Study review of the CALORRE differential calorimeter: definition of designs for different nuclear environments

Oral presentation #04-119 for the Research Reactors and Particle Accelerators session, 2021/06/24

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Summary

- **General context and background on the nuclear absorbed dose rate measurement in research reactor**
- **Introduction to the CALORRE differential calorimeter:**

  from the calibration bench and the response under laboratory conditions to the qualification under real conditions
- **Experimental and numerical studies of a specific calorimeter configuration for high nuclear dose rate measurement**
- **New design of a specific MIT-R CALORRE configuration based on feedback from previous irradiation campaign:**

  the CALOR-I project
- **Conclusion and outlooks**

General context and background on the nuclear absorbed dose rate measurement in research reactor

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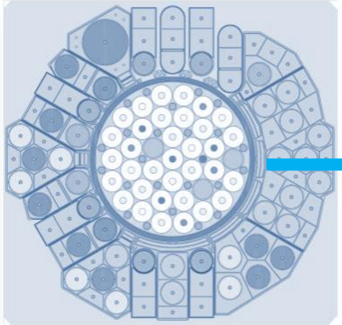
General context and background

General context

The Jules Horowitz Material Testing Reactor

- Reactor core height of 60 cm & diameter of 60 cm
- **P_{th}=100 MW**
- Thermal neutron flux ~3.5 10^{14} $n.cm^{-2}.s^{-1}$
- Fast neutron flux ~5.5 10^{14} $n.cm^{-2}.s^{-1}$ (E > 1 MeV)
- Displacement per atom and per year 16 $dpa.year^{-1}$



AMU/CEA joint research program: IN-CORE*

- To optimize advanced nuclear sensors dedicated to the **nuclear absorbed dose rate** measurement
- To improve common and recently patented sensor responses (range, sensitivity, linearity)
- To design and miniaturize new sensors
- To reduce response time and uncertainties

Nuclear absorbed dose rate of 20 $W.g^{-1}$ in aluminum

**IN-CORE : Instrumentation for Nuclear radiations and Calorimetry Online in REactor*

Nuclear absorbed dose rate:

Energy deposition rate per unit of mass induced by the interactions between rays and matter

General context and background

Background on the nuclear absorbed dose rate measurement in research reactor

Range of nuclear absorbed dose rate occurring in irradiation reactor

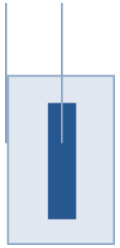
- TRIGA-JSI: 5.10^{-2} $W.g^{-1}$
- MIT-R: 2 $W.g^{-1}$
- MARIA: 5 $W.g^{-1}$
- OSIRIS: 13 $W.g^{-1}$
- BR2: 14 $W.g^{-1}$
- JHR: 20 $W.g^{-1}$

Nuclear absorbed dose rate E_n

1 $kGy.s^{-1}$=1 $W.g^{-1}$

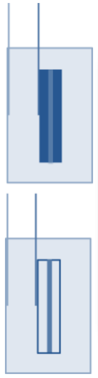
C. Reynard-Carette, Proceedings ANIMMA, 2018.

- Sufficient energy deposition rate to raise the temperature
- Temperature measurements
- **Non-adiabatic heat flow calorimeter**
  Sealed cell, K-type thermocouples, Sample, Inert gas



Single-cell calorimeter

~~Heating element~~
Size < 80 mm
Transient calibration
1 measurement method
1 displacement
Shorter response time



Differential calorimeter

Heating elements
+ Reference cell
Size ~220 mm
Steady calibration
3 measurement methods
≤ 2 displacements
Longer response time

J. Brun et al., Proc ANIMMA 2019.
R. Van Nieuwenhove et al., Proc ANIMMA 2019.

Qualification and enhancement of a CALORRE differential calorimeter

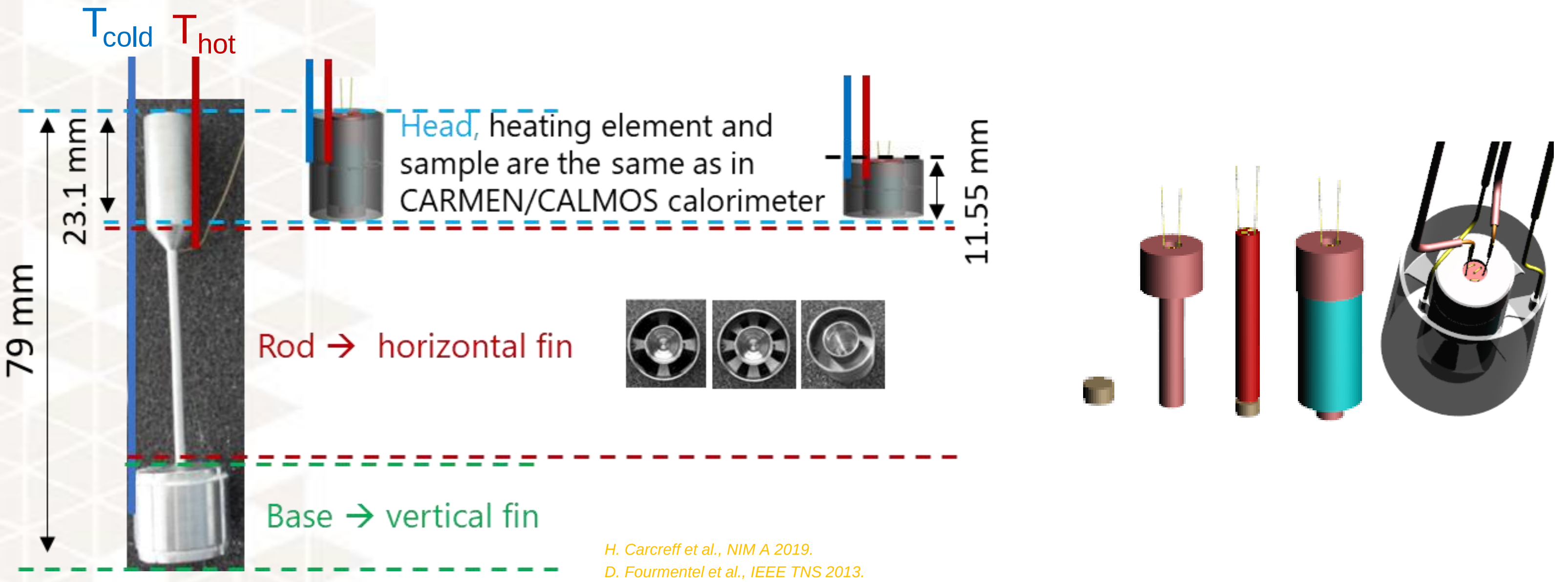
Challenges: Reduction in mass, size, response time and Increase in the measurement range while keeping a linear response

Introduction to the CALORRE differential calorimeter

CALORRE designs

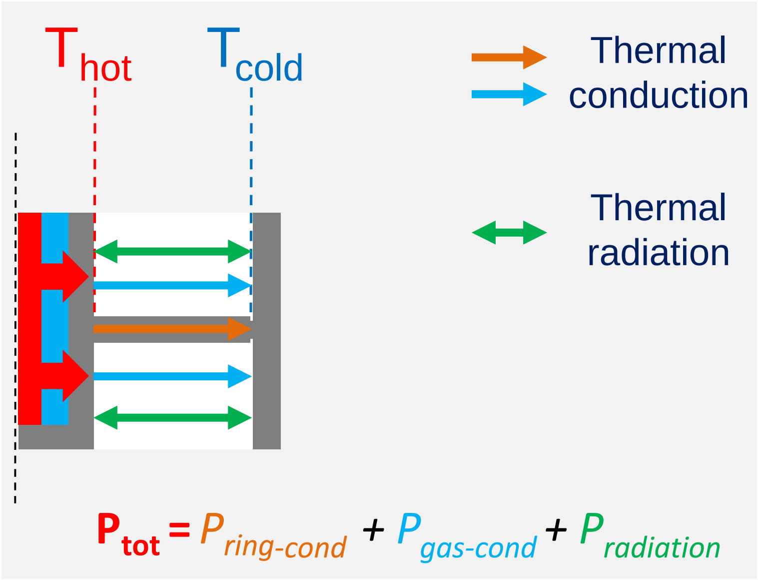
M. Carette, Brevet N°1553136, 2015.
J. Brun, PhD Thesis 2012.

- **New compact calorimeter firstly studied numerically by J. Brun (2012) and tested during the MARIA reactor campaign in 2015 (AMU/CEA Patent-1553136-2015)**
  - New design to release heat through the ring mainly in the radial direction
  - Important reduction of the axial dimension



H. Carcreff et al., NIM A 2019.
D. Fourmentel et al., IEEE TNS 2013.
C. De Vita et al., IEEE TNS 2016.

1-D Theoretical model



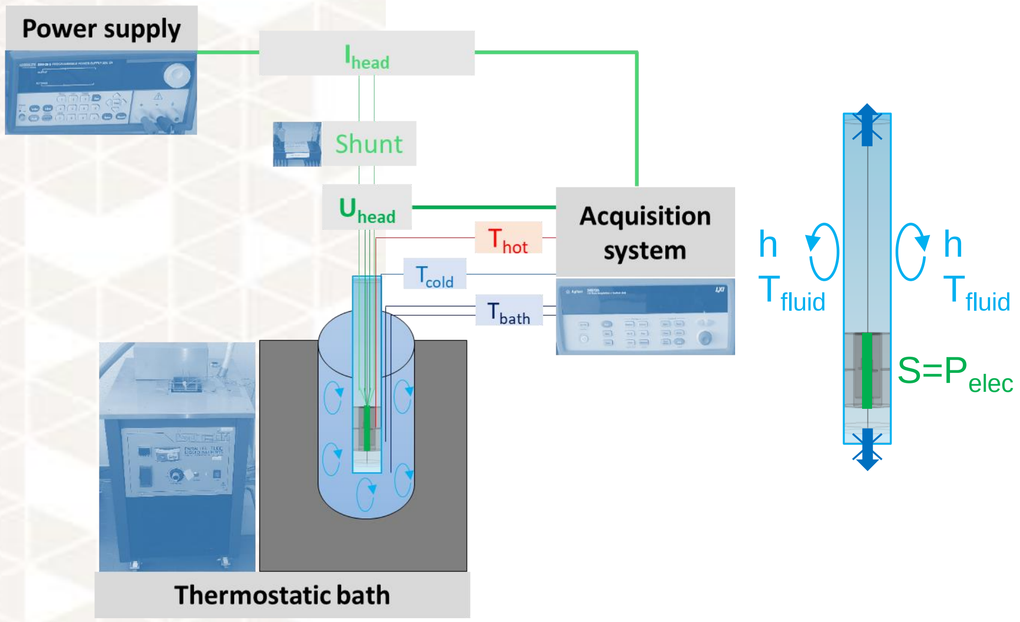
A. Volte et al., IEEE TNS 2018.

