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Simplified Thermal Creep Model of an Irradiated Fuel Pin

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Looking to the future PATRAM 2010

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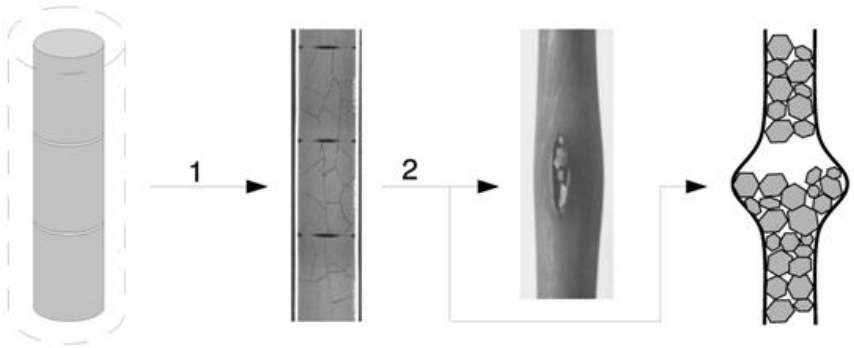
Background: Physical Basis

- **LWR fuel cladding rupture risk by thermal creep:**
  - High temperature and internal gas pressure causes progressive local swelling of cladding parts
  - As the cladding diameter increases, the cladding thickness decreases
  - Can lead to a rupture with gas and fissile material release

Creep deformation and rupture of cladding from used fuel pins



- **Calculation tools:**
  - Analytical calculations: not possible because it is a non-linear phenomenon and there is a large number of input parameters
  - Finite element analysis (FEA): time- and cost-consuming, and requires additional programming

→ TN International (TNI) is developing a simplified FORTRAN calculation tool

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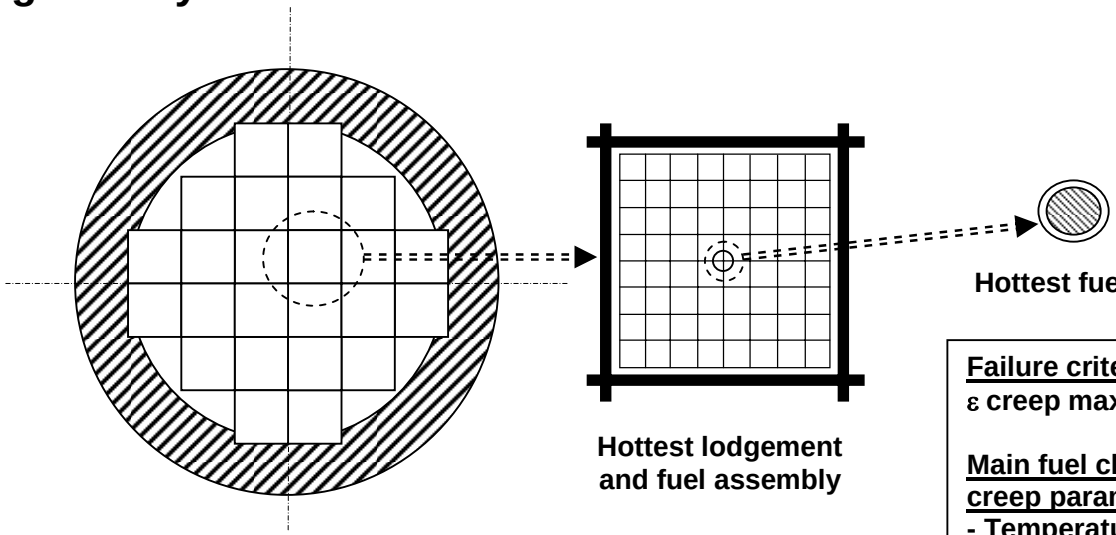
Background: in-cask configuration

