DE LA RECHERCHE À L'INDUSTRIE

Recent modelling improvements in fuel performance code GERMINAL for SFR oxide fuel pins

M.Lainet, V.Bouineau, T.Helfer, M.Pelletier

CEA DEN-CADARACHE, DEC/SESC

FR13 | 6 MARCH 2013

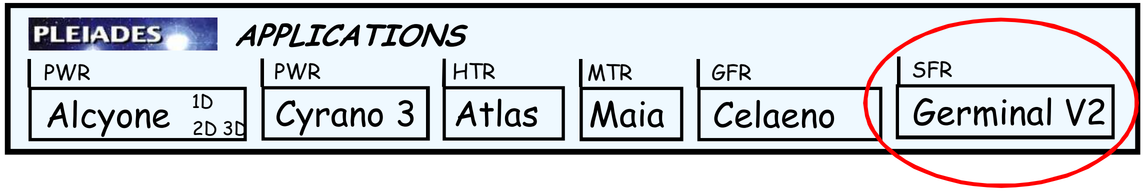
CONTENTS

1 – Context and Objectives

- **ASTRID project ⇒ General restart of R&D activities on SFR**
  - Need of a renewed fuel performance code to support the design studies
- **Starting point : the acquired knowledge on mixed oxide fuel pins $(U,Pu)O_2$**
  - **Modelling knowledge** : Fortran code **GERMINAL V1.5**
    - Developed from 1980 until 2000 ; restored operational in 2008 ; actually in use
  - **Experience benefits** : **BREF** manufacturing & experimental irradiation Data Base
    - Validation objects for the code : ≈ 90 to 100 selected objects among 5000
- **Objectives for the new code GERMINAL V2**
  - **To strengthen the modelling of mixed oxide fuel pin**
    - FE computations for thermal analysis & mechanics ; new mechanical behaviour's laws
    - State-of-the-art evolution for fuel physics
  - **To extend the simulation capability**
    - Materials with different behaviour, specific physics (fuel loaded with minor actinides)
    - By completing the validation base

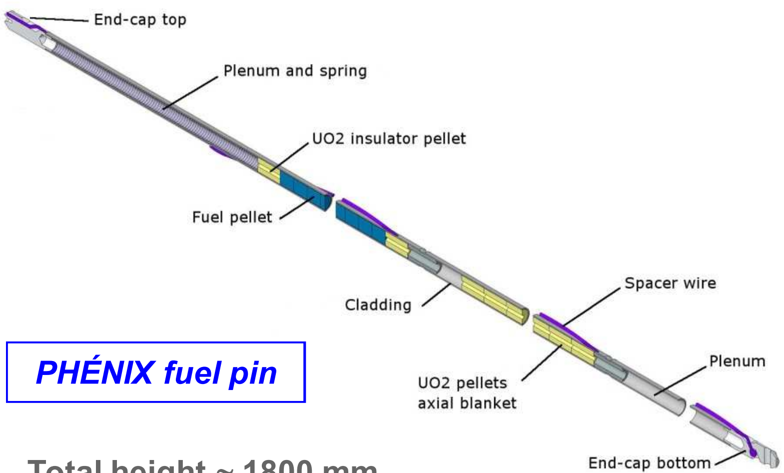
2 – Overview of GERMINAL V2

- **PLEIADES : Federative unified framework to develop fuel performances codes**
  - Co-developped by CEA, eDF and AREVA
  - **GERMINAL V2** : Modelling developed by CEA, co-financed by eDF and AREVA



