Thermal balance modelling of the ADELINE power ramp test device using a coupled NEPTUNE_CFD/SYRTHES approach

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Summary

1. **Introduction to power ramp test devices**

2. **Methods for rodlet power determination through water loops thermal balance**

3. **Validation of the coupled code methodology using ISABELLE-1 power ramp tests at the OSIRIS reactor:**

    - **Rodlet power determination reproducing ETALISA-1 qualification experiment**

4. **3D coupled model development of ADELINE device for the Jules Horowitz Reactor:**

    - **Preliminary evaluation of the thermal balance**

    - **Optimization of thermal balance measurement through thermocouples placement**

5. **Conclusions and perspectives**

1. Introduction to power ramp test devices

Power ramp devices scope

Power ramps are performed in research reactors to test nuclear fuel **for scientific purpose and safety** (fuel behaviour, fission gas release, fuel technological limit, fuel partial melting, etc.).

Power ramp devices are used to **perform ramps in a controlled environment** at a specific **fuel power** determined from calorimetric measurements of a water loop.

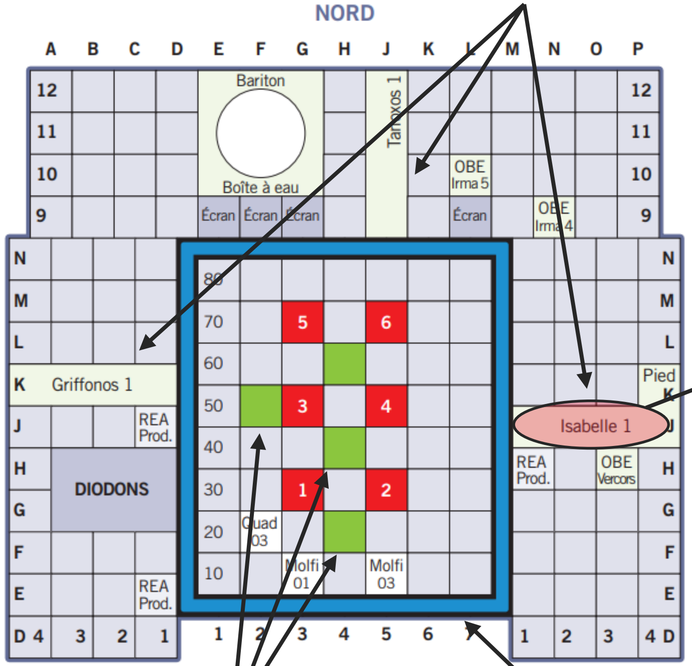
The fuel **power determination** requires stringent **accuracy ~5-6%** which is **difficult to evaluate, validate and improve**.

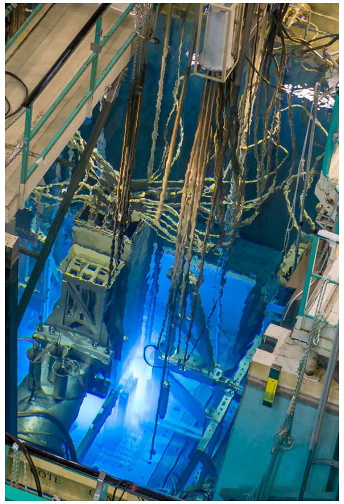
Objective: provide and validate a novel approach to optimize the rodlet power assessment through the device thermal balance calculations.

Example of power ramp device: ISABELLE-1 (Osiris)

