X-RAY COMPUTED TOMOGRAPHY: AN OUTSTANDING VISUALISATION TOOL FOR DRYING RESEARCH
Feedback on the last 20 years at ULiège

CHEMICAL ENGINEERING

PEPs – Products, Environment, and Processes

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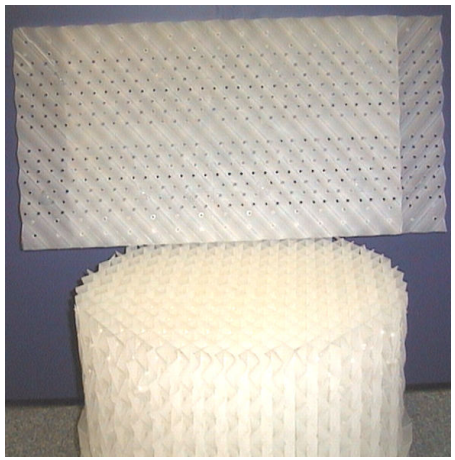
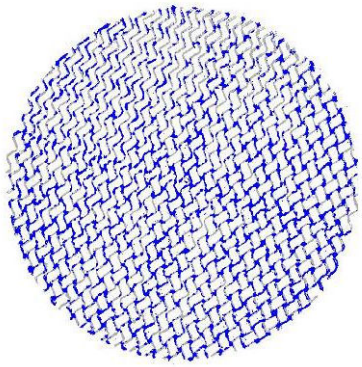
The context

Two key aspects

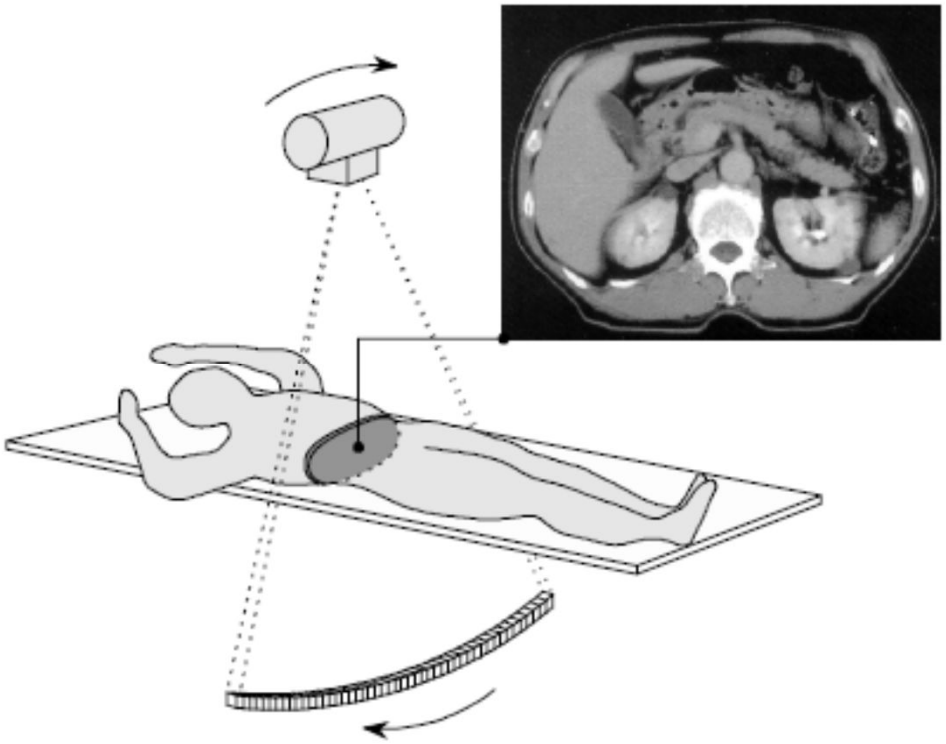
- Use of tomography
  - History of the lab: first european industrial macro-CT for chemical engineering applications (Toye et al.)



- Drying studies → needs of characterization tools

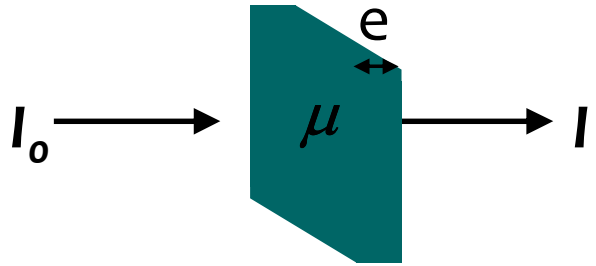
Basic principles



CT scan = computed tomography

Basic principles

- Based on X-ray attenuation



- Beer-Lambert law

$$\frac{dI}{I} = -\mu\, de$$

After integration

$$\frac{I}{I_0} = \exp(-\mu e)$$

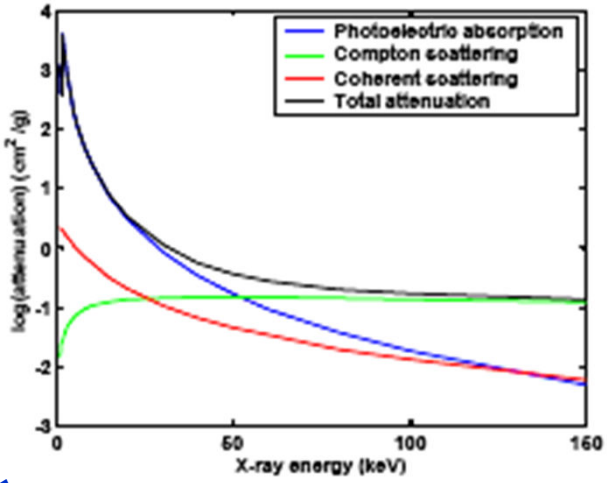
I = local beam intensity
e = material tickness (homogeneous)
μ = linear attenuation coefficient (cm^{-1})

