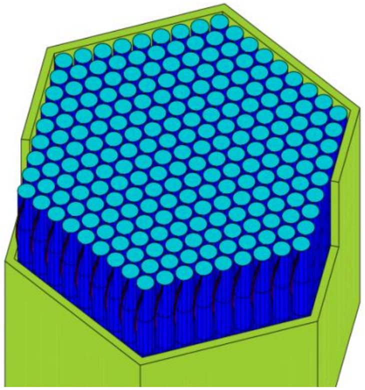
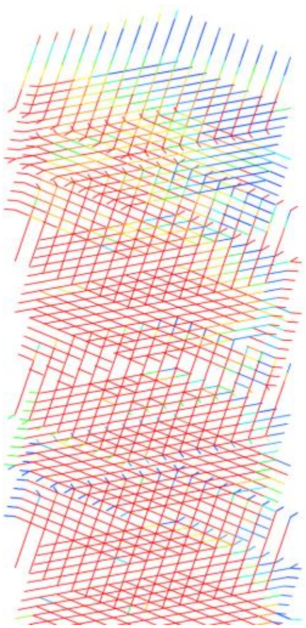
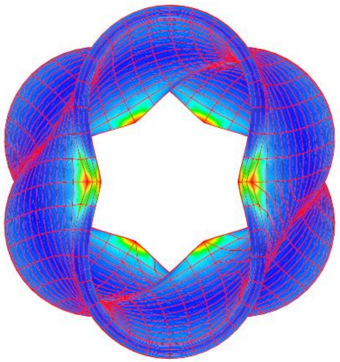
DE LA RECHERCHE À L'INDUSTRIE

A new structural behavior to perform efficient nonlinear SFR fuel bundle thermomechanical analysis







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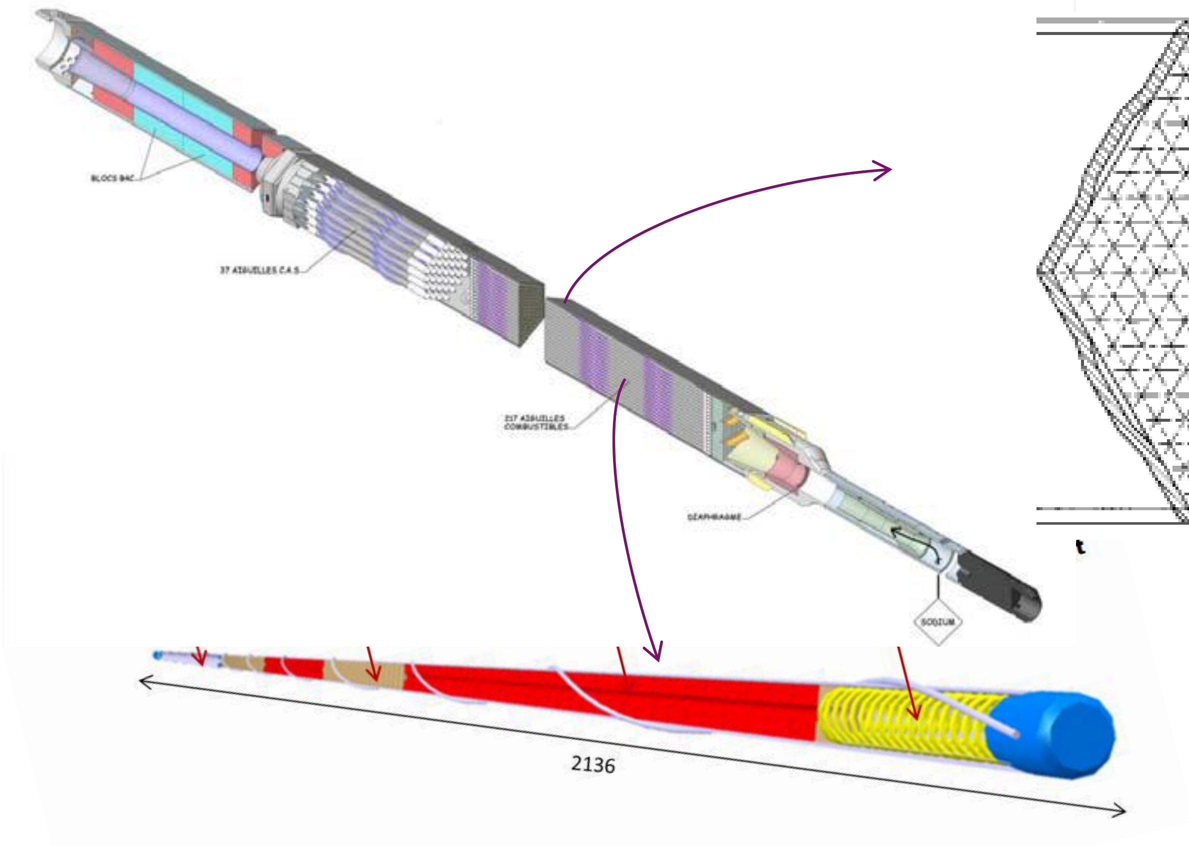
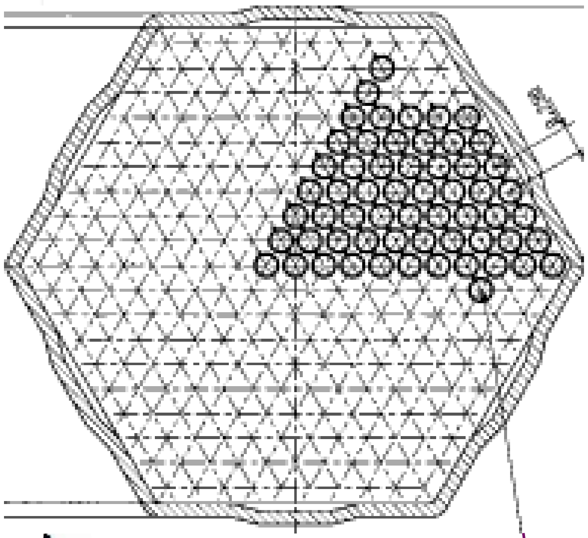
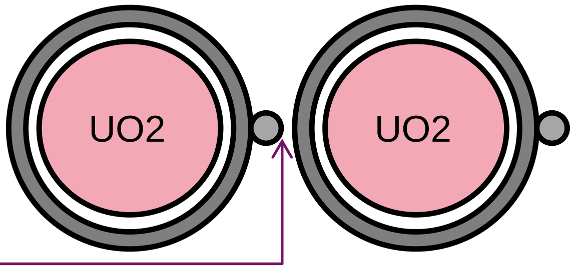
PHENIX SODIUM FAST REACTOR FUEL BUNDLE