OSIRIS reactor schematic drawing

Displacement experiments devices

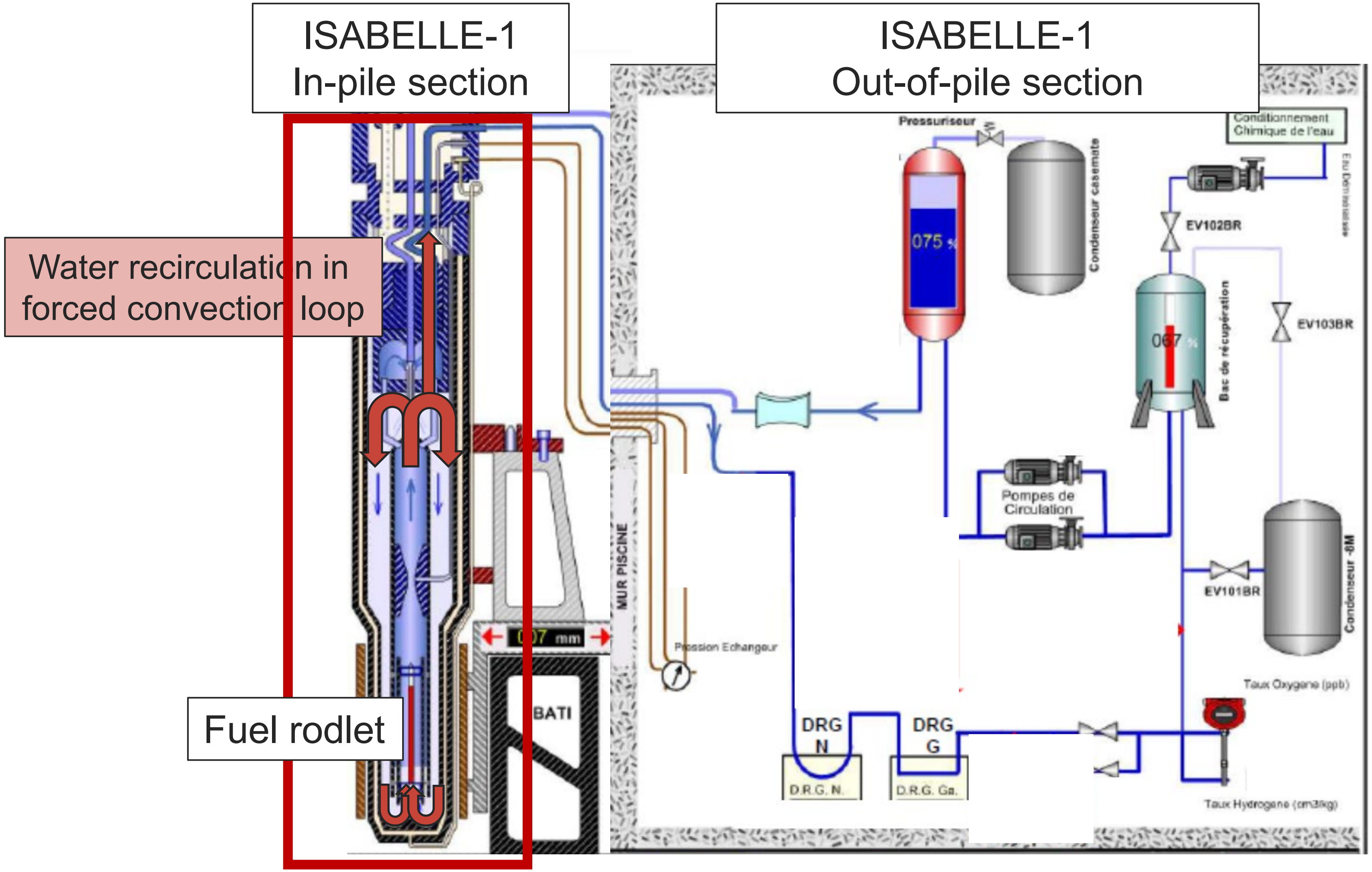




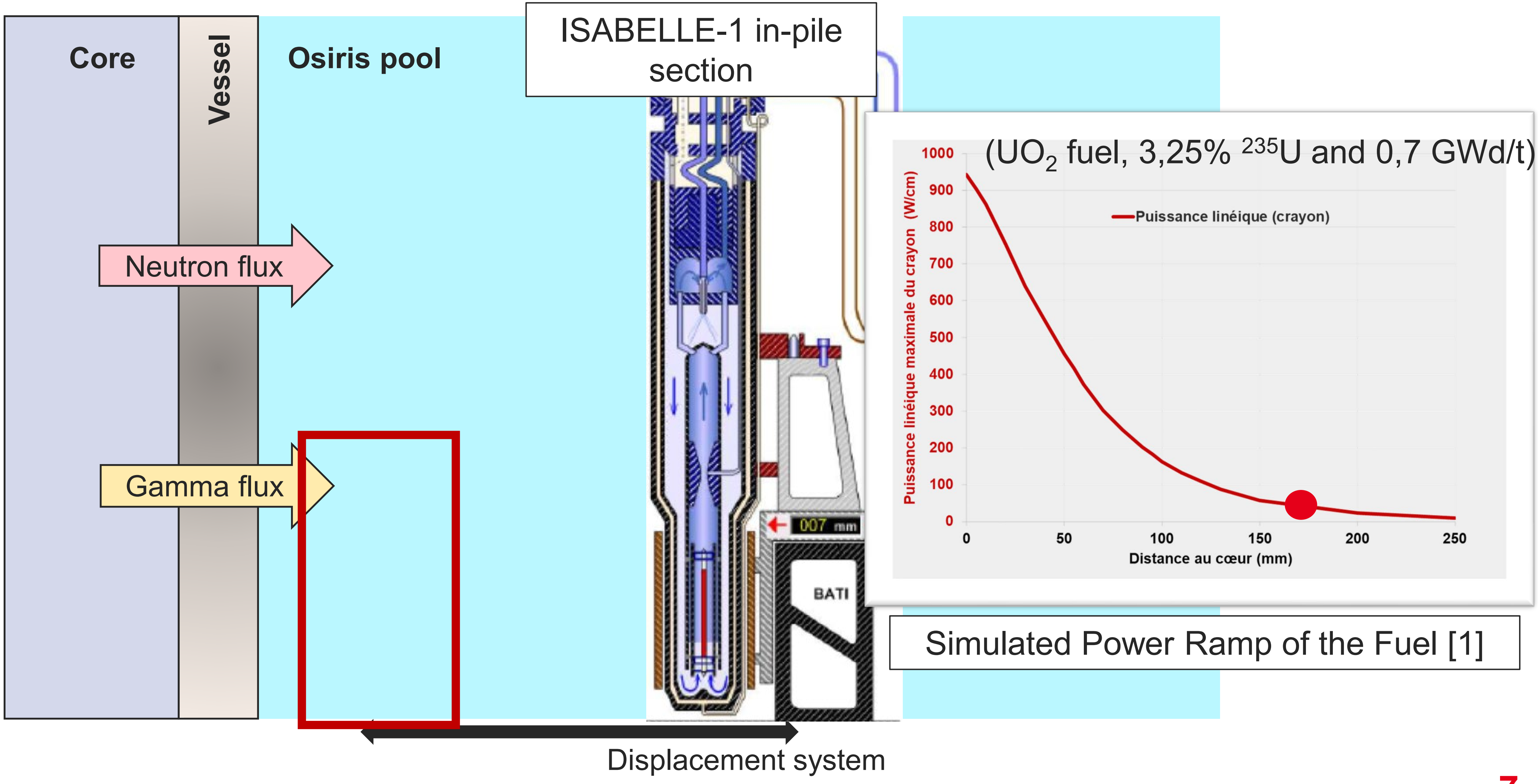
In-core experiments

Core vessel

Example of power ramp device: ISABELLE-1 (Osiris)

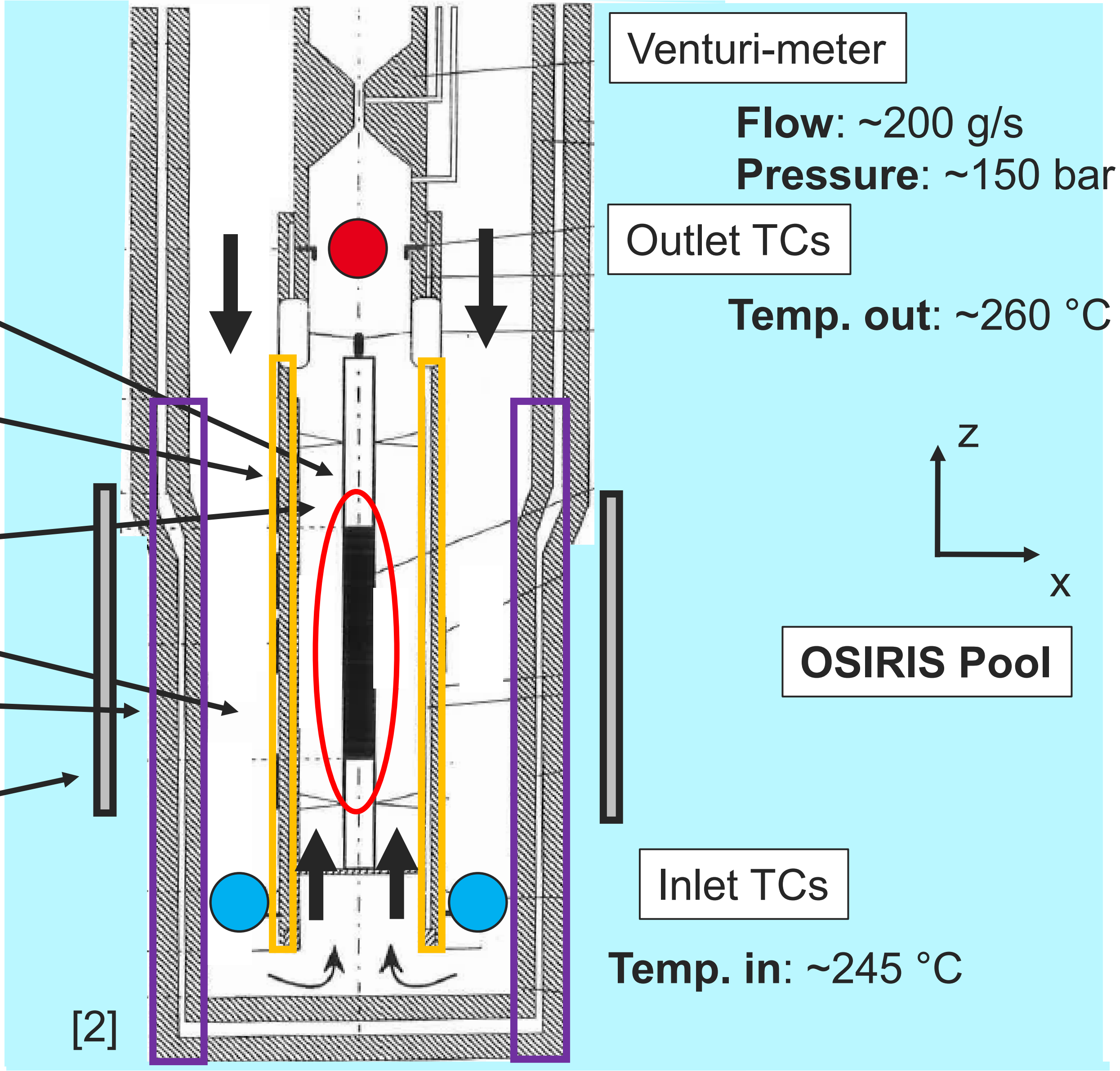


Displacement power ramps



ISABELLE-1 in-pile section description

Lower in-pile section of the device is **heavily instrumented** to calculate the thermal-balance.



2. Methods for rodlet power determination through water loops thermal balance

Total thermal power determination

The **average power** (P_{Th}) of the fuel rodlet is determined from the thermal balance of the system.

The link between ΔT measurement and P_{Th} is not easy to assess and depends **on multi-physics parameters:**

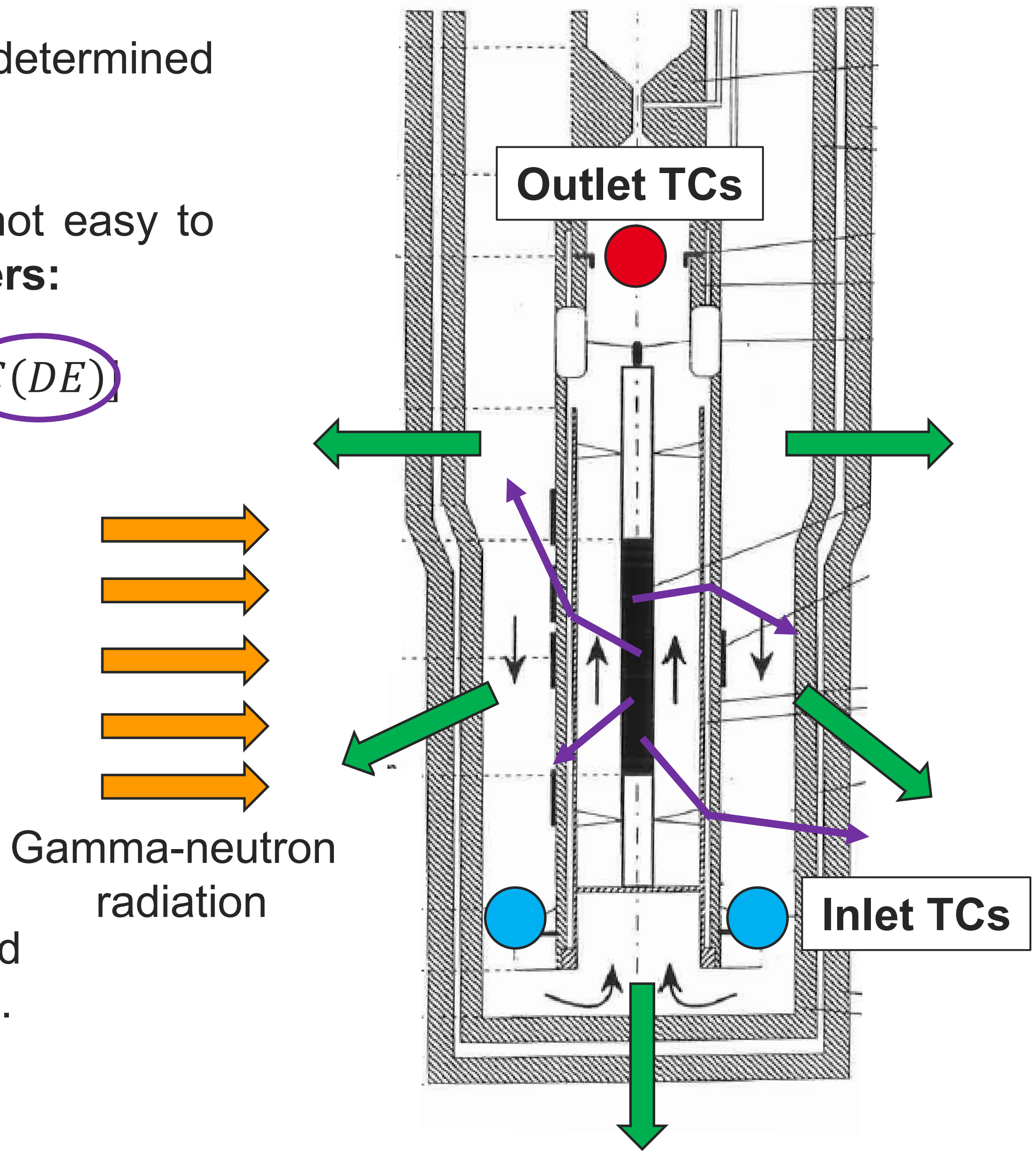
(1) $$P_{Th} = [Q\ C_p(T_{out} - T_{in}) + P_{Loss} - P_{\gamma}] \times [1 - C(DE)]$$

Q: flow rate
C_p: water heat capacity
$(T_{out} - T_{in})$: temperature variation
P_{Loss}: heat losses
P_{γ}: gamma-neutron heating
$C(DE)$: partial gamma deposition correction factor

(2) $$P_l = \frac{1}{F}\frac{P_{Th}}{L}$$

F: Shape factor
L: rodlet length.