Reduction in height by 6.8
Suitable configuration for a 1-D thermal model → heat transfer mode contributions

Introduction to the CALORRE calorimeter

Experimental set-up and operating protocol under laboratory conditions

❑ Experimental set-up

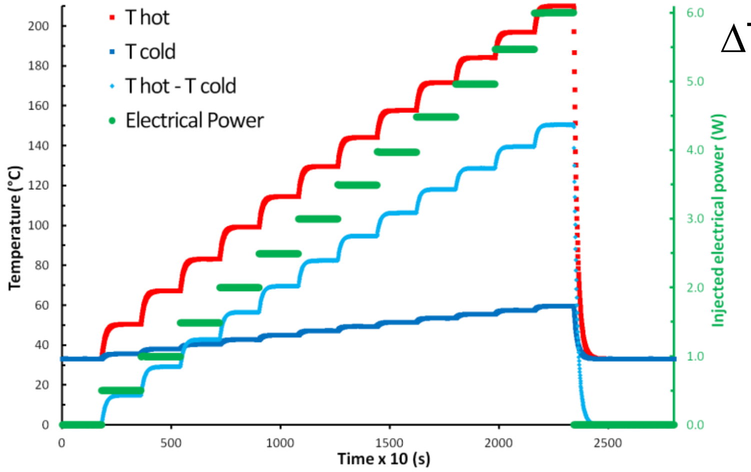


- ➢ Fluid temperature: from 23 to 63 °C
- ➢ Reynolds Number: from 609 to 1607

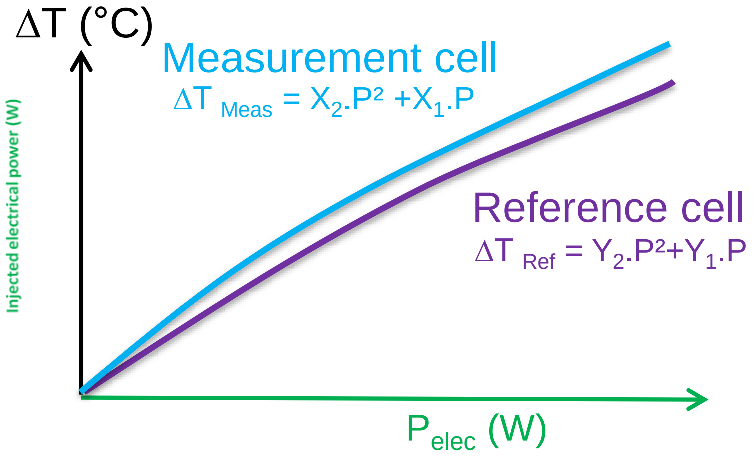
❑ Operating protocol

A. Volte et al., Proc ANIMMA 2017.
A. Volte et al., IEEE TNS 2018.

- ➢ Analyzed stationary state
- ➢ Nuclear absorbed dose rate simulated with heating element
- ➢ Increments at 30 min intervals after reaching a steady state
- ➢ Calibration range depending on the target nuclear absorbed dose rate value



Temporal response



Calibration curves

Characterisation under laboratory conditions → response time, linearity and sensitivity
Preliminary and essential step before studies under real conditions

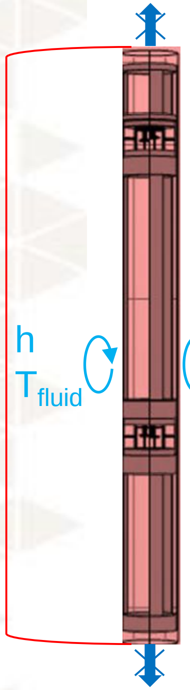
Running and measurement principles

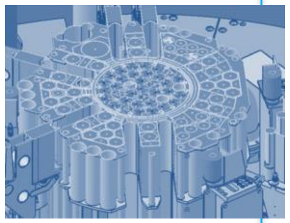
Under real conditions

$S_i = E_n * \rho_{material\ i}$

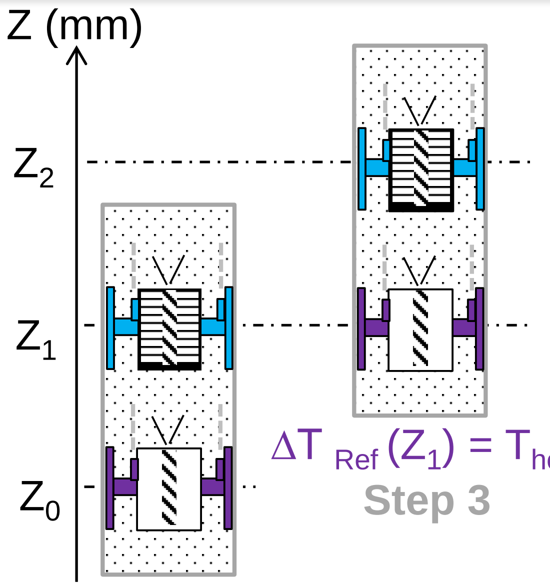
- *cell structures*
- *sample*
- *sample-holder*
- *heater*
- *wedge*
- *gas*
- *spacers*
- *jacket*

A. Volte et al., IEEE TNS 2020.





Calibration method



$\Delta T_{Meas}(Z_1) = T_{hot} - T_{cold}$

Step 2

$\Delta T_{Ref}(Z_1) = T_{hot} - T_{cold}$

Step 3

$\Delta\Delta T(Z_1) = \Delta T_{Meas}(Z_1) - \Delta T_{Ref}(Z_1)$

Without nuclear rays

$\Delta T_{Meas} = X_2.P^2 + X_1.P$

$\Delta T_{Ref} = Y_2.P^2 + Y_1.P$

Step1: laboratory

$E_n = f(\Delta\Delta T, X_2, X_1, Y_2, Y_1)$

H. Carcreff et al., NIM A 2019.

First qualification of CALORRE under real conditions in the MARIA reactor in 2015
Validation of a 3-D thermal model and a predictive model based on heat balance

Experimental and numerical studies of a specific calorimeter configuration for high nuclear dose rate measurement

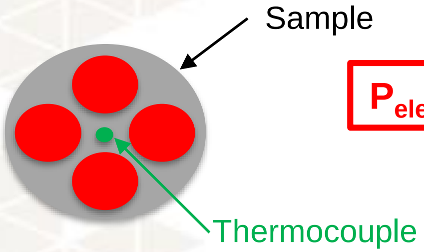
Experimental and numerical studies of a configuration for high nuclear dose rate

Chosen CALORRE configuration

- ❑ <u>Sample:</u> made of duralumin
- ❑ <u>Cell structure:</u> H=23.1 mm, D_{ext}=17 mm, half-surface horizontal fin, made of aluminum
- ❑ m_{head}=3.2 g
- ❑ 2 k-type thermocouples

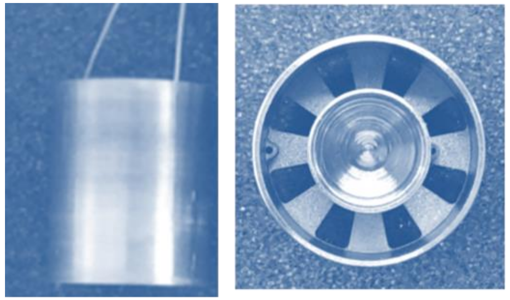
New heating-element system

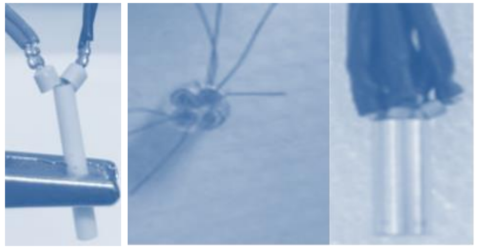
- ❑ 4 independant heating elements (NiCr alloy)
- ❑ 4-wire assembly
- ❑ 1 central k-type thermocouple



P_{elec}=60 W

~19 $W.g^{-1}$



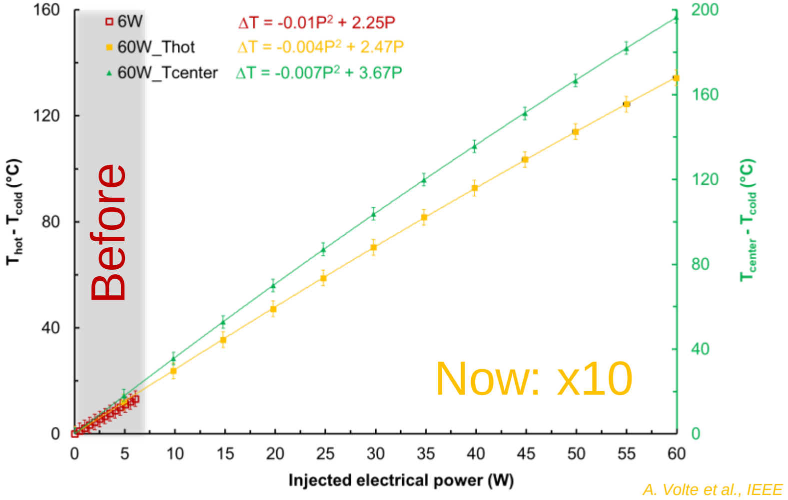


A. Volte et al., IEEE TNS 2020.
A. Volte et al., Proc ANIMMA 2019.

New range of injected electrical power multiplied by 10 (6 W → 60 W)
Simulated nuclear absorbed dose rate suitable for 20 $W.g^{-1}$

