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3D SIMULATION IN THE PLEIADES  
SOFTWARE ENVIRONMENT FOR SODIUM  
FAST REACTOR FUEL PIN BEHAVIOR  
UNDER IRRADIATION

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- Introduction
- 3D fuel pin model
- Radial fuel relocation and 3D results
- Conclusions

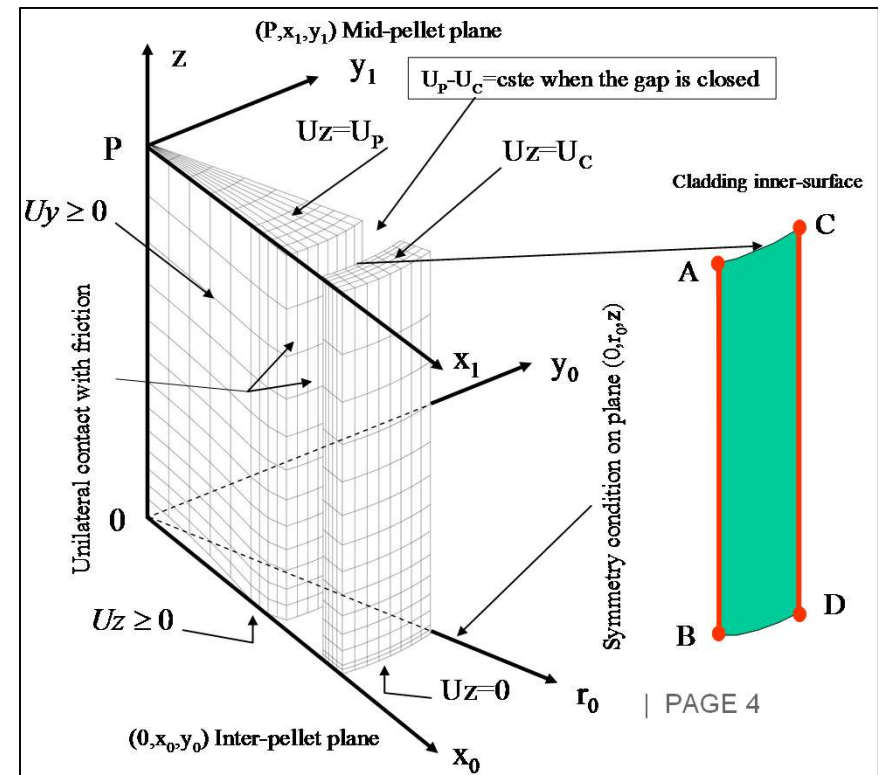
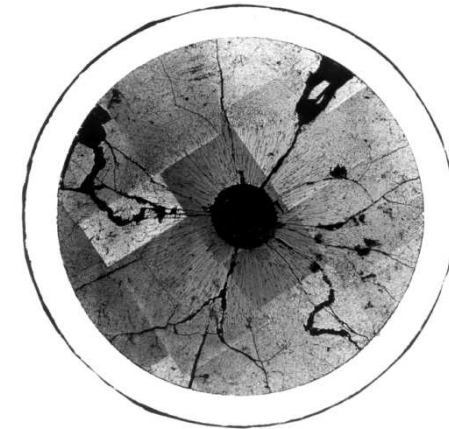
## Safety assessment of Sodium Fast Reactor fuel pins

- Detailed understanding of the fuel element multi-physic behavior under irradiation
  - French and international experimental feedback and fuel modelling knowledge
    - ✓ GERMINAL V2 fuel performance code of PLEIADES software environment
  
- Basic design of ASTRID : Advanced Sodium Technological Reactor for Industrial Demonstration
  - New developments of GERMINAL V2 fuel performance code are in progress to improve fuel modelling and reduce uncertainties

## Pellet-to-cladding gap closure mechanism

- Impact on the maximal fuel temperature under nominal irradiation and Pellet Cladding Mechanical Interaction under accidental conditions
- A 3D fuel pin model is needed to improve the one dimensional approach used in the GERMINAL V2 code
  - Development of a preliminary nonlinear thermo-mechanical computation scheme with the LICOS code of the PLEIADES platform
    - ✓ Chemo-physical state variables are pre-computed with the GERMINAL code