Sharing of modelling advances

New software technologies to link with other disciplines



PHÉNIX fuel pin

Total height ≈ 1800 mm
Fissile column height ≈ 800 mm

- **Fuel pin modelling and main physical processes**

  Axisymmetrical model 1D½

  ⇔ Geometry assimilated to a **revolution cylinder**

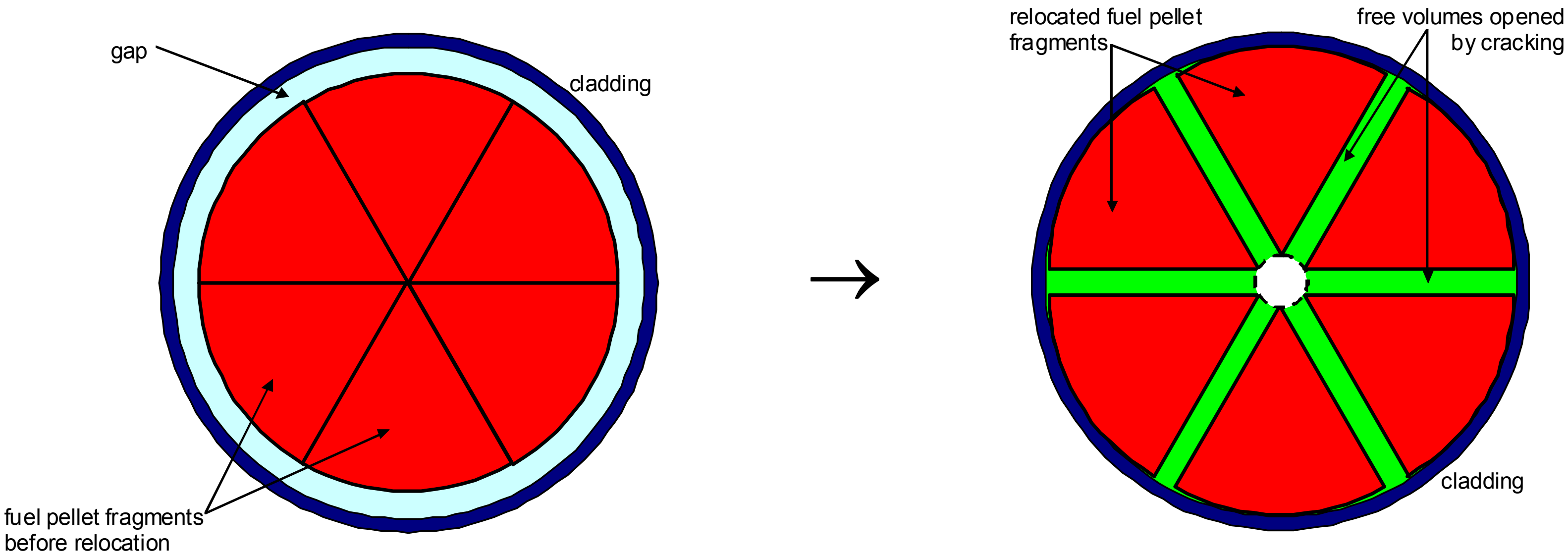
  - Fuel pin decomposed into axial slices coupled by thermalhydraulics in coolant
  - Radial resolution of coupled physical processes in each slice
    - Neutronics, thermal analysis, mechanics
    - Thermal-activated fuel physics: radial migration of porosities and species, swelling, FP release

3 – Modelling evolutions brought by GERMINAL V2

- **Mechanics of fuel pellet**

Fuel fragments relocation due to cracking

Observation: Fuel pellet cracks in many fragments very early ($P_{lin} \approx 30$ W / cm, PHENIX feedback)



To simulate this, the use of a cracking behaviour model is not adapted:

- Complete rupture of the material ⇔ Complete loss of stiffness ⇒ Singularity
- Material discontinuity and rigid body displacement of the fragments can't be handled by the behaviour's law

3 – Modelling evolutions brought by GERMINAL V2

Mechanics of fuel pellet

Fuel fragments relocation due to cracking: the modelling

- Behaviour's description: creep + plasticity, to remain representative in a compression state
- **Fuel fragments relocation model** describing the free volumes opening due to cracking
  Homogeneous stress free strain imposed to the fuel pellet
  Strain rate evaluated % current gap geometry

$$\dot{\varepsilon}_{reloc}(t) = \frac{u_r^{\max}(t) - u_r(t)}{R_{pellet}^{ext}(0)} \Big/ \tilde{t}_0$$ where $\tilde{t}_0$ time constant adjusted with power density rate

$$\dot{\varepsilon}_{reloc} \to 0 \text{ when } u_r \to u_r^{\max}$$ ⇒ no load on cladding induced by relocation

$$u_r^{\max}(t) = Min\left(1\ ,\ \frac{P_{vol}(z,t)}{P_{vol}^{ref}}\right) \times \left(R_{clad}^{\text{int}}(t) - e_{JOG}(t) - R_{pellet}^{ext}(0)\right)$$