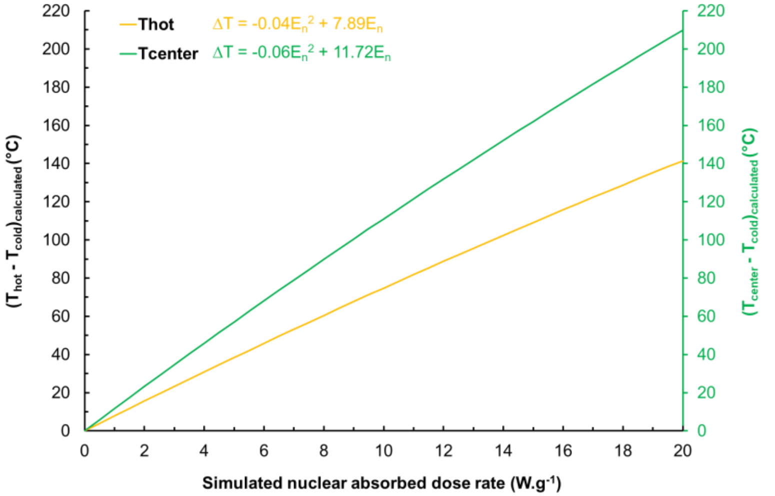
Experimental and numerical studies of a configuration for high nuclear dose rate

- **Calibration under laboratory conditions**
  - **Qualification of the new heating element system**
  - **Experimental results**
    - Response time of 90 s
    - Linear response (**A_2~-0.004 °C.W^{-2}**)
    - Sensitivity of the measurement cell (at 60 W):
      1.99 °C.W^{-1} (using T_{hot})
      2.83 °C.W^{-1} (using T_{center})



A. Volte et al., IEEE TNS 2020.

- **1-D thermal model**
  - **Thermal conduction → horizontal fin > 97 %**
  - **Thermal conduction → gas gap < 2 %**
  - **Thermal radiative transfer → head and vertical fin < 1 %**
- **Predictive model under real conditions**
  - **T_{max} < 300 °C**
  - **ΔT < 150 °C**
  - **Sensitivity of the measurement cell (at 20 W.g^{-1}):**
    6.29 °C.g.W^{-1} (using T_{hot})
    9.32 °C.g.W^{-1} (using T_{center})

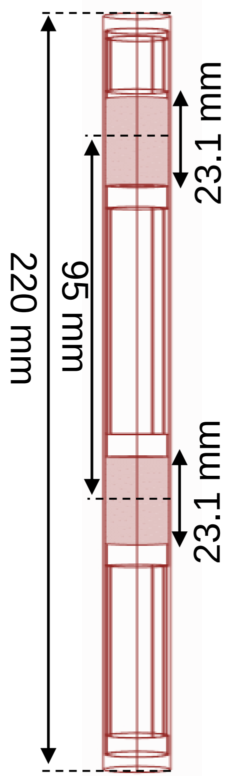


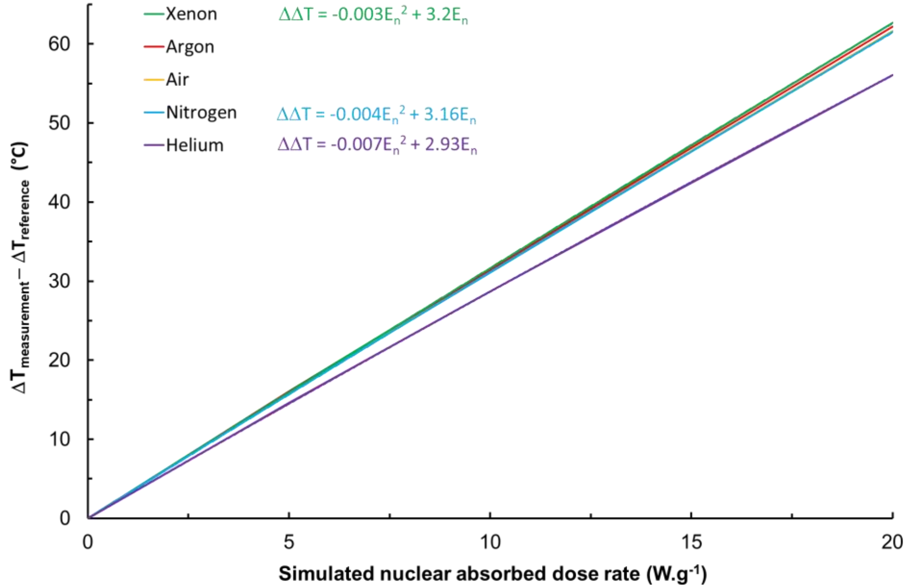
Low variation in calibration coefficients for the new range
Linear response

Experimental and numerical studies of a configuration for high nuclear dose rate

Study of the response under real conditions by 3-D numerical thermal simulations

- **Resolution with Comsol Multiphysics thanks to a finite element method**
- **3-D geometry**
  - Whole calorimeter: assembly as in MARIA (without cables, plug and nose), H_{tot}=220 mm, inter-cell space of 95 mm
  - Sample: made of graphite
  - Inert gas: xenon, argon, air, nitrogen, helium
- **3-D thermal model**
  - Heat transfers: thermal conduction (λ_i=f(T)) and thermal radiative transfers (ε=0.25)
  - Heat sources: $S_i = E_n * \rho_{material\ i}$ *with E_n up to 20 W.g^{-1}*
  - Boundary conditions: forced convection heat transfer fluid (water) with T_{fluid}=33 °C, h=7325 W.K^{-1}.m^{-2}





Gas	T_{max}	T_{wall}	$S_{calorimeter}$
Helium	239 °C	73.7 °C	2.7 °C.g.W^{-1}
Nitrogen	265 °C	73. 8 °C	3 °C.g.W^{-1}
Xenon	289 °C	73.8 °C	3.1 °C.g.W^{-1}

E_n=20 W.g^{-1}

Linear response

First configuration numerically qualified for high nuclear absorbed dose rate and different inert gases

New design of a specific MIT-R CALORRE configuration based on feedback from previous irradiation campaign

Design of a specific MIT-R CALORRE configuration based on the feedbacks

Preliminary study for an irradiation campaign in the MIT-R

Threefold objective of the campaign

- Nuclear absorbed dose rate mapping of the channels in the MIT-R core
- Study of a new CALORRE prototype for the MIT reactor water loop
- Optimization of the CALORRE differential calorimeter by 3-D thermal numerical simulations (AMU) and nuclear radiation-matter interactions (MIT)

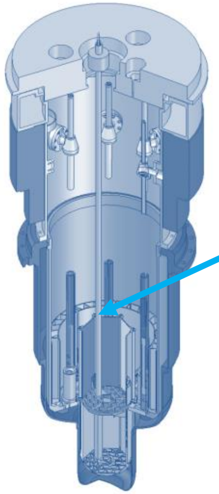
The CALOR-I* project

Aix*Marseille université Socialement engagée · cea · MIT Massachusetts Institute of Technology · Massachusetts Institute of Technology Nuclear Reactor Laboratory · Investir l'avenir · A*Midex Initiative d'excellence Aix-Marseille

*Compact-CALORimeter Irradiations inside the MIT research reactor

Experimental conditions inside MIT-R

- Reactor core height of 56 cm & diameter of 38 cm
- P_{th}=6 MW
- 3 In-core channels
- Thermal neutron flux ~3.6 10^{13} n.cm^{-2}.s^{-1}
- Fast neutron flux ~1.2 10^{14} n. cm^{-2}.s^{-1} (E > 0.1 MeV)



2 W.g^{-1} in titanium

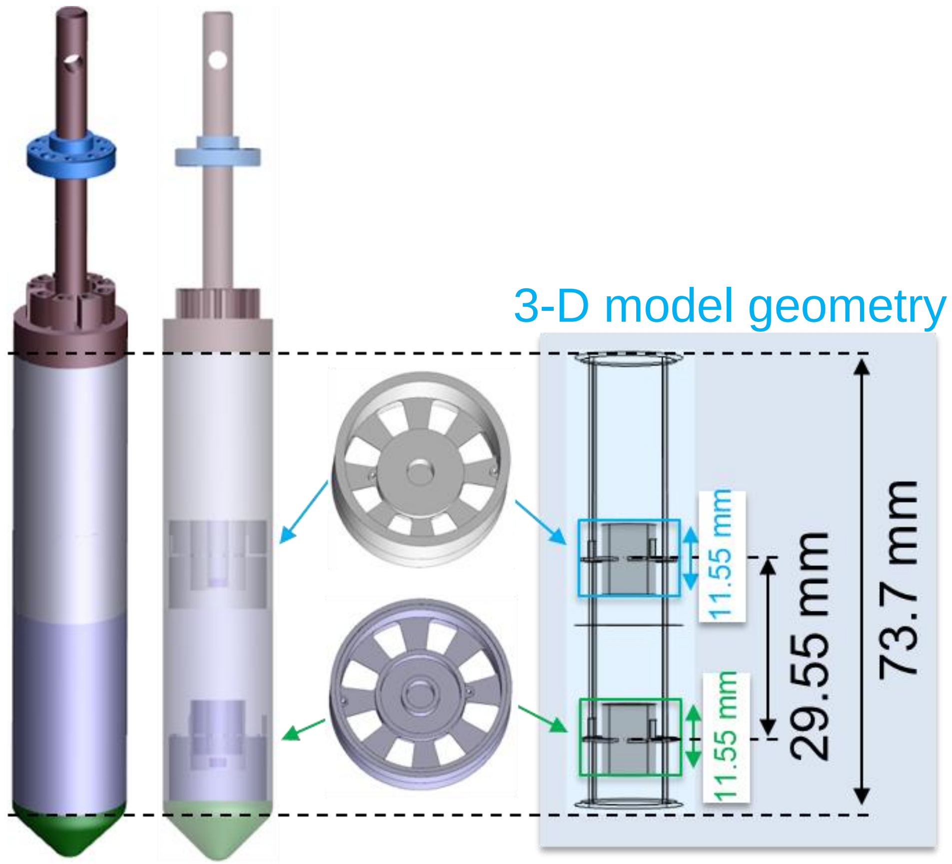
Carpenter et al., MIT User guide, 2012.
Kim, Nuclear engineering and design, 2014.

