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Porosity dependence of thermal conductivity in UO_2 nuclear fuels

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55th Annual Technical Meeting SES

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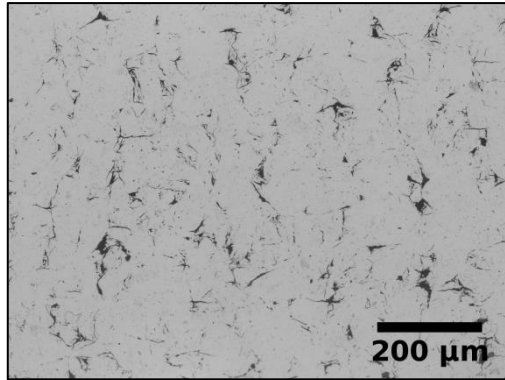
OCTOBER 12TH 2018

BACKGROUND AND KEY ISSUE

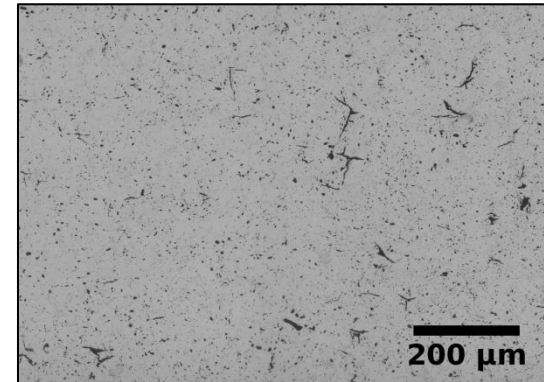
■ Limits of classic conductivity UO_2 laws

→ 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 diffusivity α (mm ² .s ⁻¹) | 2,85 ± 0,04 | 2,99 ± 0,001 |

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

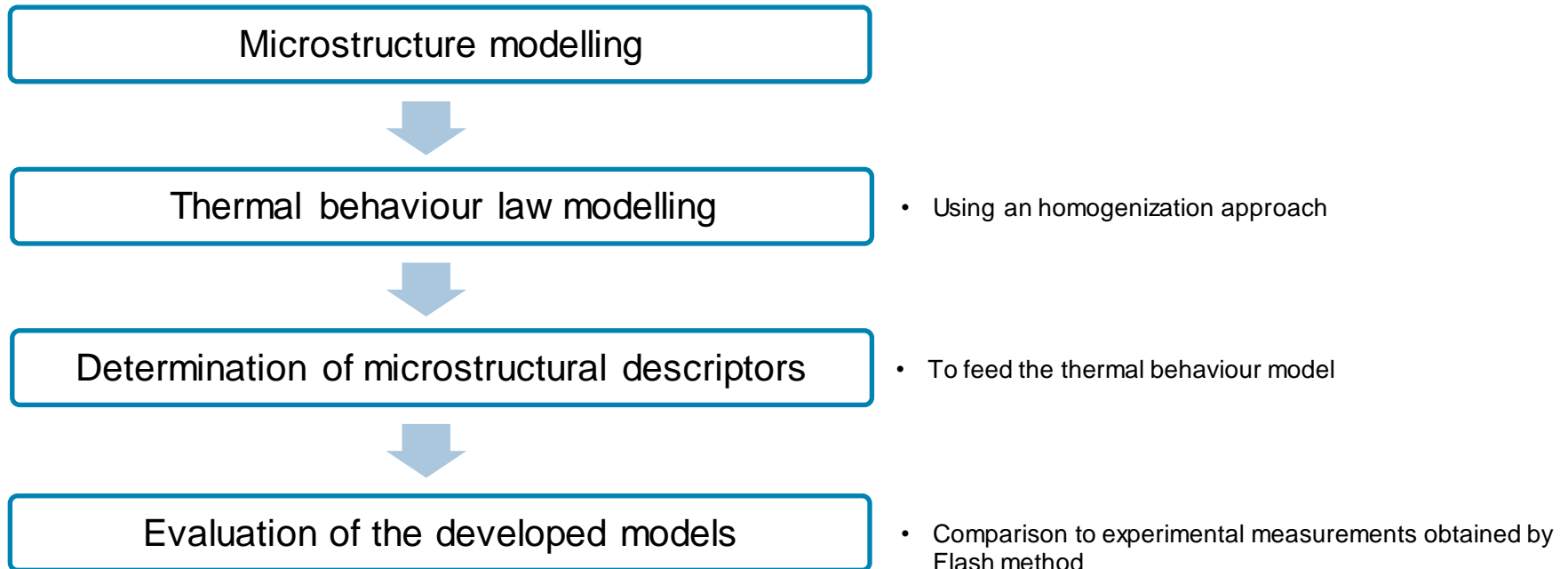
- Description of UO_2 fuels with only the % total porosity is not adequate to describe the thermal behaviour of these fuels.