The **maximum local linear power** P_l is calculated thanks to post-irradiation gamma scan of the rodlet.



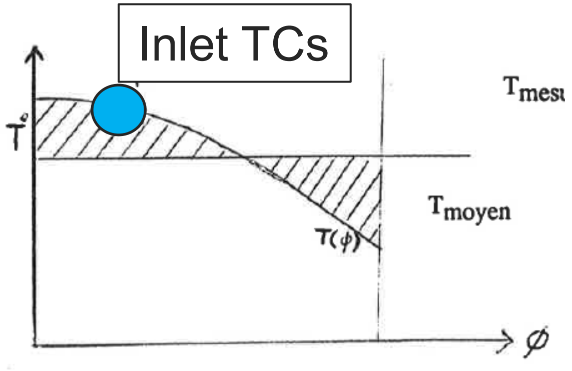
REFLET code for thermal balance calculations

1D code called **REFLET** was developed to solve ISABELLE-1 thermal balance considering radial heat transfer in **equilibrium conditions**.

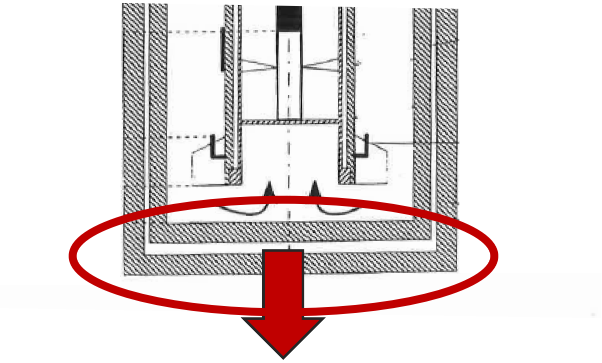
Advantages:
- Relies on well known heat exchange physics models relative fast complete the calculations (matrix solver).
- Experimentally validated (ETALISA-1, etc).

Disadvantages:
- Only radial description (1D)
- Single phase flow assumption.
- **Correction factors were used to take into account**

1/ the radial temperature profile in the inlet channel



2/ the bottom heat losses



Computational fluid dynamics modelling

Computational fluid dynamics can be used to **simulate** the thermal-hydraulic behaviour of water loop in power ramp test devices.

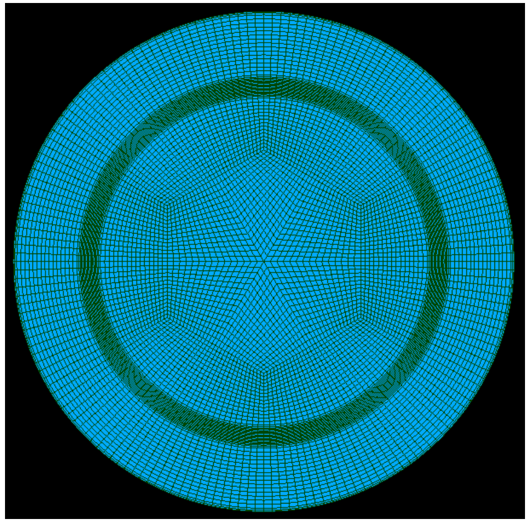
Advantages

- 3D simulation and high accuracy potentially achievable thermal balance.
  →Comprehensive simulation of the thermal-hydraulics of axial and bottom heat losses, radial profile of water temperature at the inlet thermocouple location, state of water (monophasic, diphasic), etc.
- Graphical visualization of the fluid behaviour (turbulence or two phase distribution) both for steady or transient conditions.

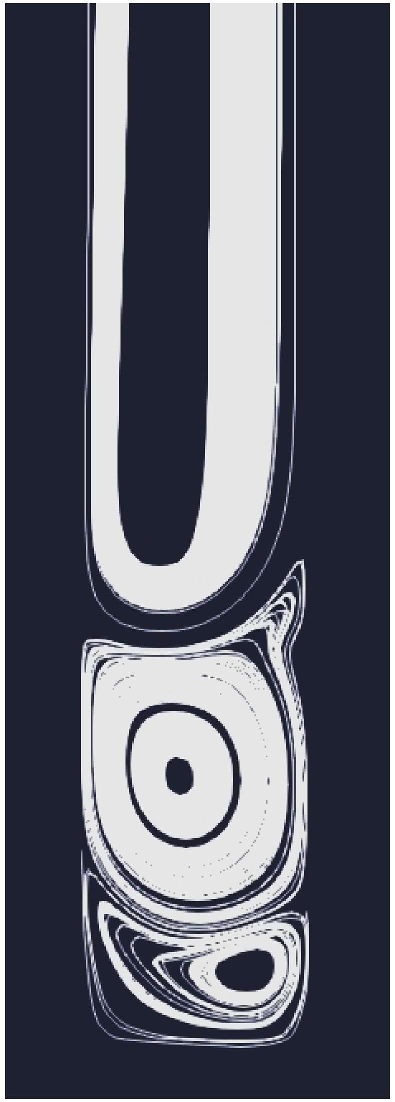
Potential issues

- Careful choices of the mesh, the simplifications, physics models and initial/boundary conditions.
- Computational limitations.
- Challenging to understand model inaccuracies if no other benchmark parameters are available.

Cross-section



Vertical slice

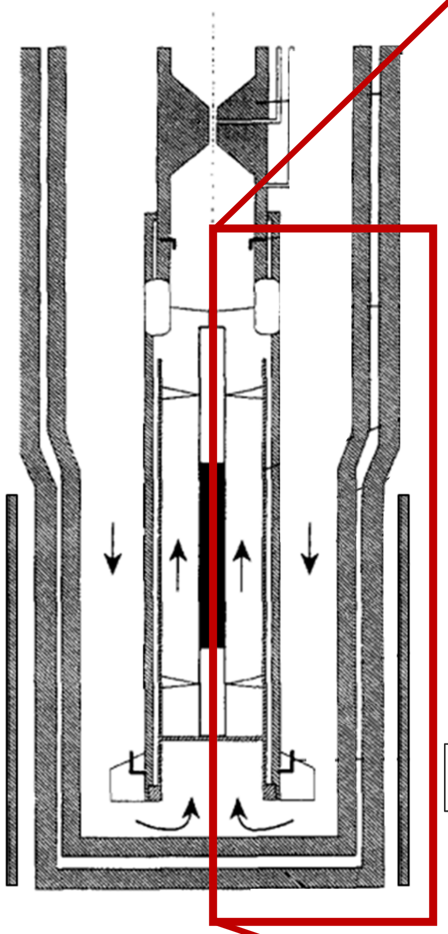


ISABELLE-1 preliminary 2D CFD modeling

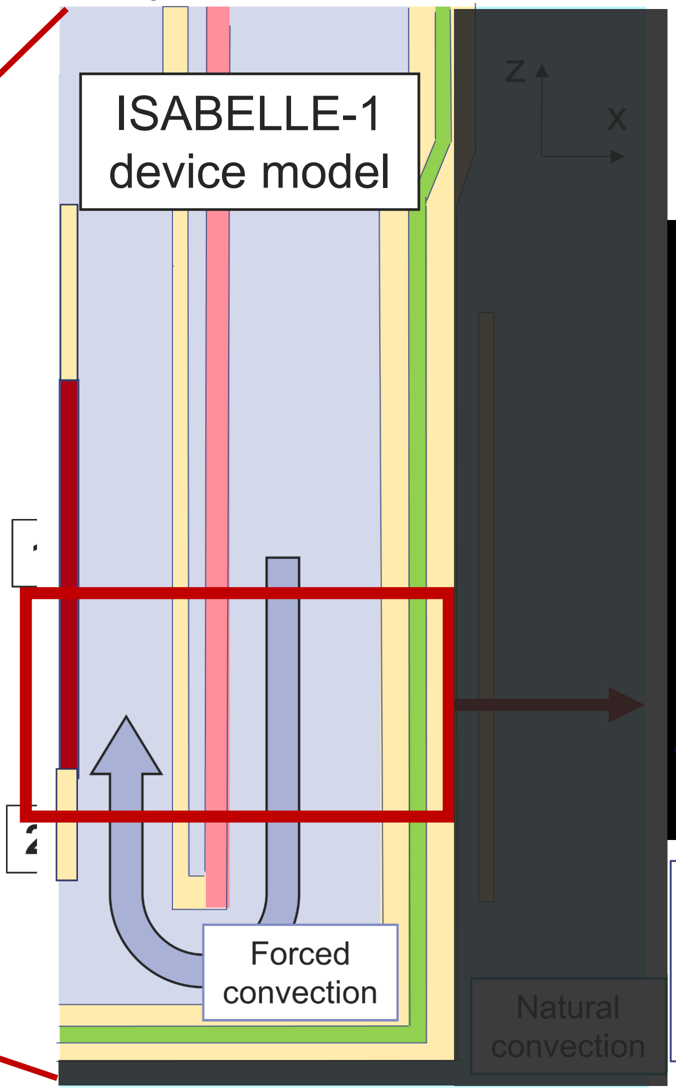
3. Validation of coupled code method using ISABELLE-1 power ramp tests at OSIRIS reactor

