



**HAL**  
open science

## Porosity dependence of thermal conductivity in UO<sub>2</sub> nuclear fuels

J. Meynard, M. Garajeu, R. Masson, Michel Bornert, C. Duguay, A. Monnier

► **To cite this version:**

J. Meynard, M. Garajeu, R. Masson, Michel Bornert, C. Duguay, et al.. Porosity dependence of thermal conductivity in UO<sub>2</sub> nuclear fuels. 55th Annual Technical Meeting SES (ses2018.org), Oct 2018, Madrid, Spain. cea-02338467

**HAL Id: cea-02338467**

**<https://cea.hal.science/cea-02338467>**

Submitted on 21 Feb 2020

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

DE LA RECHERCHE À L'INDUSTRIE

cea

CADARACHE



laboratoire de mécanique et acoustique

Navier

[www.cea.fr](http://www.cea.fr)

# Porosity dependence of thermal conductivity in $\text{UO}_2$ nuclear fuels

Joane Meynard

2<sup>nd</sup> year PhD student

55<sup>th</sup> Annual Technical Meeting SES

Thesis directors:

Mihail Garajeu

Renaud Masson

LMA, CNRS Marseille

DEC/SESC/LM2C, CEA Cadarache

Thesis supervisors:

Michel Bornert

Christelle Duguay

Arnaud Monnier

Laboratoire Navier, EP ParisTech

DEC/SA3E/LCU, CEA Cadarache

DEC/SESC/LSC, CEA Cadarache

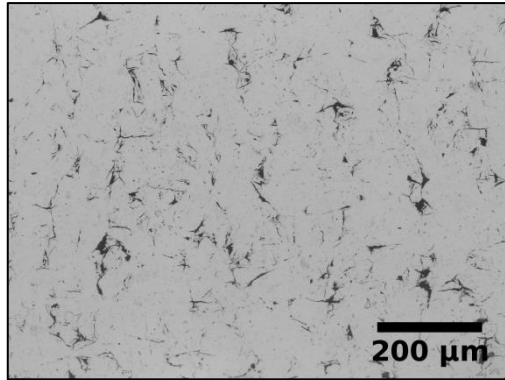
OCTOBER 12<sup>TH</sup> 2018

# BACKGROUND AND KEY ISSUE

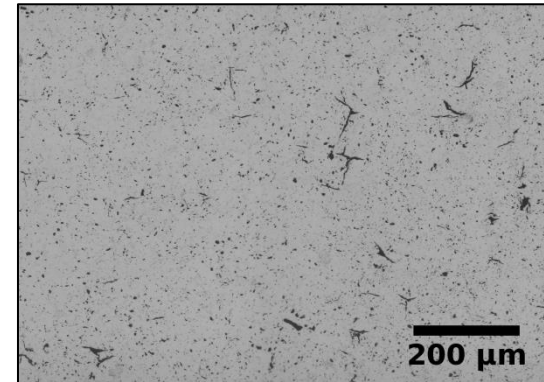
## ■ Limits of classic conductivity $UO_2$ laws

→ One parameter only: % total porosity

- Example of two  $UO_2$  fuels with the same % porosity



$UO_2$  fuel A



$UO_2$  fuel B

% total porosity (%)	4,1 ± 0,1	
Thermal diffusivité $\alpha$ (mm <sup>2</sup> .s <sup>-1</sup> )	2,85 ± 0,04	2,99 ± 0,001

$$\left(\frac{\lambda_A}{\lambda_B}\right)_{exp} = \left(\frac{\alpha_A}{\alpha_B}\right)_{exp} = 0,93 \neq \left(\frac{\lambda_A}{\lambda_B}\right)_{classic \lambda_{UO_2} \text{ laws}} = 1$$