- One single pellet fragment model for a given axial position
  - PCI model assumption for PWR [B Michel NuclTech 2012]
    - ✓ Pellet fragmentation under thermal stresses at the first power increase
- Symmetries
  - One fourth of the pellet fragment
- Mechanical interaction
  - Pellet cladding
  - Inter pellet plane
  - Inter fragment plane
- Fuel column reaction
  - Mid plane locking condition (pellet and cladding)
- Internal and external pressure
  - Stress boundary conditions



## Thermal model

Conduction  

$$\text{div}(\lambda \cdot \text{grad}T) + p_v = 0$$

Pellet cladding gap heat exchange  

$$\Phi = h(T) \cdot (T_{clad} - T_{pellet})$$

## Mechanical model

Static equilibrium

$$\text{div}\bar{\sigma} = 0$$

Non linear material behavior

$$\dot{\bar{\sigma}} = \underline{\underline{E}} : (\dot{\bar{\epsilon}}^{tot} - \dot{\bar{\epsilon}}^{th} - \dot{\bar{\epsilon}}^{ir} - \dot{\bar{\epsilon}}^{plast} - \dot{\bar{\epsilon}}^{creep})$$

$$\dot{\bar{\epsilon}}^{plast} = g(\bar{\sigma}, T) \cdot \frac{\partial \sigma_{eq}}{\partial \bar{\sigma}} \quad \dot{\bar{\epsilon}}^{creep} = (f_{ir}(\bar{\sigma}, \phi, T) + f_{th}(\bar{\sigma}, \phi, T)) \cdot \frac{\partial \sigma_{eq}}{\partial \bar{\sigma}}$$