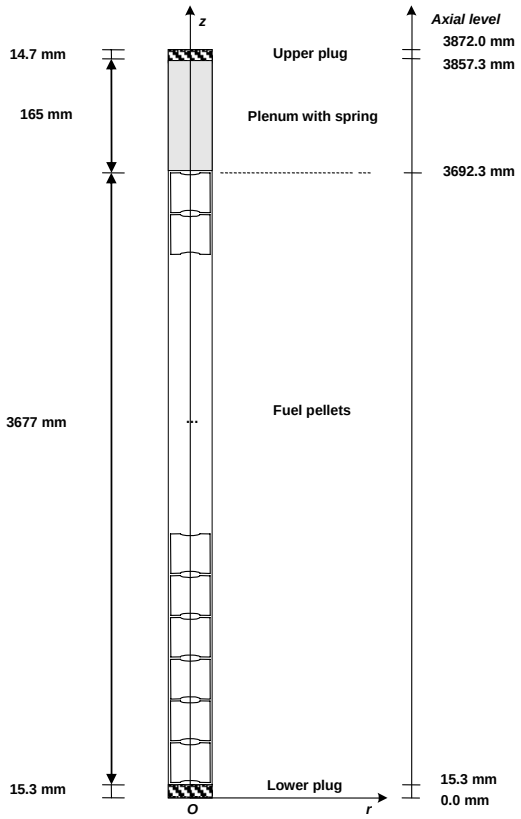
- **Phenomenon in a transport cask:**
  - **Maximum fuel pin temperatures (400 – 500 °C) in transport are generally reached at the cask centre**



  - **Cladding deformation calculation and verification of its integrity <u>in the concerned temperature and stress domains</u> require:**
    - **A creep law (which is material dependent)**
    - **A non-rupture criterion**

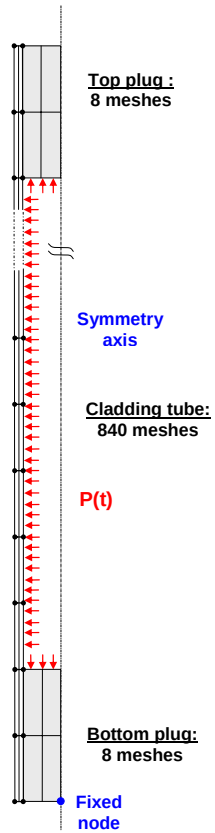
Fuel pin creep: parameters

Parameters and conditions:



Geometry of a 900 MWe used PWR fuel pin at 20 ° C and 1 bar

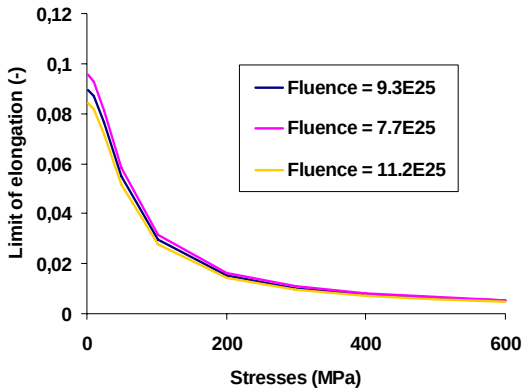
- **Parameters influencing creep rate:**
  - temperature axial profile and evolution
  - stress level (from internal gas pressure)
  - irradiation axial profile
  - oxidation axial profile
- **Axial profile combination influences:**
  - cladding maximum radial deformation
  - axial location
- **Cladding rupture occurs when a local critical strain is reached**