  Weighting by a power density factor to close gap near maximum power plan

- **Afterwards: accommodation as long as contact is maintained with cladding**
  Additional stress free strain balancing at each time step the other positive strain increments (thermal dilatation, swelling); lower bound = opposite of relocation
  ⇒ No strong interaction until complete closure of the free volumes opened by relocation
  Cracks volume fraction = $trace\left(\overline{\overline{\varepsilon}}_{reloc} + \overline{\overline{\varepsilon}}_{acco}\right)$

3 – Modelling evolutions brought by GERMINAL V2

- **Mechanics of cladding**

  Creep and plasticity rate formulation of behaviour

  Swelling taken into account as stress free strain

  - Plasticity with isotropic hardening; yield function $f = \sigma_{eq} - K\, R_{p0,2} \left(\varepsilon_{eq}^{p}\right)^{n} = 0$
  - Creep and plasticity are supposed to be isochoric
  - $\dot{\varepsilon}_{eq}^{creep}$ is evaluated first (with σ_{eq}, temperature...)
  - Consistency condition ⇒ scalar equation determining $\dot{\varepsilon}_{eq}^{p}$ (time derivative of the yield function)

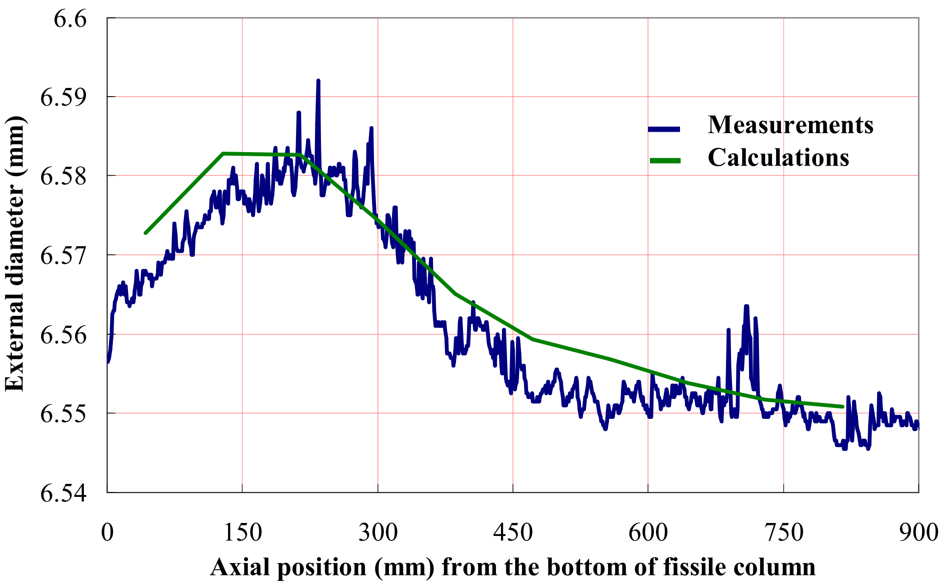
⇒ Improves the prediction of the cladding geometry changes

⇒ Determines stresses induced by swelling gradients with a discretization in the thickness