## Multiphysic computation scheme

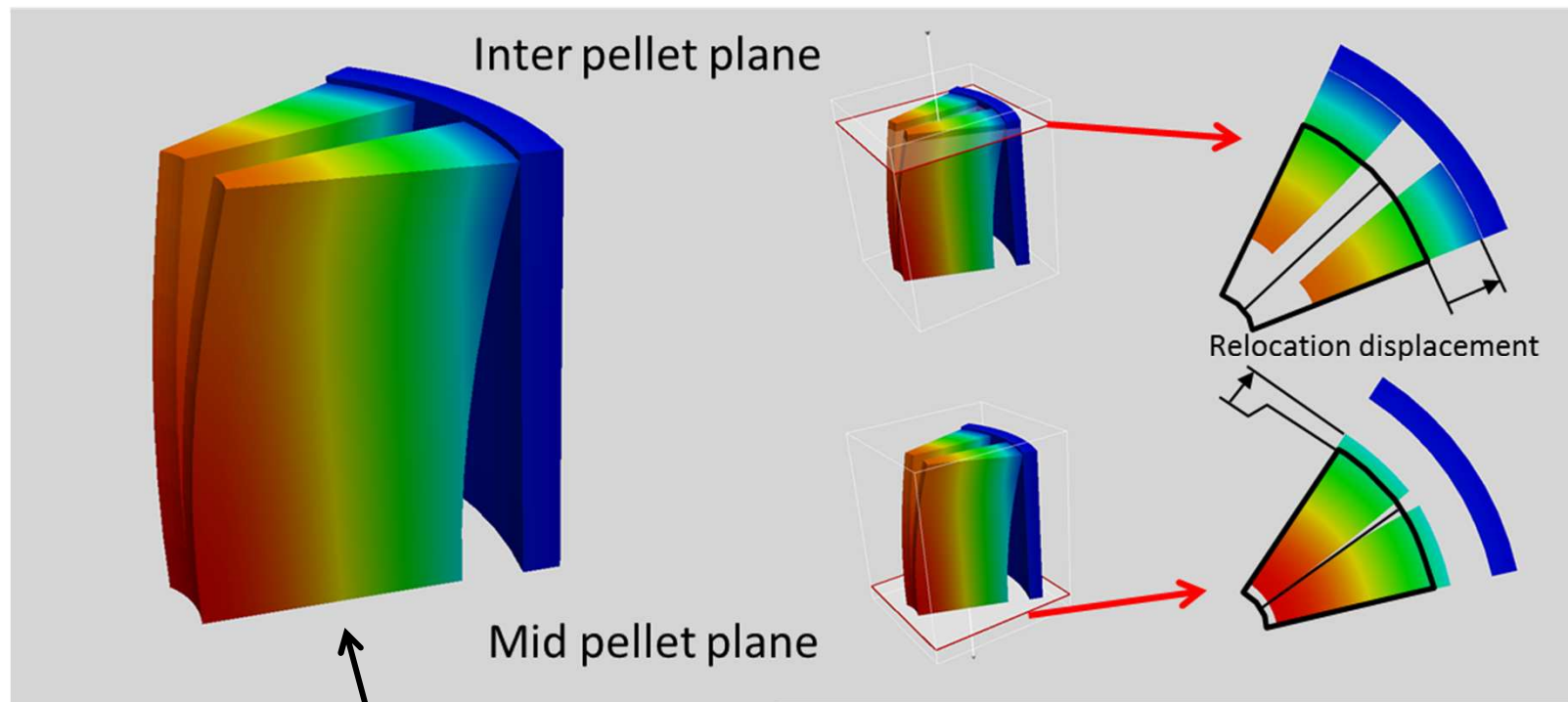
Thermo-mechanical coupling in LICOS

- Input loading data initialization at the end of the time step
- Iterative computation of the thermomechanical solution
  - thermal computation
  - nonlinear mechanical computation
  - thermomechanical convergence test
- Solution update for the next time step

Precomputed data from GERMINAL V2

gas content and pressure in the pellet-to-cladding gap  
 cladding external temperature  
 burnup in the pellet  
 mean pellet porosity  
 internal pellet hole size and associated fuel mass transfer  
 oxygen to metal ratio  
 fuel shrinkage and swelling under irradiation

- Pellet fragment hourglass shape
  - Pellet fragmentation and thermal stresses
- Radial relocation displacement
  - Gap closure at the inter pellet plane
  - Gap reduction at the mid pellet plane (approximately 20% compare to an un-fragmented pellet)



temperature at the end of the first power increase

# Central hole formation and fuel mass transfer

## ■ Mass transfer under vaporization-condensation mechanism

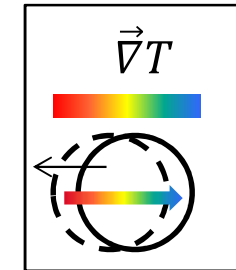
- Vapor mass transfer in porosities leads to central hole formation

Void fraction balance equation

$$\dot{f} = -div(\vec{u}_f \cdot f)$$

Porosity velocity

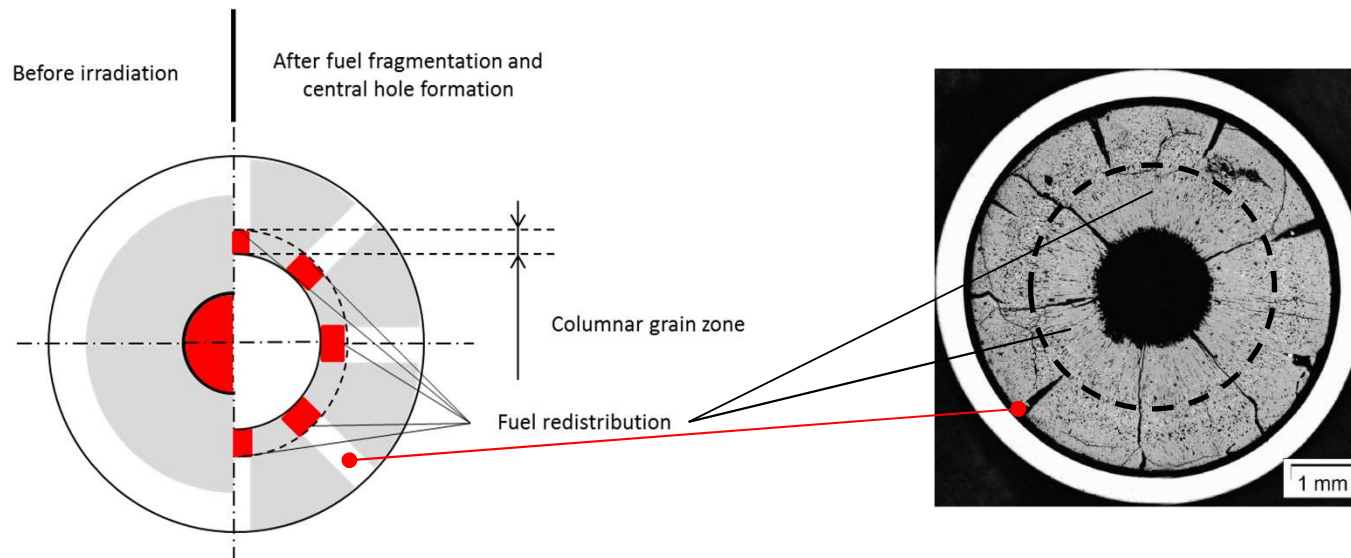
$$\vec{u}_f = \frac{\Omega \cdot D}{RT} \cdot \vec{\nabla} T \cdot \left. \frac{\partial p}{\partial T} \right|_{pore}$$