■ Objective

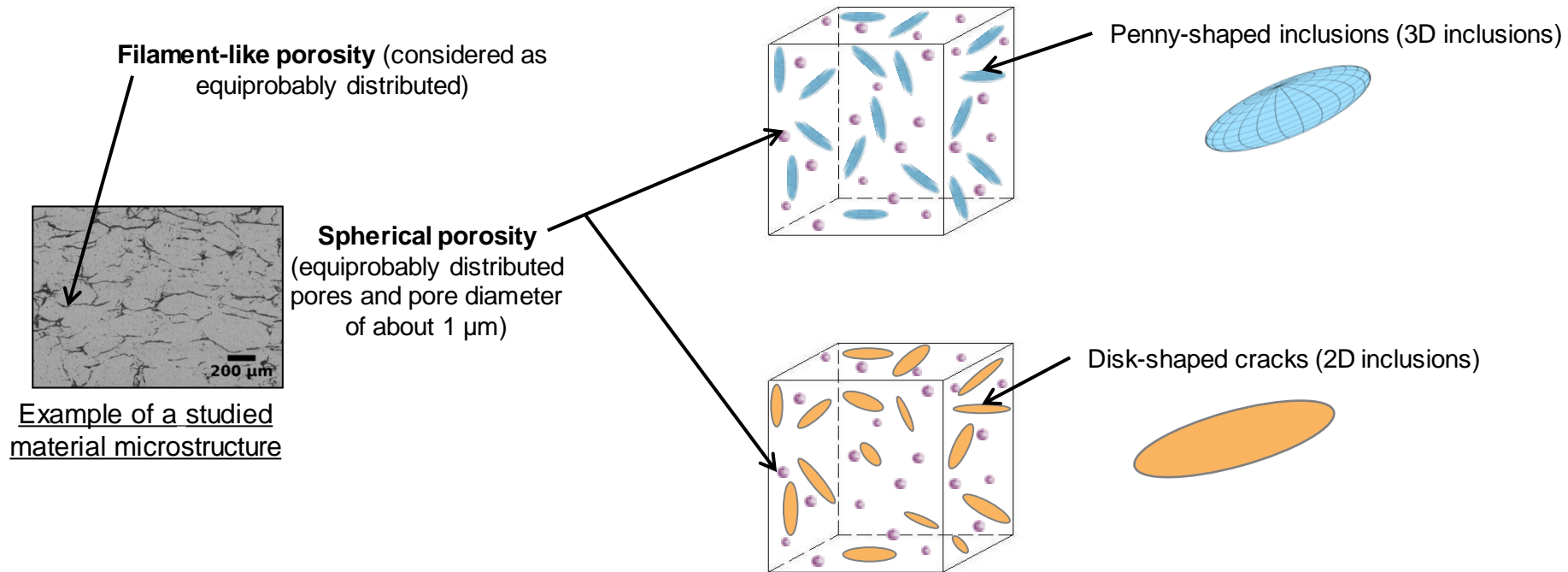
- Determination of a new thermal behaviour law which gives the influence of porosity (shape, orientation and network) on thermal conductivity for non-irradiated UO_2 fuels