Reduce the size of the complete calorimeter (< 10 cm) and increase its sensitivity

Design of a specific MIT-R CALORRE configuration based on the feedbacks

- **Drawbacks observed from previous irradiation campaign**
  - **Low range of injected electrical power for the expected nuclear absorbed dose rate**
  - **Only 2-wire heating elements**
  - **Important inter-cell space**
  - **Impact of the contact thermal resistance between:**
    - the sample and the head
    - the jacket and the vertical fin
- **New CALORRE cell design**
  - **Simplification of the assembly and the head → removal of the contact thermal resistances**
  - **Reduction in the size, mass → response time, maximum temperature (H=11.55 mm)**
  - **Sample and the cell structure made of the same material (stainless steel)**
  - **Same horizontal fin design as the previous one (half-surface)**

3-D model geometry

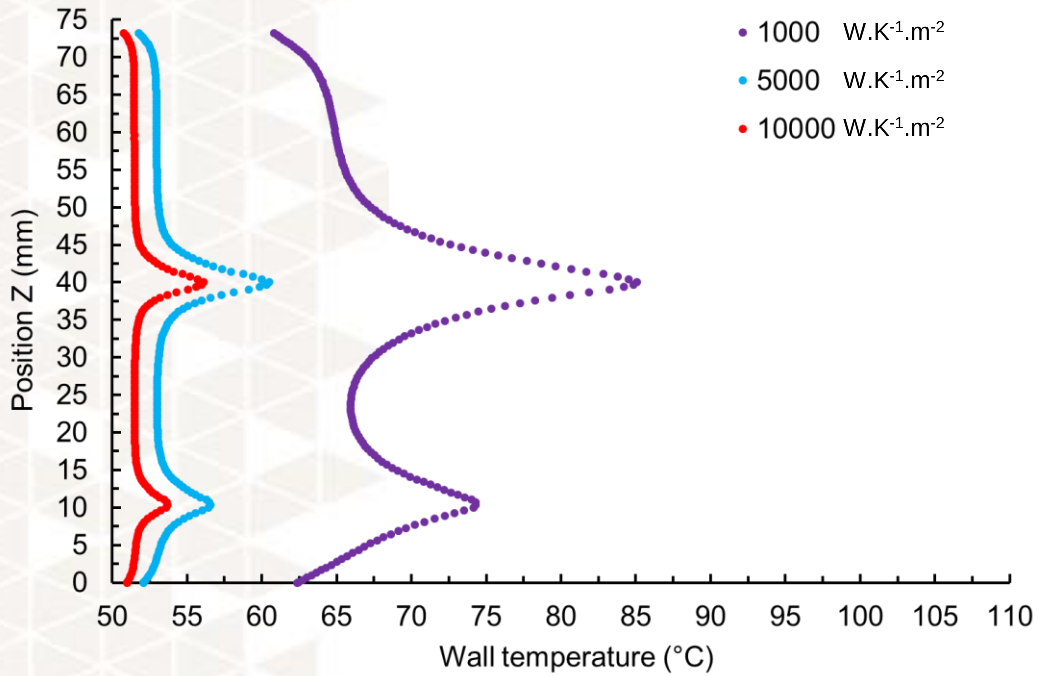


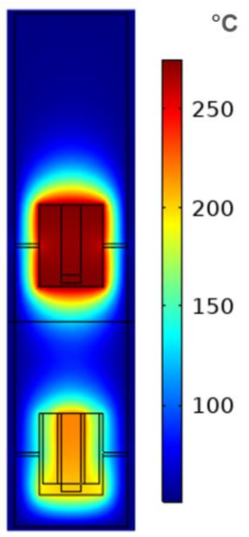
New CALORRE cell design without spacers and heater holders and with a height equal to 73.7 mm

Design of a specific MIT-R CALORRE configuration based on the feedbacks

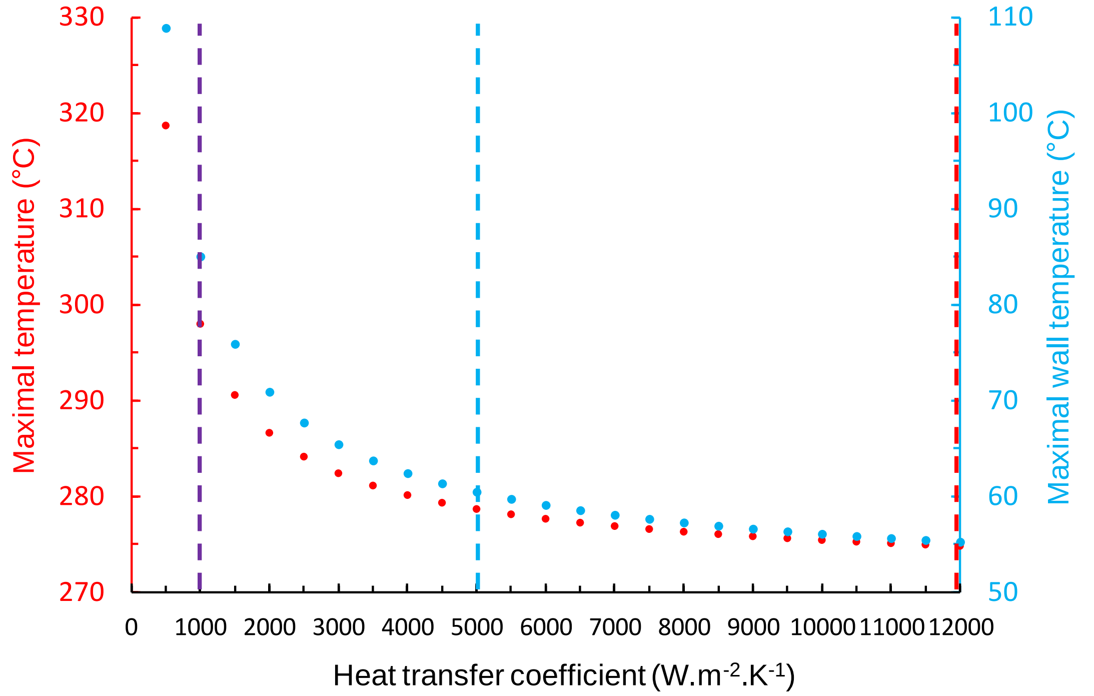
- **Study of the response under real conditions by 3-D numerical thermal simulations**
  - **Influence of the heat transfer coefficient on the maximum temperature (T_{max}) and the external wall temperature (T_{wall})**

$\lambda(i)=f(T)$
$\varepsilon(i)=0.2$
$T_{fluid}=50$ °C
$E_n=2$ W.g^{-1}





h=10000 W.m^{-2}.K^{-1}



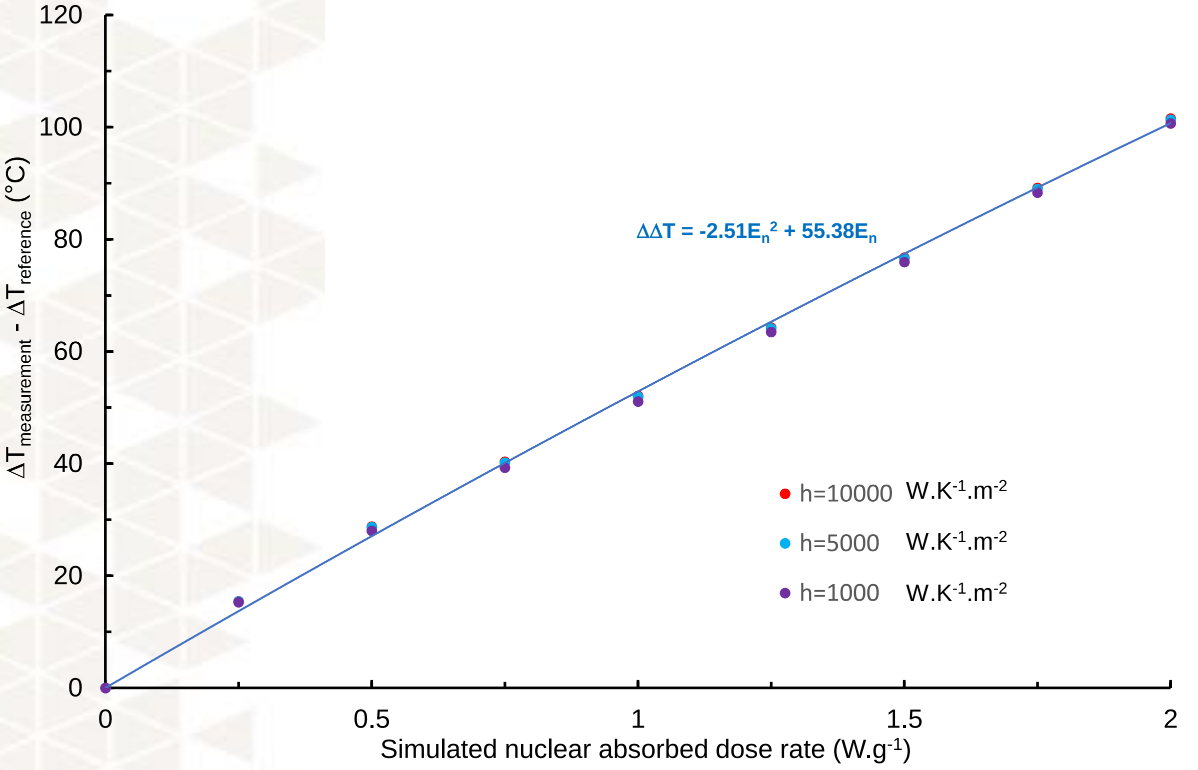
When h increases from 500 W.m^{-2}.K^{-1} to 10000 W.m^{-2}.K^{-1}:
Maximal temperature in the calorimeter decreases (from ~319 °C to 275 °C)
Maximal wall temperature decreases too (from ~109 °C to 56 °C)

Design of a specific MIT-R CALORRE configuration based on the feedbacks

Study of the response under real conditions by 3-D numerical thermal simulations

❑ Influence of the heat transfer coefficient on the response and sensitivity of the calorimeter

λ(i)=f(T)
ε(i)=0.2
T_{fluid}=50 °C
E_n=0-2 W.g^{-1}



	h=10000 W.m^{-2}.K^{-1}
S (°C.g.W^{-1})	-5.02*E$_n$+55.38
S (°C.g.W^{-1}) for 1 W.g^{-1}	50.4
S (°C.g.W^{-1}) for 2 W.g^{-1}	45.3
T_{max} (°C) 2 W.g^{-1}	275.4
$T_{wall-max}$ (°C) 2 W.g^{-1}	56.6
Response time (s)	From 150 to 90

