# Étude du comportement viscoplastique du dioxyde d'uranium par essai de compression uniaxial à pression partielle d'oxygène contrôlée et simulation du dispositif associée.

T. Helfer, J.B. Parise, P. Garcia, C. Introini

DE LA RECHERCHE À L'INDUSTRIE

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Matériaux 2018 | Thomas Helfer, Jean-Baptiste Parise, Introini Clément, Philippe Garcia

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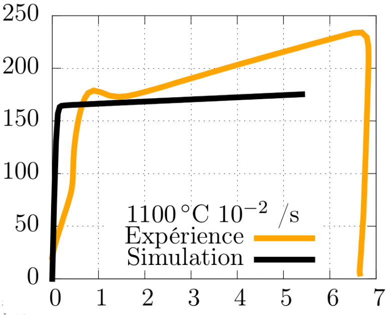
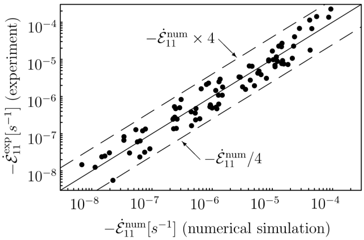
# Current state



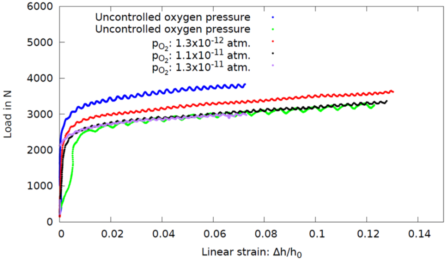

Salvo et al. (2016)




Monerie et al. (2003)

- Current identification of $UO_2$ viscoplastic behaviours can still be significantly improved.
  - Significant experimental dispersion that must be reduced.
  - Modelling of tests must be made more accurate and must include a finer description of the experimental device :
    - Consistent finite strain constitutive equations.
  - Identification must be made on the whole stress or strain history.

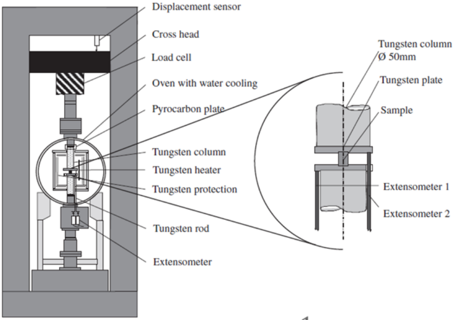
# Effect of the oxygen partial pressure on creep tests




- Results of uniaxial compressive tests at constant crosshead speed test (20 $\mu\, m/min$) at 1500$^\circ C$ on samples with identical pellet geometry and microstructure.
- Most studies so far did not control this parameter :
  - **A first order contribution to the experimental dispersion**
  - In a W furnace under "pure" Ar/H2, oxygen pressures (which should be of the order of $10^{-14}$ *atm* at 1500$^\circ C$) may vary depending upon :
    - Impurities in the gas phase (e.g. State of oxidation of W)
    - Time left for system to equilibrate

# Device

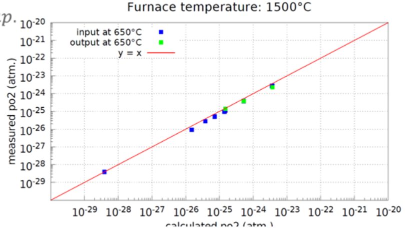
# Creep tests under controlled atmosphere




- Compression testing
  - 100 kN frame equipped with W ~1700°C furnace & –*in situ* extensometers
  - Originally all tests carried out under Ar/H2
- System equipped with $O_2$ & $H_20$ probes, up/down stream

- Buffering insured by $H_2 + \frac{1}{2}O_2 \Leftrightarrow H_2O_{vap.}$
- $p_{o2}$ controlled by YSZ oxygen pump