Basic principles

- Attenuation varies with the material
  - atomic number Z
  - atomic mass A
  - density ρ
- Attenuation varies with incident beam energy
  - photoelectric absorption
  - Compton effect
- Correlations

E < $$\mu_P(e,E) = a\,\rho\,\frac{1}{E^3}\,\frac{Z^4}{A}$$

E > $$\mu_C(e,E) = b\,\rho\,\frac{Z}{A}$$

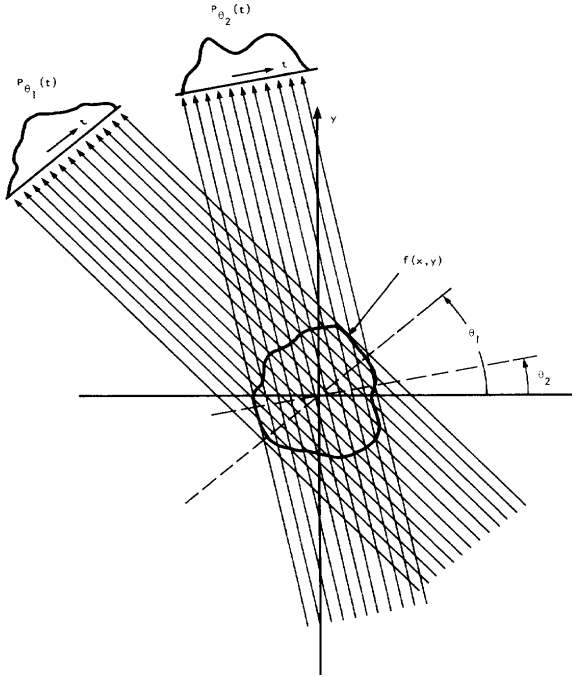


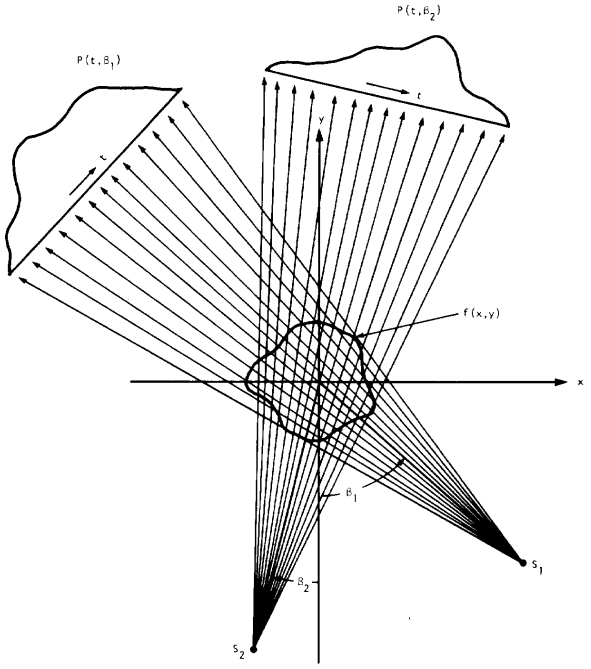
E <
(photoelectric effect)

E >
(Compton effect)

Basic principles

- Two distinct steps
  - Collection of projection data

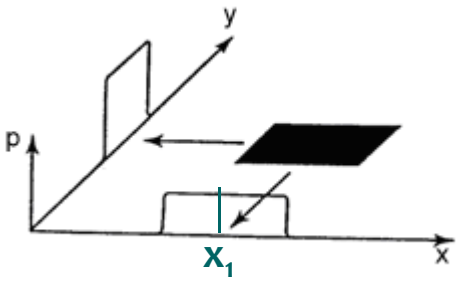




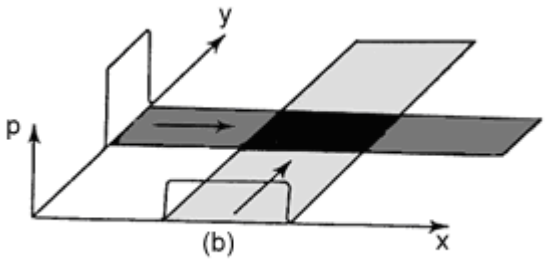
Basic principles

- Two distinct steps
  - Image reconstruction using linear back projection
  - Image = map of attenuation coefficients μ