Simulation geometry and meshing

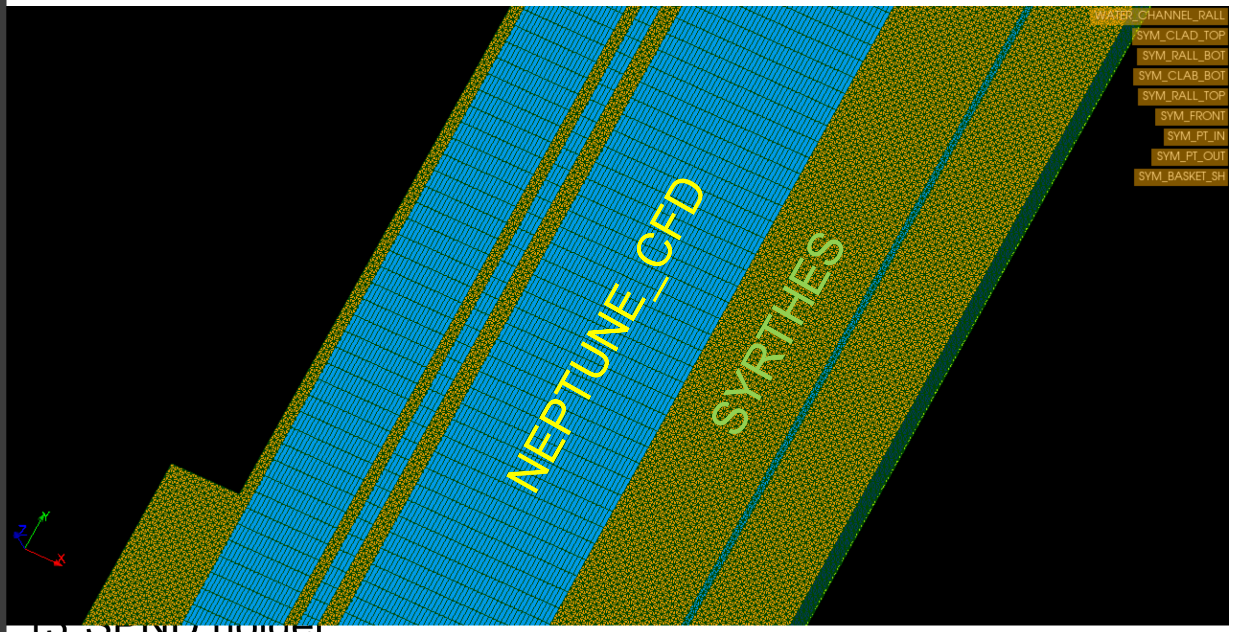
Isabelle-1 drawing



Coupled model slice sketch

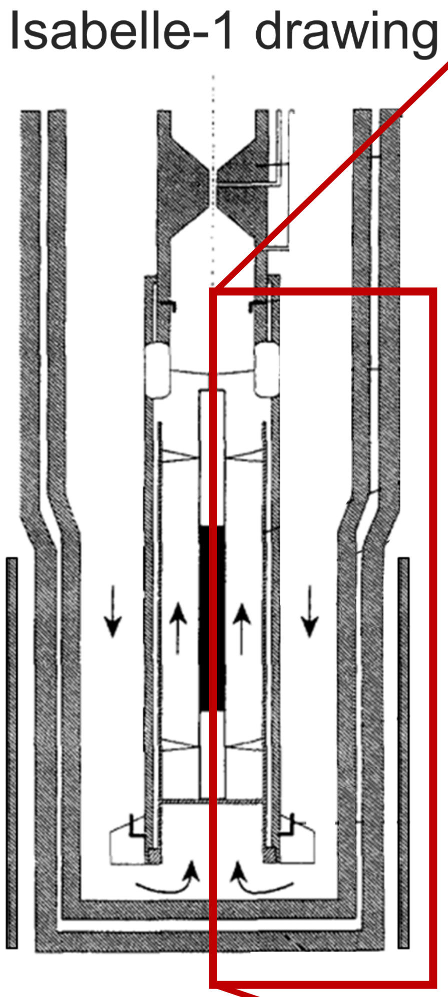


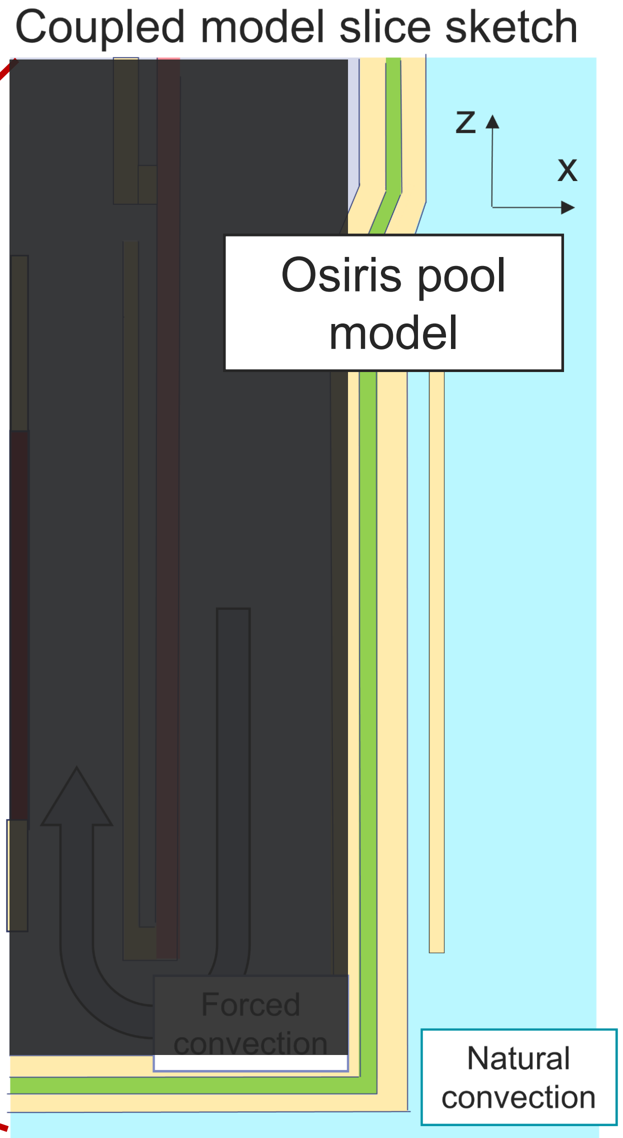
SALOME mesh of ISABELLE-1 till the PTs boundary with the pool.



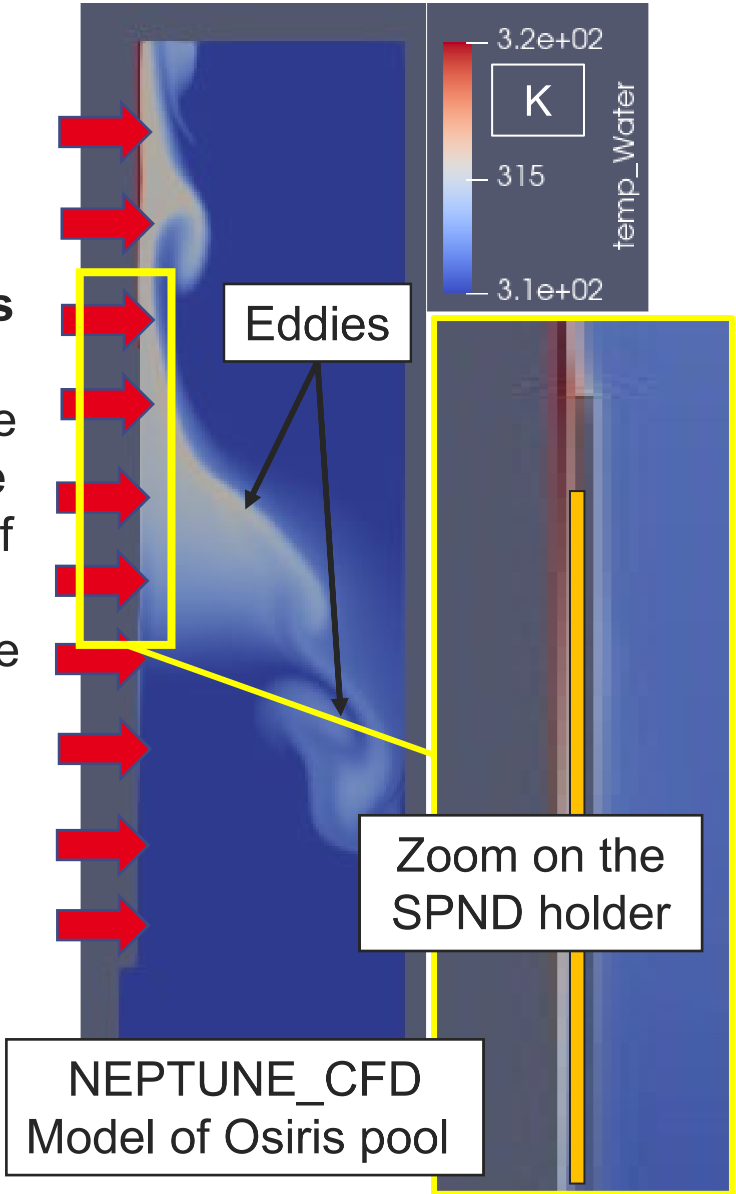
Material properties depending on temperature from Cathare2 [3]

Simulation geometry and meshing





The two models are coupled offline to provide a more accurate representation of the **boundary conditions** in the device model.



