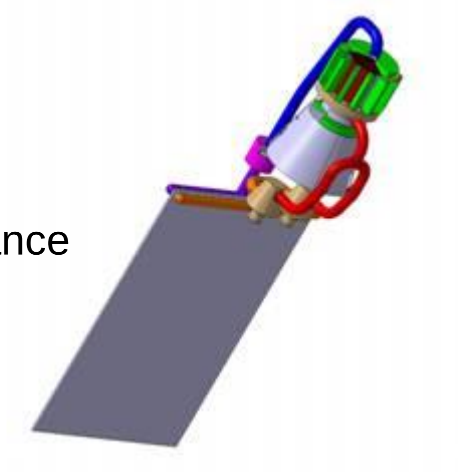
Coupled 1D thermohydraulic – 3D thermomechanical study of a space nuclear reactor



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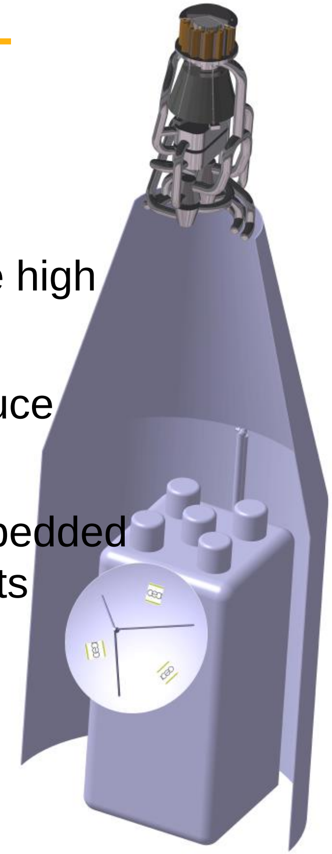
The OPUS System



To maintain a waking state activity

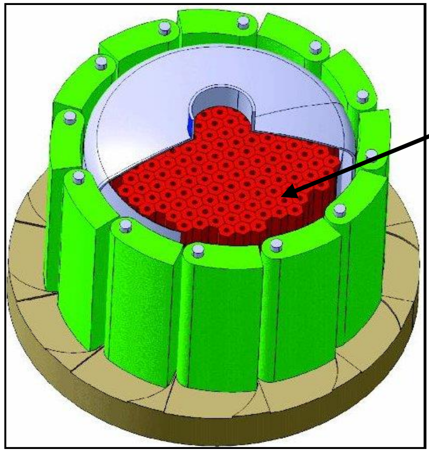
Pre-conceptual design studies of what would be a NEP system in the range 100-500 kW^e
⇒ OPUS studies

Preliminary basic options

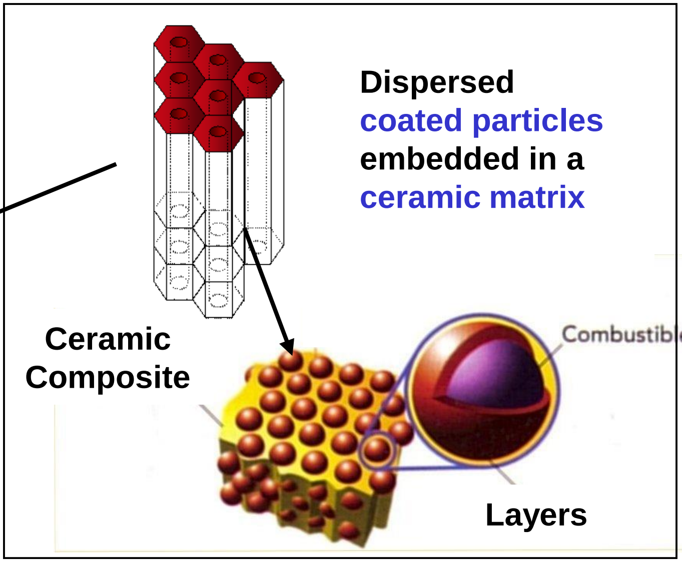
- Gas-cooled reactor
- Fast neutron spectrum
- Dynamic conversion cycle

Basic core design

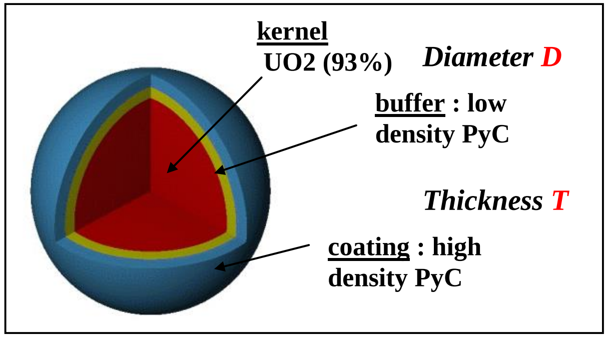
- Refractory material ⇒ to achieve high temperature (1300 K at the outlet)
- Fast neutron spectrum ⇒ to reduce the critical mass
- Coated fuel particles (BISO) embedded in hexagonal graphite fuel elements



Reactor Core



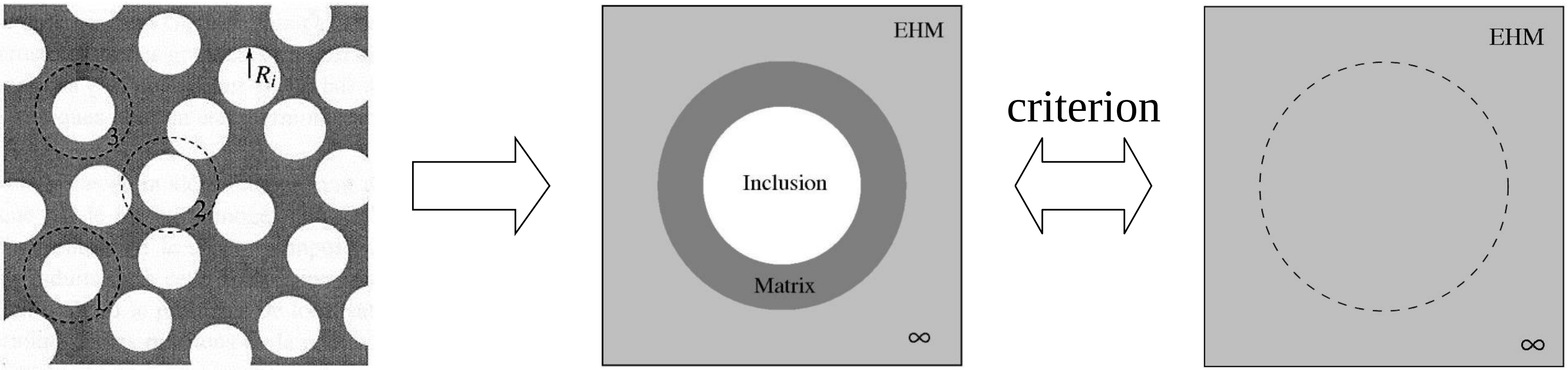
Nuclear fuel elements



Particle design

Composite fuel modeling*

- Material heterogeneity simplification
- Equivalent Homogeneous Media



- <u>Effective thermoelastic properties</u> :

  λ^*, E^*, ν^*, α^* functions of $\{\lambda_i, E_i, \nu_i, \alpha_i\}_{1\leq i\leq n}$ and phase proportions $\{c_i\}_{1\leq i\leq n}$

- <u>Local strains and stresses</u> :

$$\underline{\underline{\varepsilon}}_i = \mathcal{A}_i : \left(\underline{\underline{E}} - \underline{\underline{E}}^{th} - \underline{\underline{E}}^{ir}\right) + \sum_i \mathcal{P}_{ij} : \left(\underline{\underline{\varepsilon}}_j^{th} + \underline{\underline{\varepsilon}}_j^{ir}\right) \quad \text{avec :} \quad \underline{\underline{E}}^{ir} = \sum_i \chi_i \mathcal{B}_i : \underline{\underline{\varepsilon}}_i^{ir}$$