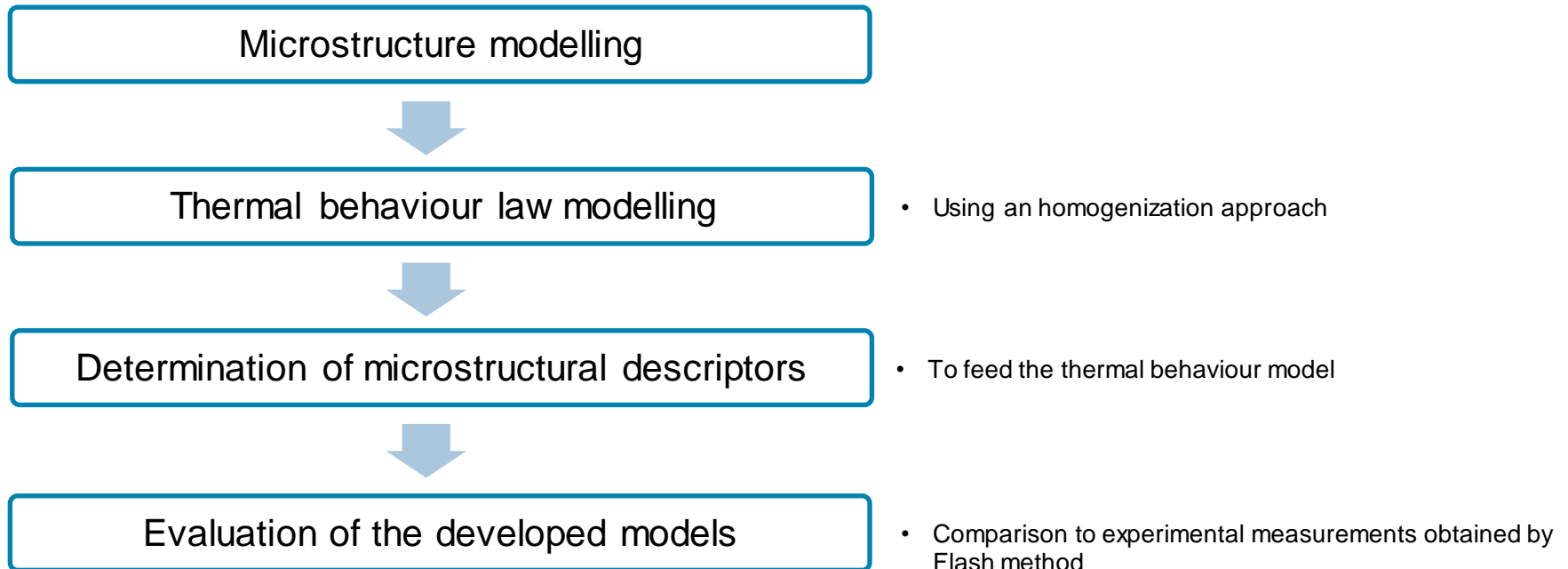
- Description of  $UO_2$  fuels with only the % total porosity is not adequate to describe the thermal behaviour of these fuels.