ISABELLE-1 qualification experiment ETALISA-1

Reference experiment for qualification of power determination of ISABELLE-1.

- A **fresh UO_2 fuel rodlet** was irradiated at a maximum power of about 400 W/cm for about 12 days.
- After irradiation gamma spectrometry, dosimetry and isotopic composition measured were performed.
- On-line **measured data available** in the Osiris general XGDEX database available at DEC and previous thesis work.

ETALISA-1 results comparison between different methods:

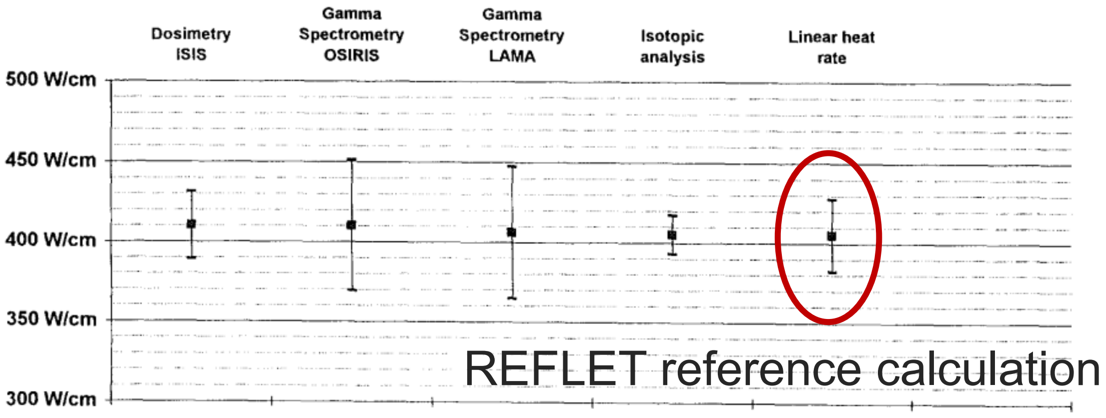
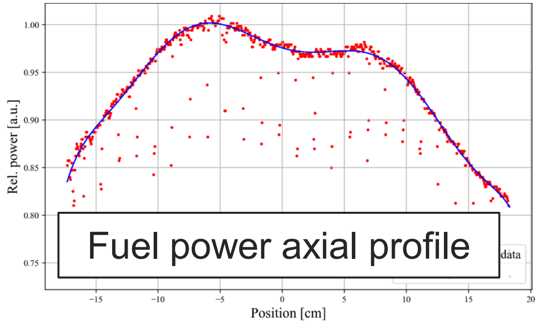
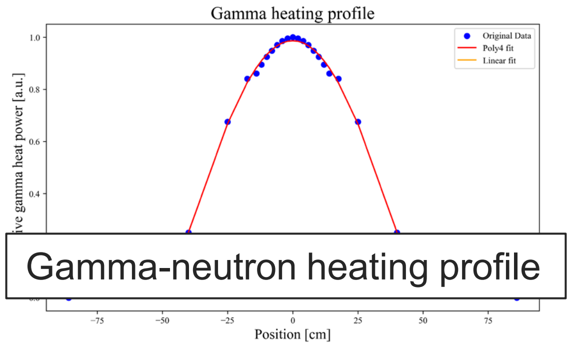


Fig. 5. Inter-laboratory comparison of power measurements.

[2]

ISABELLE-1 digital twin input parameters:





[4]

Additional conditions:

Parameter		ETALISA-1
Pressure [bar]		148.87
Average T [°C]	TC in	239.9
	ΔT	13.80
	Pool	31
Specific radiation heating [W/g]	H_2O	0.81
	Zy4	1.03
	SS316	0.86
Inlet flow ETALISA-1 [kg/s]		0.21

Determination of ETALISA-1 fuel rodlet power

The proposed methodology aims <u>to calculate the fuel power based on the input conditions of ETALISA-1 experiment.</u>

Once introduced the relevant phenomena in the simulations such as:

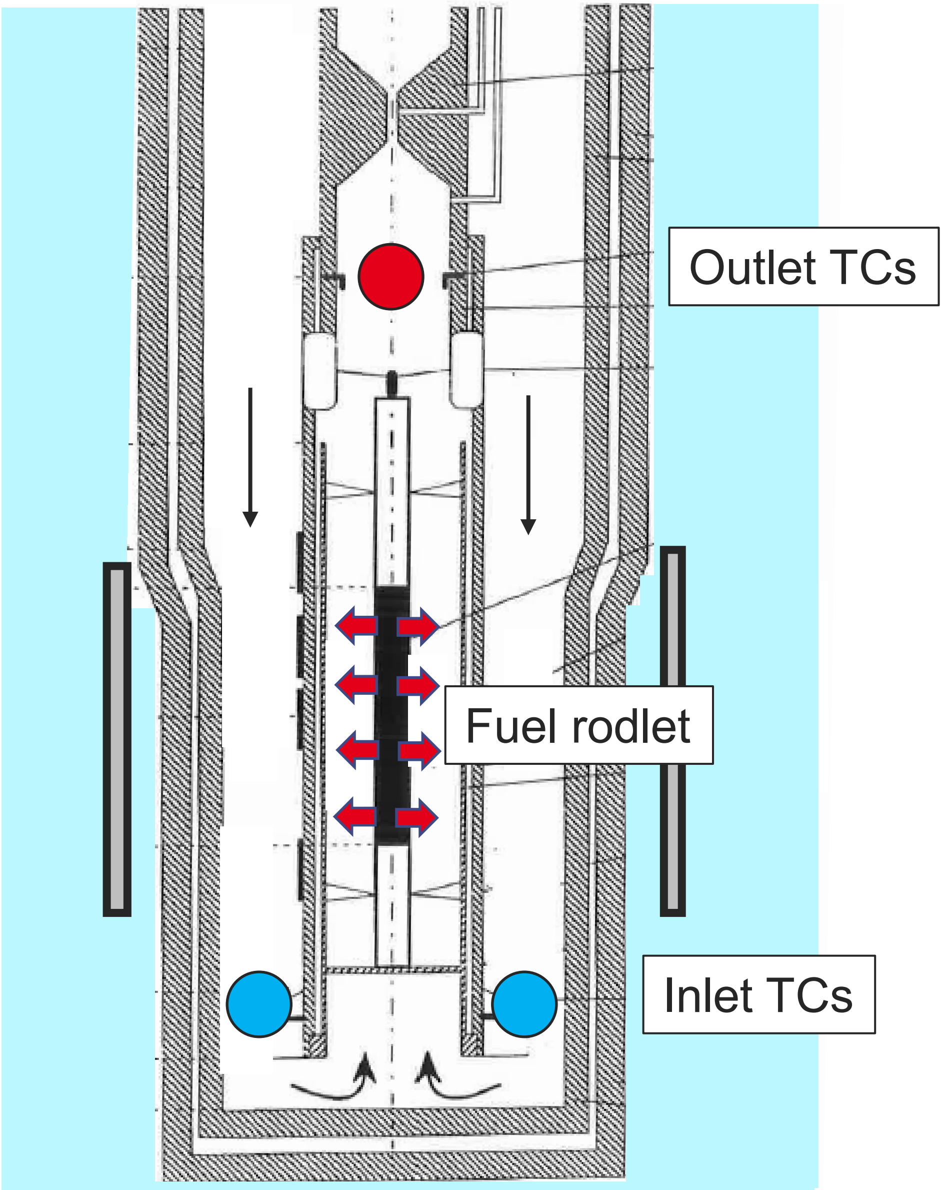
- Thermal-hydraulic conditions
- Gamma-neutron heating
- Material properties

The power is iteratively adjusted by repeating the simulation procedure until the calculated ΔT (both T_{out} and T_{in}) matches the values experimentally measured in ETALISA-1.

