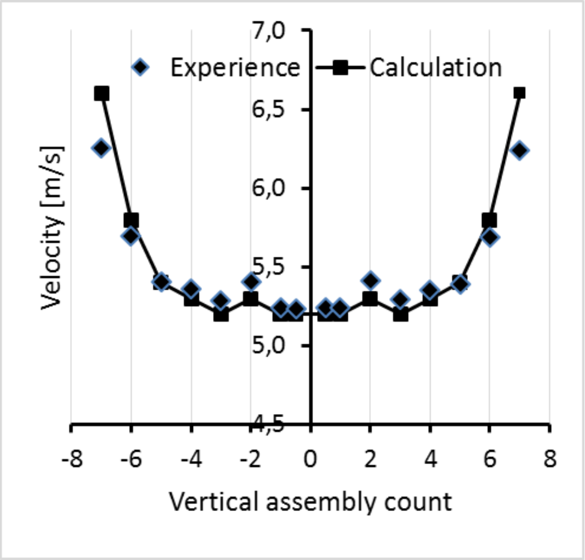
Vertical cut through RPV



Horizontal cup through the core support plate



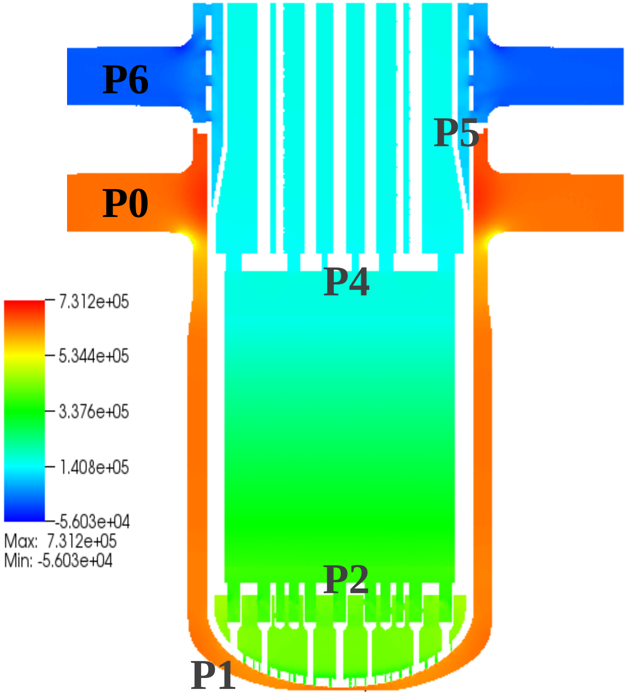
Radial velocity distribution



- Important gradients are observed in the region of perforated plates and walls,
- Velocity is constant in the active core region (porous media);
- Higher velocities are predicted in the periphery of the core, which was also observed in the Kozloduy-5 experiment.

Pressure losses in the RPV

Dynamic pressure in the RPV in kPa



Difference kPa	Design	CFD
P0-P6	380	602
P0-P1	120	22
P1-P2	90	258
P2-P4	140	209
P4-P5	30	63
P5-P6	10	50

- Significant overestimation of the calculated pressure losses (6 bar instead of 3.8 bar),
- However, design pressure losses are not real pressure losses (GIDROPRESS),
- Most important overestimation of pressure loss through perforated plates and walls (all holes calculated with sharp edges)
- Improvement needed for core pressure loss correlation

Conclusions and perspectives

- **Conclusions**

  The CFD model reproduces well the:
  - Temperature distribution at the outlet of the reactor core
  - Loop-to-assembly and loop-to-loop mixing coefficients
  - Core inlet velocity profile

  However:
  - Significant overestimation of calculated pressure loss, especially in perforated plates

- **Perspectives**
  - Further mesh refinement of perforated plate, walls, support columns (information on the form of the holes are needed)
  - Better prediction of pressure loss at the cold leg nozzle with better adapted turbulent models
  - Improved pressure loss correlation are needed for the core region

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