Low influence of the heat transfer coefficient on the calorimeter response
Good sensitivity, maximal temperature and response time
Resolution ~0.1 W.g^{-1}

Conclusion and outlooks

Conclusion

- **Experimental and numerical studies of a specific configuration for high nuclear dose rate measurement (JHR)**
  - Definition, development and experimental characterization under laboratory conditions thanks to a new heating element system → increase in the calibration range by a factor of 10
  - Studies under real conditions by means of a predictive model and 3-D numerical simulations
  - Reduction of the calorimeter size
- **Design of a specific MIT-R CALORRE configuration based on the feedbacks from previous irradiation campaign**
  - Studies under real conditions by means of 3-D numerical simulations

New 3-D thermal simulations

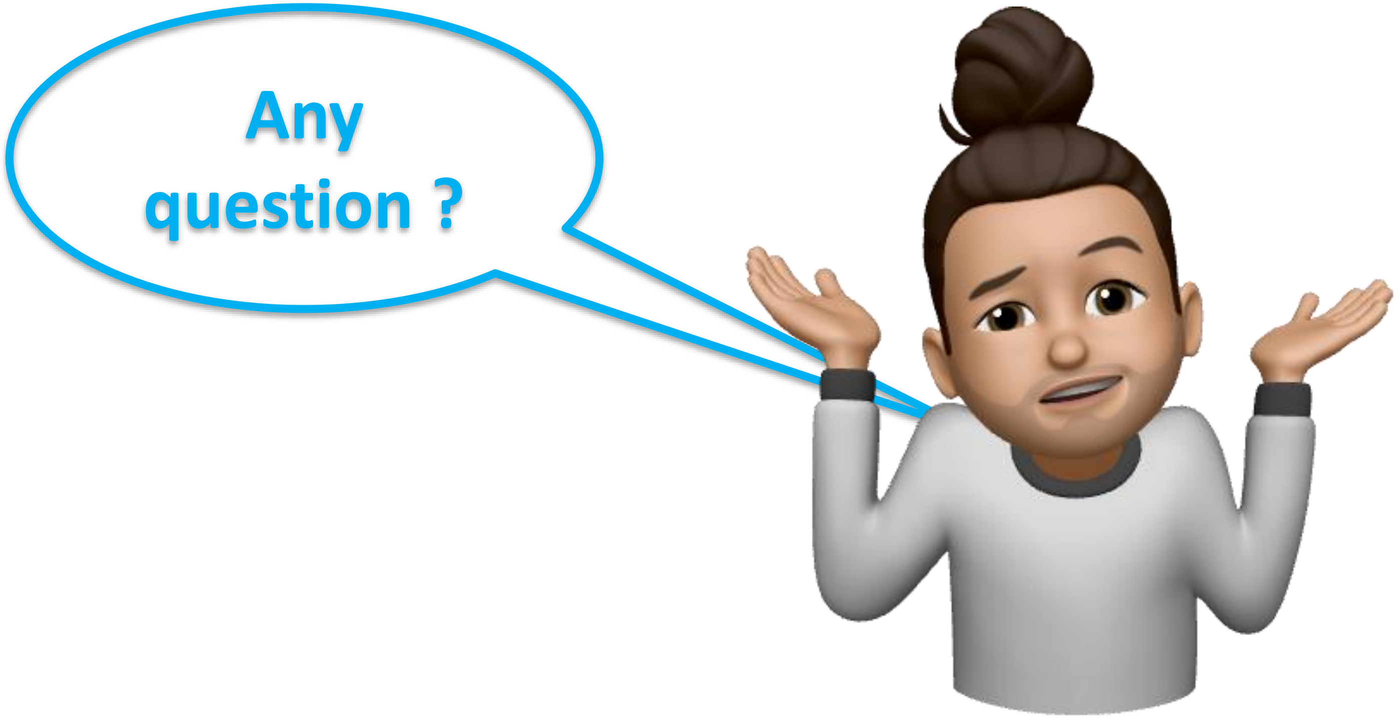
Outlooks

- **Simulations of the interactions between radiations and matter with the MCNP Monte-Carlo transport code and nuclear data library by the NRL**
  - Considering the neutron and photon spectra (as a function of the reactor power)
  - Applying photon-electron and neutron-photon-electron MCNP modes
  - Determining the nuclear absorbed dose rate for each part of the calorimeter

Local heat sources for each part

- **Experimental characterization under laboratory conditions and under MIT-R conditions with the full-assembly calorimeter**
- **Thermal property measurements for the right temperature range**

Thank you for your attention

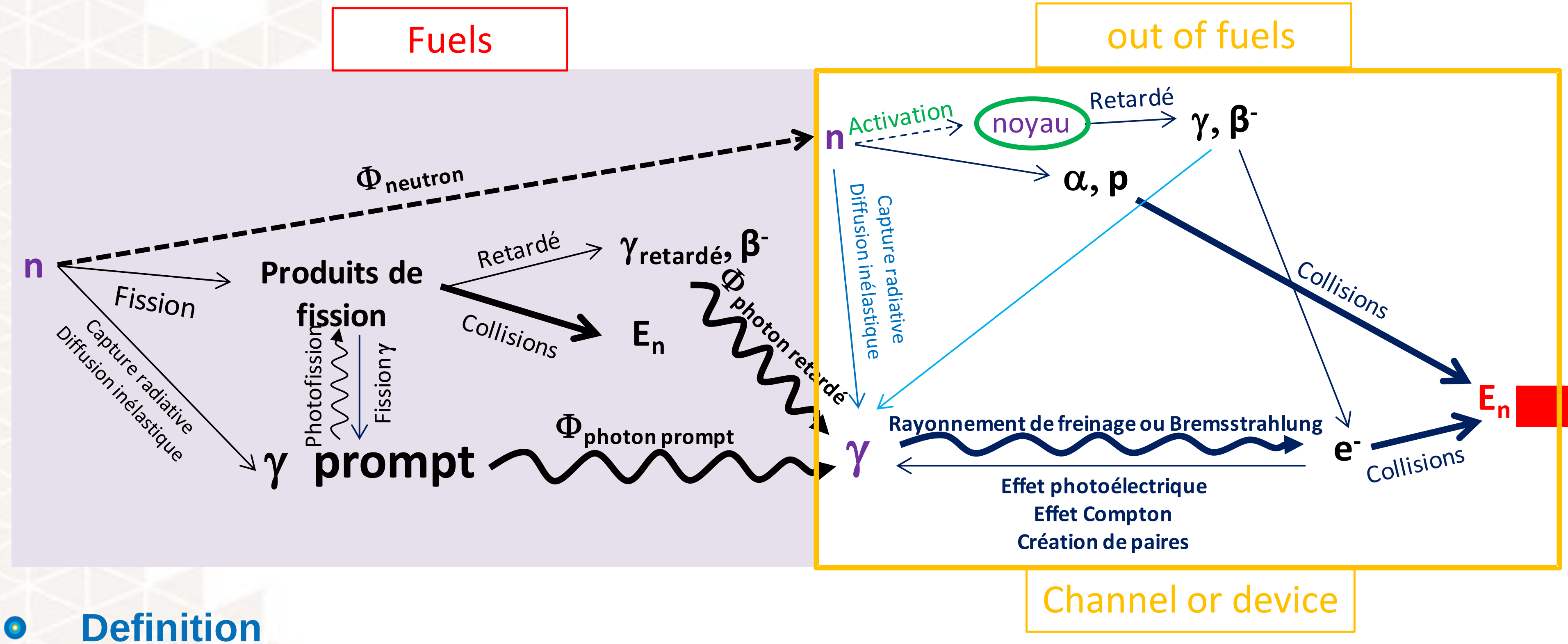


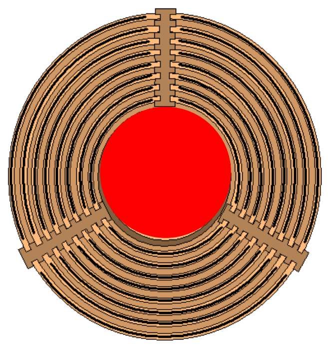
Acknowledgements: *"The CALOR-I project leading to this publication has received funding from the Excellence Initiative of Aix-Marseille University - A*Midex, a French "Investissements d'Avenir" programme".*

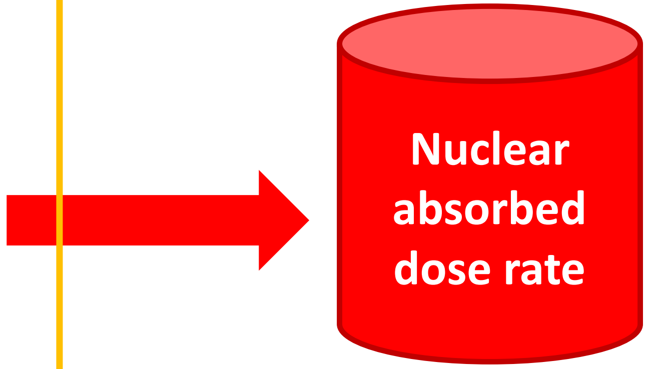
Back-up

Origin

- from neutron to radiation interactions with matter







Definition

⇒ E_n = Energy deposition rate per unit of mass induced by the interactions between rays and matter

M. Lemaire, Thèse, 2015. C. Reynard-Carette, Proceedings ANIMMA, 2018. A. Lyoussi, EDP sciences, 2010.

General context

❑ Irradiation devices

- <u>In reflector:</u>
  - ❑ ADELINE
  - ❑ MADISON
  - ❑ LORELEI
  - ❑ CLOE
  - ❑ OCCITANE
  - ❑ MOLFI
- <u>In core and reflector:</u>
  - ❑ CALIPSO, MICA
  - ❑ CARMEN
  - ❑ FUSERO

❑ Measured quantities

- <u>physical quantities in the heat transfer fluid and devices:</u>
  - ❑ *Temperature*
  - ❑ *Pression*
  - ❑ *Flow rate*
  - ❑ *Composition of fission gazes*
  - ❑ …
- <u>physical quantities in the heat transfer fluid and devices:</u>
  - ❑ *Neutron and Photon fluxes*
  - ❑ *Fluence*
  - ❑ *Activation*
  - ❑ *Nuclear absorbed dose rate*
  - ❑ …