- Buffering checked by
  - Output=input
  - Experimental value=calculated value



# Finite strain constitutive equations

# Constitutive equations - Kinematics

- Kinematic based on the Hencky lagrangian strain :

$$\underline{\epsilon}^{to}_{\log} = \frac{1}{2}\log\left(\underline{\mathbf{C}}\right) = \log\left(\underline{\mathbf{U}}\right) = \frac{1}{2}\log\left(\underline{{}^{\mathbf{t}}\underset{\sim}{\mathbf{F}}.\underset{\sim}{\mathbf{F}}}\right)$$

Note : $\underset{\sim}{\mathbf{F}}$ : deformation gradient, $\underline{\mathbf{C}}$ : right Cauchy tensor, $\underline{\mathbf{U}}$ : stretch tensor

- The dual stress $\underline{\mathbf{T}}$ is defined as the work conjugate of $\underline{\epsilon}^{to}_{\log}$ :

$$J\,\underline{\sigma} : \underline{\mathbf{D}} = \underline{\tau} : \underline{\mathbf{D}} = \underline{\mathbf{S}} : \underline{\dot{\epsilon}}^{to}_{GL} = \underline{\mathbf{T}} : \underline{\dot{\epsilon}}^{to}_{\log}$$

Note : in $1D$, $\underline{\mathbf{T}}$ is the Kirchhoff stress $\underline{\tau}$

- Direct link between the trace of the Hencky strain and the change of volume $\det\left(\underset{\sim}{\mathbf{F}}\right) = \exp\left(\mathrm{tr}\left(\underline{\epsilon}^{to}_{\log}\right)\right)$
  - **Standard viscoplastic behaviours' formalisms, based on an additive split of the total strain, can be re-used**.
- Implementation based on *Miehe at. al.*' work (Computer Methods in Applied Mechanics and Engineering, 2002)

# Constitutive equations : viscoplasticity

- Viscoplasticity follows an associated Norton-Hoff law :

$$\underline{\dot{\varepsilon}}^{\mathrm{vp}}_{\mathrm{log}} = \dot{p}\,\underline{\mathbf{n}} \quad \text{with} \quad \boxed{\dot{p} = \dot{\varepsilon}_0 \left(\frac{\left(\underline{\mathbf{T}} - \underline{\mathbf{X}}\right)_{eq}}{T_0}\right)^{n}} \quad \text{and} \quad \underline{\mathbf{n}} = \frac{3\,dev\left(\underline{\mathbf{T}} - \underline{\mathbf{X}}\right)}{2\left(\underline{\mathbf{T}} - \underline{\mathbf{X}}\right)_{eq}}$$

  where $A_{eq}$ and $dev\,(A)$ denote respectively the von Mises norm and the deviatoric part of a tensor $\underline{\mathbf{A}}$
- Following Colin (Phd Thesis, 2004), kinematic hardening is described using the Armstrong-Frederick law (1966) :

$$\underline{\mathbf{X}} = \frac{2}{3}C\,\underline{\mathbf{a}} \quad \text{and} \quad \underline{\dot{\mathbf{a}}} = \dot{p}\,\underline{\mathbf{n}} - D\,\dot{p}\,\underline{\mathbf{a}}$$

- $\dot{\varepsilon}_0$ is a function of the **temperature**, the **grain size** and **stoechiometry**.
- Numerical implementation using the open-source `MFront` code generator (Helfer et al., 2015) `http://tfel.sourceforge.net`

The behaviour does not distinguish scatterring and disclocation creep. Porosity evolution (Monerie et al.2006, Salvo et al. 2015) is not yet taken into account.

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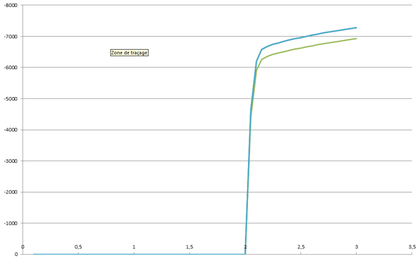
# On the reference state

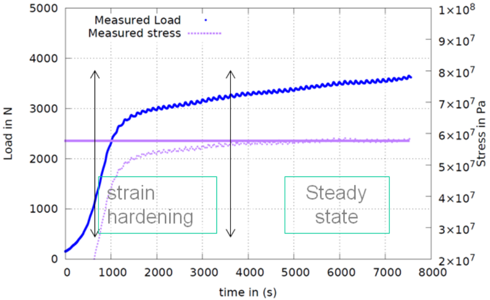



- The lagrangian approach implicitly introduces a reference state :
- The figures compares two computations of the same experiment :
  - The first one starts from room temperature. **Good approach**
  - The second one starts from the experiment temperature (with actualised geometry) **Incorrect approach**.
  - Up to 5 % error on the computed force. Can be higher in some cases.