<u>Final ETALISA-1 simulation</u>

Simulation input: **<u>Final adjusted power</u>**

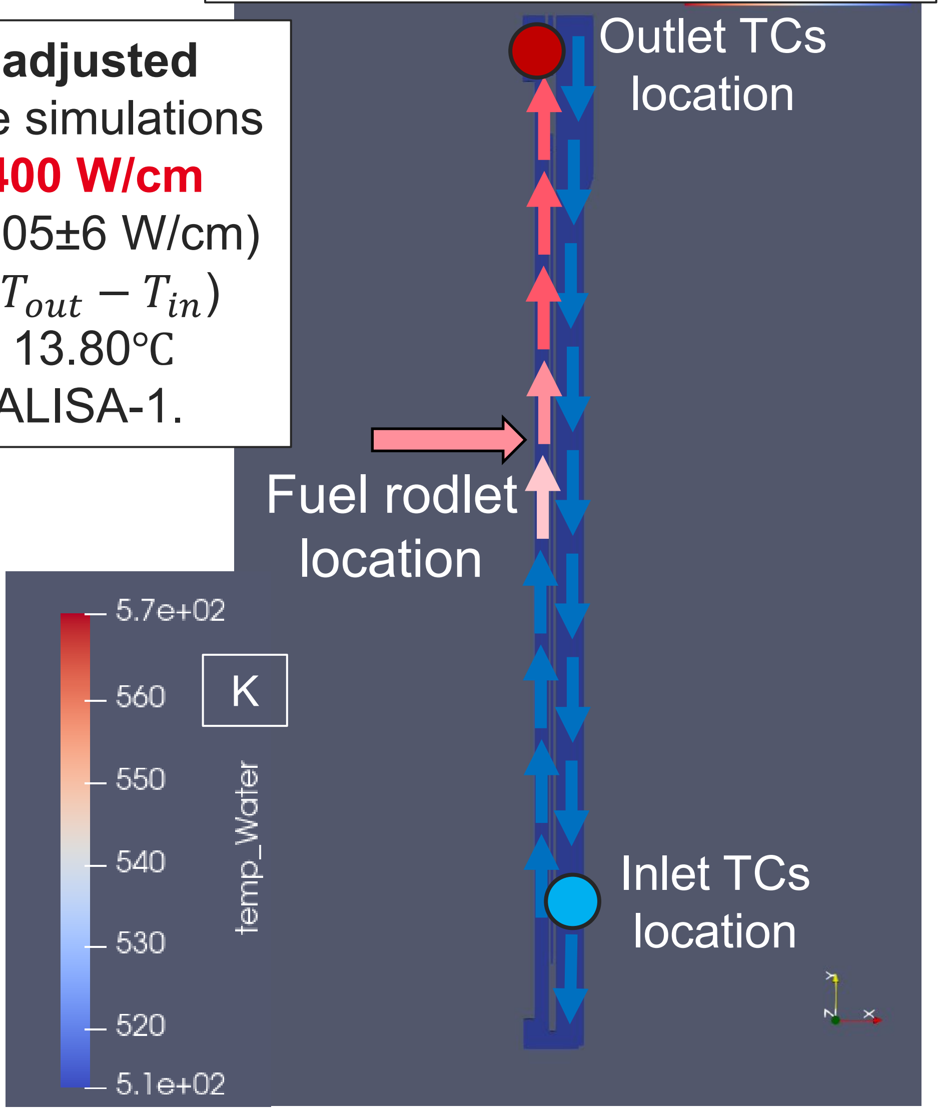
→ Simulation output: As-measured ETALISA-1 ΔT



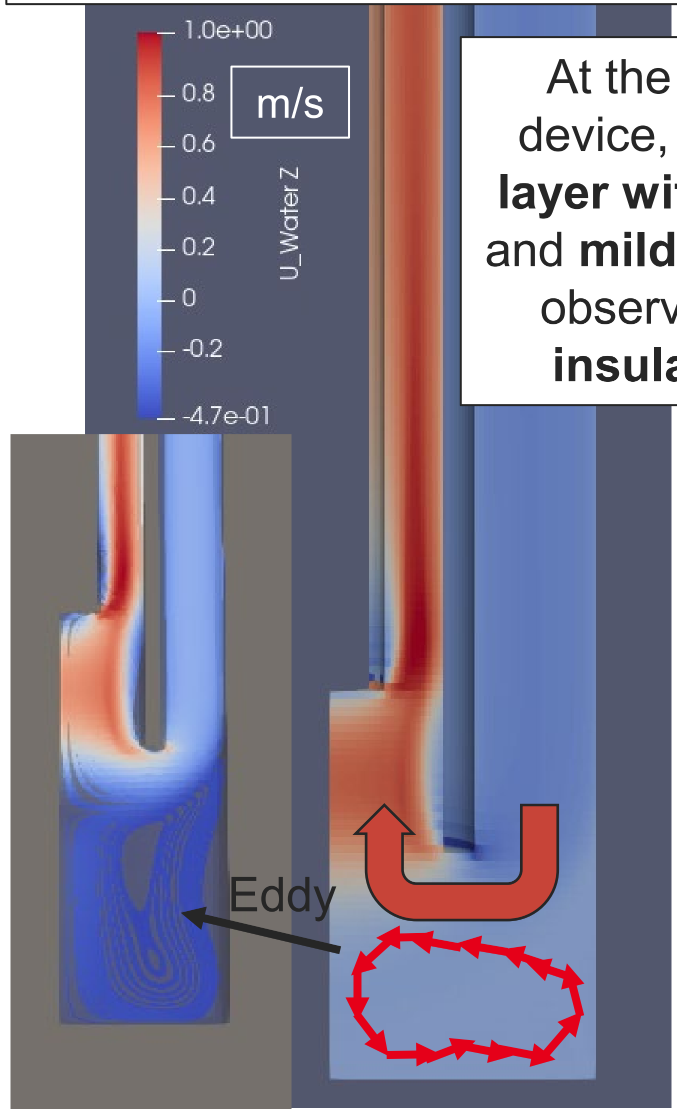
ETALISA-1 simulation results

The final **adjusted power** in the simulations equal to **400 W/cm** (reference 405±6 W/cm) lead to a $(T_{out} - T_{in})$ equal to 13.80℃ as in ETALISA-1.

NEPTUNE_CFD
Temperature distribution



NEPTUNE_CFD
Velocity distribution at device bottom

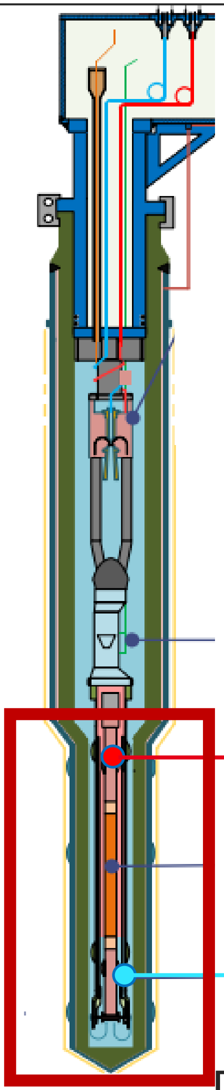


At the bottom of the device, a cooler **water layer with** low velocities and **mild recirculation** is observed enhancing **insulating effects**.

4. 3D coupled model development of ADELINE device for the Jules Horowitz Reactor

ADELINE simulation geometry

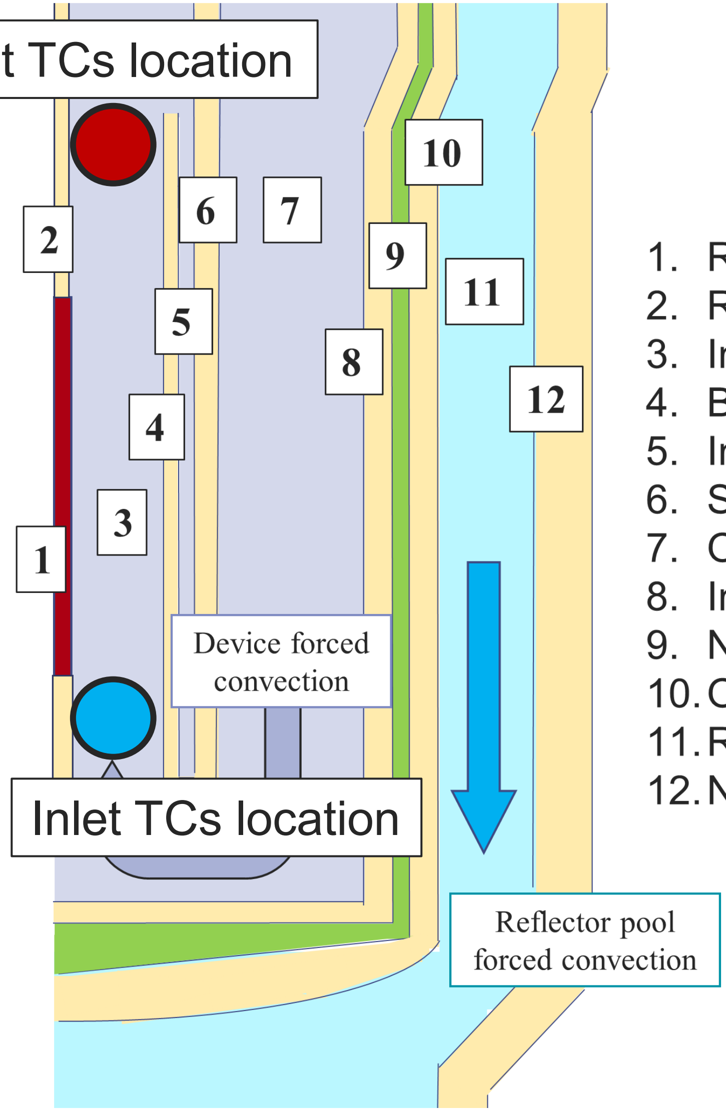
ADELINE in-pile section



[5]