← Porosity  
→ Mass

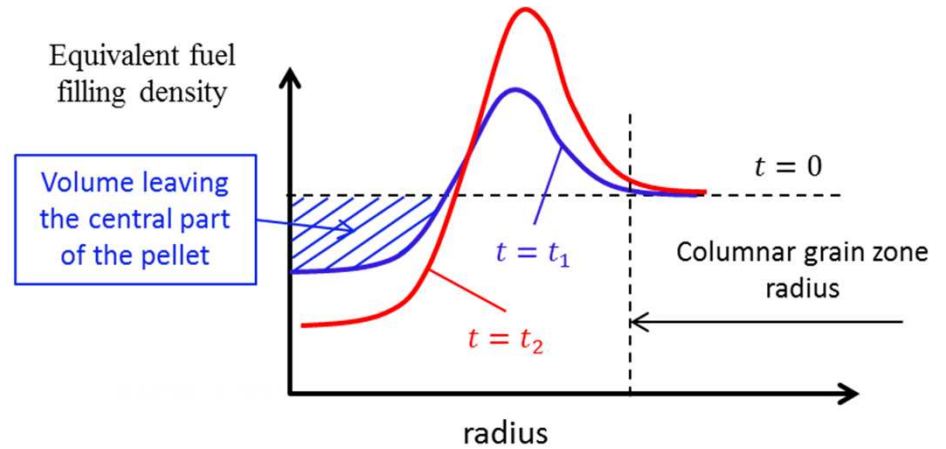
## ■ Central hole size after irradiation

- 80% of the central hole volume is linked to the free volume available in the fuel pin
- A simplified mechanism has been propose to simulate the mass transfer



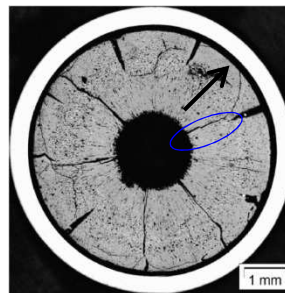
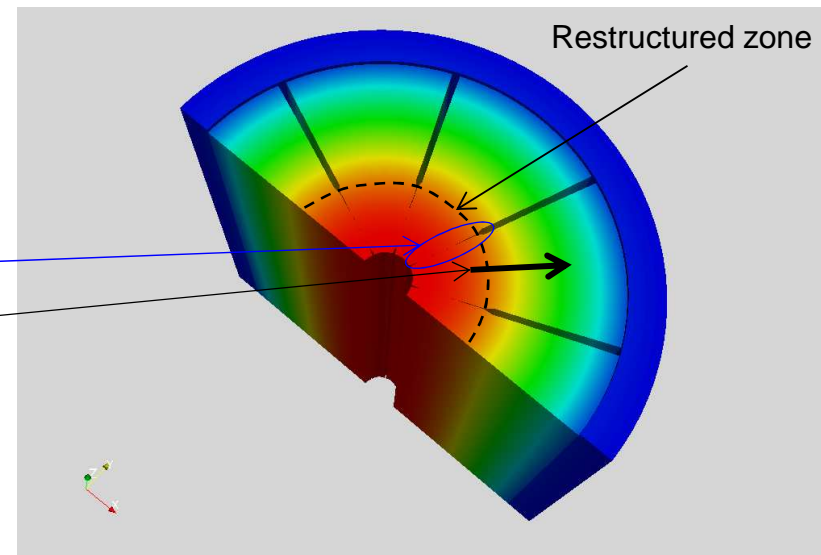
## ■ Germinal results post processing

- The equivalent fuel filling density is derived from the results of the porosity diffusion model
- The fuel mass leaves the center of the pellet to reach intermediates radii between the central hole radius and the columnar grain zone radius