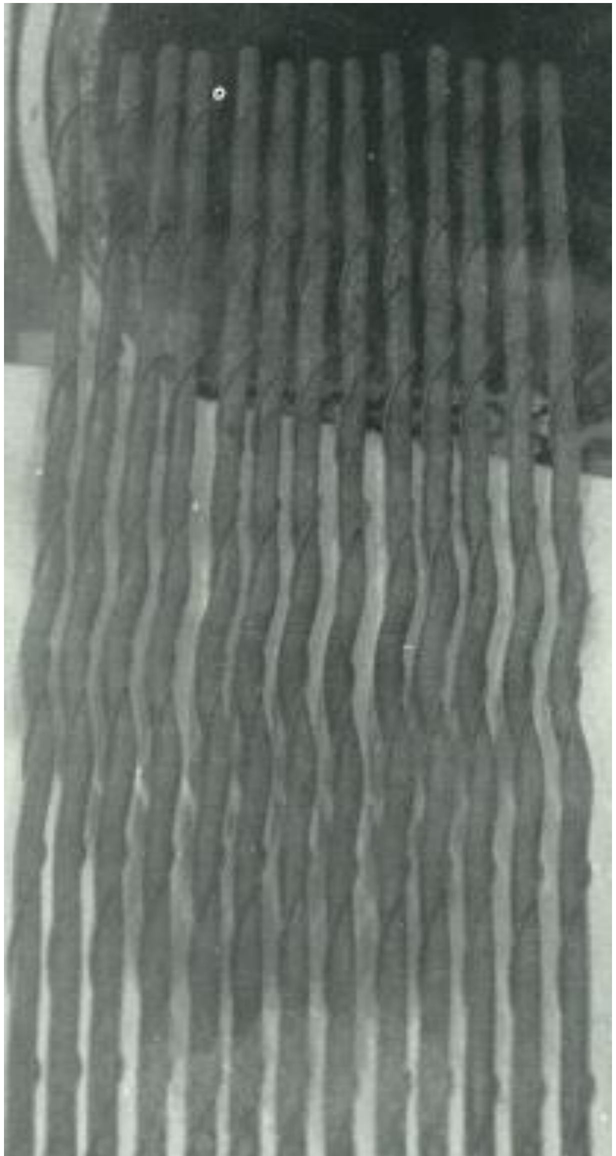






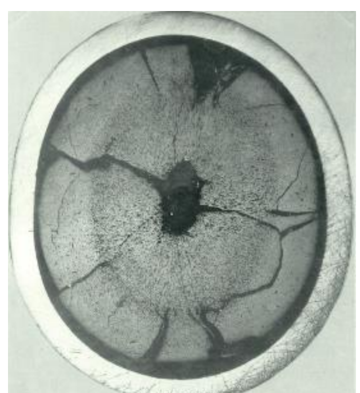
- **SFR fuel assembly used in PHENIX**
  - ~200 pins + 200 wrapping wires (steel)
  - 1 hexagonal box (steel)
  - Small wire/pin gaps ~0,1mm
  - Sodium flux through the bundle

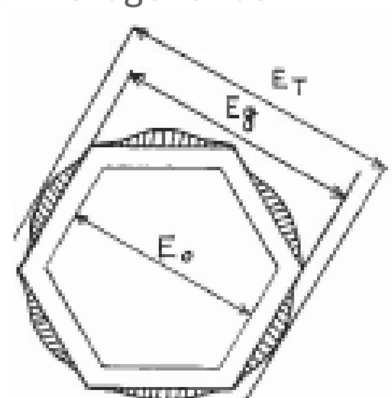
OBJECTIVE : FUEL BUNDLE BEHAVIOR PREDICTION



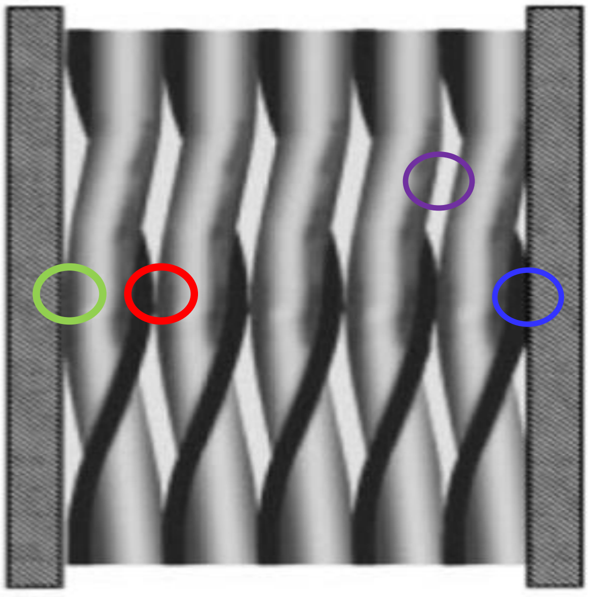
- **Phenomena**
  - Loadings : T°, Dose, FP gaz pressure
  - Thermal expansion
  - Irradiation isotropic **swelling**
  - Thermal creeping (low in normal conditions)
  - Irradiation **creeping**

- **Experimental results for severe irradiations**
  - Numerous contacts activated : wire vs pin or HT
  - Pins swelling and creeping
  - Pins helical bow
  - Pins ovality after hard contacts (« phase 3 »)
  - Hot points if contact between claddings
  - Potential cladding crack by thermal creeping
  - Bumps on hexagonal box





A NUMERICAL CHALLENGE



- **A multi-body problem**
  - 1 hexagonal box + 217 pins + 217 wires
  - **7000 to 14000 contact areas**
  - Etc.

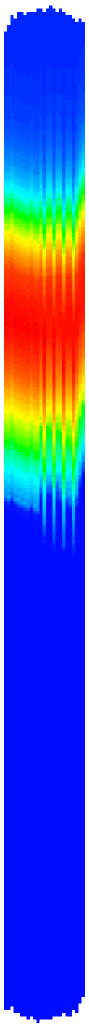
- **Materials are highly non linear**
  - Swelling ➔ T° , dose
  - Irradiation creeping ➔ T°, $stress^1$, dose
  - Thermal creeping ➔ T°, $stress^8$, dose

Extreme precision required locally

- **Different scales to look at**
  - Contacts and helical bow ➔ assembly scale
  - Local damage by thermal creeping ➔ cladding skin scale

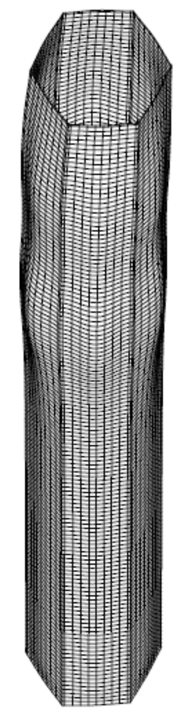
A fully detailed mesh would require ~10^{10} cubic elements!

THE BUNDLE MODEL (LARGE SCALE)



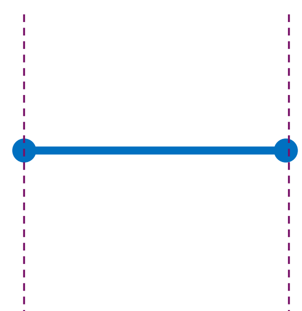
- **Simplifications**
  - Wire tension neglected : fast relaxation
  - UO2 pellet mechanical presence neglected : « soft contact with cladding»
  - Cladding temperature and dose given by dedicated CEA codes

- **Hexagonal tube**
  - Massive or Shell elements



- **Pins axial models**
  - Hollow beam model on the neutral fiber (TUYA element in Cast3M):
    - Stresses due to Internal pressure
    - Modified to access the diametre change

- **Contact and local pin model**
  - Modified barr element

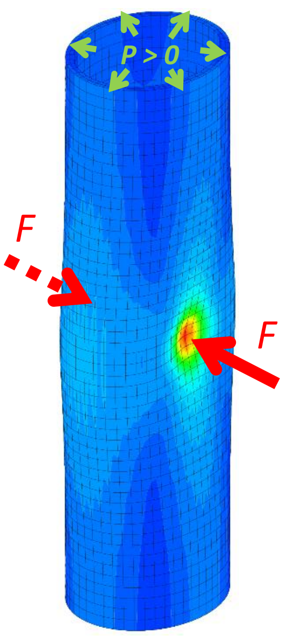


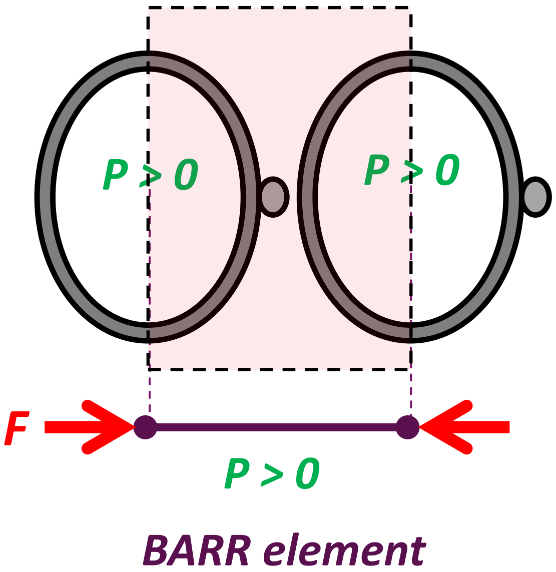
THE EXTENDED BARR ELEMENT (LOCAL SCALE)