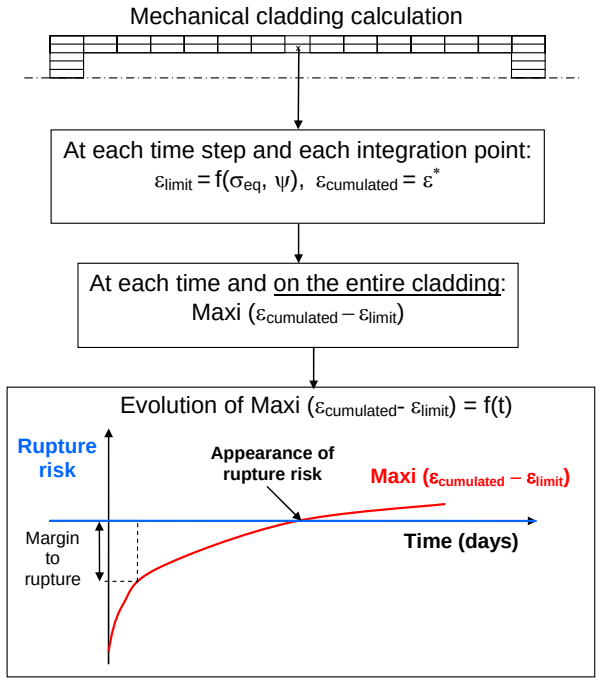
Meshes, loading and boundary conditions

Fuel pin creep: law and rupture criterion

- **Thermal creep law takes into account irradiation defect hardening recovery and depends mainly on temperature and stress / pressure levels**
- **Non-rupture criterion: limit strain depending on stress and irradiation levels**



Thermal creep non-rupture criterion for high-tin Zr4 cladding



- **The non-rupture criterion can be used with:**
  - **local parameters**
  - **semi-local parameters (envelope on entire cladding)**
  - **global values (envelope on whole cladding and plugs)**

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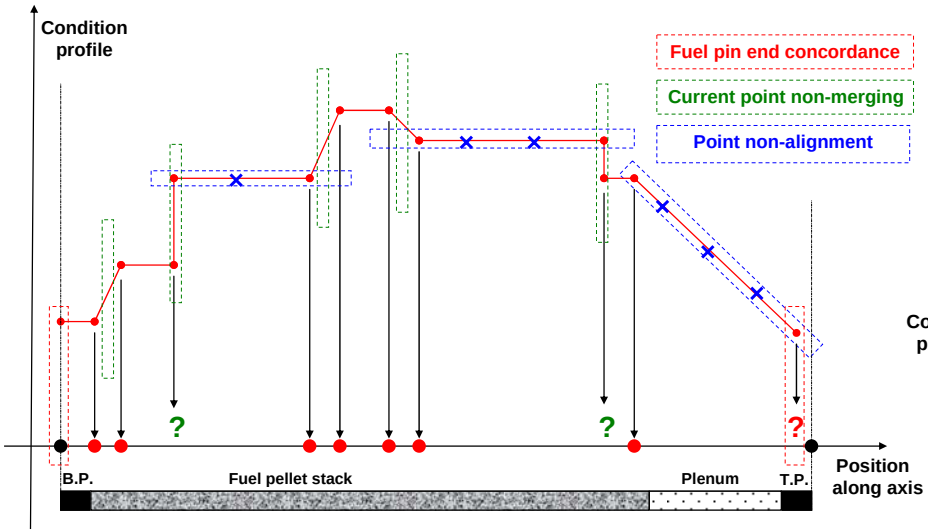
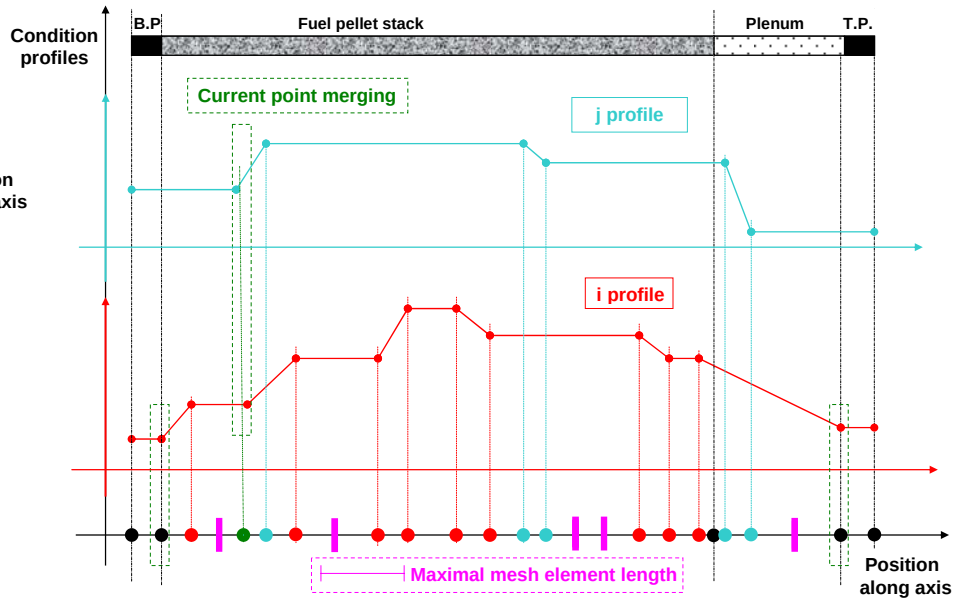
Simplified model: meshing