## ■ Objective

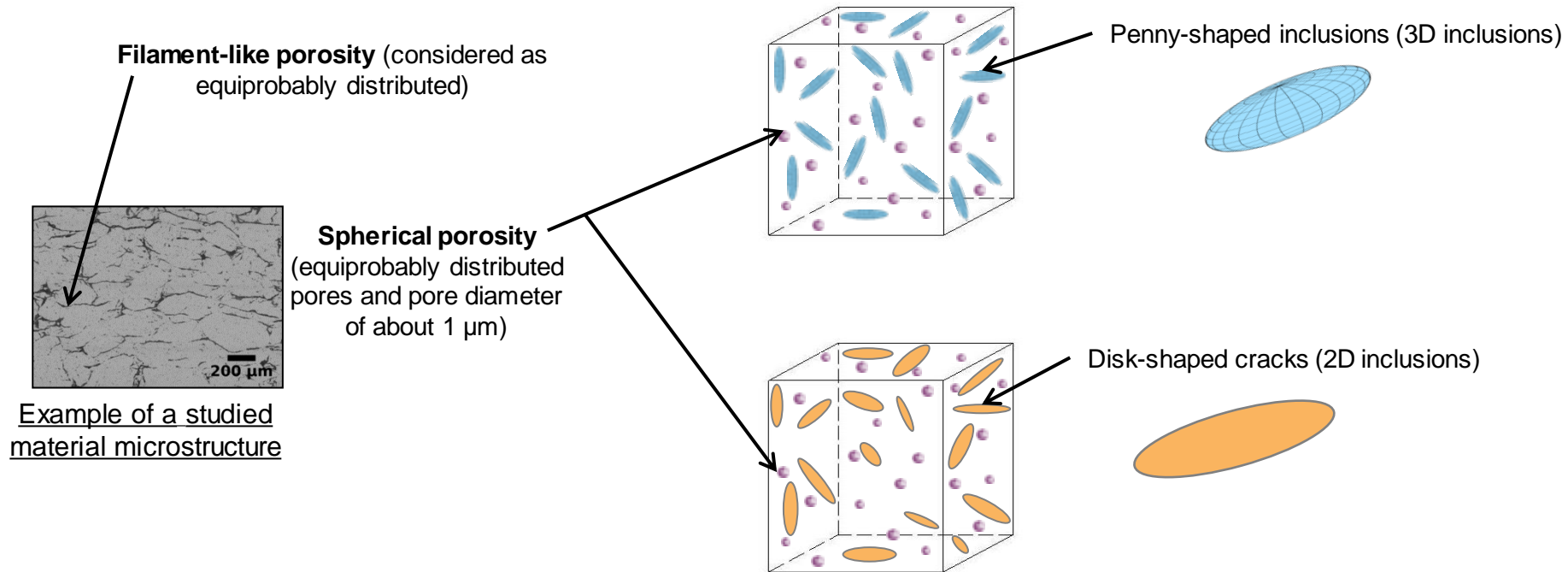
- Determination of a new thermal behaviour law which gives the influence of porosity (shape, orientation and network) on thermal conductivity for non-irradiated  $\text{UO}_2$  fuels

## ■ Presentation outline



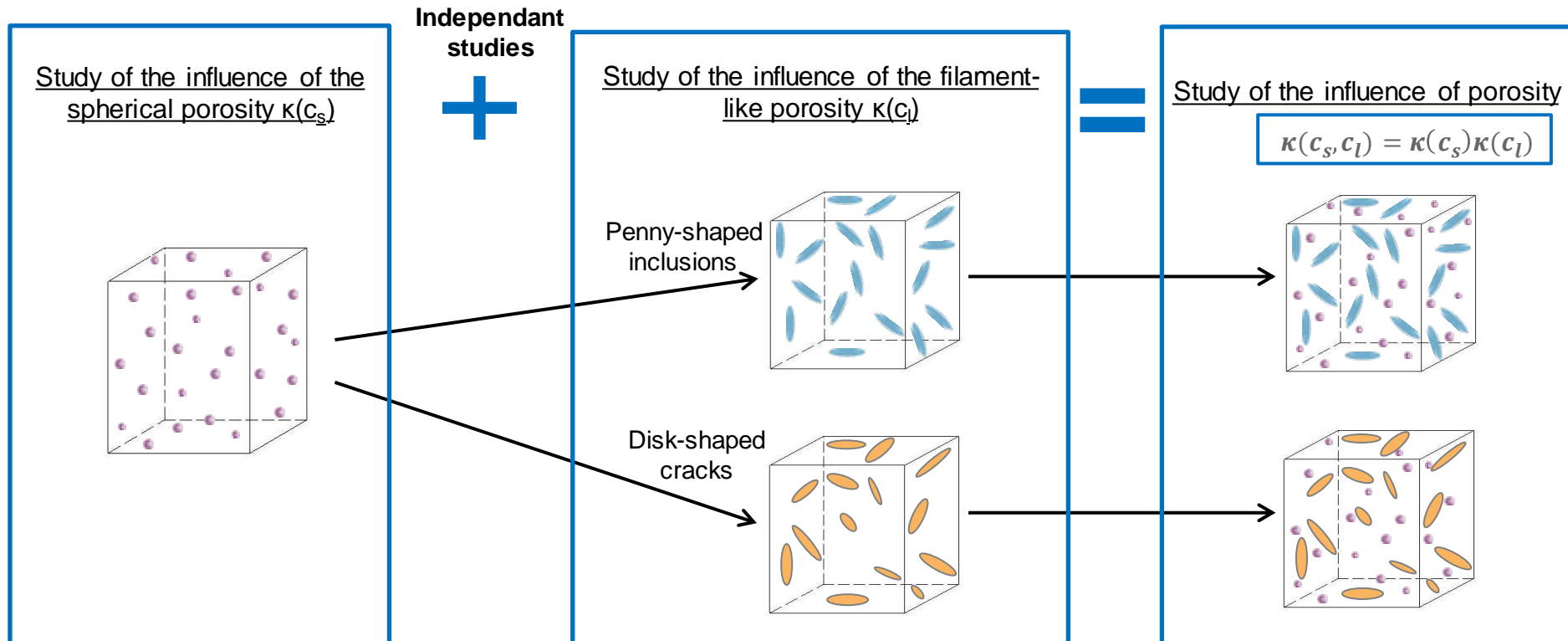
## ■ Descriptions of the studied material