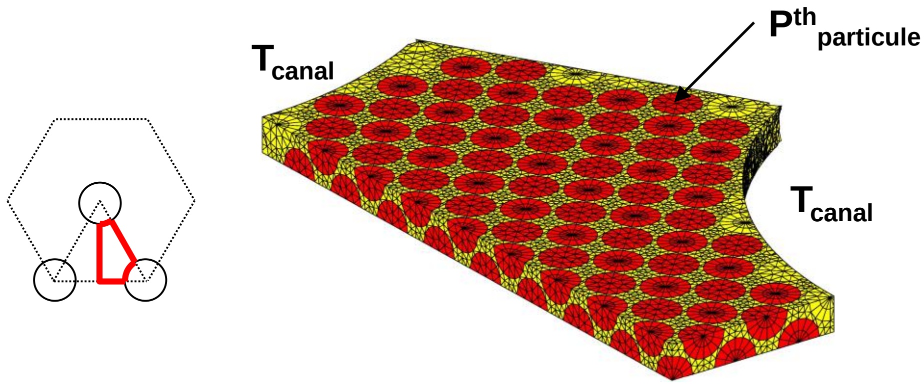
$$\underline{\underline{\sigma}}_i = \mathcal{C}_i : \left(\underline{\underline{\varepsilon}}_i - \underline{\underline{\varepsilon}}_i^{th} - \underline{\underline{\varepsilon}}_i^{ir}\right)$$

(*) E. Hervé, A. Zaoui, "N-layered inclusion-based micromechanical modelling", Int. J. Engng Sci., **31** (1993) 1-10.

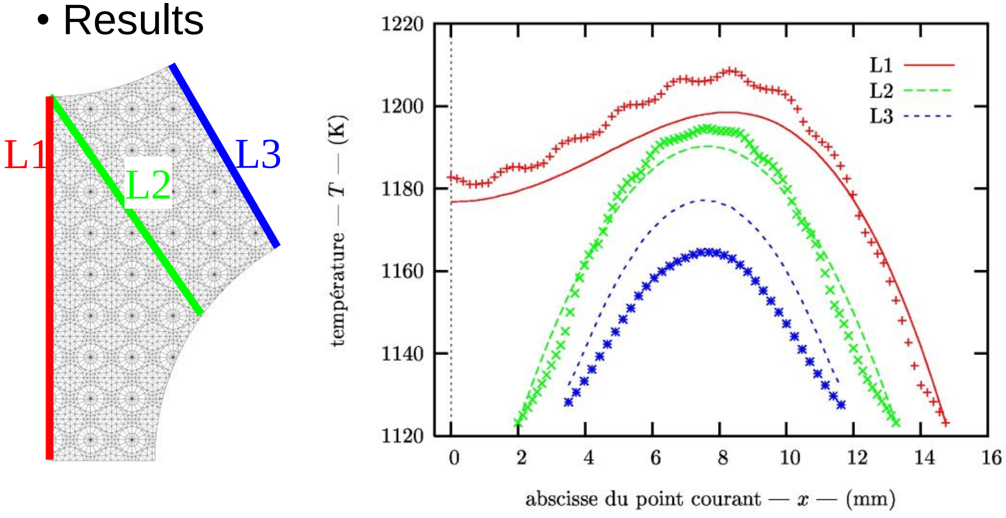
Composite fuel modeling: validation & ongoing studies

Fuel Element cross-section modelling

- Thermomechanical modelling



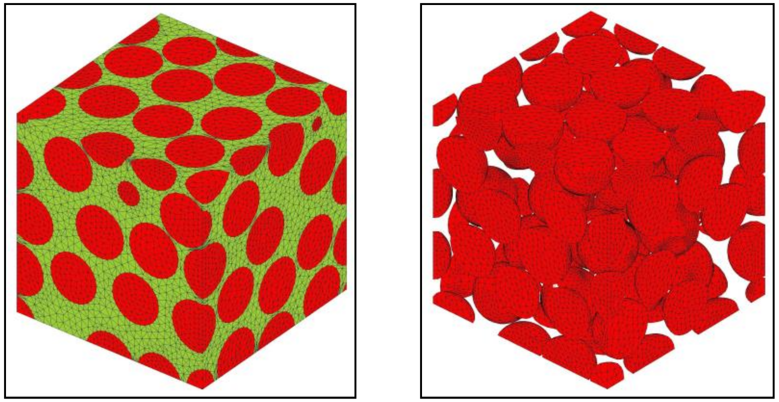
- Results



Heterogeneous media modelling

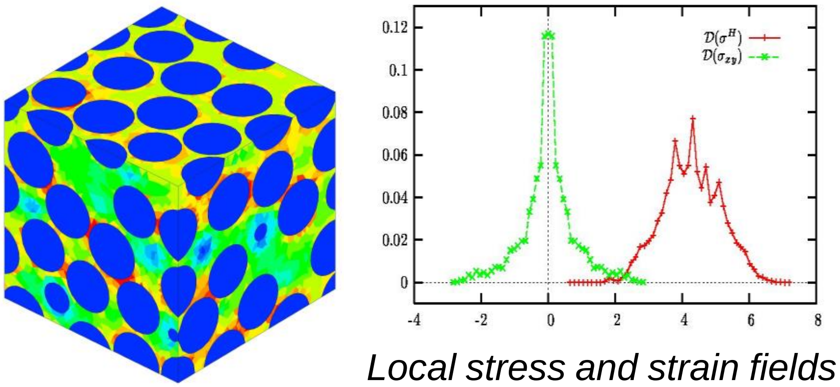
(F. Di Paola PhD Thesis)