■ Presentation outline



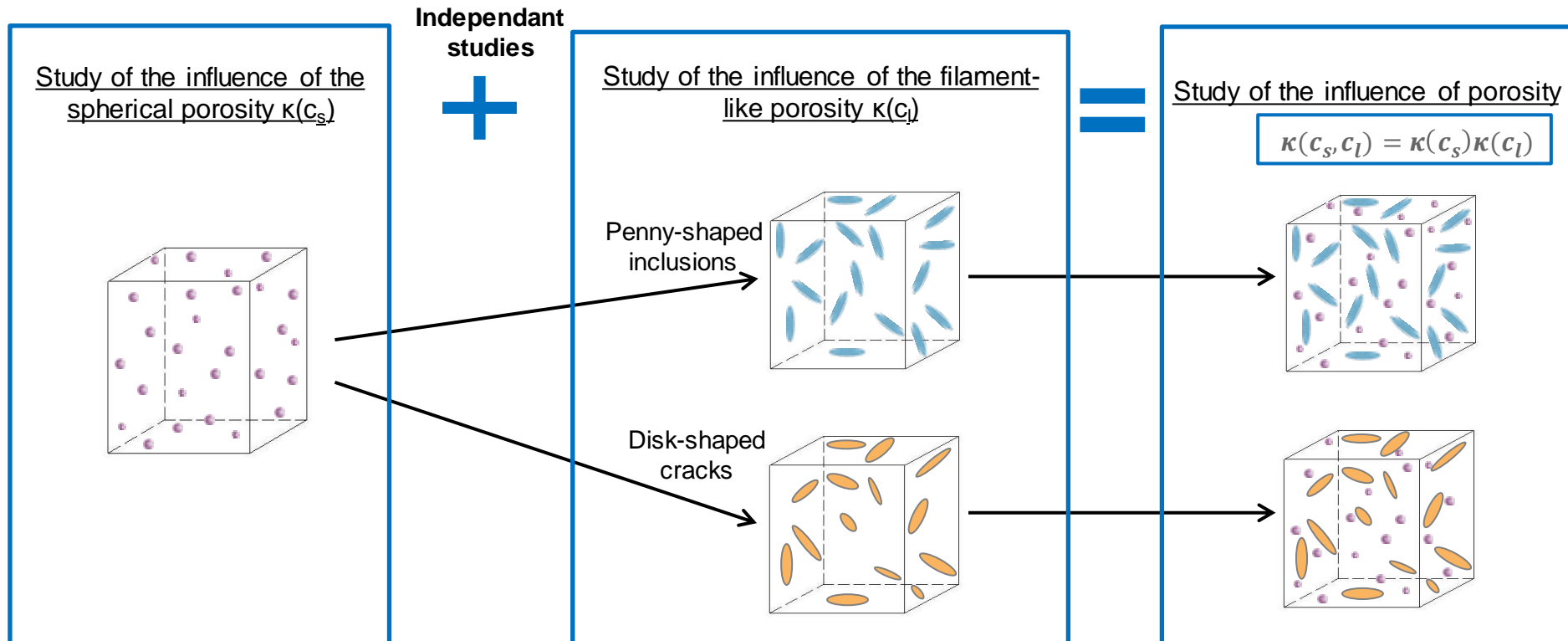
■ Descriptions of the studied material

- 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

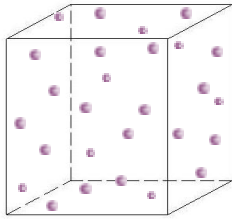


Models developed

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

→ **Determination of microstructural descriptors**

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



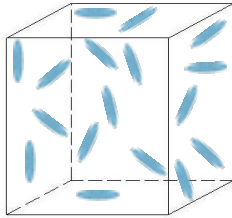
« Diluted medium » model for spherical pores equiprobably distributed in the matrix (first-order approximation of Maxwell model*)

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

→ % spherical porosity

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

Penny-shaped inclusions

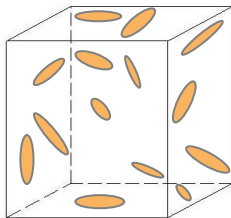


« Diluted medium » model** for penny-shaped pores equiprobably distributed in the matrix (first-order approximation in c_l/ω)

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

→ % 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

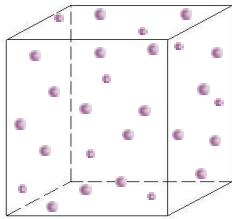
*** B. SHAFIRO et M. KACHANOV, *J. Appl. Phys.*, Vol. 87, No. 12, 2000

■ 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 $\kappa(c_s)$

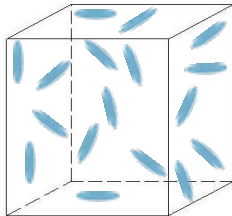


$$\kappa(c_s) = \left(1 - \frac{3}{2}c_s\right)I$$

% spherical porosity

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

Penny-shaped inclusions

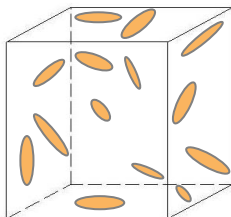


$$\kappa(c_l) = \left(1 - \frac{2}{3\pi\omega}c_l\right)I$$

% 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

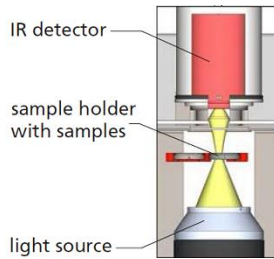
■ Principle

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

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

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

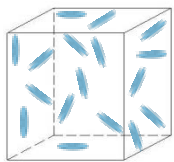
- Protocol of thermal diffusivity measurements by Flash method*



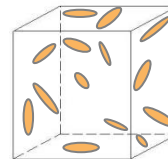
- Delivery of a short-term excitation pulse to the sample
- Heat transfer by conduction
- Thermogram recorded at the rear of the sample
- Signal fitting to the Cape-Lehman model (which considers radial and facial thermal losses and pulse duration)