Projections



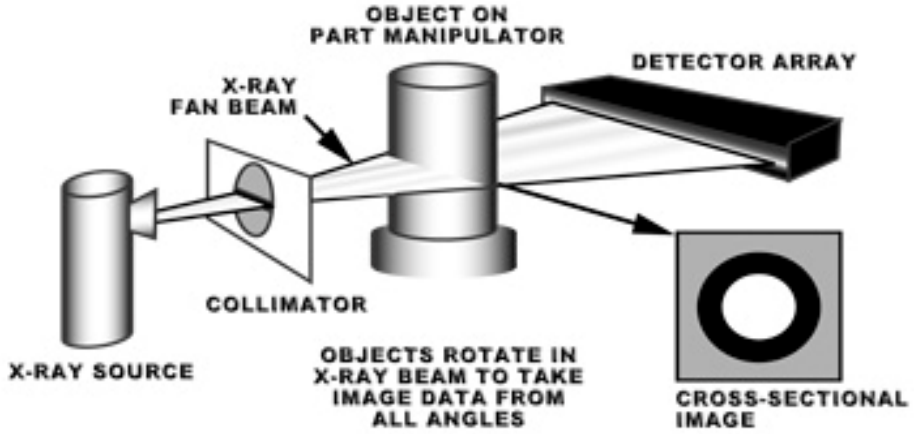
Back projection



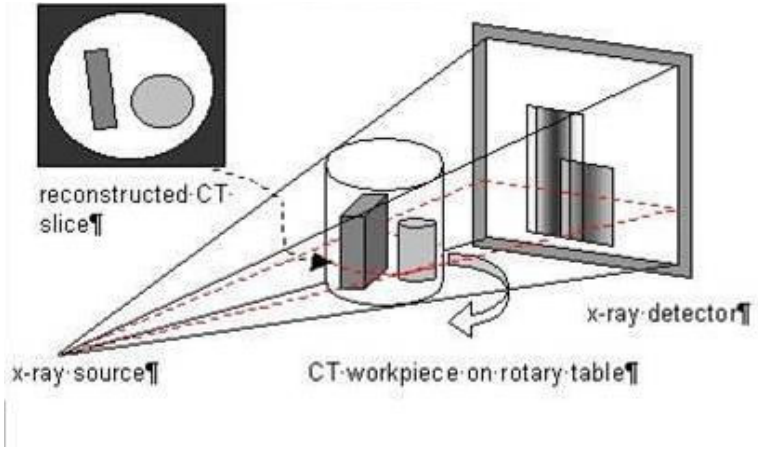
$$P_\theta(x_1) = -\ln\left(\frac{I}{I_0}\right)$$