- **Initialisation profiles and meshing generation:**



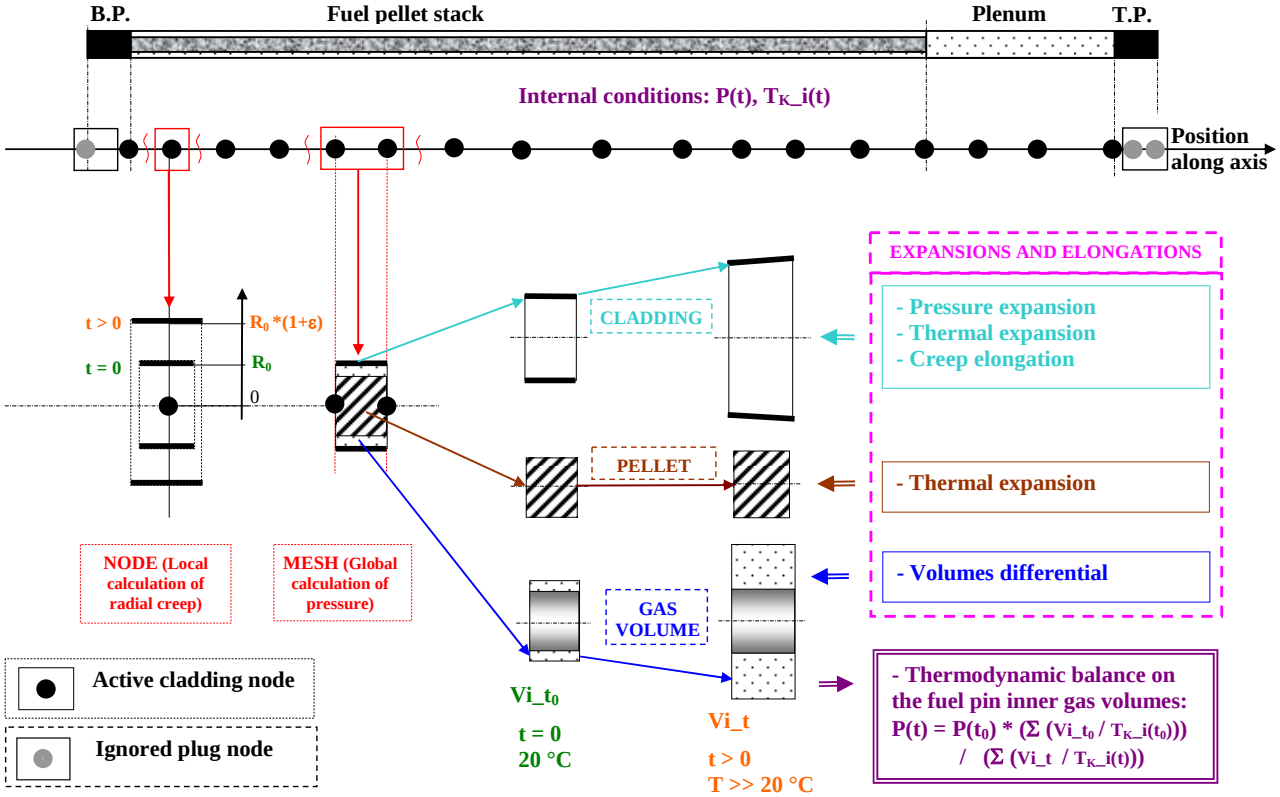
Preliminary filtering of the profile



Meshing generation

Simplified model: principles

- **Calculation of a complete fuel pin:**



- **Parallel creep calculations at cladding nodes**