- Two porosity types classified by pore morphology embedded into an urania matrix
- Two different descriptions of the studied material have been considered.



## ■ Homogenization approach

- Study of the characteristic dimensions of both porosity types  
→ Spatial scale separation between both porosity families
- Opportunity to study separately the influence of each family

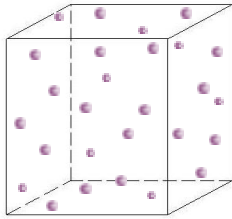


## Models developed

$$\kappa(c_s, c_l) = \kappa(c_s)\kappa(c_l)$$

→ **Determination of microstructural descriptors**

Study of the influence of the spherical porosity  $\kappa(c_s)$



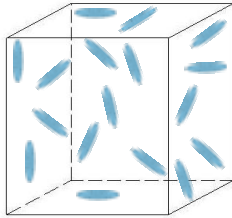
« Diluted medium » model for spherical pores equiprobably distributed in the matrix (first-order approximation of Maxwell model\*)

$$\kappa(c_s) = \left(1 - \frac{3}{2}c_s\right)I$$

→ % spherical porosity

Study of the influence of the lenticular porosity  $\kappa(c_l)$

Penny-shaped inclusions

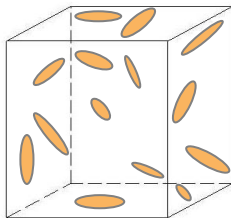


« Diluted medium » model\*\* for penny-shaped pores equiprobably distributed in the matrix (first-order approximation in  $c_l/\omega$ )

$$\kappa(c_l) = \left(1 - \frac{2}{3\pi} \frac{c_l}{\omega}\right)I$$

→ % filament-like porosity  
→ Penny-shaped inclusion aspect ratio

Disk-shaped cracks



« Diluted medium » model\*\*\* for disk-shaped cracks equiprobably distributed in the matrix

$$\kappa(\rho_f) = \left(1 - \frac{8}{3}\rho_f\right)I$$

→ Crack density

\* J.C. MAXWELL, *A treatise on electricity and magnetism*, 1873

\*\* H. L. DUAN et al., *Phys. Rev. B* **73**(17): 174203(13), May 2006

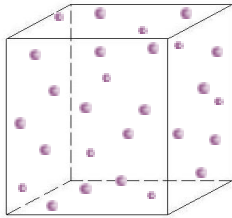
\*\*\* B. SHAFIRO et M. KACHANOV, *J. Appl. Phys.*, Vol. 87, No. 12, 2000