Basic principles

- Several configurations



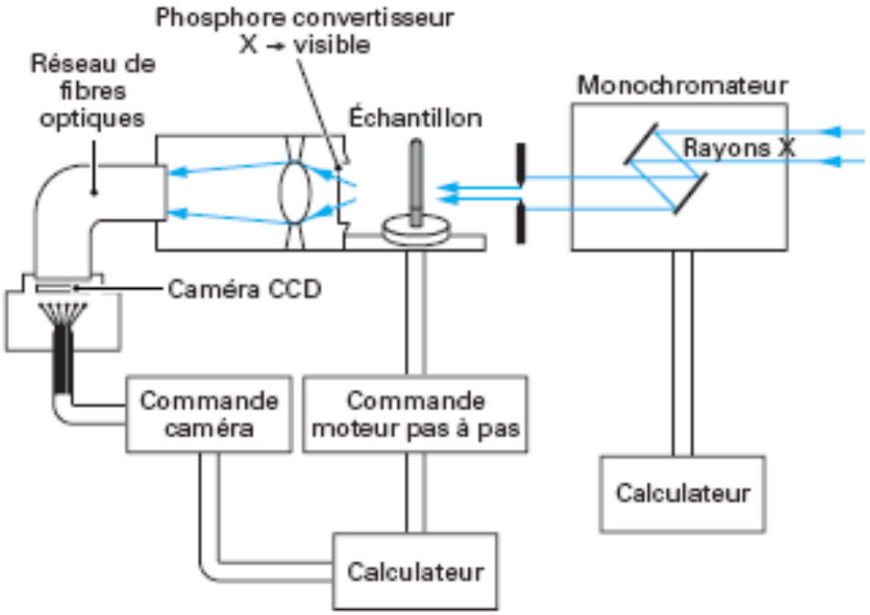
Fan beam
Linear detector



Cone beam
2D CCD detector

Basic principles

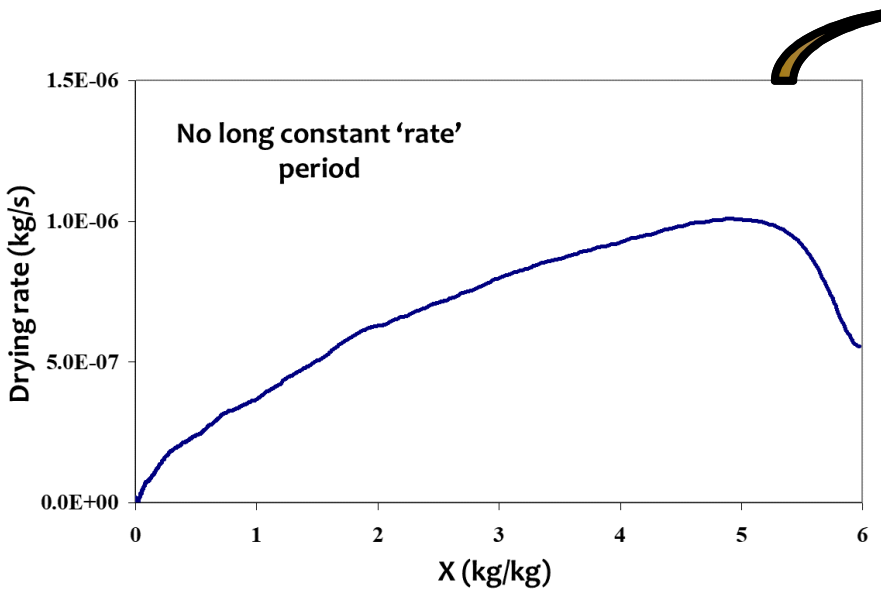
- Several configurations

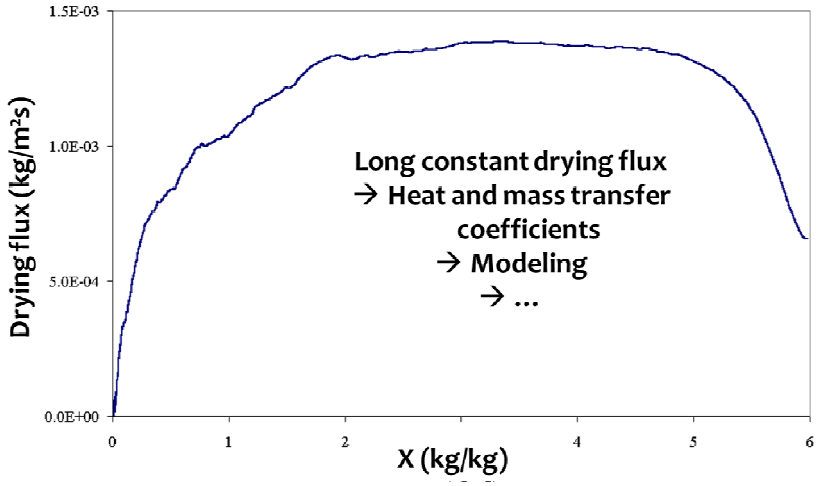


Parallel beam
2D detector
Synchrotron tomography

Interest for drying ?

- CRP or CFP ?
  - Confusion between drying rate and drying flux
  - Needs to follow exchange area for shrinking materials





Interest for drying ?

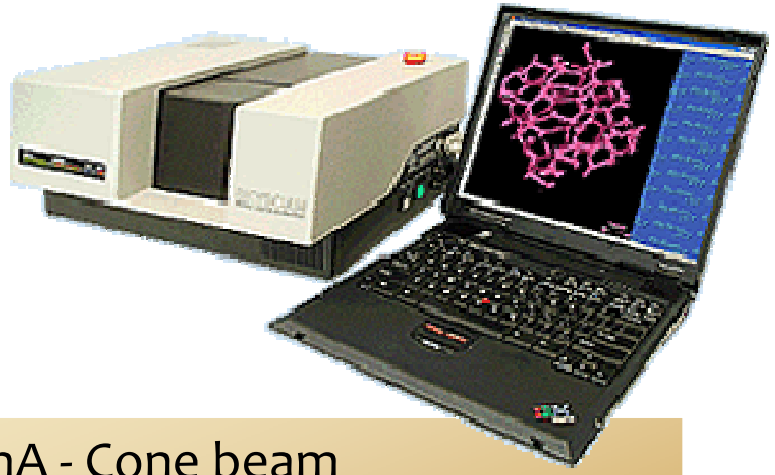
- No sample preparation but requires interruption for the measurement
- Clear constrast between pore and solid phases
- Possible calibration between density and μ
- Follow-up of sample texture
  - External exchange area → drying kinetics
  - Cracks/internal porosity → drying quality
  - Internal moisture profiles → model validation
  - Fixed bed characterization → kinetics, porosity, permeability, …

Facilities at ULiège

Commercial systems

- 1074 Desktop microtomograph (Bruker)

Purchase year: 2000



- Source: 40 kV - 1 mA - Cone beam
- Detector: 768 x 576 pixels

  8-bit CCD Camera
- Pixel size: 41 µm
- Max sample size: ∅: 30 mm – h: 25 mm

Commercial systems

- 1172A Skyscan Microtomograph

Purchase year: 2006

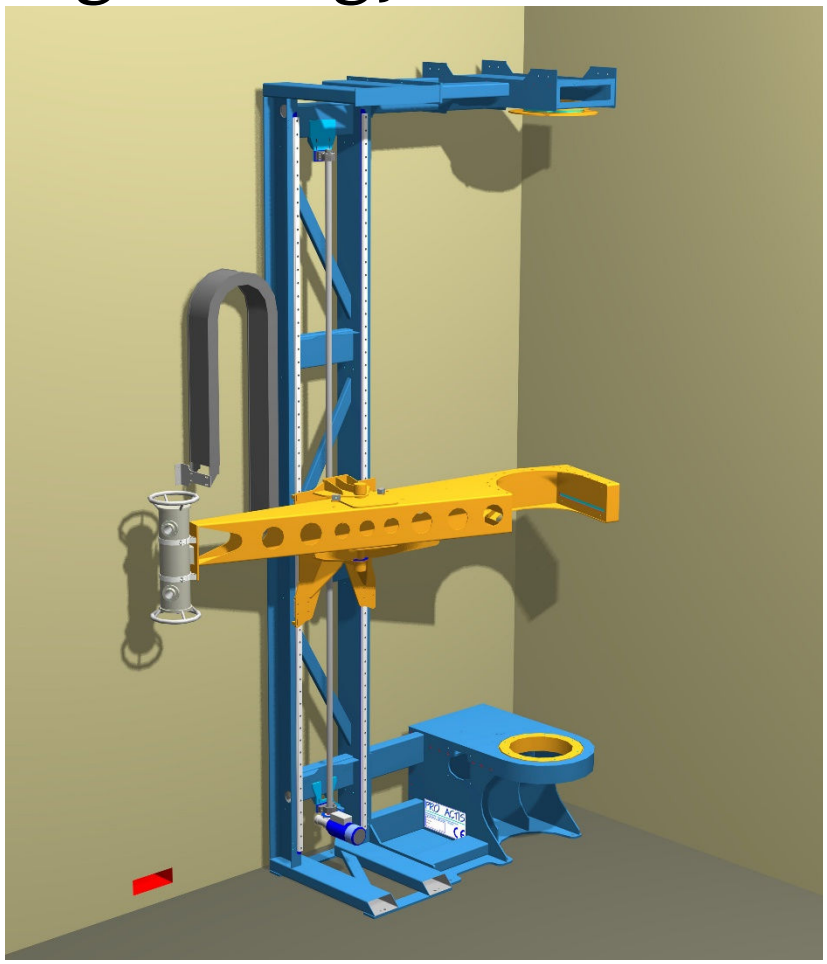
- Source: 100 kV - 250 mA - Cone beam
- Detector: 4000 x 2300 pixels