- Mesh generation



Particle Volume Fraction ~ 43%

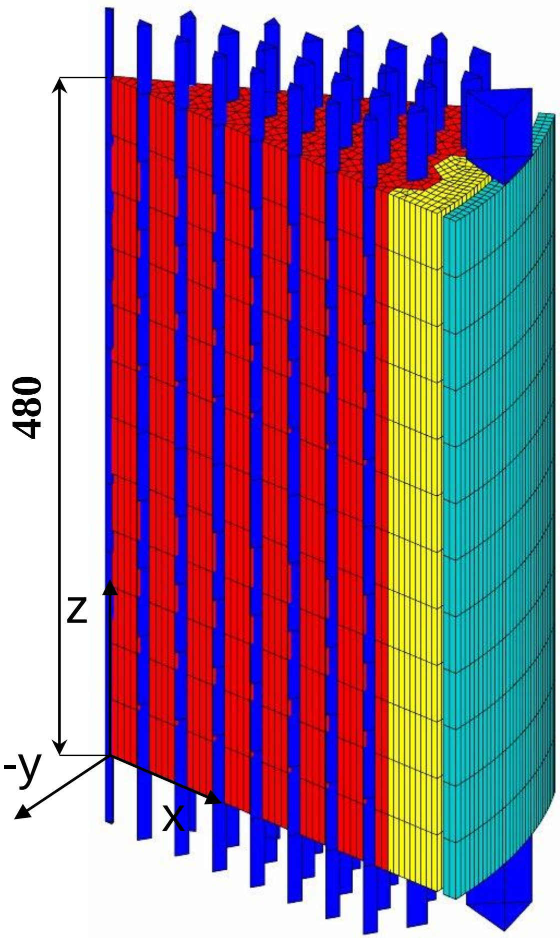
- Mechanical Characterisation



Local stress and strain fields

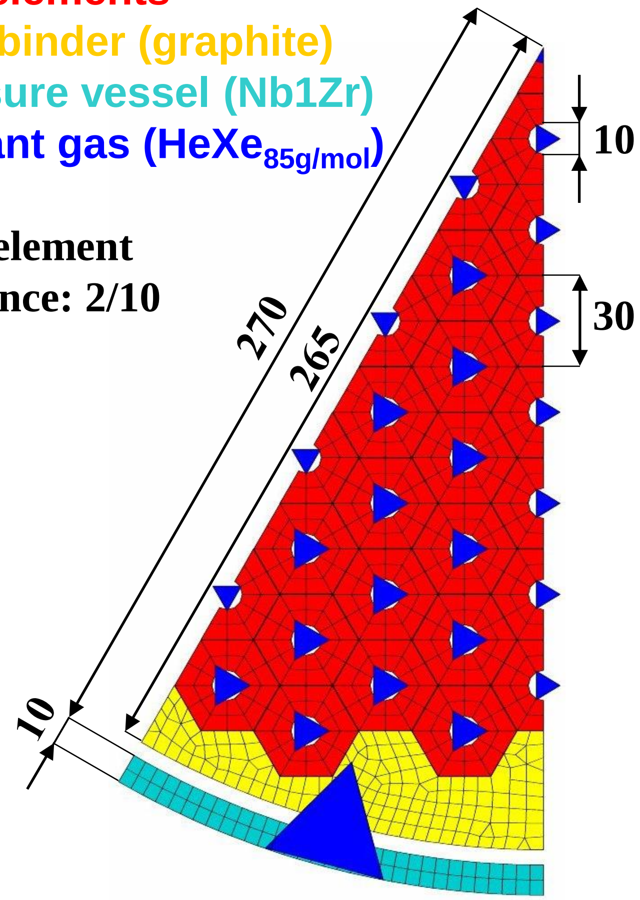
Geometry / Finite Element Mesh

1/12th of the Reactor

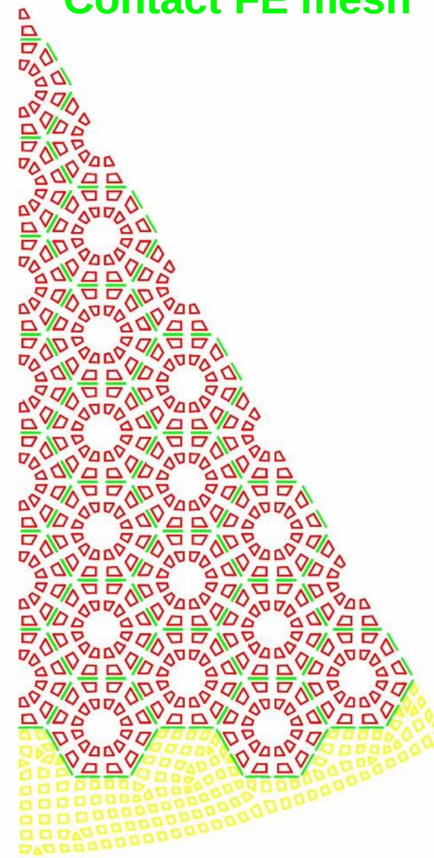


Fuel elements
Core binder (graphite)
Pressure vessel (Nb1Zr)
Coolant gas (HeXe$_{85g/mol}$)

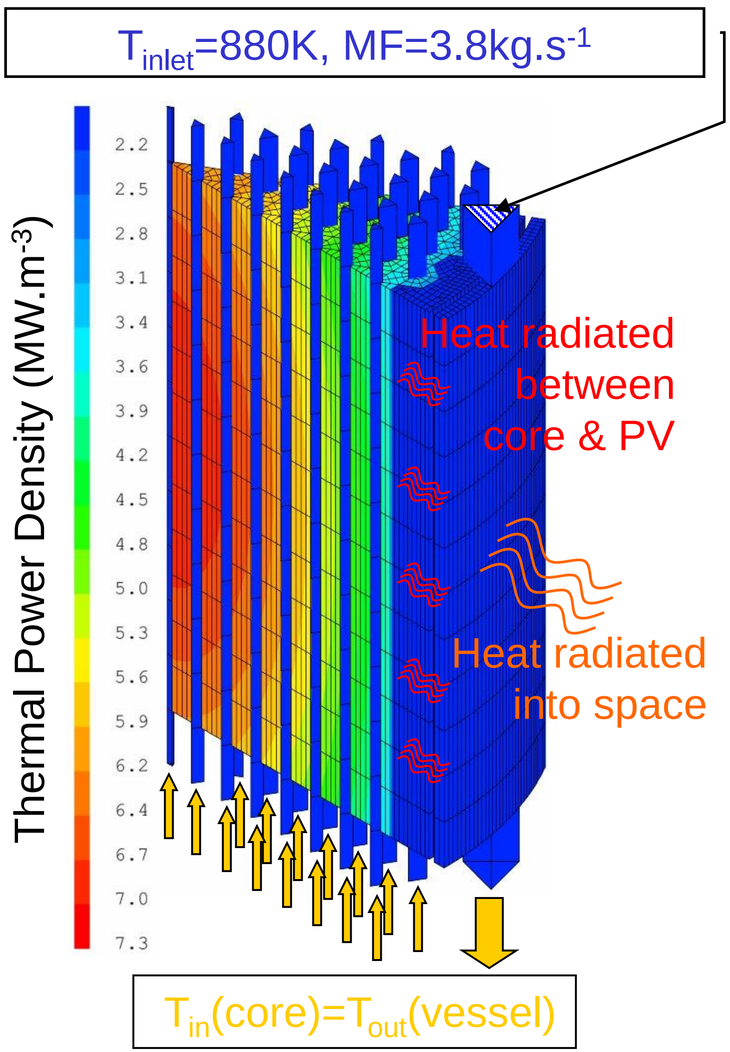
Inter-element clearance: 2/10



Contact FE mesh



1D-thermohydraulic / 3D-thermal coupling



Thermohydraulic:

- **1D modelling:** Mass conservation & Energy balance, but pressure drop neglected
- **He-Xe proportion parameterized**
- **State law:** ideal gas law
- **Boundary conditions**

  T_{inlet} = 880K

  MF_{inlet} = 3.8kg/s $\Rightarrow$ T_{oulet} = 1300K
- **Convective heat exchange:** Colburn or Dittus-Bolter

  $Nu = 0.023 Re^{0.8} Pr^{(1/3 \text{ or } 0.4)} \Rightarrow h = Nu\, \lambda_{He}(T_m)/d$

Thermal:

- **3D modelling:** core = continuous media
- **Thermal loading:** Power density fit to TRIPOLI results