## ■ Determination of microstructural descriptors

$$\kappa(c_s, c_l) = \kappa(c_s)\kappa(c_l)$$

→ Evaluation of the models representativeness

Study of the influence of the spherical porosity  $\kappa(c_s)$

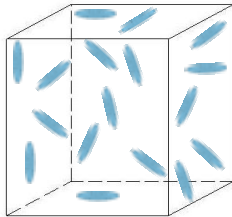


$$\kappa(c_s) = \left(1 - \frac{3}{2}c_s\right)I$$

% spherical porosity

Study of the influence of the lenticular porosity  $\kappa(c_l)$

Penny-shaped inclusions

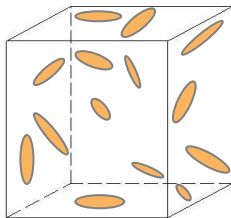


$$\kappa(c_l) = \left(1 - \frac{2}{3\pi\omega}c_l\right)I$$

% filament-like porosity

Penny-shaped inclusion aspect ratio

Disk-shaped cracks



$$\kappa(\rho_f) = \left(1 - \frac{8}{3}\rho_f\right)I$$

Crack density

Bromobenzene saturation method

Image analysis

\* J.C. MAXWELL, *A treatise on electricity and magnetism*, 1873

\*\* H. L. DUAN et al., *Phys. Rev. B* **73**(17): 174203(13), May 2006

\*\*\* B. SHAFIRO et M. KACHANOV, *J. Appl. Phys.*, Vol. 87, No. 12, 2000



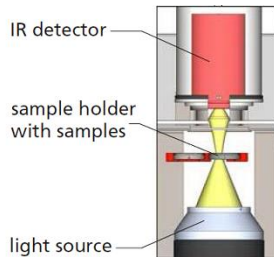
## ■ Principle

- Comparison of the developed models to thermal diffusivity measurements (indirect thermal conductivity measurements)

$$\lambda = \rho c \alpha$$

Thermal conductivity ( $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ) ←      → Thermal diffusivity ( $\text{m}^2\cdot\text{s}^{-1}$ )  
 Density ( $\text{kg}\cdot\text{m}^{-3}$ ) ←      → Specific heat capacity ( $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ )

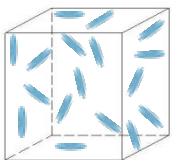
- Protocol of thermal diffusivity measurements by Flash method\*



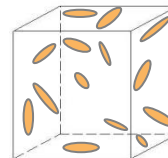
- Delivery of a short-term excitation pulse to the sample
- Heat transfer by conduction
- Thermogram recorded at the rear of the sample
- Signal fitting to the Cape-Lehman model (which considers radial and facial thermal losses and pulse duration)

Basic diagram of the Flash method apparatus

## ■ Evaluation of the representativeness of the filament-like model

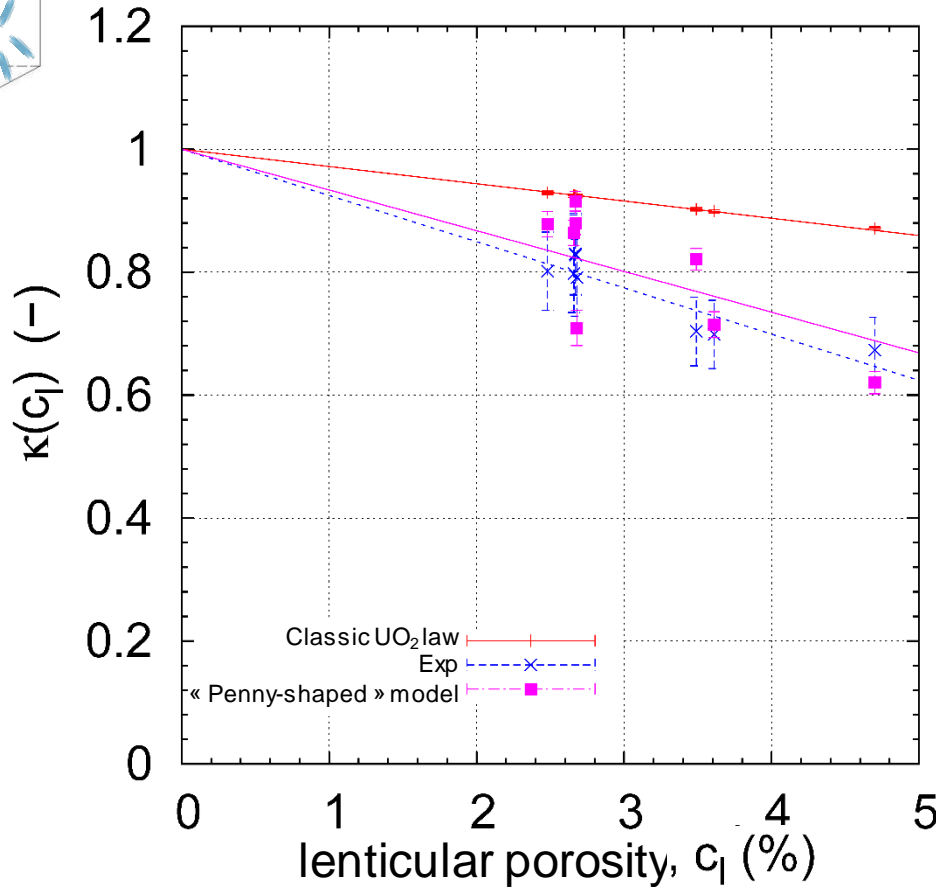
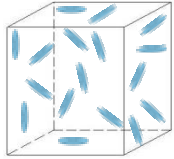