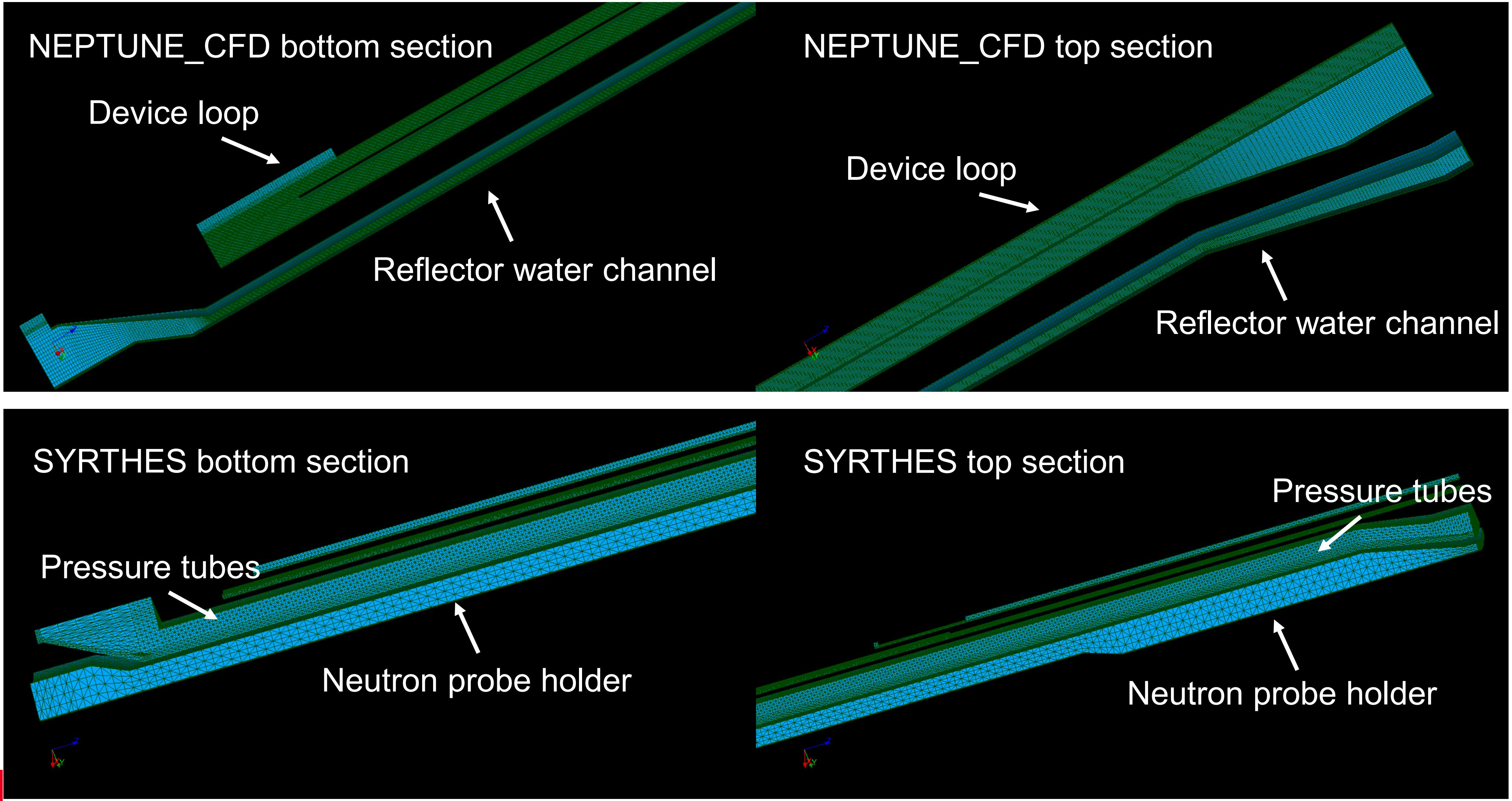
The NEPTUNE_CFD analysis of ISABELLE-1 suggested **positioning the inlet thermocouple within the test channel** to mitigate the temperature gradient previously observed in ETALISA-1.

ADELINE model slice sketch



1. Rodlet sample
2. Rodlet extension
3. Inner water channel
4. Basket
5. Insulating water channel
6. Sample holder tube
7. Outer water channel
8. Inner pressure tube
9. Nitrogen insulation layer
10. Outer pressure tube
11. Reflector water channel
12. Neutron probe holder tube

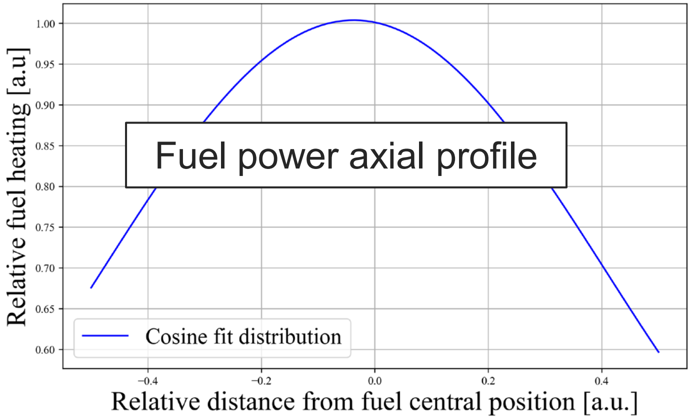
NEPTUNE_CFD and SYRTHES meshes for ADELINE

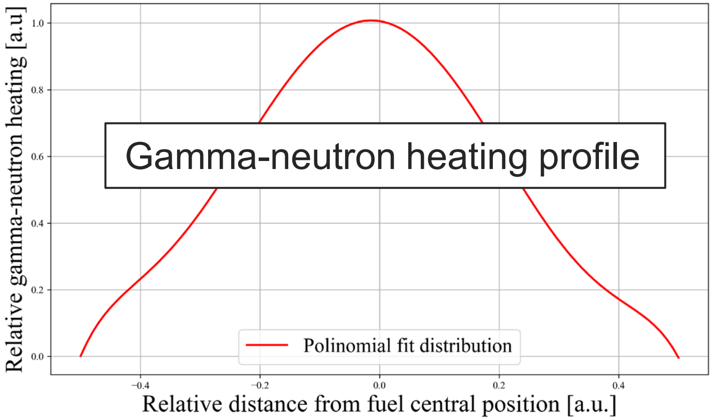


ADELINE qualification experiment and simulation scope

Preliminary evaluation of the foreseen qualification experiment of ADELINE using:

- **Fresh UO_2** fuel rodlet irradiated at **500 W/cm** is planned in the ADELINE qualification plan.
- Performed at a reactor power of **70 MWth**.
- **Nominal thermal-hydraulic operating conditions** of the ADELINE and reflector cooling channels.



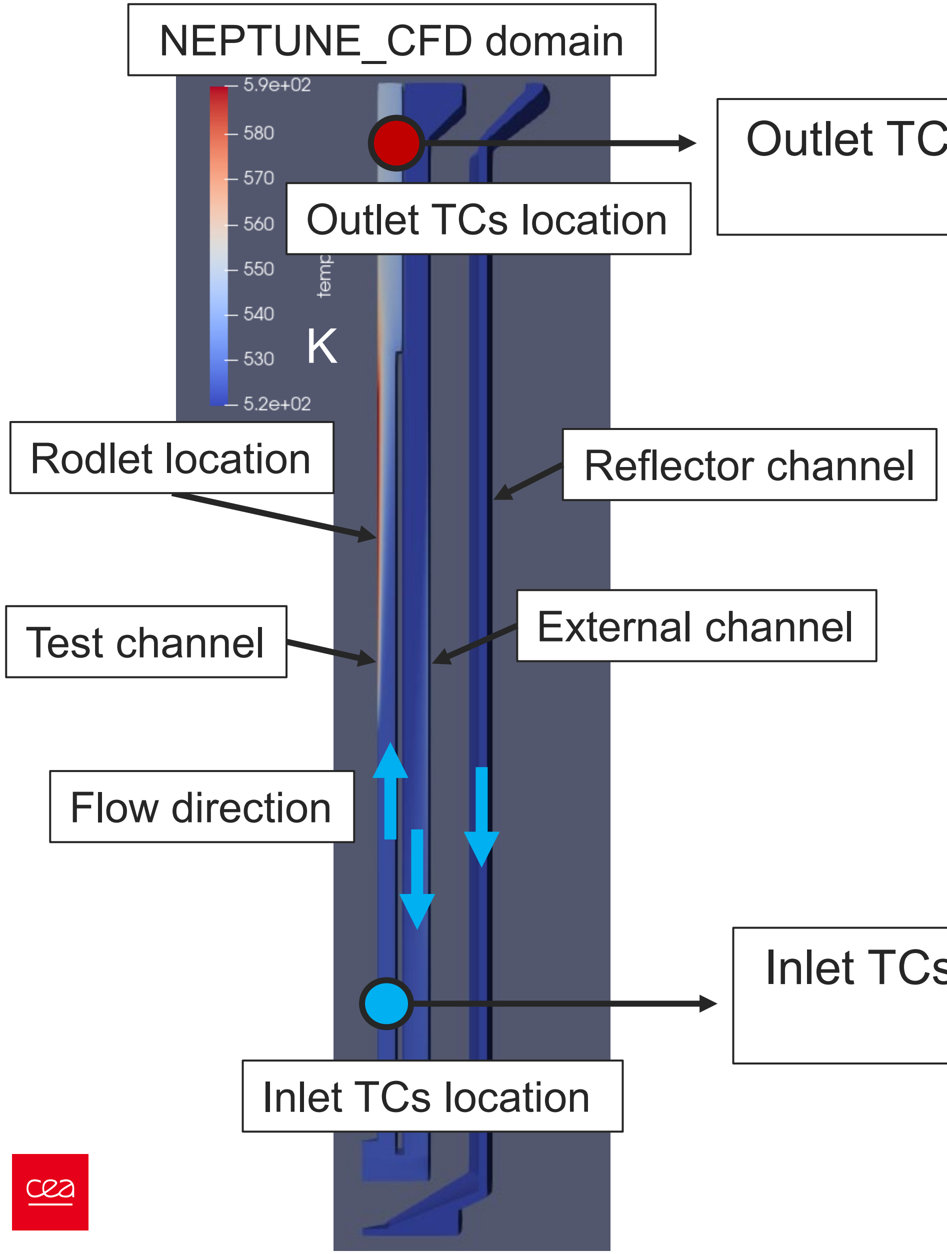


ADELINE NEPTUNE_CFD simulation parameter		Value
Water flow [Kg/s]	ADELINE device	0.025
	Reflector pool	0.063
Pressure [bar]	ADELINE device	155
	Reflector pool	1.84
Temp. inlet [°C]	ADELINE device	240
	Reflector pool	51
Specific radiation heating [W/g]	Zircaloy4	1.3-1.7
	Water	2.0-3.3

Information of interest:

- **Preliminary quantification of the thermal balance** expected accounting the fuel heating as well as the intense neutron-gamma heating expected from JHR.
- Preliminary assessment of the **water temperature distribution** in the test channel.
- Evaluation of the **thermocouple positioning** in the test channel.
- **Observe the water behaviour** in the device forced convective loop.