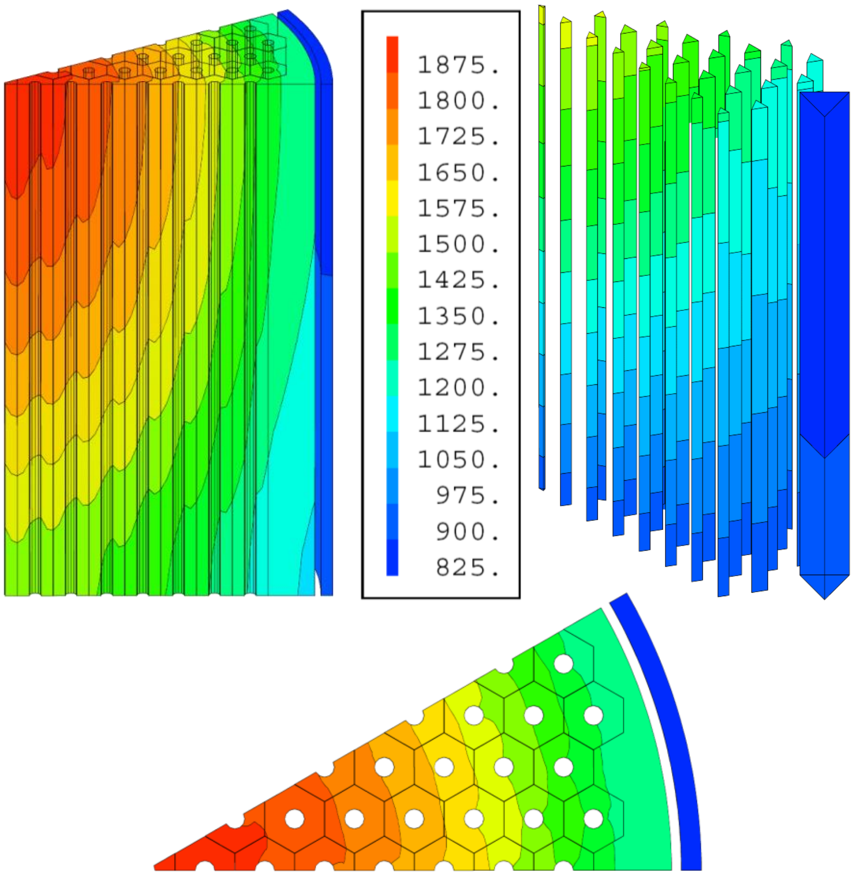
$$p(r,z) = p_{max} J_0(\alpha r) cos(\beta \tilde{z}),$$)0kW

- **Boundary conditions:**

  - Convective heat exchange with the coolant gas on: Channel / outer Core / inner Pressure Vessel surfaces
  - Radiant heat exchange between: outer Core / inner PV surfaces & outer PV surface

Temperature

T_{outlet} = 1300K



Temperature (K) Structures & Coolant gas

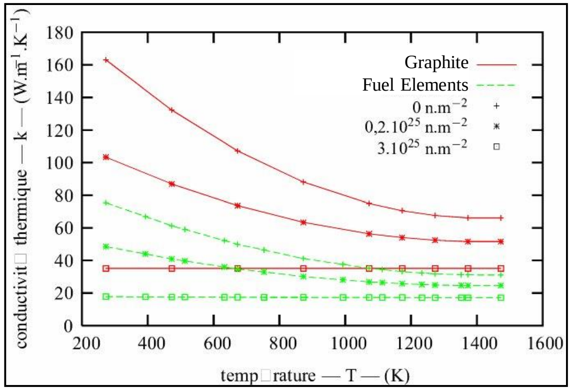
Results & Evolution from 0 to 2000 EFPD

Structures		
	0 JEPP	2 000 JEPP
Température maximale	**1 807**	**1 870**
Extrema en sortie du cœur (centre > périphérie) et écart / gradient radial	1 807 > 1 203 604 / **2 279** K.m^{-1}	1 870 > 1 137 735 / **2 774** K.m^{-1}
Extrema assemblage le plus chaud et écart / gradient axial	1 807 > 1 427 380 / 792 K.m^{-1}	1 870 > 1 417 453 / 944 K.m^{-1}
Extrema baffle	1 302 > 1 130	1 280 > 1 076
Extrema cuve	946 > 906	926 > 894

Gaz caloporteur		
Température maximale	**1 474**	**1 491**
Température moyenne en sortie du cœur	1 301,6	1 302,1
Extrema en sortie du cœur (centre > périphérie) et écart entre le canal le plus chaud et le plus froid	1 474 > 1 153 321	1 491 > 1 124 367
Extrema dans le canal le plus chaud et écart / gradient axial	1 474 > 953 521 / 1 085 K.m^{-1}	1 491 > 936 555 / 1 156 K.m^{-1}

Due to the decrease of thermal conductivity under irradiation :

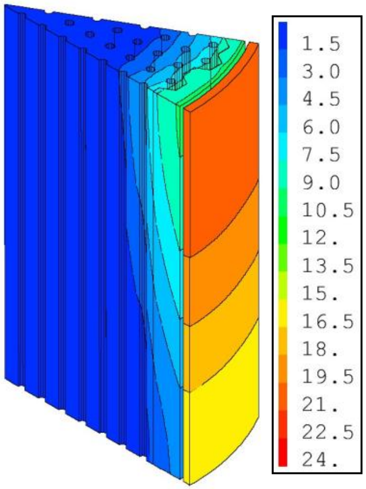
Thermal conductivity
Vs. Temperature
& Irradiation Dose



Thermohydraulic-Thermal Simulations : Summary

Main results

- T_{max} : 1909K → 2001K (~1730°C) !
- Max. Temp. ↗ under irradiation due to ↘ Graphite Thermal Conductivity
- Radiant Heat Exchange ↘ PV Temperature Gradients (ΔT ↘ ~20K) ➡
- Convective Heat Exchange Analogy not fully satisfying:
  Experimental data on He-Xe coolant in such conditions ?



Modelling improvements

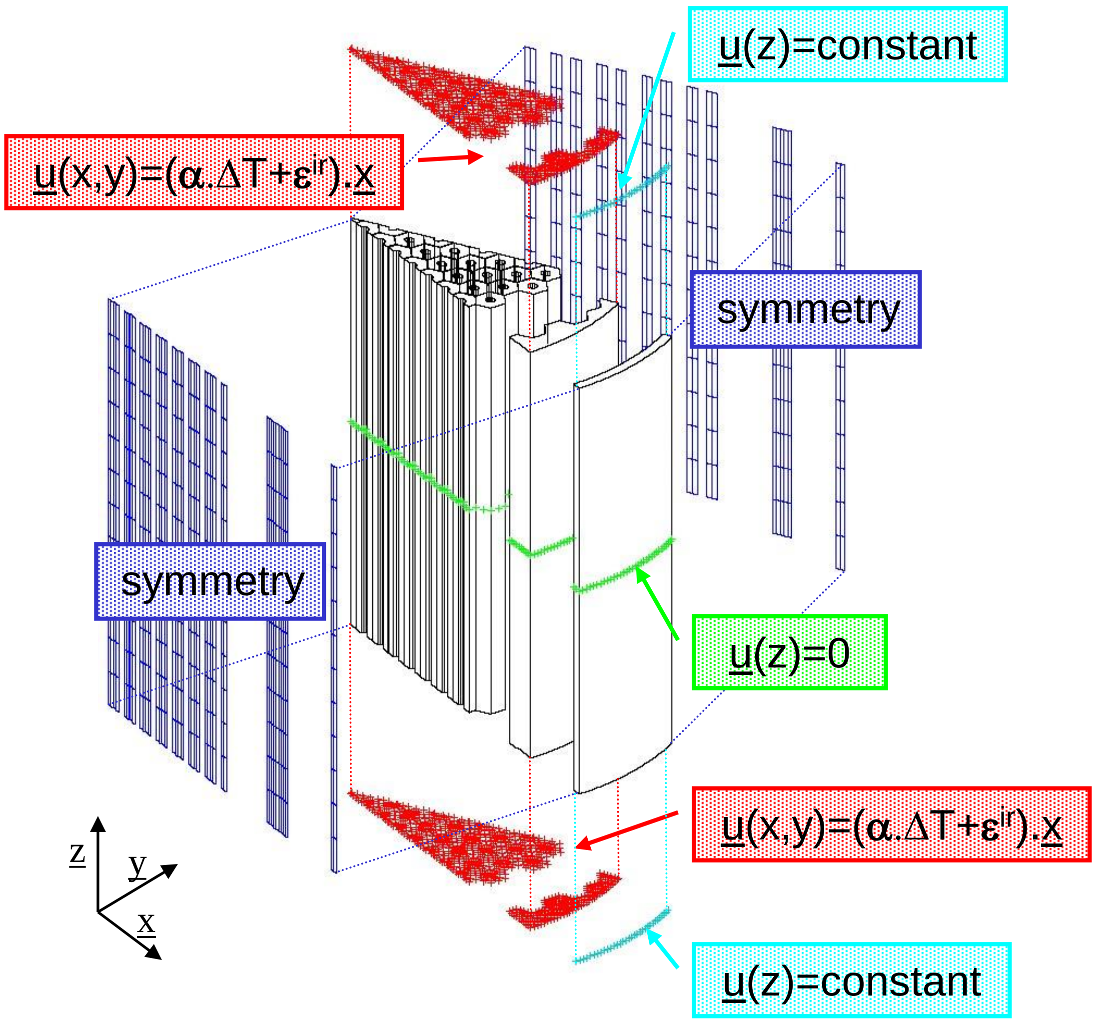
- Thermal modelling: reactor core modelled as a continuous media
  but temperature jumps at the fuel element interface should be very important…
- Thermohydraulic BC: mass flow prescribed at the core inlet
  but coolant flow should not uniformly distributed over the channels
  ⇒ thermal gradients could be even more important in the core