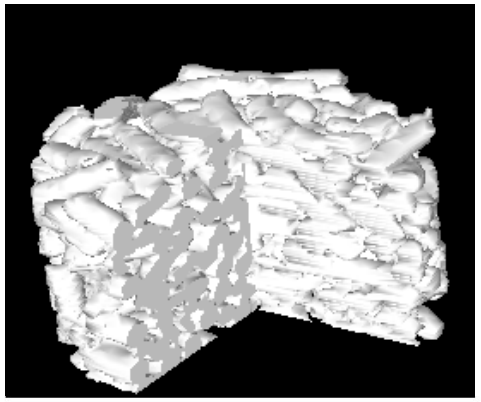
  12-bit CCD Camera
- Pixel size: from 34 to ≈ 2-3 µm
- Max sample size: ∅: 35 mm (68 mm with camera offset)

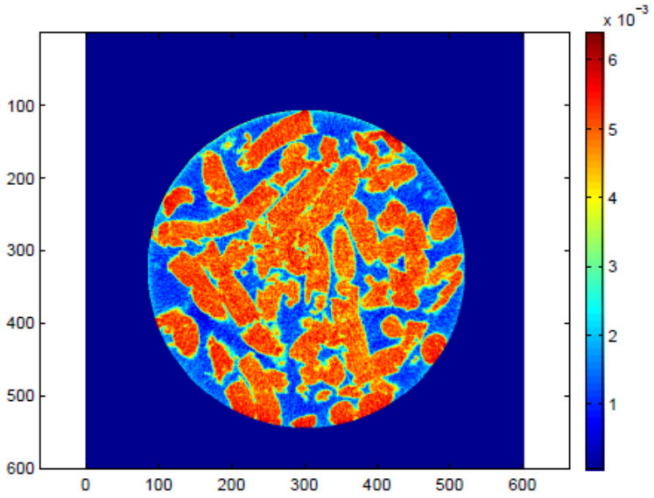
  h: 35 mm (70 mm with camera offset)

Home made system

- High energy ‘macro’ tomograph (pixel size: 0,4 mm)







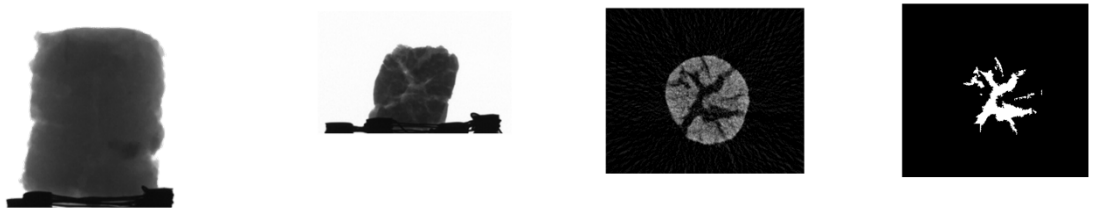
3 convective dryers

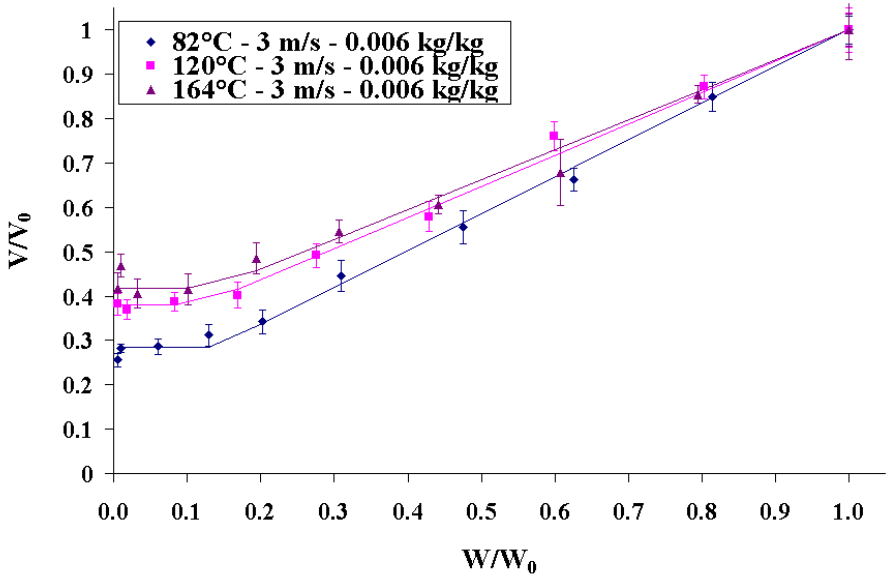
- Dual cell dryer (superheated steam or air)