ADELINE thermal balance determination

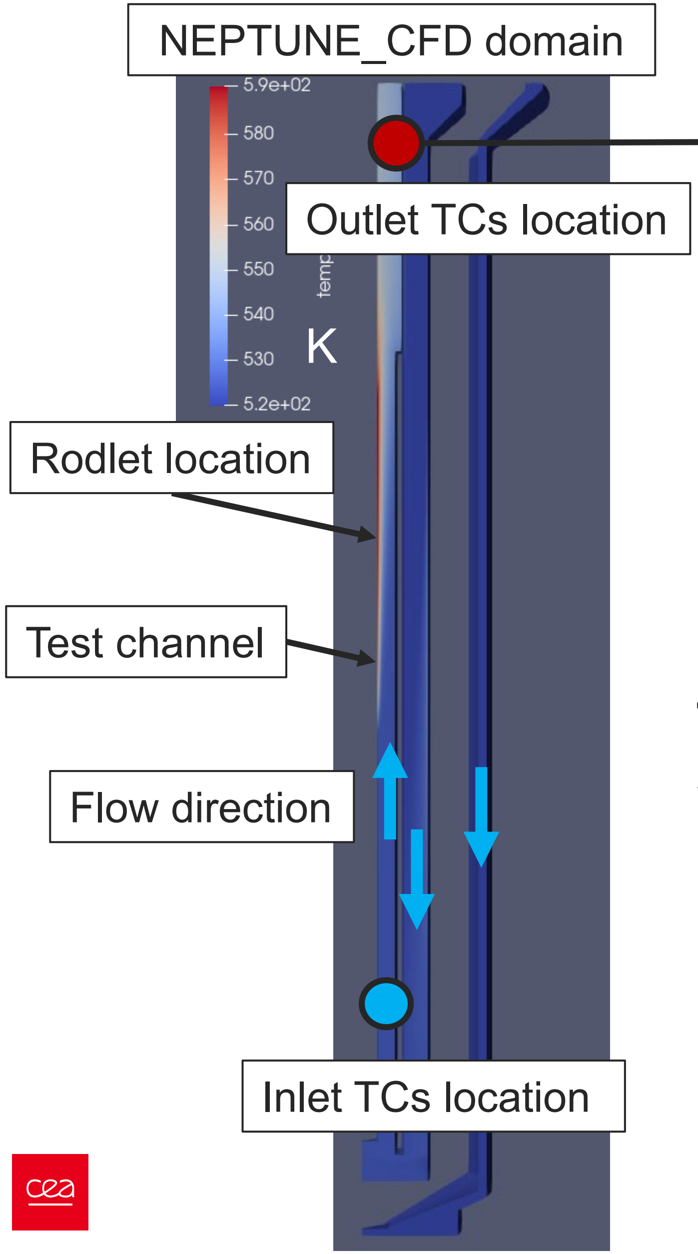


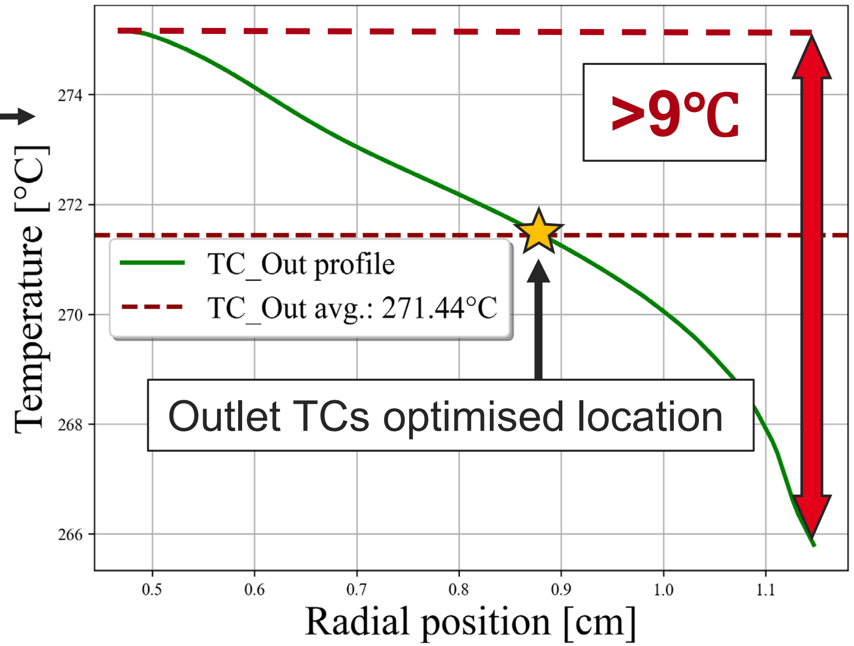
Outlet TCs average temperature
271.44 ℃

Inlet TCs average temperature
250.29 ℃

Max. linear heat rate of the fuel 500 W/cm	Value
$T_{out} - T_{in}$	**21.15 ℃**

ADELINE radial profile of water temperature





A significant radial profile of water temperature is observed at the **preliminary optional locations of the outlet TCs**, not observed in ISABELLE-1 (different TCs axial elevations, hydraulic diameters and water speeds as well as additional mixing features in ISABELLE-1).

The uncertainty in the radial position of the outlet TCs may lead to a significant **uncertainty in the ΔT measurement**, and consequently in the rodlet power determination in ADELINE.

NB: No issues at inlet TCs with a flat radial profile of temperatures.

Possible solutions:

- Move ADELINE outlet TCs **further upstream**.
- Improve the **water mixing** by introducing mixing components.

5. Conclusions and perspectives

Conclusions ISABELLE-1

1. A **3D coupled NEPTUNE_CFD/SYRTHES model of ISABELLE-1 was developed** as well as a simulation strategy.
2. Using the thermal balance, a **maximum fuel linear heat rate of 400 W/cm** was obtained, consistent (within 1σ) with PIE measurements (405 ± 6 W/cm) and the past REFLET evaluation (405 ± 12 W/cm).
3. A 3D model is available **not needing any correction factors** and allowing an accurate description of device and water behaviour.

Conclusions ADELINE

1. A **3D coupled NEPTUNE_CFD/SYRTHES model of ADELINE was developed** and successfully used to assess a **preliminary evaluation of the thermal balance** of the foreseen qualification irradiation in ADELINE.
2. The results also revealed a significant radial temperature profile at the outlet TC locations, which **adversely affects the accuracy of the fuel power determination**. Several solutions to flatten the radial profile were proposed and currently under discussion with the JHR project team.
3. The model gives valuable insights to the water behaviour for a possible **design optimization**.

Prospects of the work

- **Uncertainty analysis on NEPTUNE-CFD_SYRTHES simulations** to evaluate the impact of parameter variability on the ISABELLE-1 and ADELINE model results, reinforcing the method's potential for digital twin applications.

- **Enhanced fuel rodlet modelling** incorporating a more detailed fuel rodlet representation in SYRTHES, enabling improved temperature mapping to refine the interpretation of data from instrumented rodlets, particularly for components sensitive to temperature such as pressure sensors.

- **Include additional physics** such as gamma-neutron radial heating distributions.

References

[1] Y. Peng thesis: “*Modélisation avancée des dispositifs expérimentaux à déplacement du réacteur Jules Horowitz*”, Commissariat à l'Energie Atomique, 2023.

[2] A. Alberman, M. Roche, P. Couffin, S. Bendotti, D.J. Moulin, J.L. Boutfroy, *Technique for power ramp tests in the ISABELLE 1 loop of the OSIRIS reactor, Nuclear Engineering and Design*, Volume 168, Issues 1–3, 1997, Pages 293-303.

[3] G. Geffraye, O. Antoni, M. Farvacque, D. Kadri, G. Lavialle, B. Rameau, A. Ruby *CATHARE 2 V2.5_2: A single version for various applications. Nuclear Engineering and Design,* Volume 241, Issue 11, November 2011, Pages 4456-4463

[4] D. Moulin, “*Controle des conditions neutroniques et thermohydrauliques des rampes de puissance dans une boucle d'irradiation de combustibles de reacteur a eau pressurisee,* Commissariat à l'Energie Atomique, Saclay”, 1992.

[5] F. Huet and C. Neyroud conférence IGORR 2023

Thank you for your kind attention
ご清聴ありがとうございました。

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