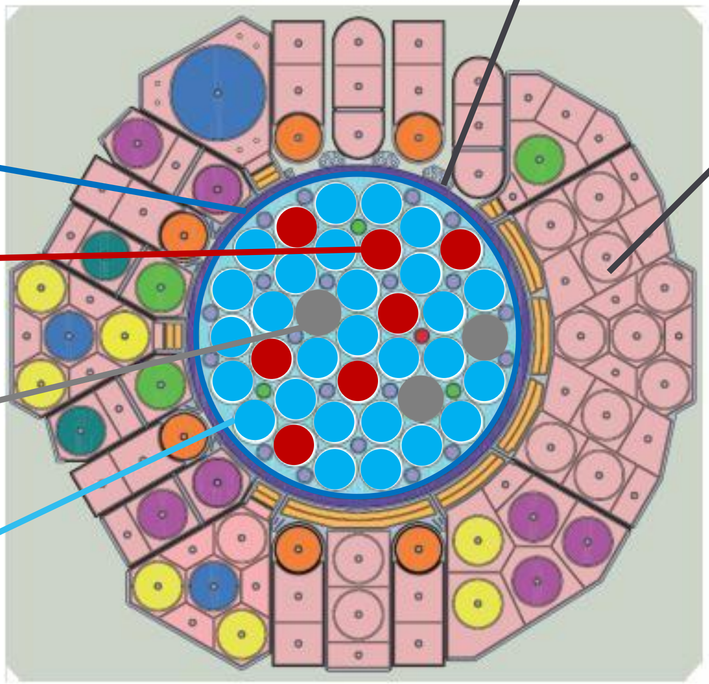
<u>Key parameter → Nuclear absorbed dose rate:</u>

Energy deposition rate per unit of mass induced by the interactions between rays and matter

Jules Horowitz Reactor (JHR)

Core and reflector geometry

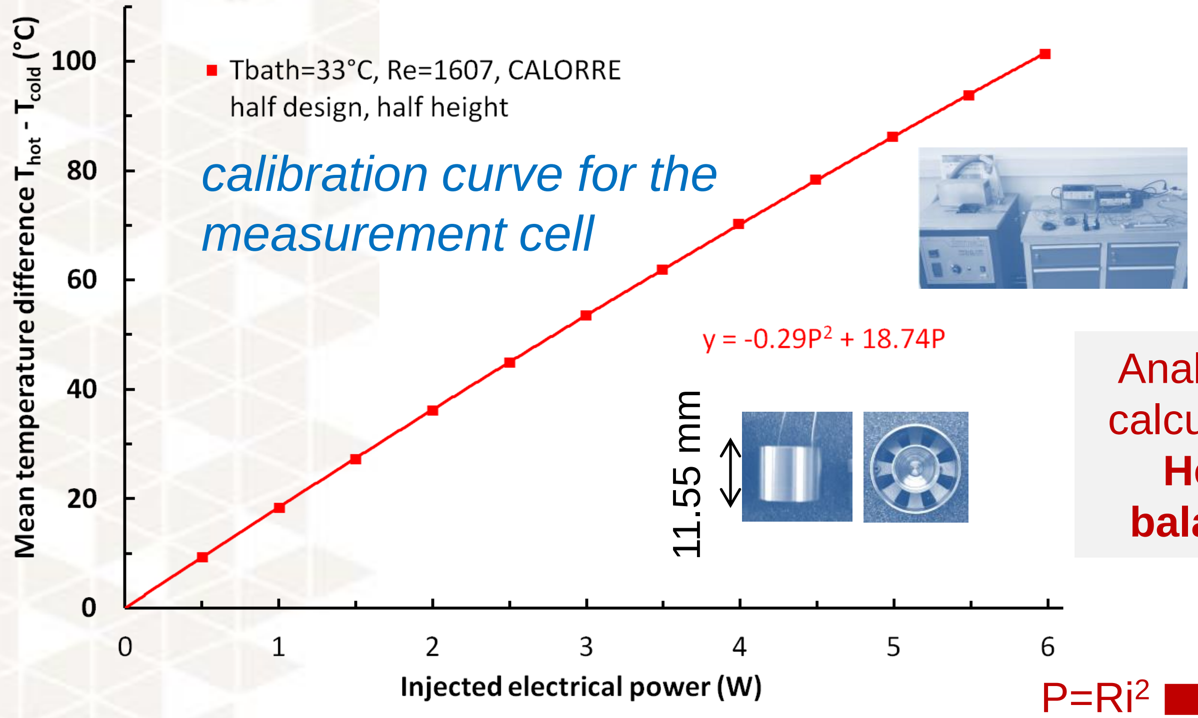
- 37 cells of which 34 with fuel
- 27 with control bars
- 7 + 3 with experimental or irradiation devices



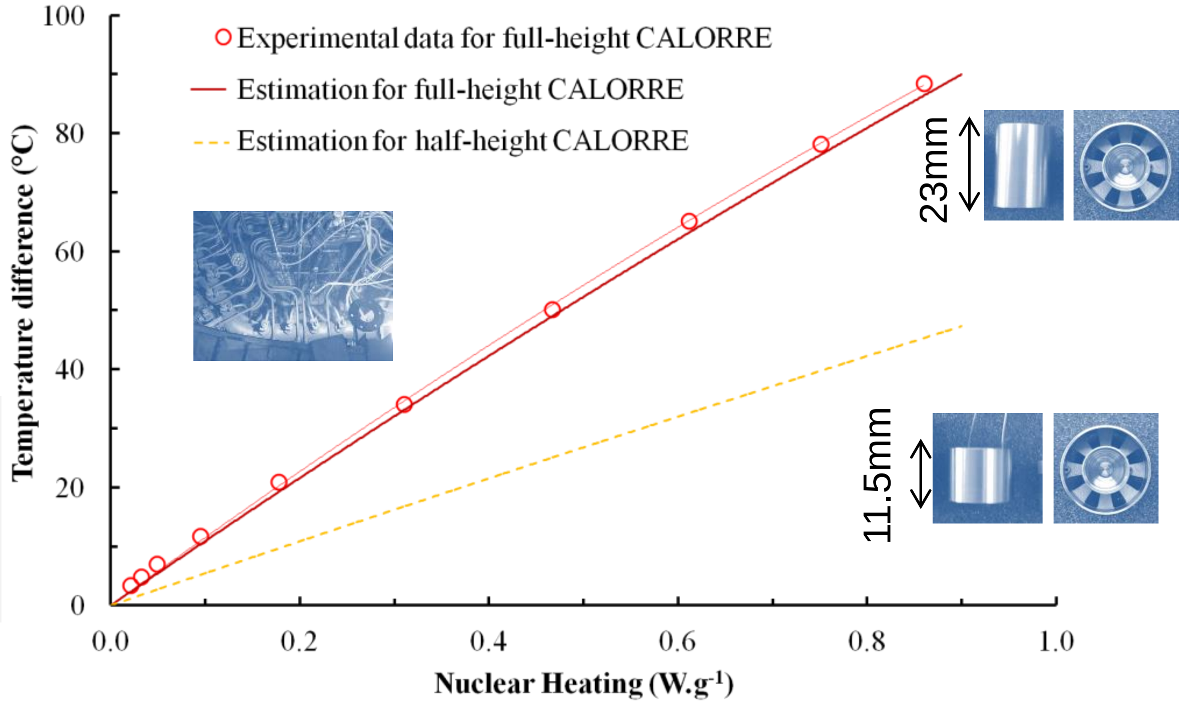
20 simultaneous experiments (mobile or static devices) in core or reflector

Estimation under real conditions

❑ Validation of the predictive model



Analytical calculation
Heat balance



$P=Ri^2$ → $P = (m_{graphite}+m_{head\ structure})*E_n$ → ΔT

-**nuclear heating** expected [$W.g^{-1}$]
-**mass** of head structure, shim, sample holder, heating element and sample [g]

Calculation of **Power deposition in the head**

Prediction of the **Temperature difference** of the half-height configuration inside the reactor

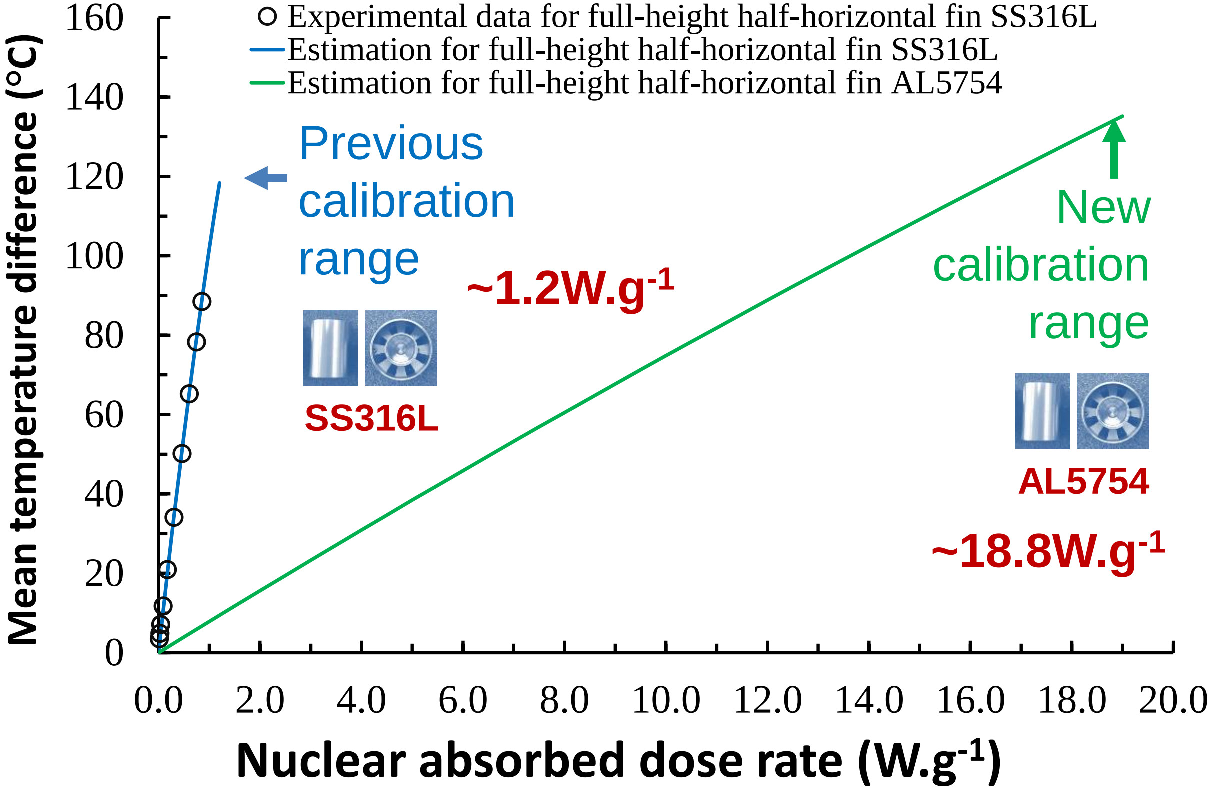
Estimation under real conditions

Predictive response under nuclear conditions

- **Prediction of Temperature difference of the calorimetric cell inside the reactor for a nuclear dose rate range:**
  - by an Heat balance with an analytical calculation by considering:
    - nuclear heating values [W.g^{-1}]
    - mass of head structure, shim, sample holder, heating element and sample [g]