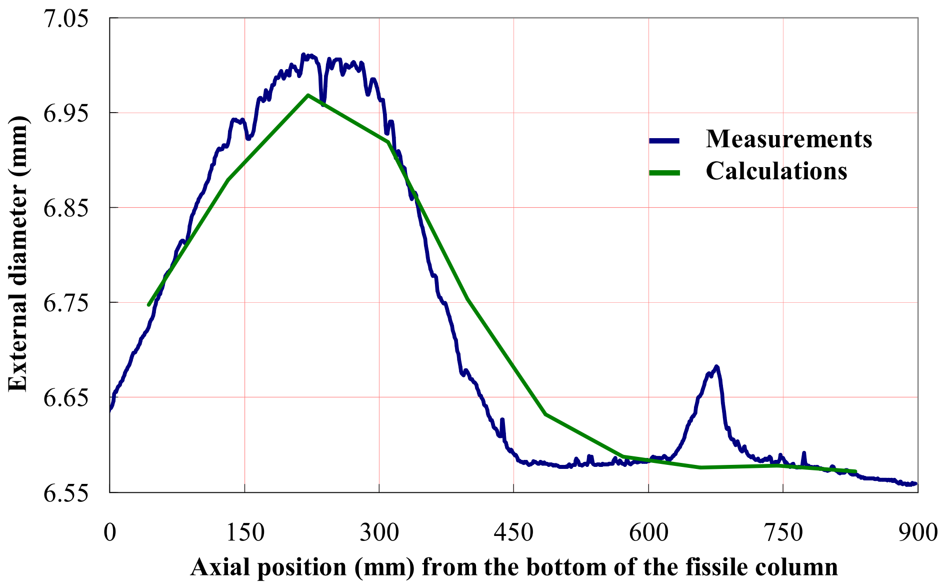
3 – Modelling evolutions brought by GERMINAL V2

Mechanics of cladding

Cladding deformation at the end of irradiation: calculation results



Final burn-up: 7 at% – Maximum deformation: 0,6%
Swelling threshold just exceeded



Final burn-up: 13 at% – Maximum deformation: 6%
Important swelling increase

Same cladding material for both fuel pins (austenitic steel)

Cladding swelling law calibration ⇒ satisfactory predictions of geometry changes at very different stages of swelling evolution

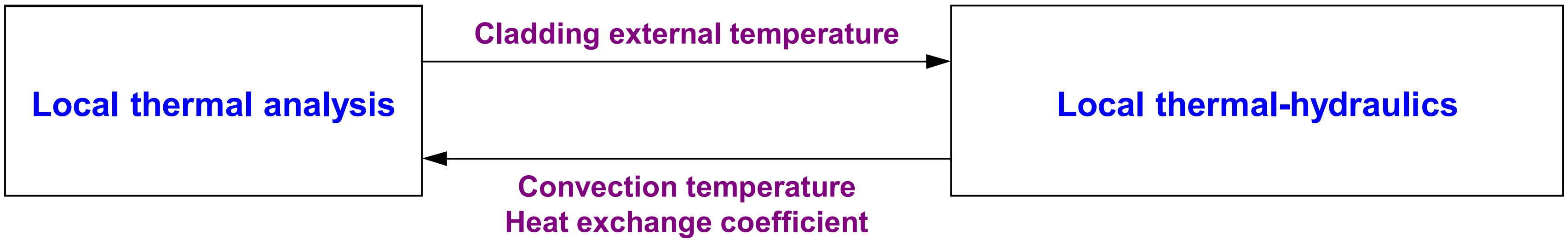
3 – Modelling evolutions brought by GERMINAL V2

Transient thermal analysis

Coupling of thermal analysis and thermal-hydraulics of coolant

Coupled resolution in each axial slice of the fuel pin, because of inertial effects (energy storage)

- Thermal model with convection on cladding external bound
- Thermal-hydraulics model called at each iteration of thermal resolution