## ■ 3D radial displacement computation

- The fuel mass transfer in the columnar zone region is considered as a volume expansion in the pellet
- **Inter fragment contact boundary condition** leads to a **radial displacement of the pellet fragments**

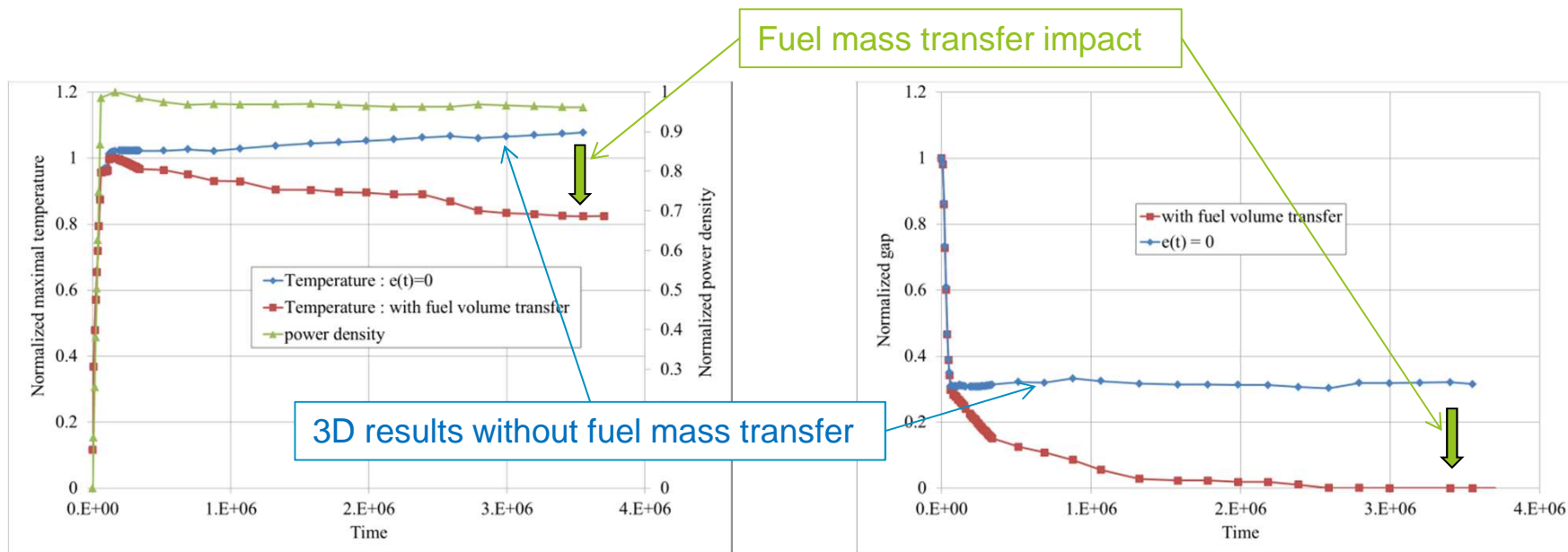




# 3D Simulation results

## Impact of the fuel mass transfer for a full pellet under nominal irradiation

- A first 3D computation has been done without fuel mass transfer
- The fuel mass transfer leads to a significant pellet-cladding gap reduction after the central formation
- Consequently the maximal fuel temperature is reduced of approximately 25% after an irradiation period of 45 days



Maximal fuel temperature at mid pellet plane

Pellet- cladding gap at mid pellet plane

## Conclusions

- A 3D model has been proposed to study the pellet-cladding gap closure mechanism
- Two gap closure mechanisms have been considered
  - Hourglass shape of the fragmented fuel pellet under thermal gradient
  - Radial pellet fragment relocation due to the fuel mass transfer associated to the central hole formation
- Simulation results show a significant impact of the second mechanism after the first power increase (solid and annular pellets)

## Perspectives

- On going activity
  - Extension of the post-processing 3D model studies : experimental validation, initial annular pellet, ...
  - Development of a fully coupled formulation between the porosity diffusion and the radial relocation displacement in the 1D computation scheme of GERMINAL
- Further development : extension of the GERMINAL fuel performance code to the 3D simulation

**THANK YOU FOR YOUR ATTENTION**