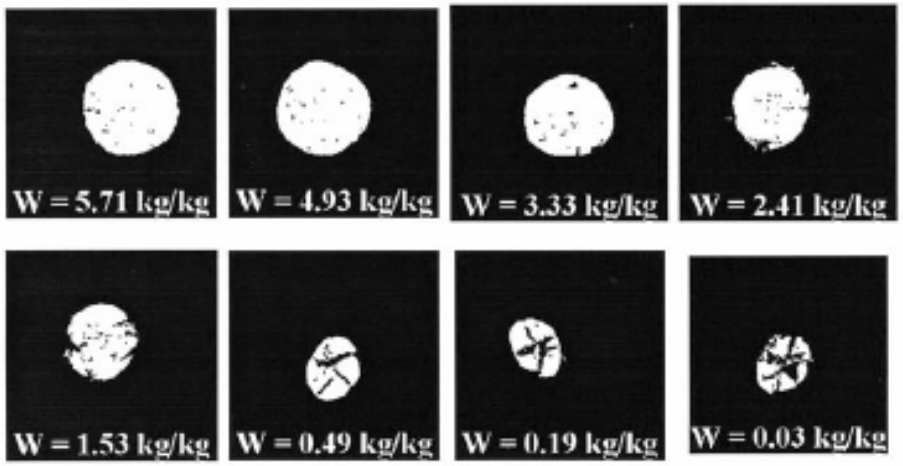
Some examples of results

In the context of sludge drying

- Shrinkage and cracking (PhD, 2003)







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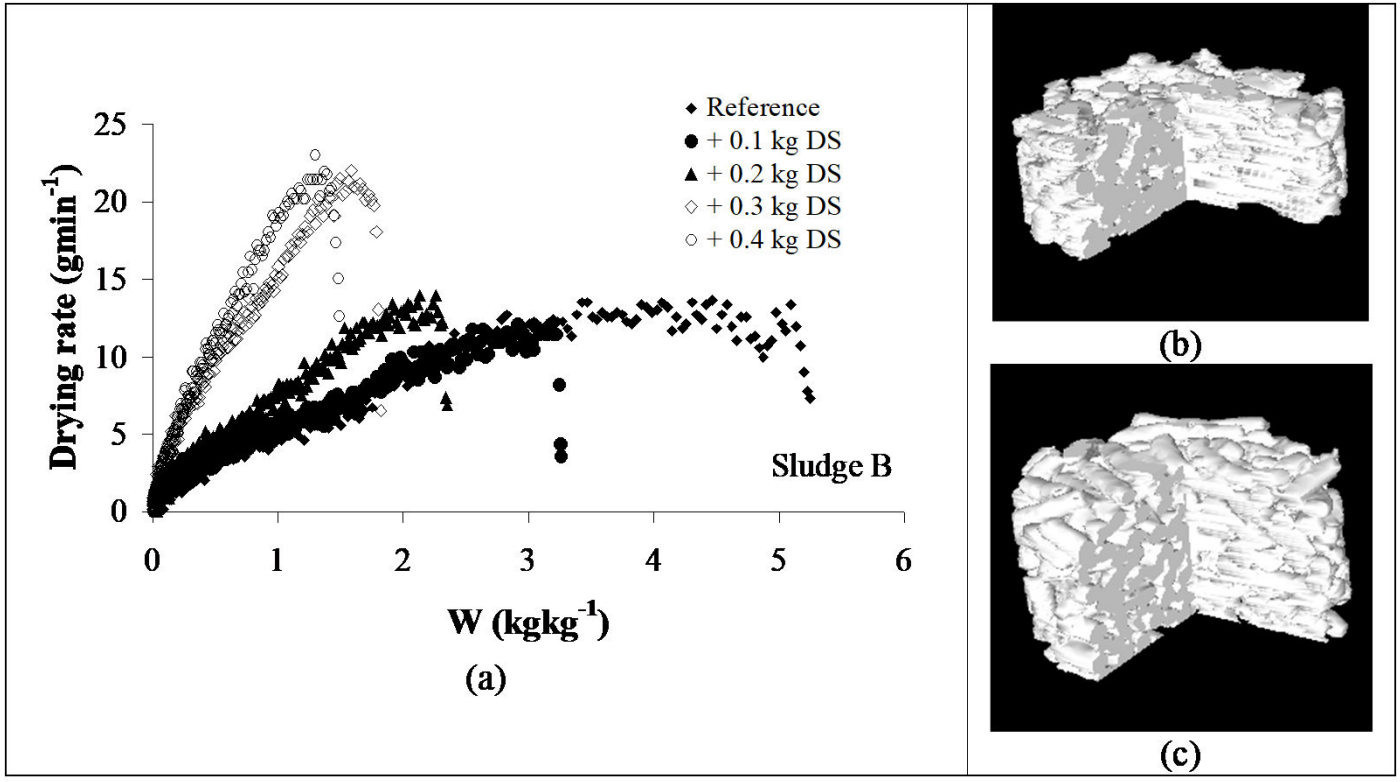
In the context of sludge drying

- Impact of sludge conditioning/dewatering
  - PhD Y.B. Pambou (2016)