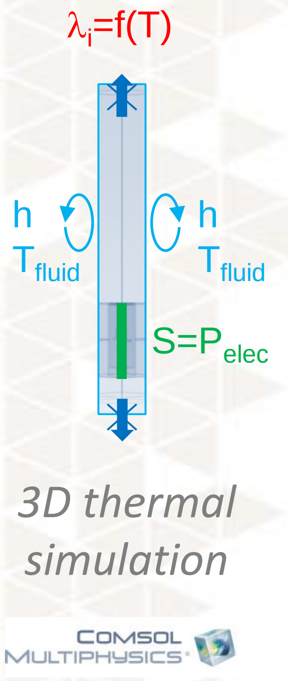
    - out-of pile calibration results (**A_1=2.47°C.W^{-1}, A_2=-0.004°C.W^{-2}**)

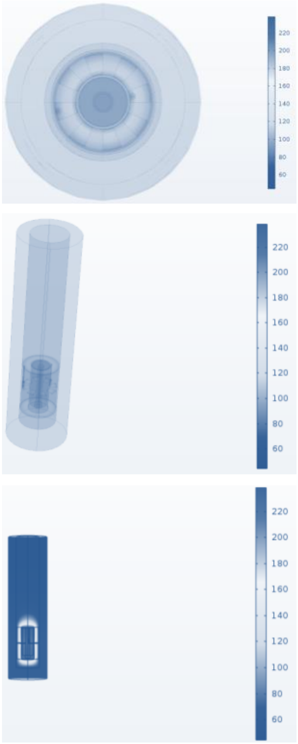
MARIA
Mapping of H-IV-B

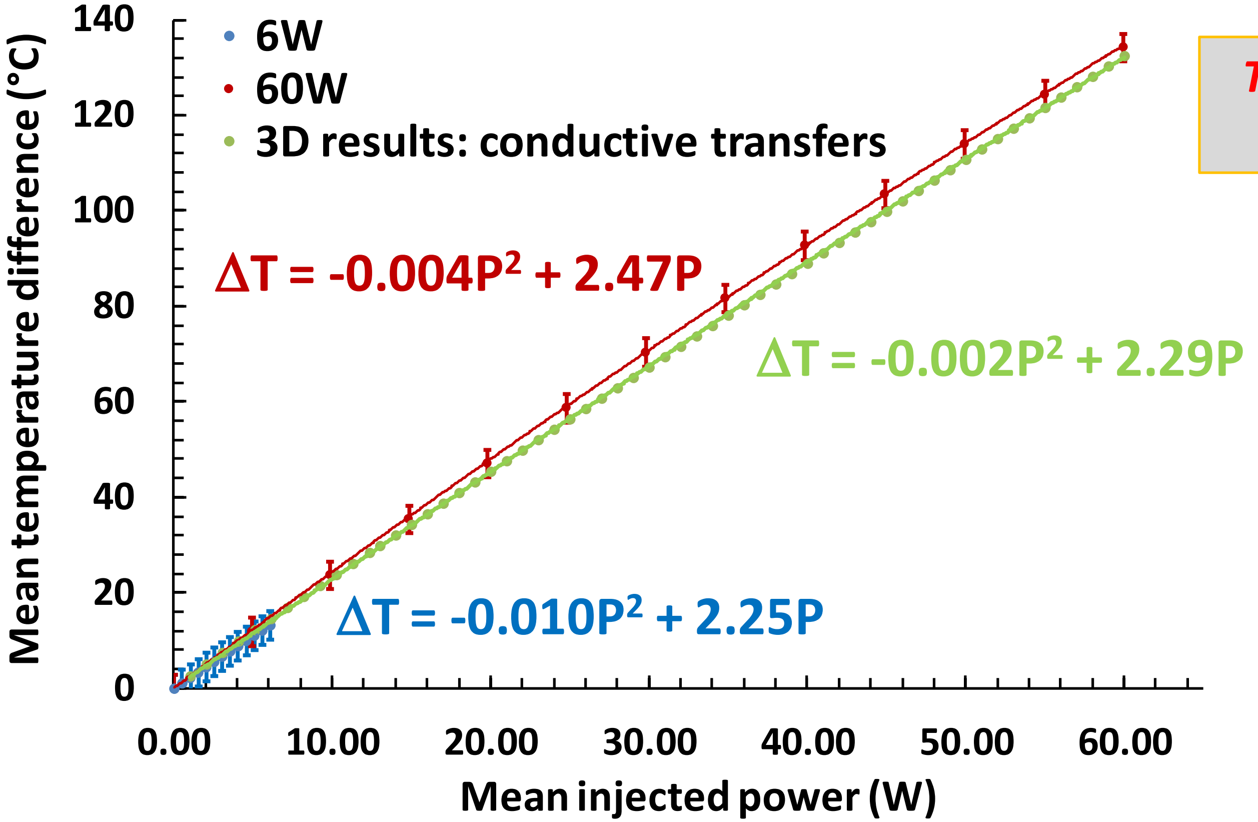


Predictive model validated with previous CALORRE irradiation campaign
At 18.8W.g^{-1} → ΔT<150°C → T_{abs}< 300°C

3-D thermal simulations & experimental comparison under laboratory conditions







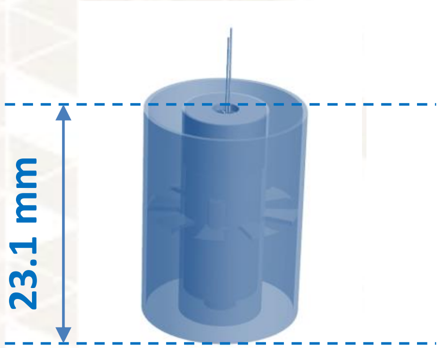
T_{bath}=33°C
Re=1607

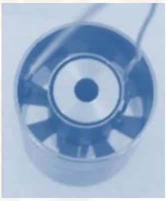
Model taking into account conductive transfers only (1D results, low temperatures)
Good agreement between experiments and 3D simulations C/E -1=-2.5%

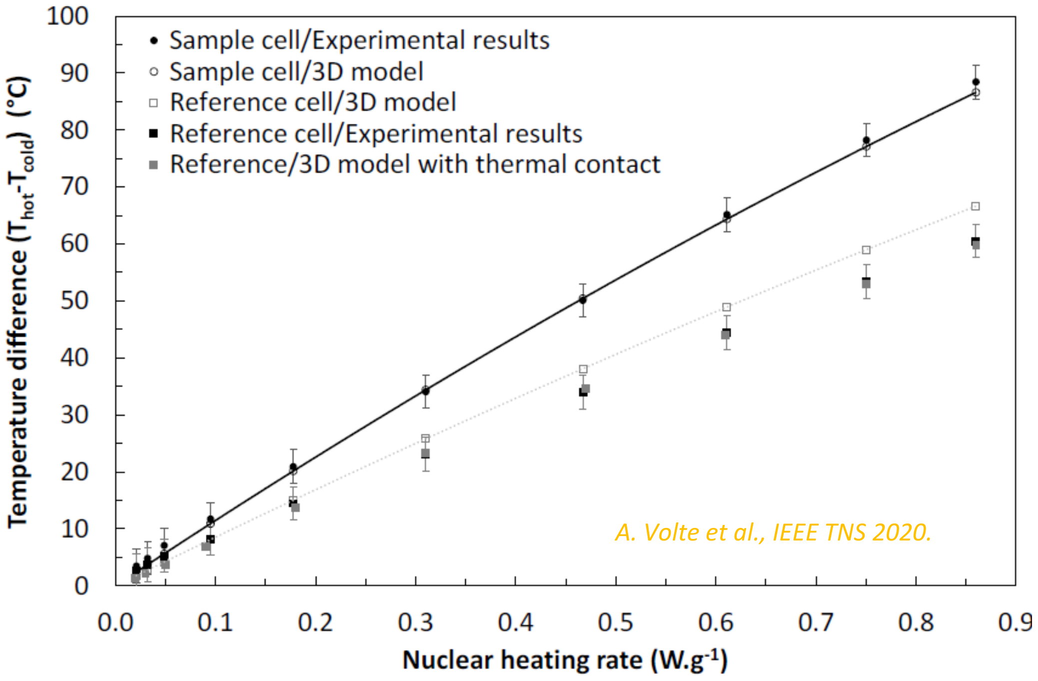
3-D thermal simulations under real conditions for the new cell design