Connections : a new BARR element with strain localization

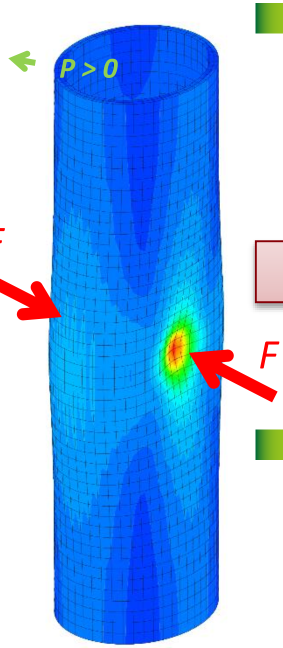
- **A 1D model to represent the 3D non linear pinching of a cladding portion under pressure**

- **On the base of a BARR element, enriched** :
  a) gap / contact function
  b) internal pressure ➔ stress addition + ovality opposition
  c) behavior : thermal elasticity + swelling + thermal & irradiation creepings
  d) damage evaluation ➔3D strain tensor localization on the inner skin

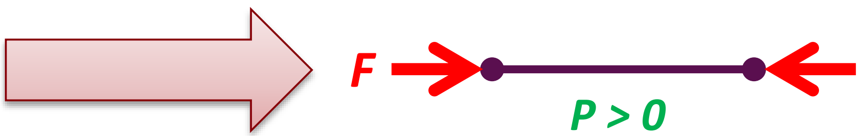




THE EXTENDED BARR ELEMENT



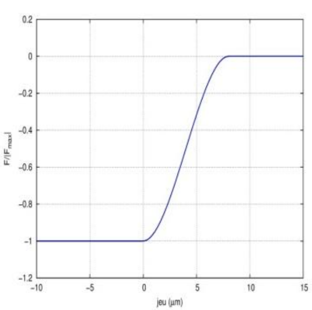
- **Only one integration point required to describe the local & global states !**
  - Irradiation creeping is stress linear ($\sigma_{eq}{}^{1}$), and predominant (in std cond.)

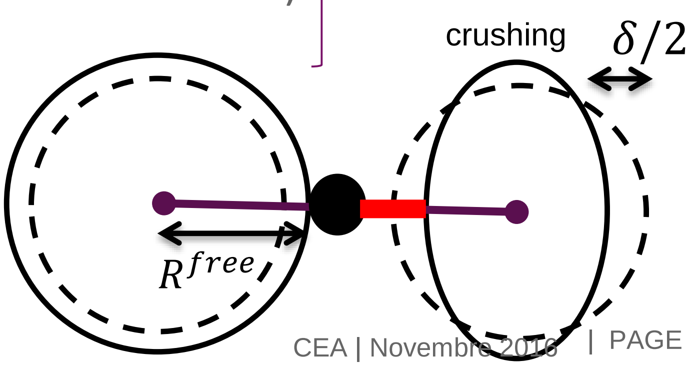


- **Gap evaluation / contact function**
  - Initial gap
  - Relative movement of the 2 pins
  - Gap reduction due to cladding + wire swelling
  - Gap reduction due to creeping (internal Pressure) with wall thickness variation

  } Given by pin elements

  - Gap increase due to ovalisation
  - Ovality induced by pin bending
  - Contact smoothing on 5 µm

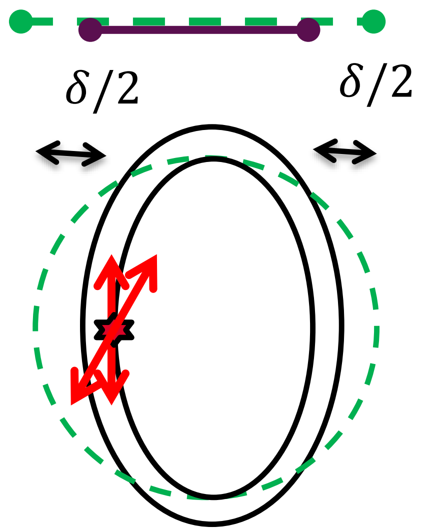




THE EXTENDED BARR ELEMENT

Strain concentration at the hot point (going local)

- Free strain already known (everything but ovality)
- Strain concentration due to ovalisation only (stamping δ<0)
- δ is an internal variable of the barr , similar to plastification
- 2D strain tensor required for precision (+ pressure axial stress)



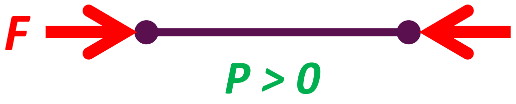
$$d\varepsilon_{\theta\theta}(R_i) = d\varepsilon_{\theta\theta}^{\text{libre}}(R_i) - \lambda_{\theta\theta}(\delta) \, . \frac{d\delta}{R_e}$$

$$d\varepsilon_{zz}(R_i) = d\varepsilon_{zz}^{\text{libre}}(R_i) - \lambda_{zz}(\delta) . \frac{d\delta}{R_e}$$

- $\lambda_{\theta\theta}(\delta)$ and $\lambda_{zz}(\delta)$ identified on an elastic detailed cladding crushing calculation

Complete behavior integration at the hot point only → $\sigma_{\theta\theta}$, σ_{zz}

Contact force in the barr (going back global)

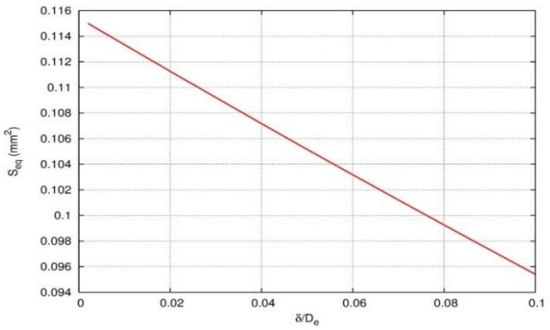


- Both local stresses computed

$$F_{barr} = \frac{S_{eq}}{k_{\theta\theta}}\left(\sigma_{\theta\theta} - \sigma_{\theta\theta}^{free}\right)$$

- S_{eq} similar to a barr section, **but non linear due to ovality change** (stiffness decrease)

$$S_{eq}(\delta) = S_{eq}(0)\left(1 + S_1\frac{\delta}{D_e} + S_2\left(\frac{\delta}{D_e}\right)^2\right)$$



- $k_{\theta\theta}(\delta)$: stress concentration factor, related to $\boldsymbol{\lambda_{\theta\theta}}$ and $\boldsymbol{\lambda_{zz}}$

$$\lambda_{\theta\theta} = k_{\theta\theta} - \nu k_{zz}. \qquad \lambda_{zz} = k_{zz} - \nu k_{\theta\theta}. \qquad \nu = 0{,}5 \text{ (isochore)}$$

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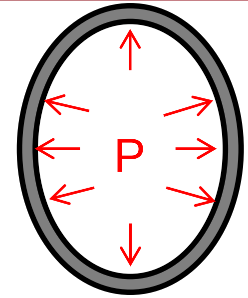
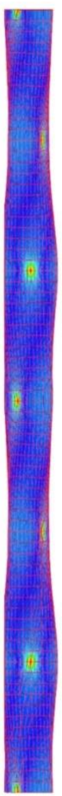
THE EXTENDED BARR ELEMENT