Remark on the Simulation Tool

- Temperature field of the reactor fully determined in 3D by setting only 3 parameters:
  ⇒ Inlet Coolant Temp. / Inlet Mass Flow / Thermal Power of the Core

Mechanics: Boundary Conditions and Loadings

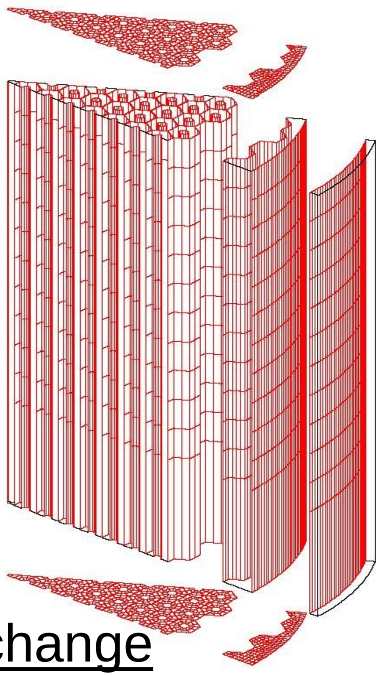
Cinematic B.C.



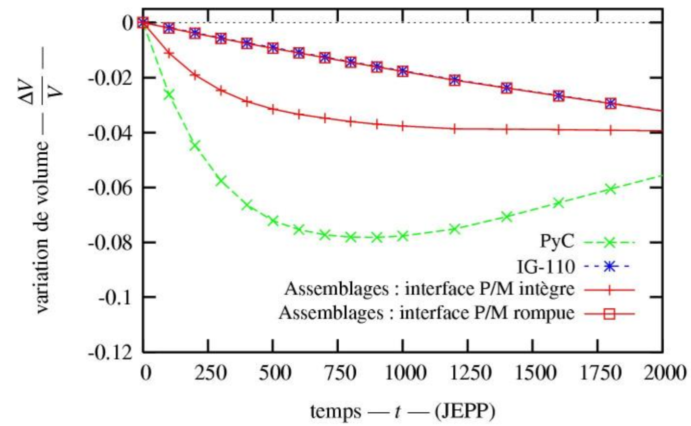
Static B.C.

Pressure loading applied on the red surfaces :

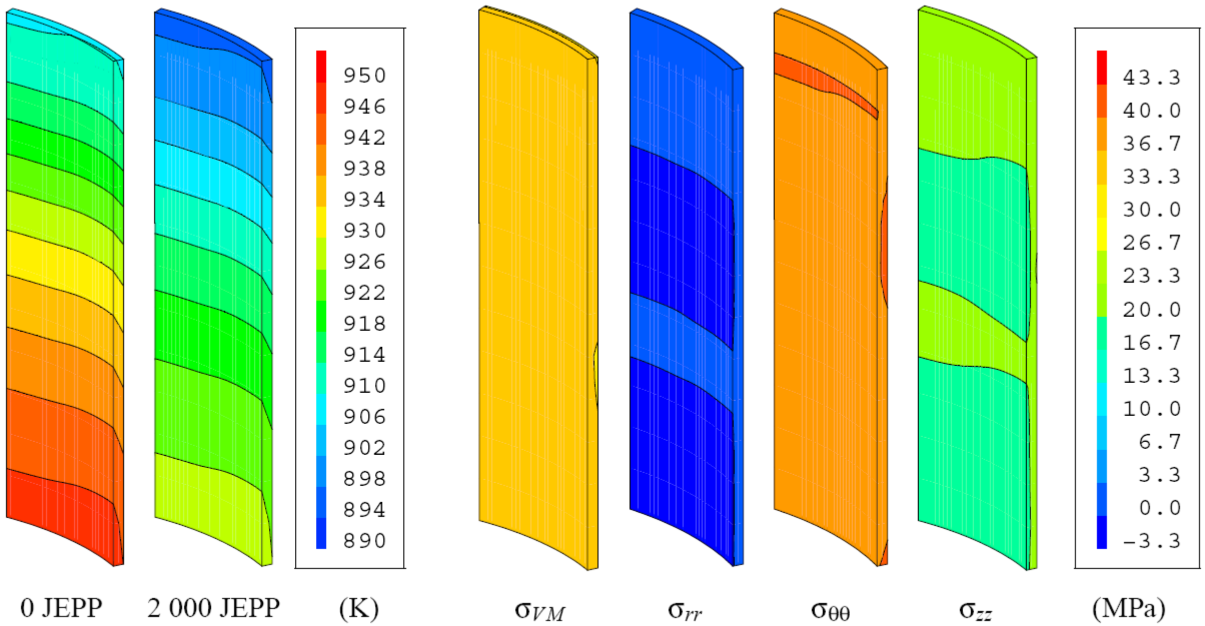
P=1,4 MPa



Irradiation vol. change



Mechanics: Pressure Vessel



Summary

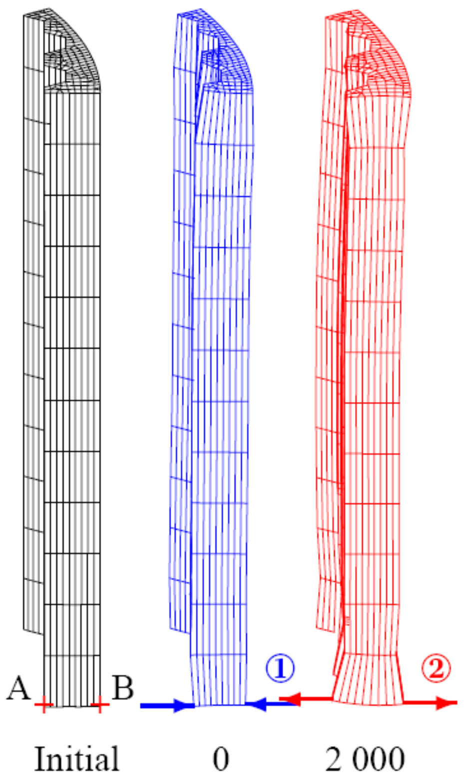
- Stress state
  Max ($\sigma_{\theta\theta}$) ~ 41MPa
  ~ $P.R_m/e$ (38.5MPa)
  Max (σ_{zz}) ~ 23MPa
  ~ $P.R_m/2e$ (19.5MPa)
  ⇒ thermal stresses very low
- Mechanical Design
  Static : σ^y ~ 110 MPa ~ σ^{max} / 3
  ⇒ thickness = 10 mm ~ ok

  But : M(core) ~ 700kg
  ⇒ PV design = dynamic loadings
  (lift-off ~ 4g)