In the context of sludge drying

- Impact of back mixing for soft sludges

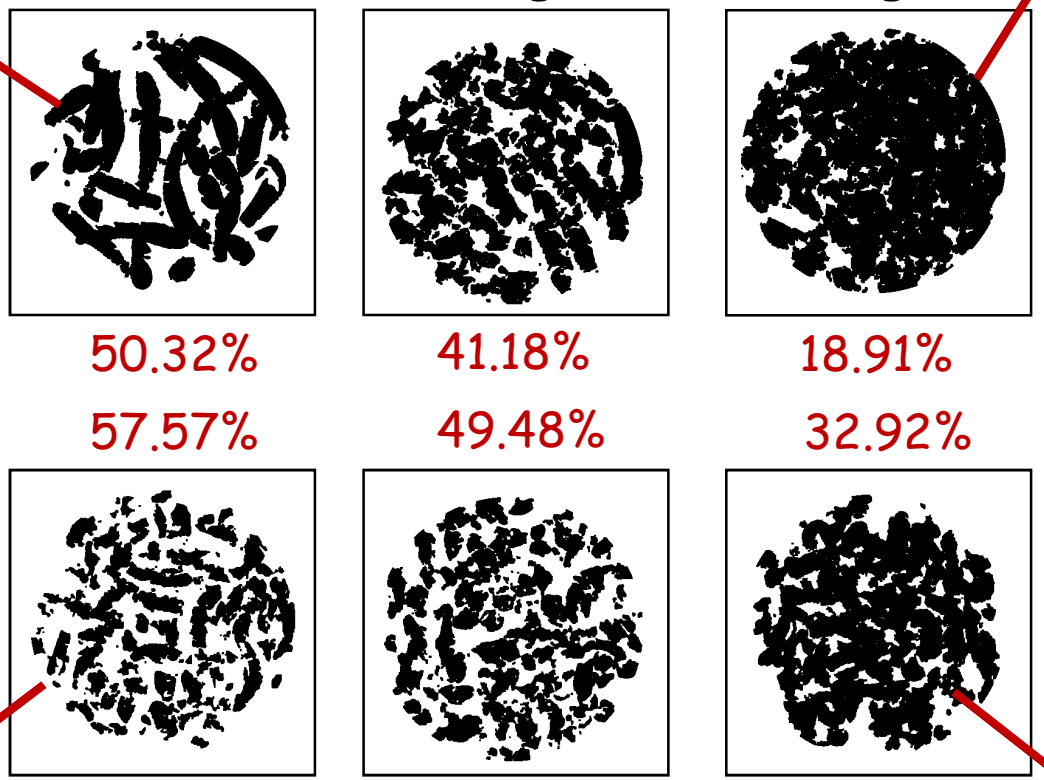


In the context of sludge drying

Height: 8.8 mm from bottom

•Good columnar shape
•Big void

•Gelatinous shape
•Small void



+ saw dust addition

•Diameter and length become smaller
•More granules

•Extrudates separate
•Void becomes obvious

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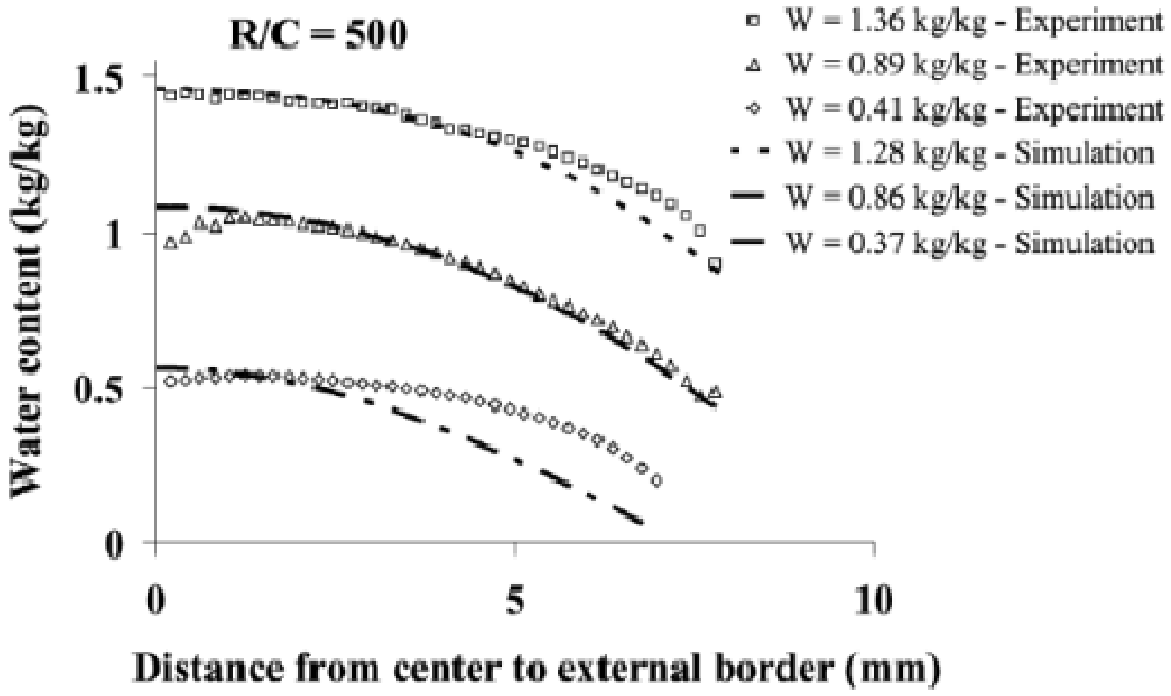
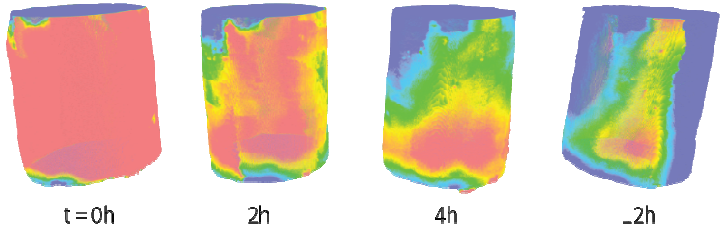
In the context of xerogel drying