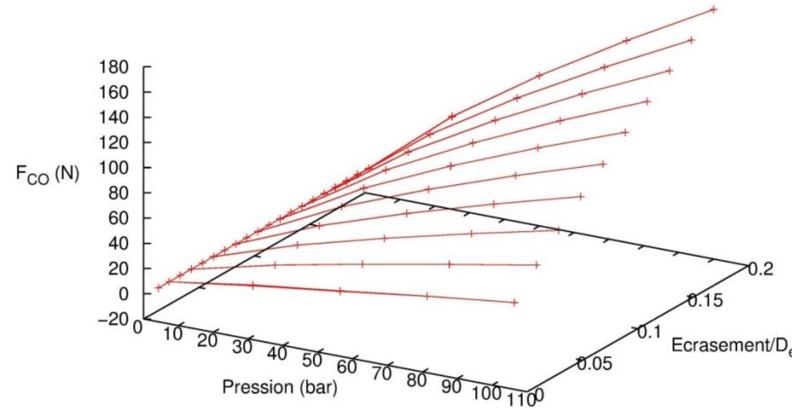


Anti ovality effect of inside pressure

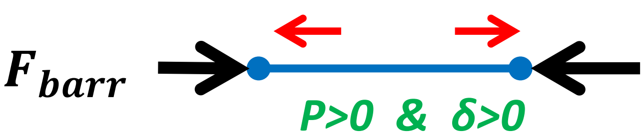
- Absolutely not neglectable ➔ $F_{barr} = \frac{S_{eq}}{k_{\theta\theta}}\left(\sigma_{\theta\theta} - \sigma_{\theta\theta}^{free}\right)$ **-- F_{CO}**



- Internal opposition force :



$$F_{CO} = -P.\delta.L_{eq(\delta)}$$



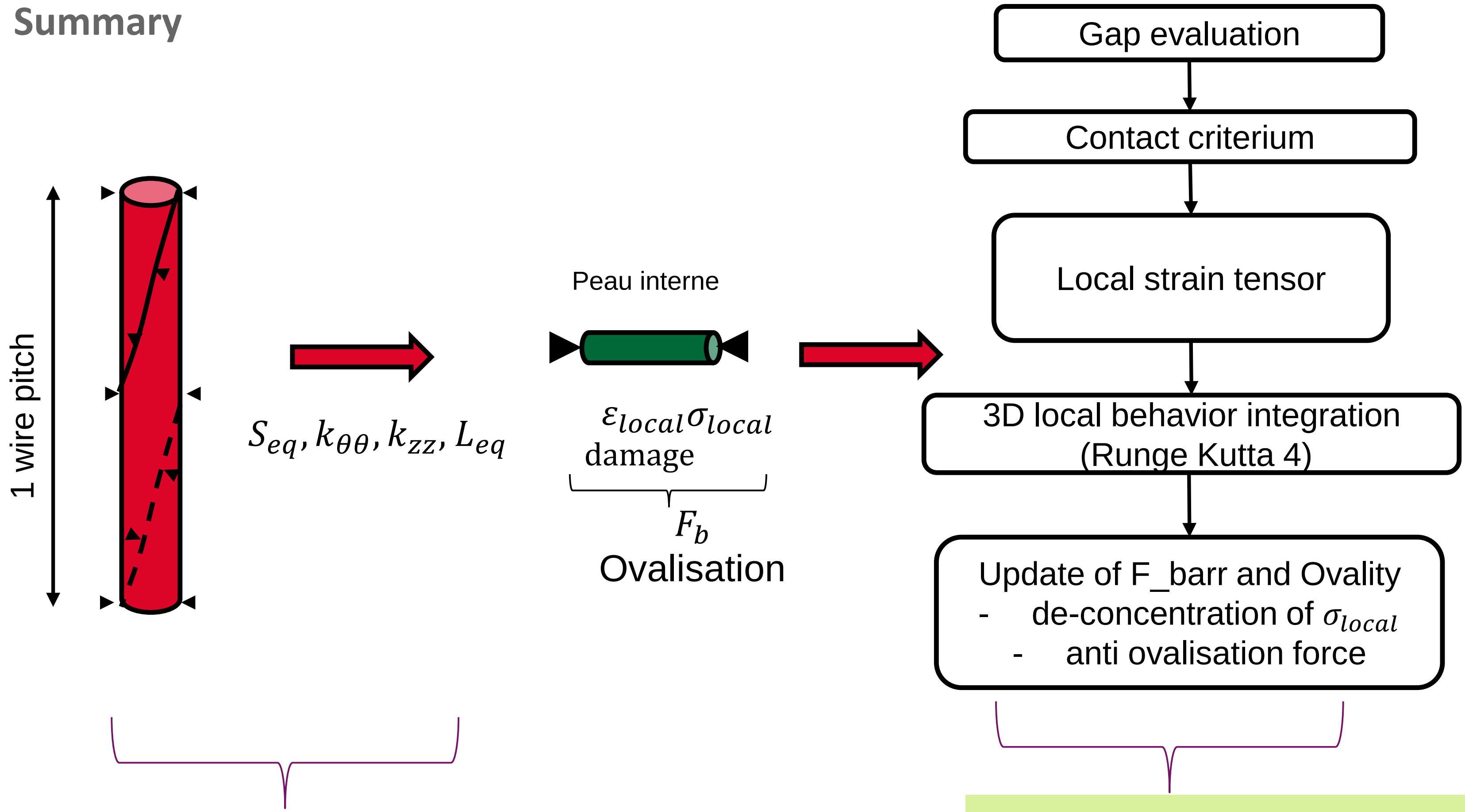
- The vertical extension of the ovality shape depends on δ (elastic characterisation)

$$L_{eq} = \frac{wire\_pitch}{6}\left(L_0 + L_1\frac{\delta}{R_e}\right)$$

- Non linear effect of pressure and creeping on the shape not taken into account

THE EXTENDED BARR ELEMENT

Summary

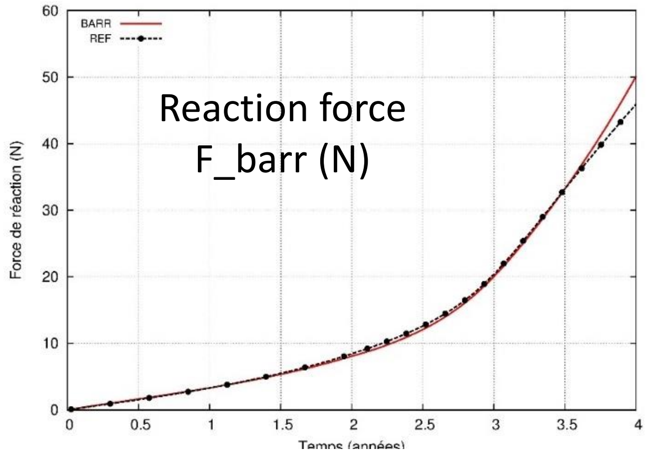


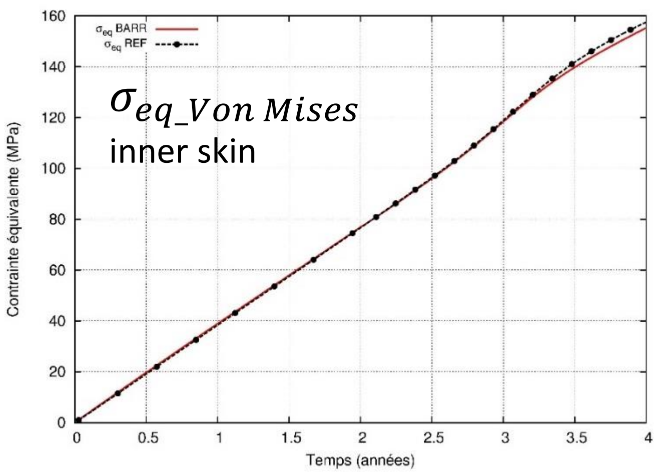
3D elastic characterisation

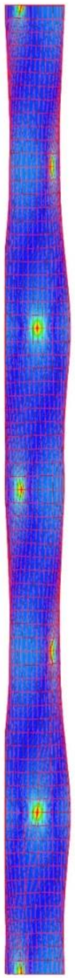
Hot point and contact Force computation in the barr