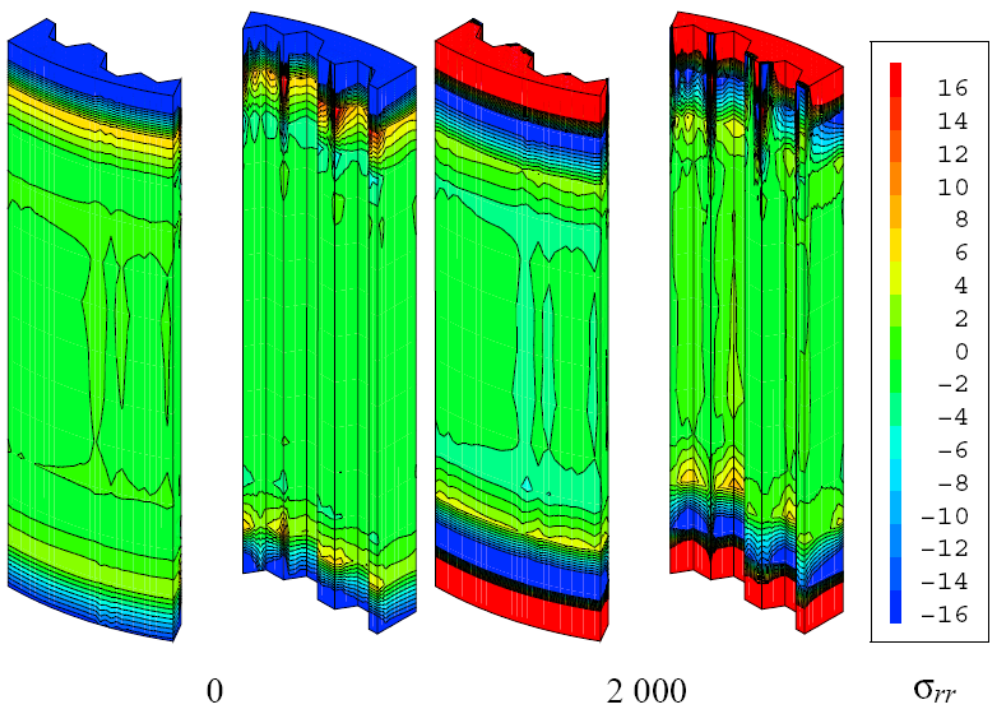
Temps (JEPP)	σ_{VM} (MPa)	$\sigma_{\theta\theta}$ (MPa)	σ_{zz} (MPa)	Autres composantes (MPa)
0	$31 < \sigma_{VM} < 35$	$34,5 < \sigma_{\theta\theta} < 41,5$	$16 < \sigma_{zz} < 23$	$\lvert\sigma\rvert < 6$
2 000	$32 < \sigma_{VM} < 35$	$34,5 < \sigma_{\theta\theta} < 41,0$	$16 < \sigma_{zz} < 22$	$\lvert\sigma\rvert < 6$

Mechanics: Core Binder

<u>with Top & Bottom Cinematic B.C.</u>



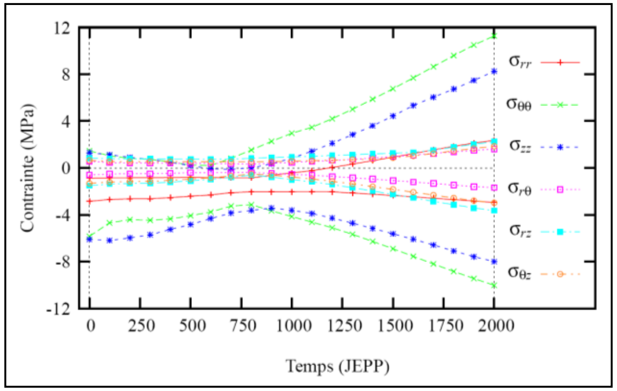
Deformed shape (x50)



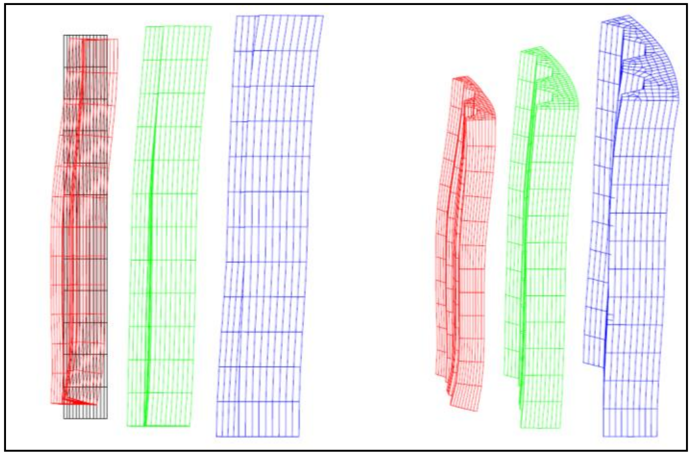
σ_{rr} (MPa) at 0 & 2000 EFPD

Mechanics: Core Binder

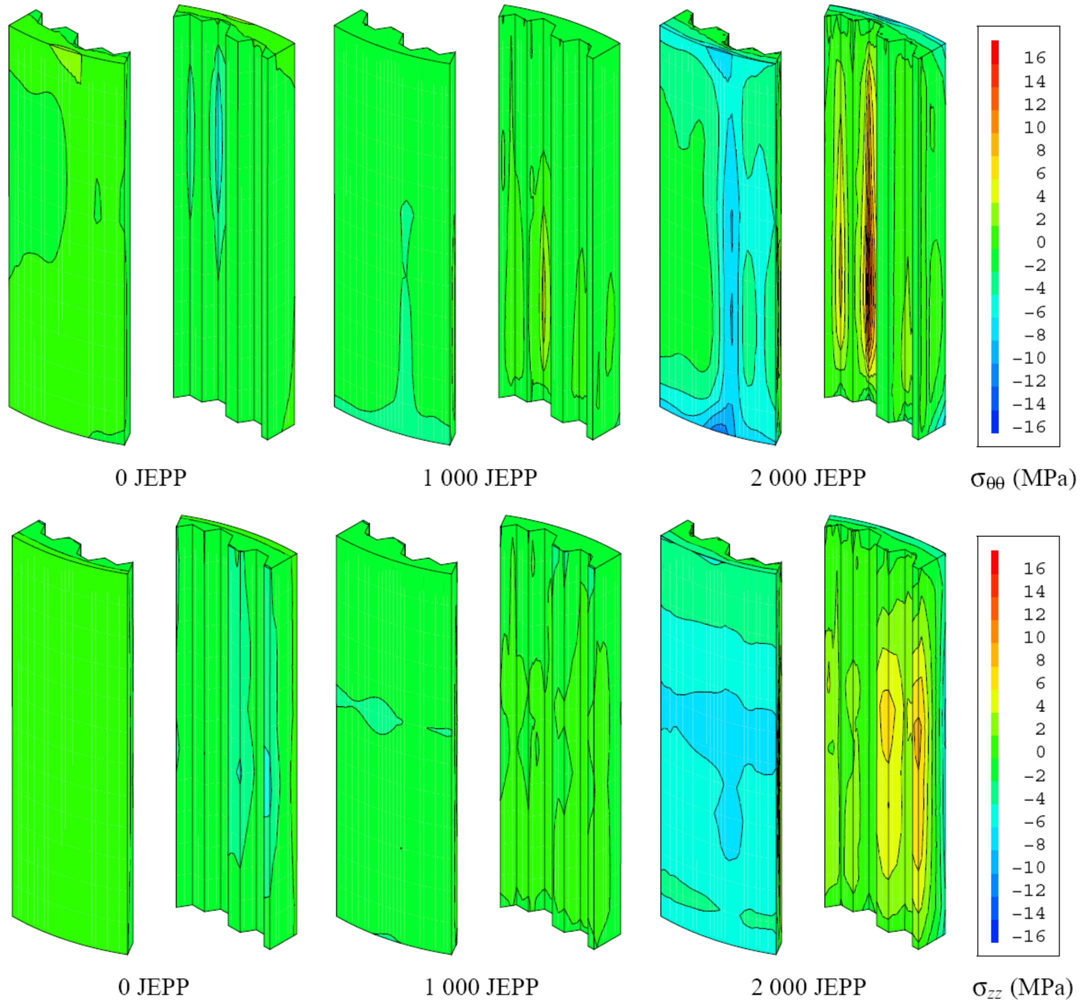
without Top & Bottom Cinematic B.C.