- **Local free volumes updated at all iterations**
- **Internal pressure obtained by integration of the gas state equation**

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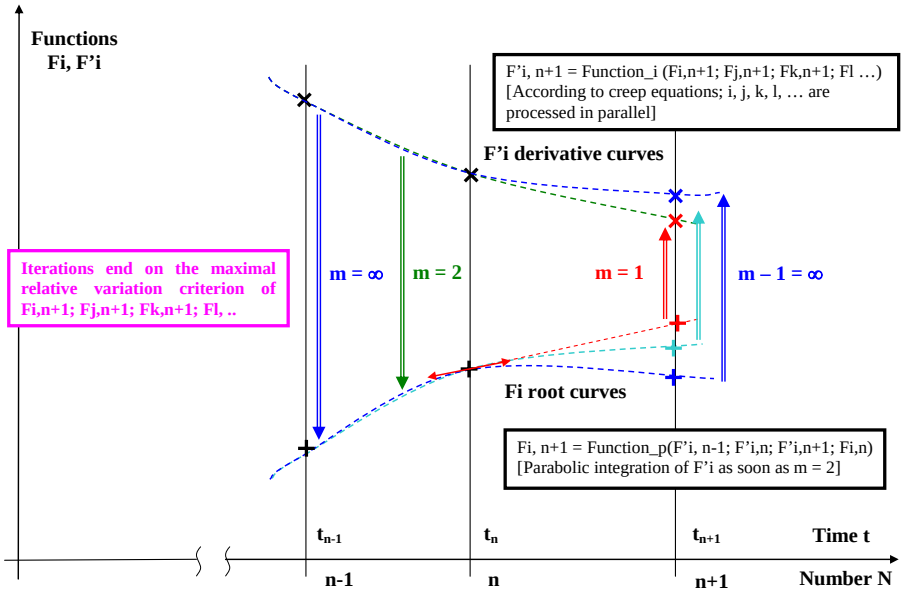
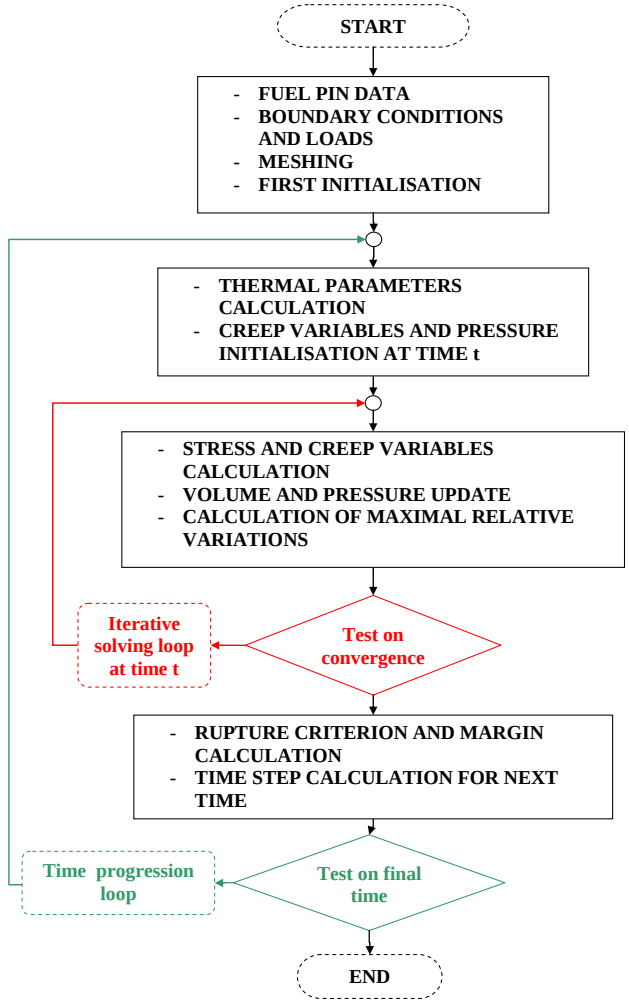
Simplified model: equation solving