Penny-shaped inclusion model



Disk-shaped crack model  
→ **Still in process**

## Evaluation of the penny-shaped inclusion model



- + Penny-shaped inclusion model more representative than the classic conductivity  $UO_2$  law
- Remaining model/experience bias which does not allow a distinction between  $UO_2$  fuels based on their thermal behaviour

$$\kappa_{model}(c_l) = \left( 1 - \frac{2}{3\pi} \frac{c_l}{\omega} \right) I$$

Bias induces by the characterization of the aspect ratio  $\omega$

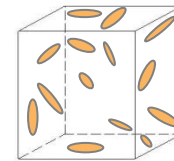
Evaluation of the representativeness of the “penny-shaped” model

## ■ Conclusions

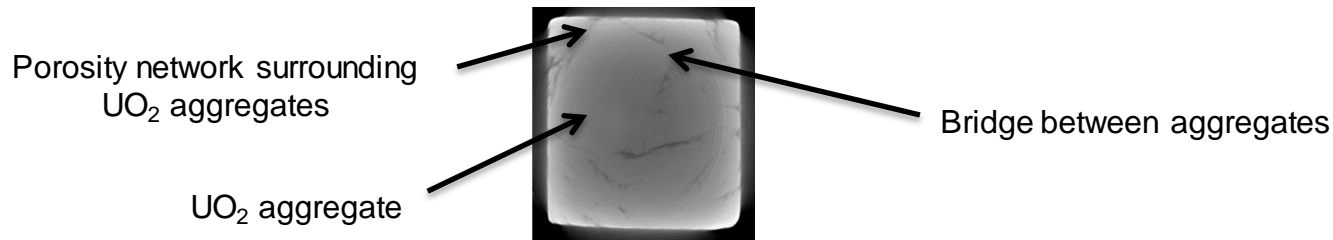
- Development of the penny-shaped inclusion model which is more representative than classic  $\text{UO}_2$  laws → The modelling of porosity dependency of thermal conductivity in  $\text{UO}_2$  nuclear fuels is improved.
- The penny-shaped inclusion model is not sufficient to discriminate different  $\text{UO}_2$  nuclear fuels. → Necessity to improve modelling

## ■ Work in progress

- Finalization of the disk-shaped crack model
  - Determination of the crack density  $\rho_f$
  - Evaluation of the representativeness of filament-like pores by disks
- Evaluation of filament-like pore interconnectivity with additional porosity imaging



$$\kappa(\rho_f) = \left(1 - \frac{8}{3}\rho_f\right) I$$



3D tomography experiment (slice of a  $\text{UO}_2$  sample)

---

Commissariat à l'énergie atomique et aux énergies alternatives  
Centre de Cadarache | DEC/SESC bt151 - 13108 Saint-Paul lez Durance  
T. +33 (0)4.42.25.23.66 | F. +33 (0)4.42.25.47.47  
Établissement public à caractère industriel et commercial | RCS Paris B  
775 685 019

Direction de l'énergie nucléaire  
Département d'études des  
combustibles  
Service d'études et de simulation du  
comportement des combustibles