Stresses (MPa) Vs. Time (EFPD)

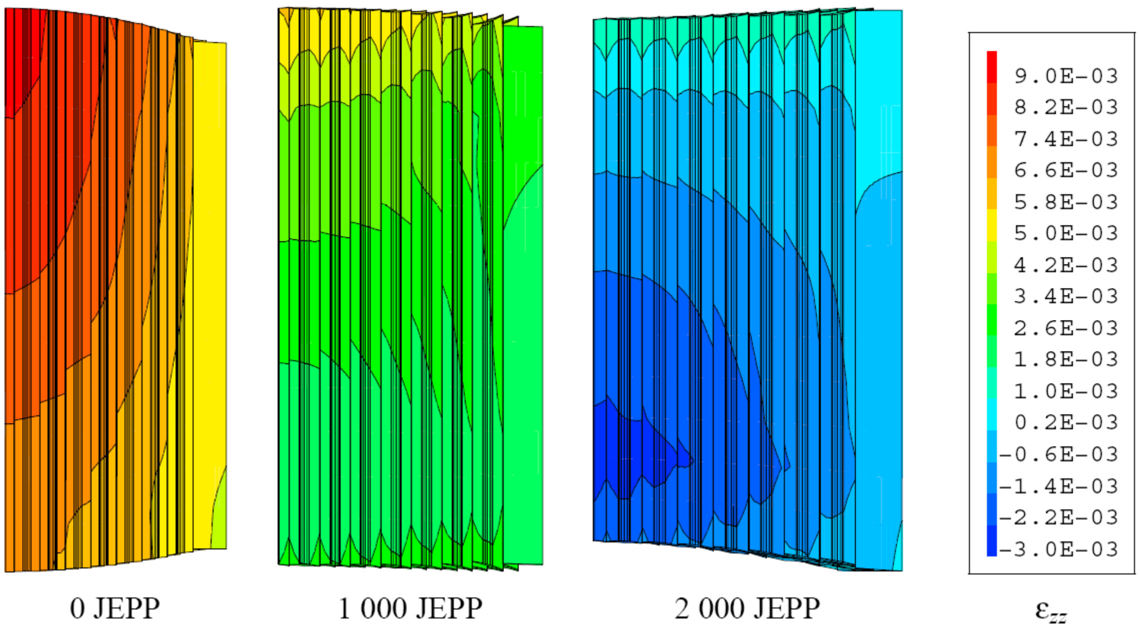


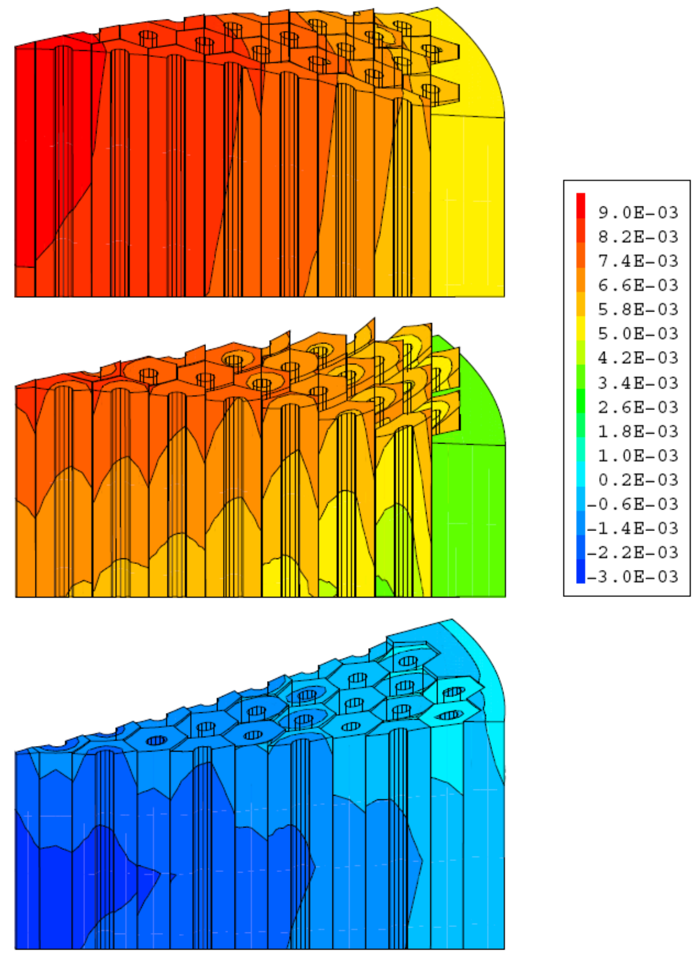
Deformed Shape : (x20) axially, (x200) in the (O,r,θ) plane



Mechanics: Reactor Core

Deformed Shape (x50)



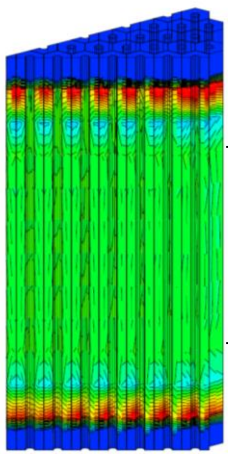


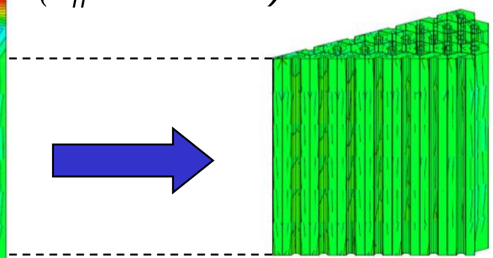
	0 JEPP	2 000 JEPP
Partie inférieure (z = 0)	$\Delta u_z = 0{,}56$ mm	$\Delta u_z = -0{,}52$ mm
Partie supérieure (z = H1)	$\Delta u_z = 0{,}83$ mm	$\Delta u_z = -0{,}2$ mm

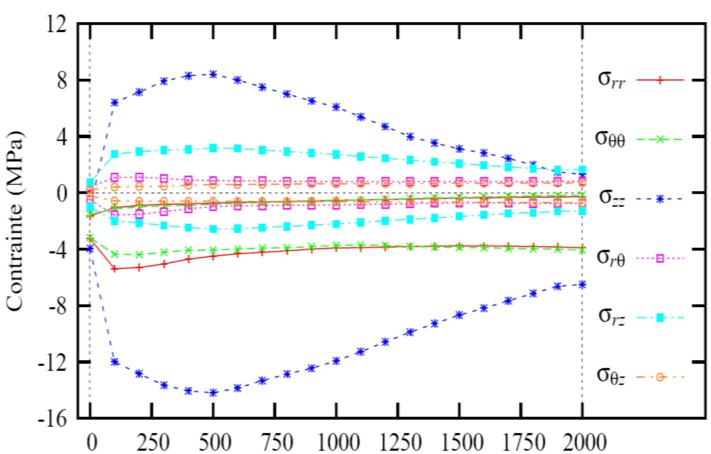
Difference of Axial Displacements (Core Top & Bottom)