BARR VALIDATION

- 1 of the **Validation tests** on a severe cladding pinching (Ref. = detailed 3D simulation)

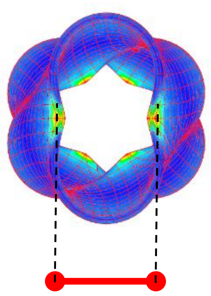






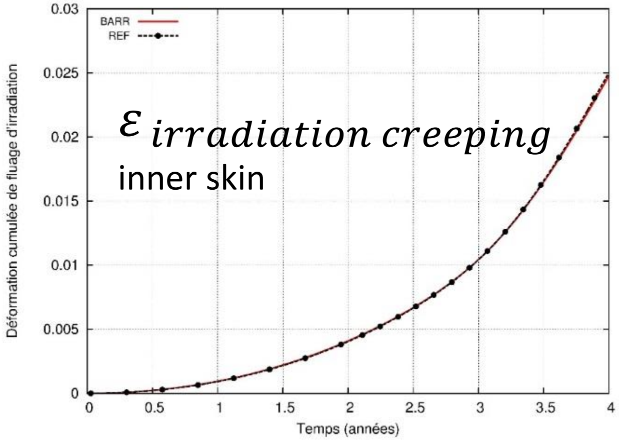
σ_{eq}

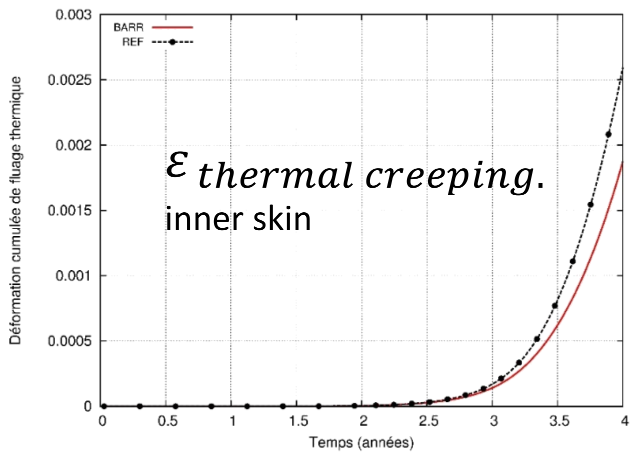
déformée x10



Contact points radially blocked

- **T = 650°C**
- **Dose : 0 to 190 dpa**
- **Pressure : 0 to150 bars**



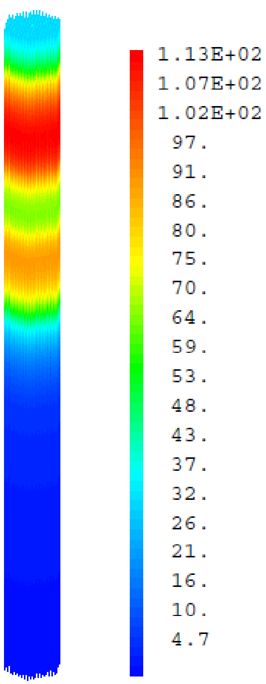


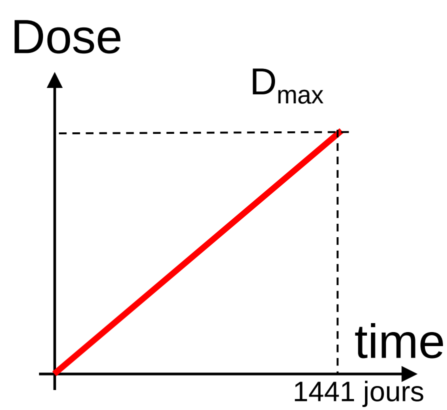
- \+ Whole model validation on 3 PHENIX integral experiments ➔ OK

SIMPLIFIED BUNDLE LOADINGS

Irradiation Dose

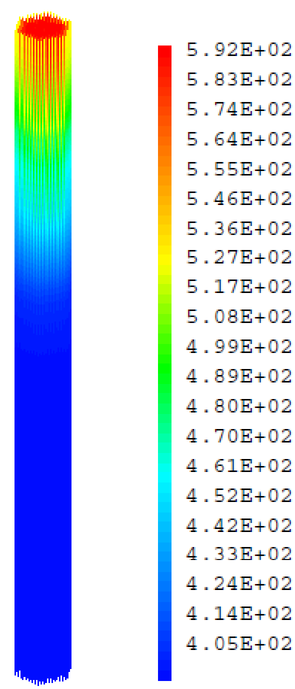
- Radial decrease
- D_{max} = 113 dpa

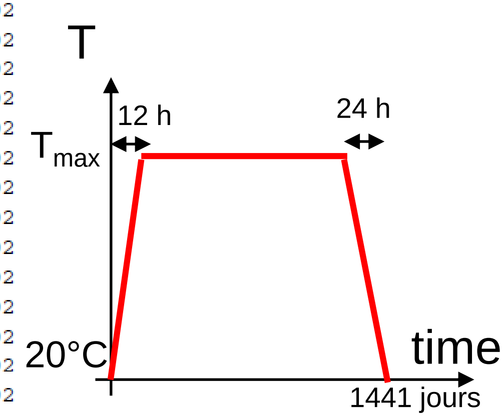




Temperature

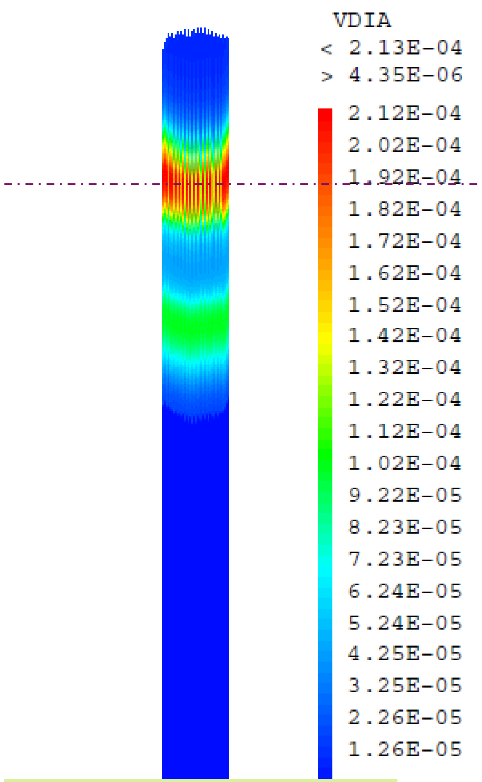
- Axial and radial gradients
- T_{max} ~ 600°C