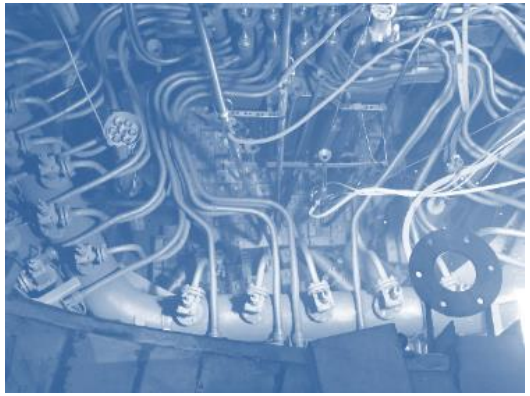
❑ 3-D model validation

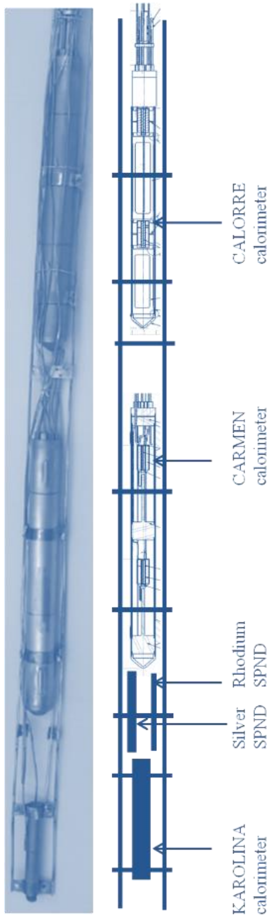
➢ Differential calorimeter under real conditions in the polish MARIA reactor











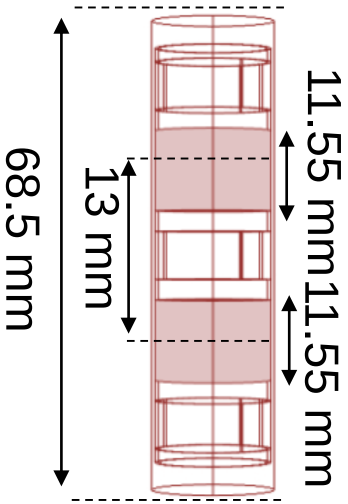
CALORRE tested successfully for the first time in MARIA reactor
But impact of the thermal resistance between the vertical fin and the jacket

Study of the response under real conditions by 3D numerical thermal simulations

❑ Reduction of the total height of the calorimeter

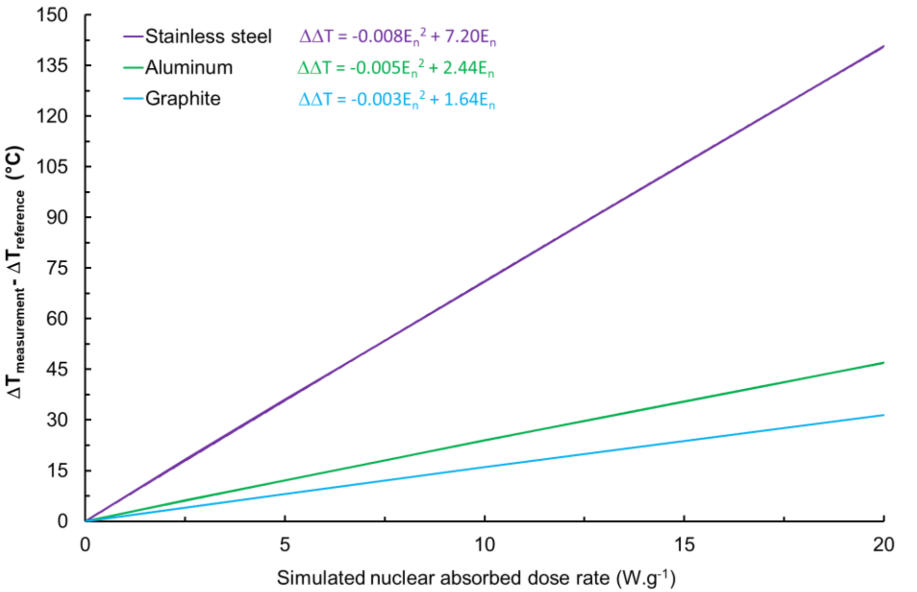
❑ 3-D geometry

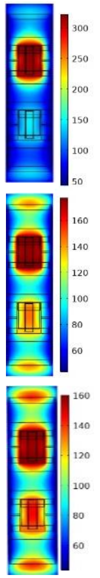
- Whole calorimeter: assembly (without cables, plug and nose), H_{tot}=68.5 mm, inter-cell space of 13mm
- Sample: made of graphite, aluminum, stainless steel
- Inert gas: nitrogen



❑ 3-D thermal model

- Heat transfers: thermal conduction (λ_i=f(T)) and thermal radiative transfers (ε=0.25)
- Heat sources: $S_i = E_n * \rho_{material\ i}$ *with* E_n *up to 20W.g*$^{-1}$
- Boundary conditions: forced convection heat transfer fluid (water) with T_{fluid}=33 °C, h=7325W.K^{-1}.m^{-2}





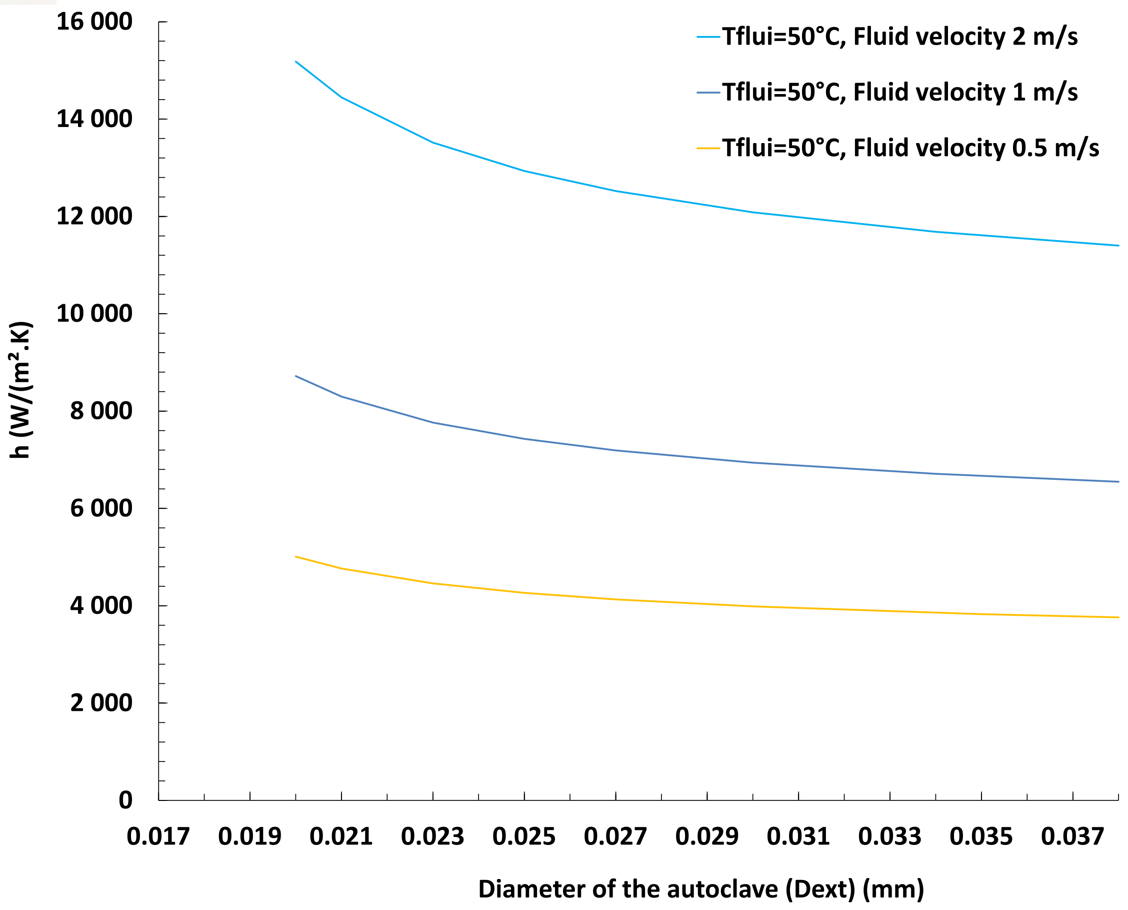
Sample	T_{max}	T_{wall}	$S_{calorimeter}$
Graphite	160 °C	73.6 °C	1.51 °C.g.W^{-1}
Aluminum	177 °C	73.6 °C	2.25 °C.g.W^{-1}
Stainless steel	322 °C	73.7 °C	6.86 °C.g.W^{-1}

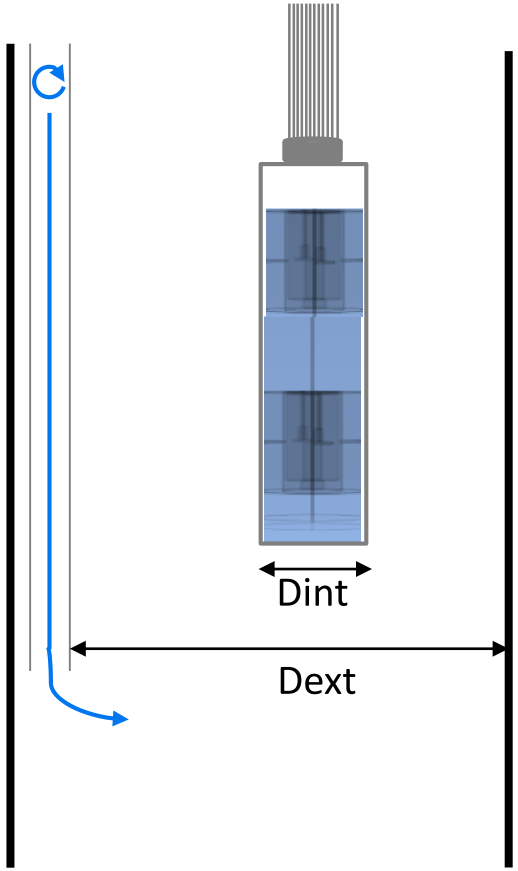
E_n=20 W.g^{-1}

Reduction of H_{cell} → reduction of the m_{sample} → reduction of the sensitivity and T_{max} under real conditions
Change in nature material → ΔΔT from 31.5 °C (graphite) to 140 °C (stainless steel)

3-D thermal simulations under real conditions for the new cell design

Heat transfer coefficient value





$$Nu = 0.023Re^{0.8}Pr^{0.4}\left(0.86\left(\frac{D_{int}}{D_{ext}}\right)^{-0.16}\right)$$