Mechanics: Fuel Elements

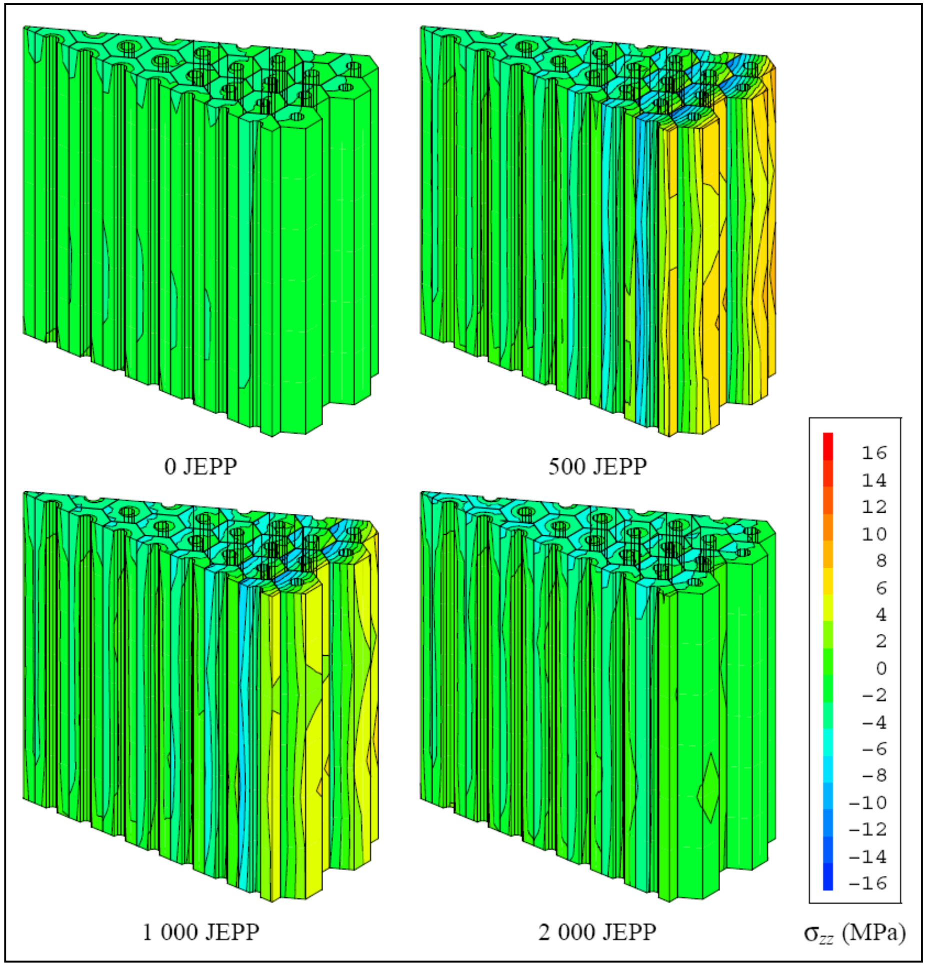
Problem with the Cinematic B.C. at the Fuel Element Top & Bottom (σ_{rr} at 0 EFPD)







Stresses (MPa) Vs. Time (EFPD)

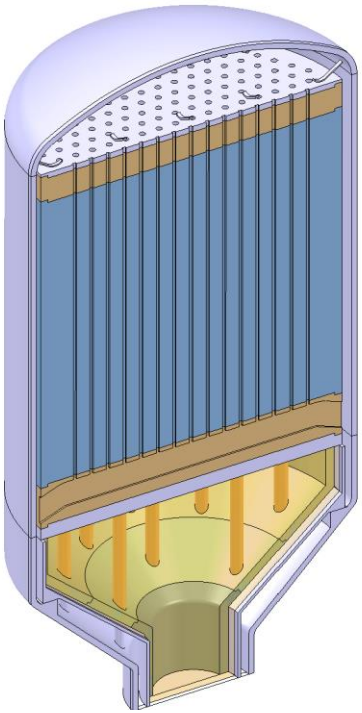


Effective stress $\sigma_{\theta\theta}$ in the fuel element graphite matrix

Space Reactor Design: Main Conclusions

Thermal-Thermohydraulic

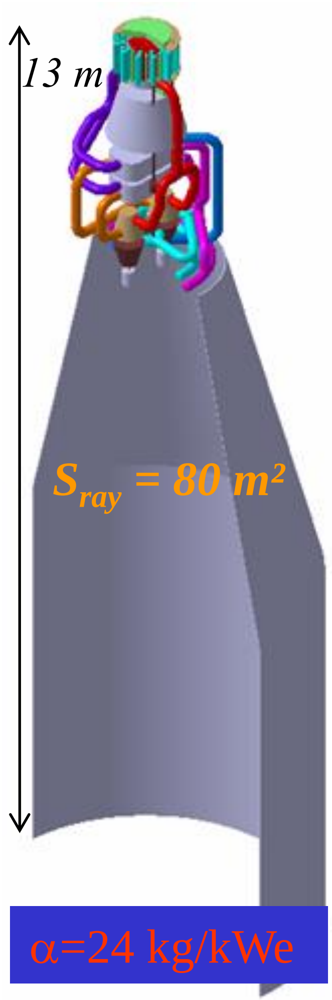
- T_{max} : 1909K → 2001K (~1730°C)
- Temperature jumps and coolant flow distribution ⇒ T_{max} ~ 2300 K (~ 2000°C)
  ⇒ To optimize channel diameter to homogenize core temperature
- Temperature field fully determined over the reactor only by setting :
  ⇒ Inlet Coolant Temp. / Inlet Mass Flow / Thermal Power of the Core



Mechanics

- PV: Current design satisfied nominal static loading but:
  Mechanical design should more depend on dynamic loadings (lift-off)
- Core Binder: Δu (BC) ~ 1/10mm ⇒ design ok
- Fuel elements: Idem Core Binder and:
  - 100 kWe OPUS version seems feasible ⇒ fuel fabrication?
  - 500 kWe OPUS version needs fuel design improvements

Conversion Systems

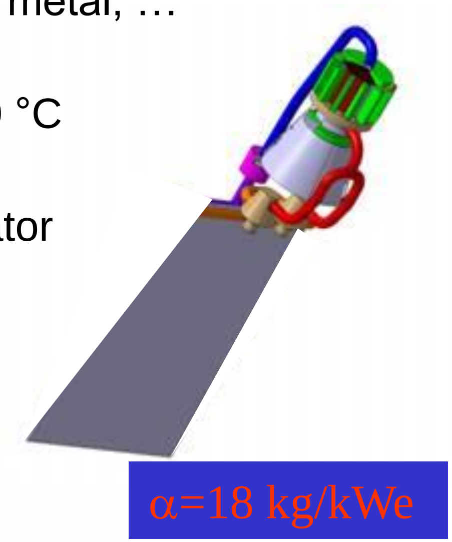


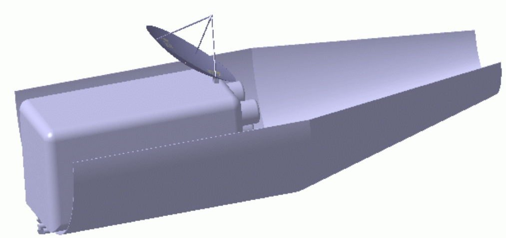
❶ Brayton cycle

- He-Xe (85 g/mol)
- 3.6 kg/s
- DT_{core} = 427 °C
- h = 27 %
- 50 m² of radiator
- 14 bars
- 900 kg

❷ Hirn cycle

- Sulfur, Alkali metal, …
- 1 kg/s (S)
- DT_{core} = 600 °C
- h > 50 %
- 7 m² of radiator
- 8 bars
- 620 kg





100 kWe – 1300 K