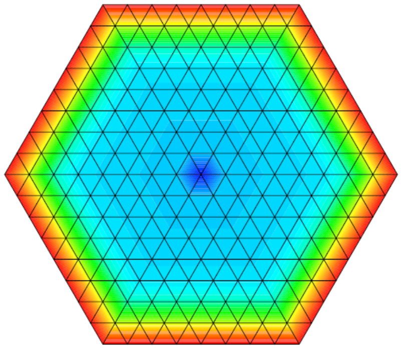


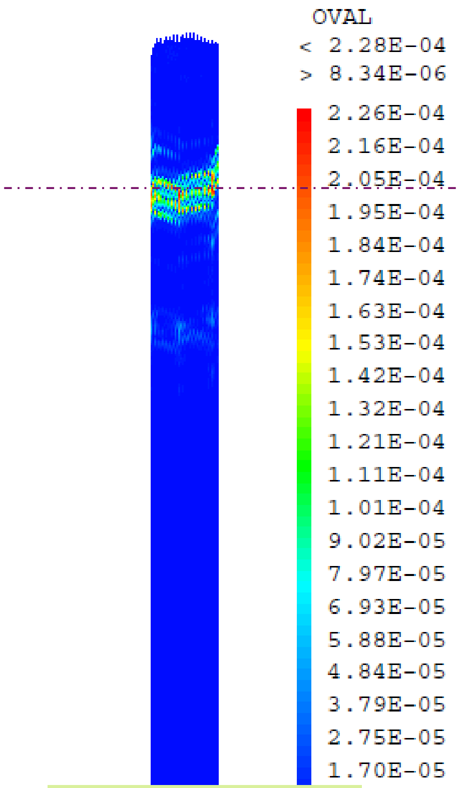
- **Inside sodium pressure:** Profil axial constant 4 bar -> 1,79 bar au sommet
- **Outside sodium pressure** : 1,85 bar bottom -> 1,66 bar top
- **FP pressure**: from 10 to 40 bar
- **Matérials : 1515 Ti E variants and EM10(TH)**

TYPICAL ASSEMBLY RESULTS AT THE END OF LIFE

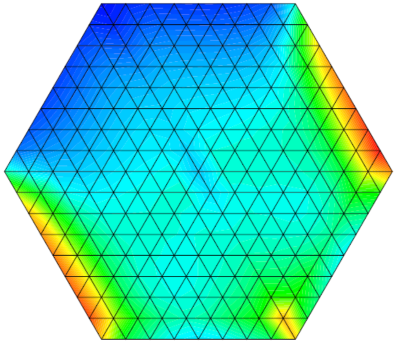


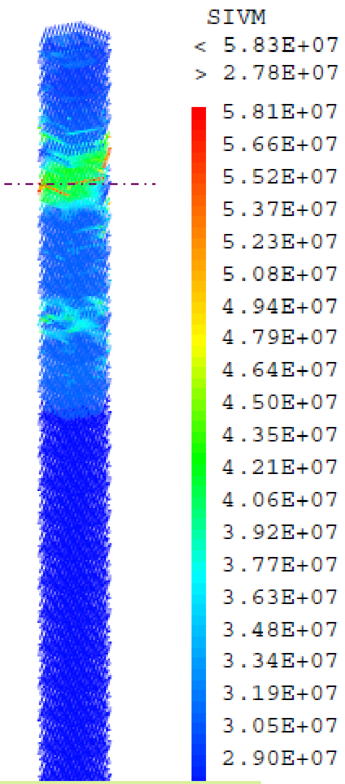
Δ Diametre (m)



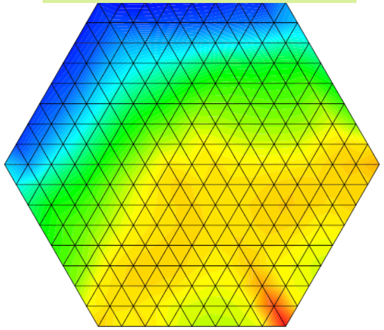


Ovality (m)