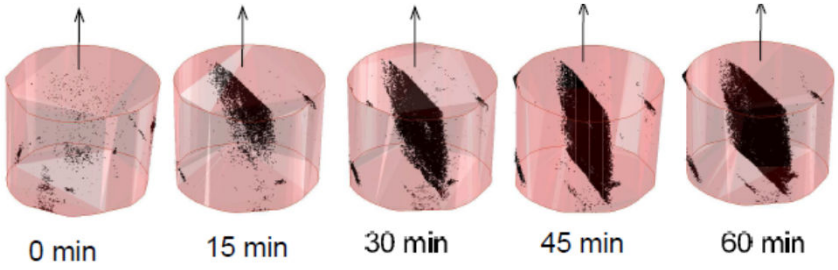
- THM validation
  - Comsol simulation vs. Experimental moisture profiles



In the context of clay/limestone drying

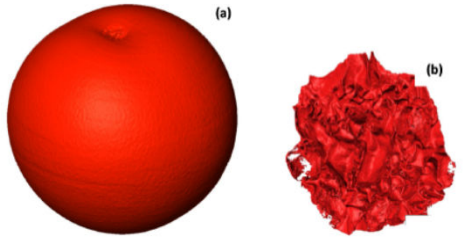
- Shrinkage and cracking follow-up
  - Lagamine modeling with Geomechanics team

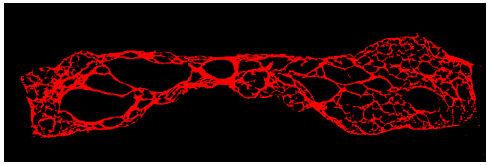


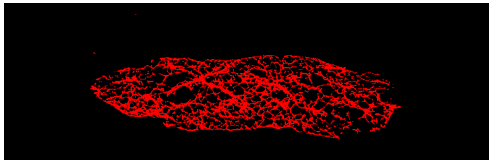


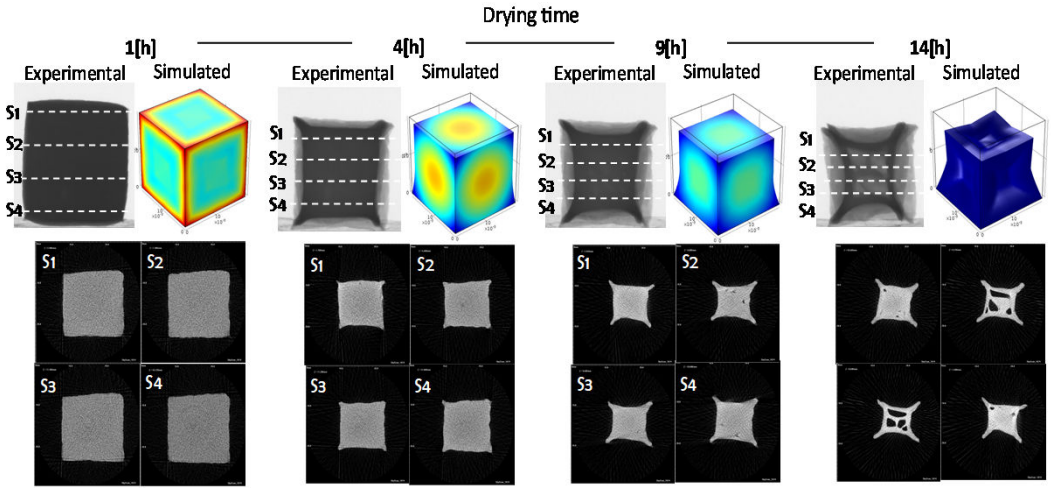
In the context of food drying

- Lots of collaboration with agro-food teams
  - Tomatoes (R. Khama, Algeria)
  - Bananas (S. Devahastin, Thailand)
  - Potatoes (S. Sandoval, Mexico)
  - Macadamia nuts (G. Srzednicki, Australia)









Increasing use

Other groups using X-CT

- Rapid look at the program of Eurodrying …
  - Capozzi et al. → CFD based on CT for lyophilized products
- 23 papers in 2018 with ‘drying’ and ‘tomography’ in title or keywords
  - Group of Tsotsas in Magdeburg (Germany)
  - Group of Carmeliet in Leuven (Belgium)
  - Group of Tao in Shanghai (China)
  - …

Conclusions

Take-home message

- X-ray CT = 3D non destructive imaging tools
- Lots of potential applications in drying
  - But requires knowledge in image analysis
  - But requires drying interruption
    - Future: dryers inside CT system …
- We are open for new ideas and collaborations…

Questions ?