Fuel melting

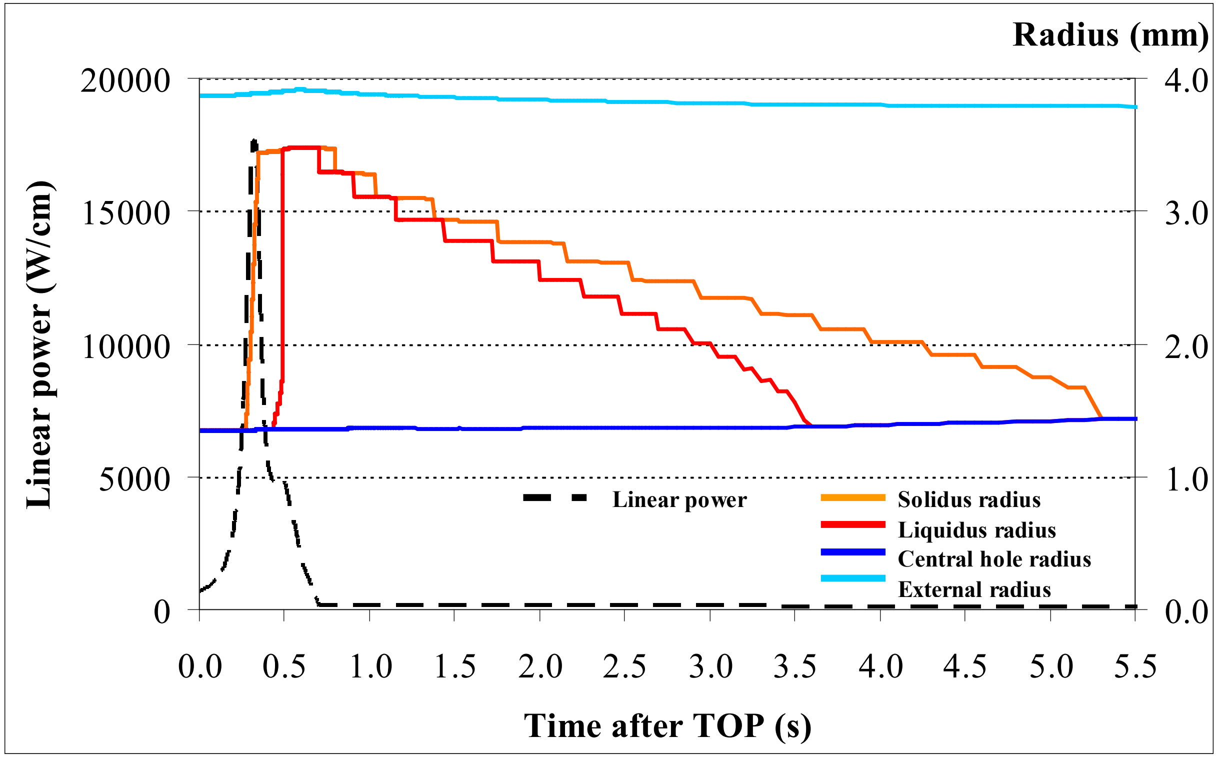
- Solidus and liquidus temperatures laws ⇒ liquid fraction evaluation with current temperature
- "Biphasic" laws for all fuel properties
- Heat of fusion taken into account by formulation of heat capacity law

$$C_p = (1 - x_{liq}) C_{p_{sol}} + x_{liq} C_{p_{liq}} + x_{liq}(1 - x_{liq}) \frac{6L}{T_{liq} - T_{sol}} \quad \Rightarrow \quad \int_{T_{sol}}^{T_{liq}} C_p(\tau) d\tau = \frac{C_{p_{sol}} + C_{p_{liq}}}{2} \times (T_{liq} - T_{sol}) + L$$

3 – Modelling evolutions brought by GERMINAL V2

Transient thermal analysis

Melting front progression: calculation results



Simulation of E5 power ramp (RIA)

Molten radius to external radius ratio
Predicted ≈ 0,89
Observed ≈ 0,83

First verification of the model

Inertial effects not yet satisfactory represented : temperature peak not as wide as this observed

Validation for off-normal conditions to be continued with other objects

4 – Working perspectives

Finalise GERMINAL V2 validation

- Already 70 validation objects: fissile pins, normal conditions
  - Different geometries (PX, SPX, CABRI), cladding materials, burn-ups
- Fertile and **heterogeneous** fuel pins; off-normal conditions; absorber pins

⇒ **90 to 100 validation objects**

GERMINAL V2 delivery

- To replace GERMINAL V1.5
- To be used for **ASTRID design studies**

⇒ **At the end of 2013**

Further modelling improvements

- Fission gases behaviour: retention, gas swelling
- Volatile fission products radial migration and release ⇒ effects on heat transfert, corrosion
- Oxide fuel thermochemistry ⇒ coupling with thermodynamics code
- Off-normal conditions: axial displacement of molten fuel
- Fuels for transmutation with high minor actinide content

⇒ **GERMINAL V3: 2014 and after**

Linked with ASTRID project needs

Thank you for your attention