# Results

# Macroscopic experimental data available and preliminary analysis

- *In situ* experimental data available: $h(t)$, load $F(t)$
- Vertical axis oriented downwards




- Initial phase: combined response of setup and apparent pellet hardening
- Second phase: linear increase in load

$$\sigma_{eq}(t) \approx \sigma_z(t) \approx \frac{F(t)}{S(t)} \approx \frac{F(t)h(t)}{h_0 S_0}$$

- Uniaxial hypothesis
- Creep occurs at constant volume: $S(t)h(t) = S_0\, h_0$
- Primary & secondary creep

<u>macroscopic hardening ⇔ primary creep & increase in section</u>

<u>Uniaxial temptation is strong</u>

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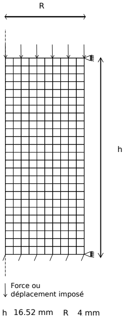
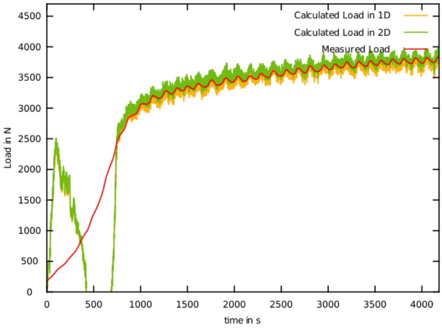
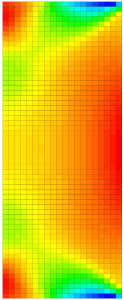
Ph. Garcia et al., "Effect of Oxygen Activity on the High Temperature Mechanical Behaviour of Uranium Dioxide", MRS Spring Meeting, Phoenix 2018

# Identification of $UO_2$ viscoplastic behaviour : Comparison 1D and 2D modelling



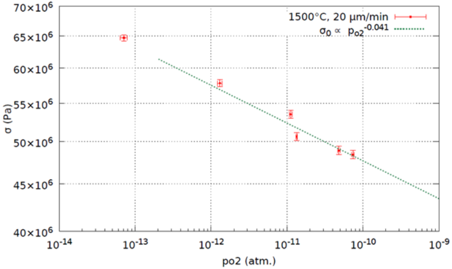



- Various models of the device have been set-up :
  - $1D$ models based on `MTest`
  - $2D$ and $3D$ models based on `Licos/Cast3M`
- Very close results of simple 1D and 2D models on the force/displacement curve

# Effects of the oxygen partial pressure

- If X<<σ, analysis is straightforward
- Plotting $Log(\sigma) = f(Log(po2))$ ⇒ –α/n

$$\dot{\varepsilon} \propto K {po_2}^{\alpha} \sigma^{n}$$




- Data points lie in ~ straight line
- Flow stress Decreasing f(po2) ⇒ consistent with α > 0 and [Vu] increasing function of $p_{O2}$
- –α/n ~ -0.041 ⇒ if n~ 4, α ~ 1/6

# Conclusions

# Conclusions

- This talk shows recent improvements to the description of $UO_2$ viscoplasticity :
  - The control of oxygen partial pressure is crucial :
    - to derive more physical constituve equations.
    - to reduce experimental dispersion.
  - Consistent models of the device based on proper finite strain constituve equations have been set-up
- Those results are preliminary and the experimental data used covers only a limited range of loadings (stress,temperature, grain size, etc..)
- In particular, the constitutive equations shown here will evolve.
- More compressive tests required :
  - non monotonic loadings
- Four points bendings tests.

# Acknowledgements

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INSPYRE

Investigations Supporting MOX Fuel Licensing in ESNII Prototype Reactors