Basic diagram of the Flash method apparatus

■ Evaluation of the representativeness of the filament-like model

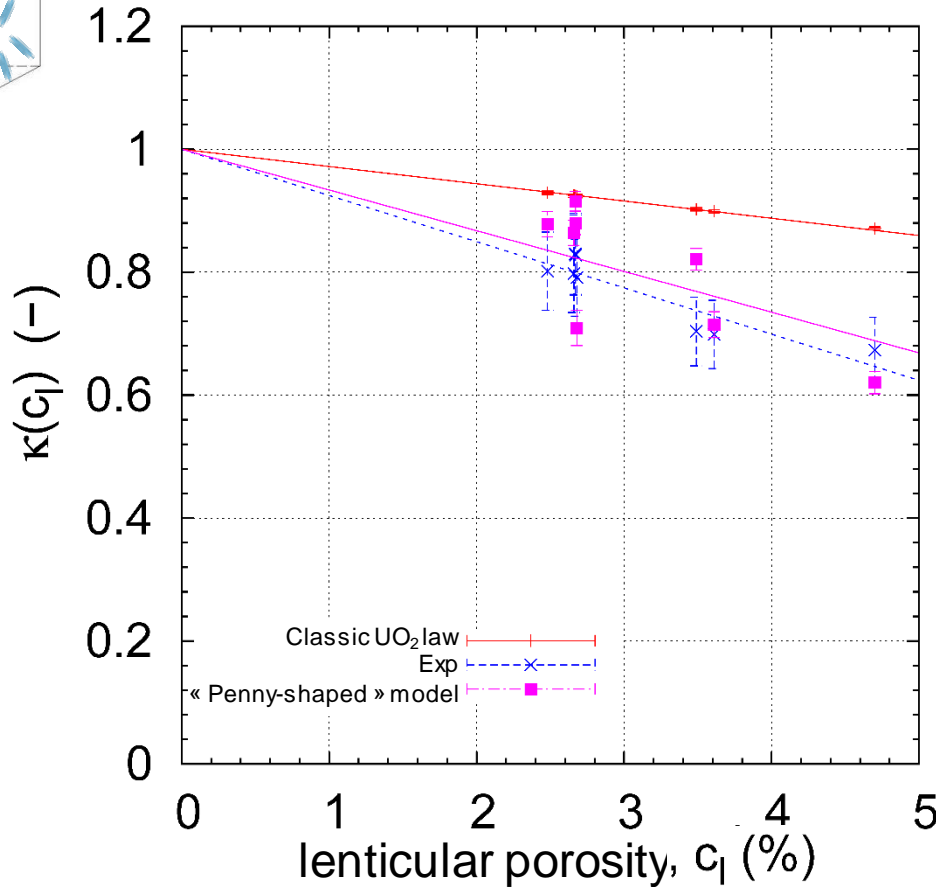
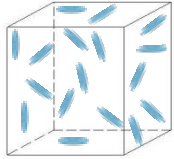


Penny-shaped inclusion model



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 ω

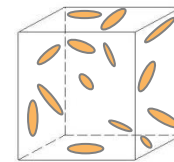
Evaluation of the representativeness of the “penny-shaped” model

■ Conclusions

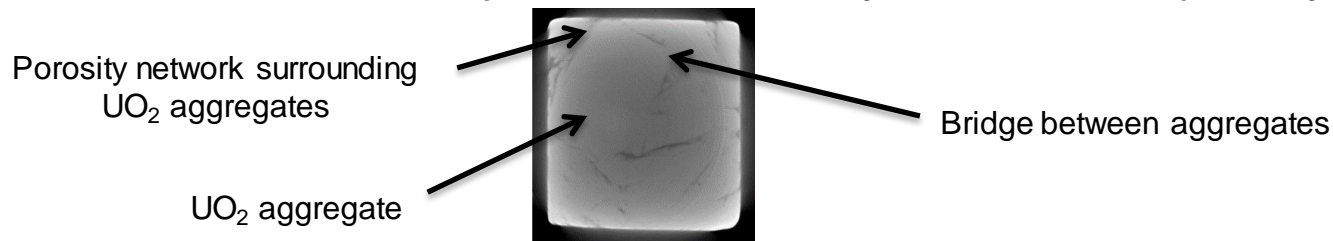
- Development of the penny-shaped inclusion model which is more representative than classic UO_2 laws → The modelling of porosity dependency of thermal conductivity in UO_2 nuclear fuels is improved.
- The penny-shaped inclusion model is not sufficient to discriminate different UO_2 nuclear fuels. → Necessity to improve modelling

■ Work in progress

- Finalization of the disk-shaped crack model
 - Determination of the crack density ρ_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 UO_2 sample)

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