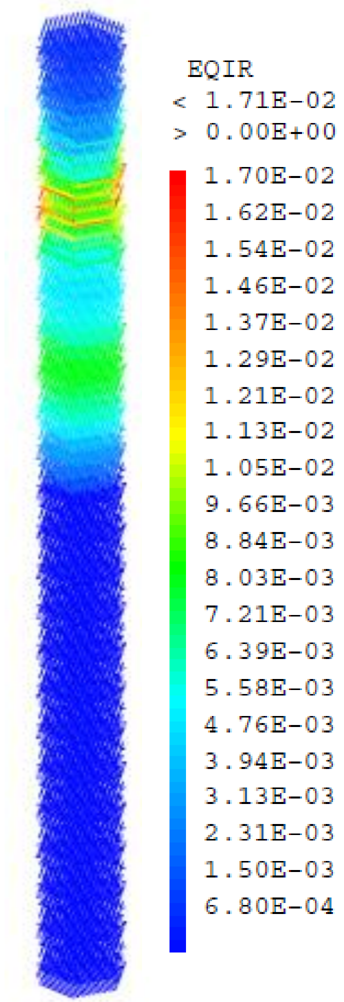


$\sigma_{Von\ mises}$

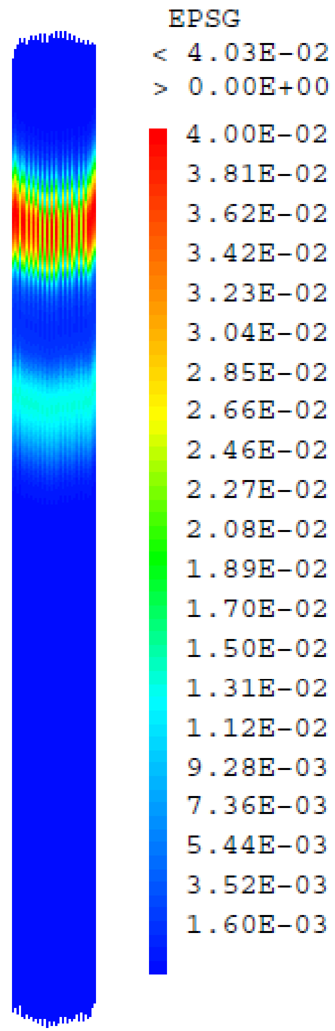


TYPICAL RESULTS AT THE END OF LIFE

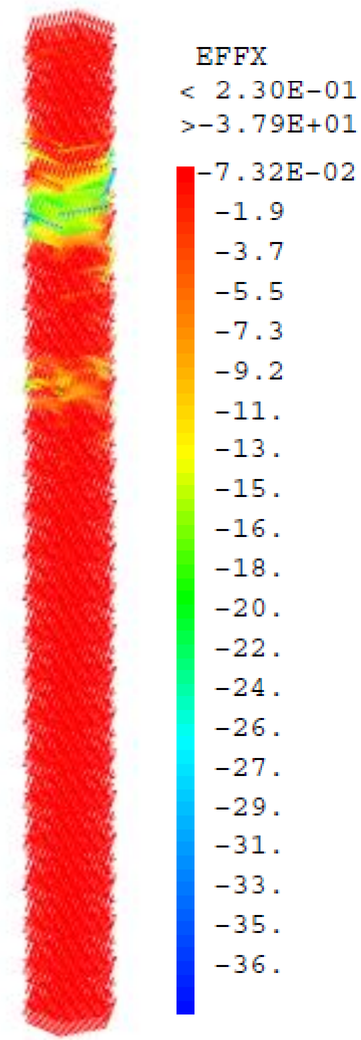
$\varepsilon^{irrad.creeping}$



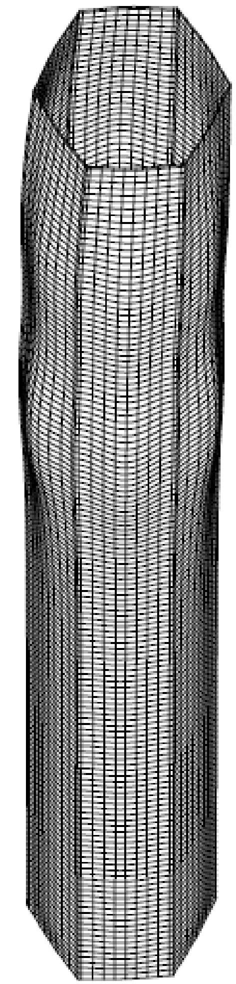
Vol. swelling



Contact forces

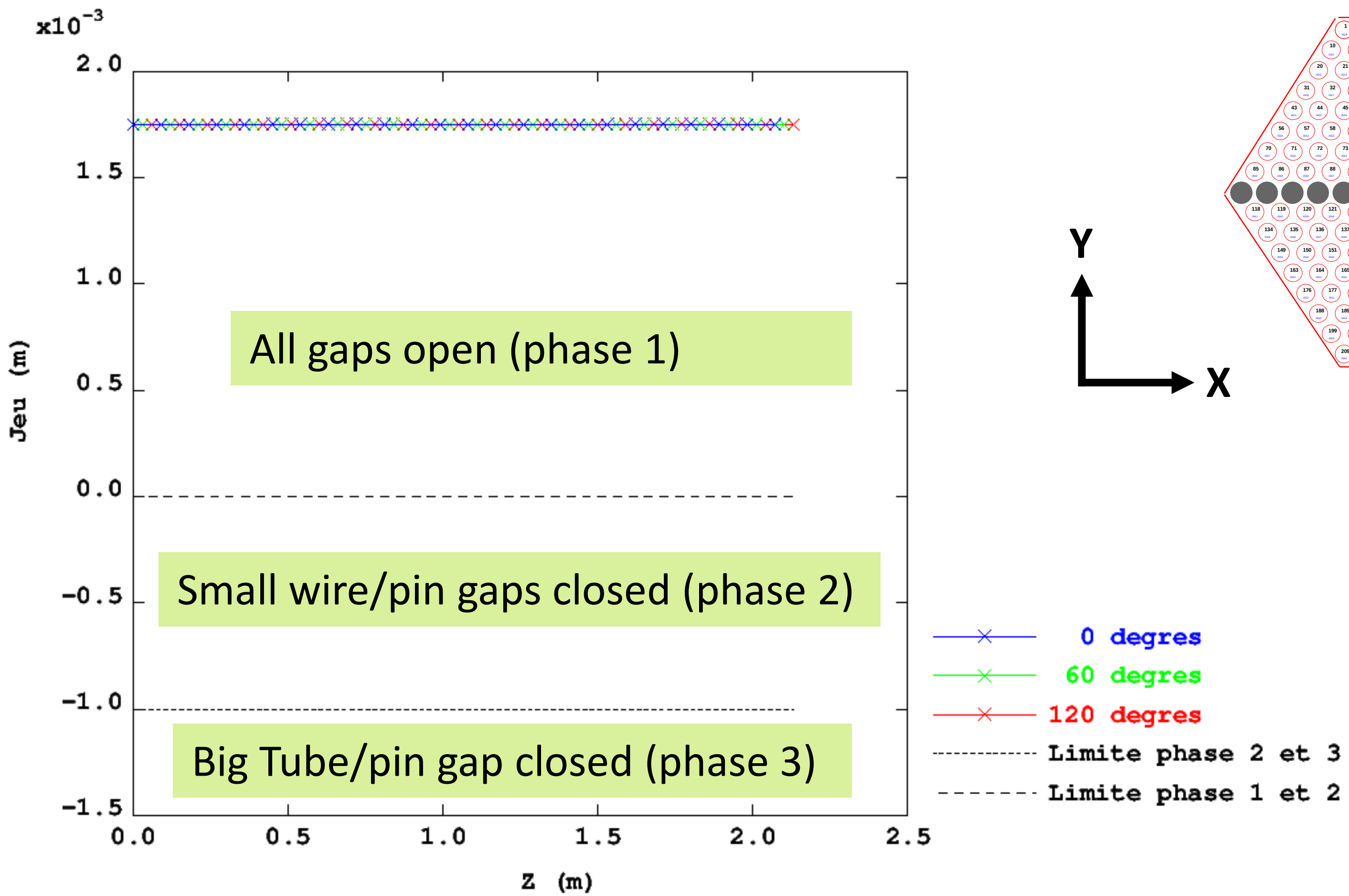


H. T. deformation
X100

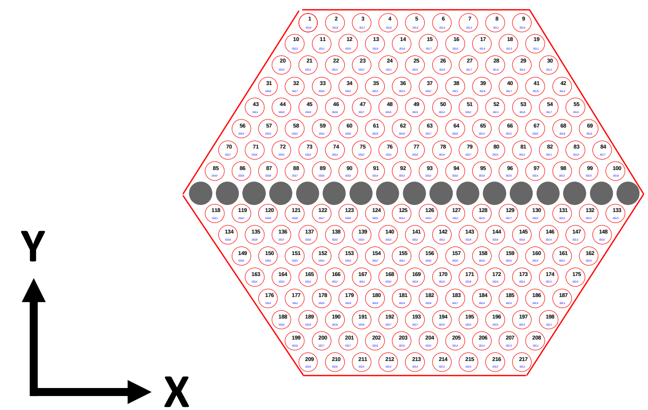


TYPICAL RESULTS AT THE END OF LIFE

- Gap indicator in the diagonal versus altitude (time animation)



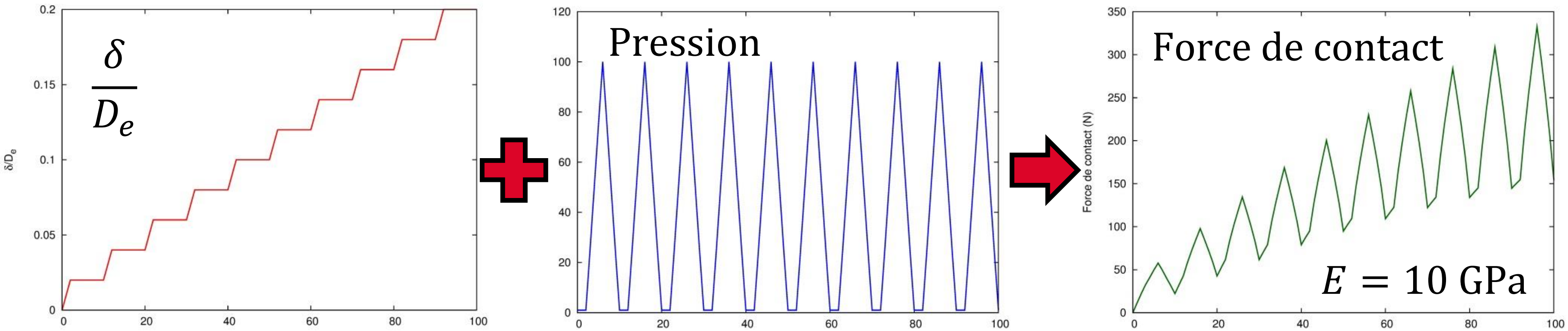
Jeu avant phase 2 vs. hauteur a t = 0.00000E+00 s (0%)



APPENDICES

ONE ELASTIC CHARACTERISATION MODEL FOR 4 PARAMETERS

➢ **Elastic 3D detailed calcuation + stiffness / pressure loading actualisations**



- **Parametres $\boldsymbol{S}, \boldsymbol{k_{\theta\theta}}, \boldsymbol{k_{zz}}$ depending on crushing δ**

$$S_{eq}(\delta) = S_0\left(1 + a_1\frac{\delta}{D_e} + a_2\left(\frac{\delta}{D_e}\right)^2\right) \qquad k_{\theta\theta}(\delta) = k_0\left(1 + k_1\frac{\delta}{D_e} + k_2\left(\frac{\delta}{D_e}\right)^2\right)$$

- **Counter-ovalisation force** $F_{CO} = P.\delta.L_{eq}$ $\quad L_{eq} = \frac{wire\_pitch}{6}\left(L_0 + L_1\frac{\delta}{R_e}\right)$

- **Relation ovalisation / crushing** $\omega \sim \mathbf{1,6} \times \delta$ in 3D

GAP COMPUTATION (OPEN CONTACT)

- **Géométrie à jeu ouvert**

Sous l'effet combiné de la pression interne des gaz de fission, de la température et de l'irradiation, l'incrément de rayon externe est donné par : $\mathrm{d}R_e = R_e.\mathrm{d}\varepsilon_{\theta\theta}^{\mathrm{libre}}(R_e)$ avec $\mathrm{d}\varepsilon_{\theta\theta}^{\mathrm{libre}}(R_e) = \mathrm{d}\varepsilon_{\theta\theta}^{e}(R_e) + \mathrm{d}\varepsilon_{\theta\theta}^{fl}\left(\sigma_{eq}(R_e)\right) + \mathrm{d}\varepsilon^{th} + \mathrm{d}\varepsilon^{g}$

L'état de contrainte est imposé par la pression interne, supposée uniforme dans la gaine fermée à ses extrémités (effet de fond) :

$$\sigma_{rr}(r) = \frac{PR_i^2}{R_e^2-R_i^2}\left(1-\left(\frac{R_e}{r}\right)^2\right) \qquad \sigma_{\theta\theta}(r) = \frac{PR_i^2}{R_e^2-R_i^2}\left(1+\left(\frac{R_e}{r}\right)^2\right) \qquad \sigma_{zz} = \frac{PR_i^2}{R_e^2-R_i^2}$$

L'état de contrainte permet de calculer directement l'incrément de déformation par fluage $\mathrm{d}\varepsilon_{ii}^{fl}\left(\underline{\sigma}\right)$ ainsi que la déformation élastique :

$$\varepsilon_{rr}^{e}(r) = \frac{\sigma_{rr}(r)}{E} - \frac{\nu}{E}(\sigma_{\theta\theta}(r) + \sigma_{zz}) \qquad \varepsilon_{\theta\theta}^{e}(r) = \frac{\sigma_{\theta\theta}(r)}{E} - \frac{\nu}{E}(\sigma_{rr}(r) + \sigma_{zz}) \qquad \varepsilon_{zz}^{e}(r) = \frac{\sigma_{zz}}{E} - \frac{\nu}{E}(\sigma_{rr}(r) + \sigma_{\theta\theta}(r))$$

On calcule aussi l'incrément d'épaisseur de gaine :

$\mathrm{d}e_g = e_g.\mathrm{d}\varepsilon_{rr}^{\mathrm{libre}}(R_{moy})$ avec $\mathrm{d}\varepsilon_{rr}^{\mathrm{libre}}(R_{moy}) = \mathrm{d}\varepsilon_{rr}^{e}(R_{moy}) + \mathrm{d}\varepsilon_{rr}^{fl}\left(\sigma_{eq}(R_{moy})\right) + \mathrm{d}\varepsilon^{th} + \mathrm{d}\varepsilon^{g}$

De la même manière, l'incrément de rayon interne de la gaine est calculé : $\mathrm{d}R_i = R_i.\mathrm{d}\varepsilon_{\theta\theta}^{\mathrm{libre}}(R_i)$

L'incrément de diamètre du fil est calculé en ne considérant que la dilatation thermique et le gonflement :

$$\mathrm{d}D_{fil} = D_{fil}(\mathrm{d}\varepsilon^{th} + \mathrm{d}\varepsilon^{g})$$

Incrément du jeu prédit

$$\mathrm{d}jeu = \mathrm{d}L - n_R\mathrm{d}R_e - n_D\mathrm{d}D_{fil}$$

Jeu en fin de pas de temps

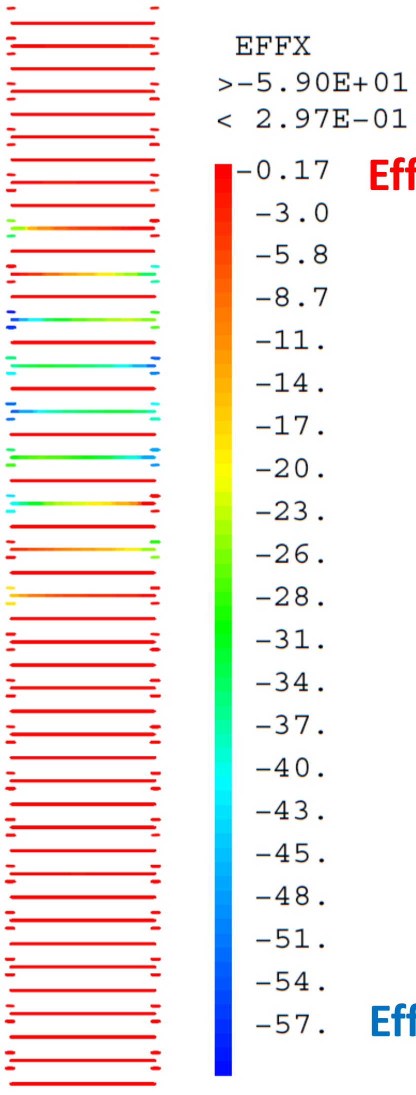
$$jeu(t+\mathrm{d}t) = jeu(t) + \mathrm{d}jeu$$

avec $\mathrm{d}L = L\mathrm{d}\varepsilon_b$ l'incrément de longueur de la barre, $n_R$le nombre de rayon considéré dans la liaison (1 ou 2) et n_D le nombre de diamètre de fil considéré (0 ou 1).

Si $jeu(t+\mathrm{d}t) > 0$, le jeu est ouvert, sinon, il est fermé.

TYPICAL RESULTS AT THE END OF LIFE

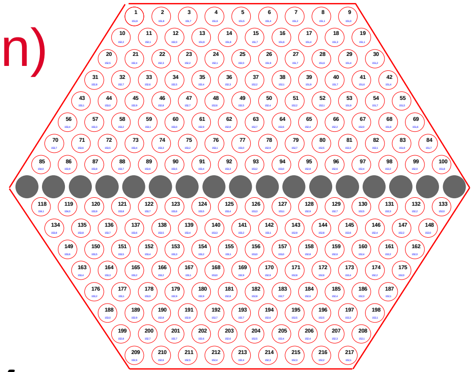
Exemple d'efforts de réaction (autre configuration)

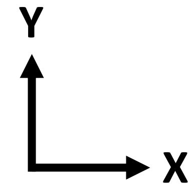


Z

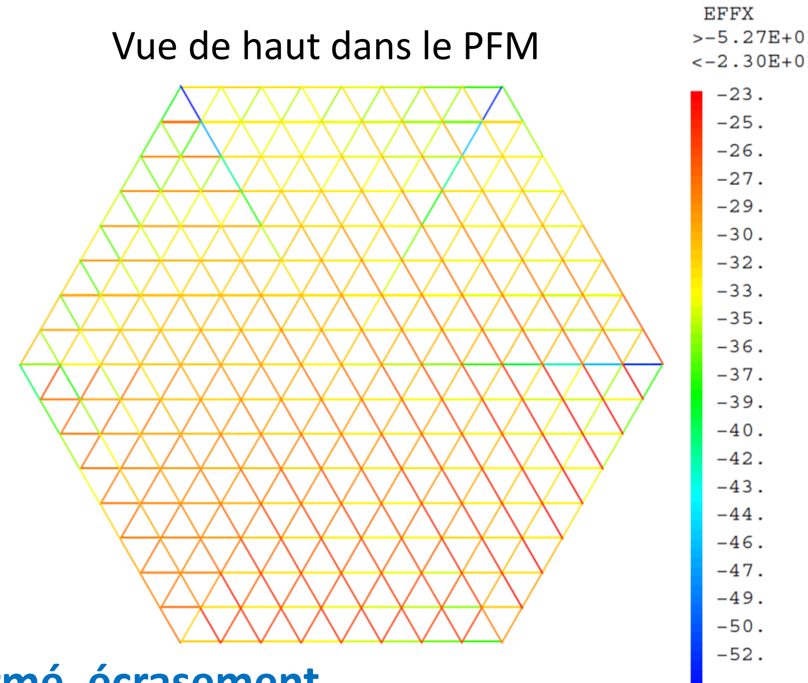
Vue de côté sur la diagonale X

Effort nul ⇔ jeu ouvert





Vue de haut dans le PFM



Effort négatif ⇔ jeu fermé, écrasement