Iterative resolution and algorithm:



Iterative resolution at calculation time n+1



- **Time step for all calculated nodes is defined by:**
  - **Avoiding calculation divergence in the irradiation variable equation**
  - **Good precision of the numerical scheme**
  - **Lessons learned: time step should have a low initial value followed by an exponential evolution up to an asymptotic limit value**

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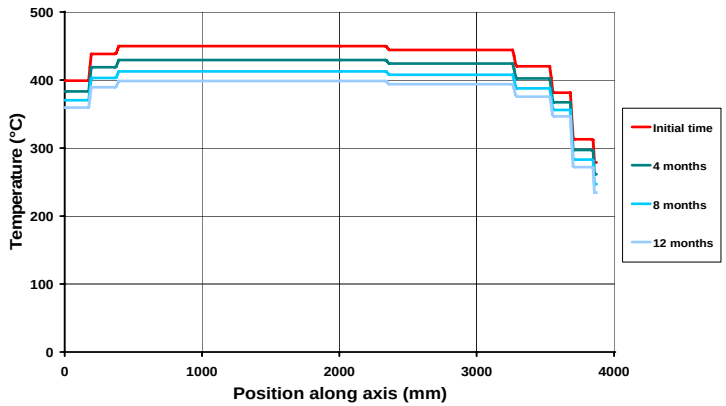
FEA vs. Simplified Model: Hypotheses

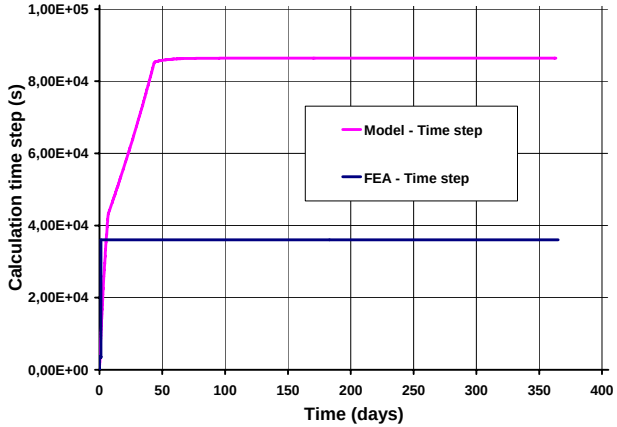
- **Data:**
  - **FEA code CAST3M vs. TNI simplified program**
  - **17x17 fuel pin coming from a 900 MWe PWR reactor**
  - **High-tin Zr4 with 4 cycles in-reactor irradiation**
  - **Outer corroded cladding thickness not differentiated from un-corroded metal (in accordance with the method used to establish creep laws)**
  - **Irradiation defect hardening recovery with temperature and stress**
  - **Creep margins to rupture are established with:**
    - **local deformation and rupture criterion values in the simplified model (points with minimum local margin)**
    - **local, semi-local and global margins to rupture in FEA calculations**
  - **Absolute internal pressure at room temperature: 62 bars**
  - **Calculation example for an initial maximum temperature of 450 °C with consideration of cooling during transport**



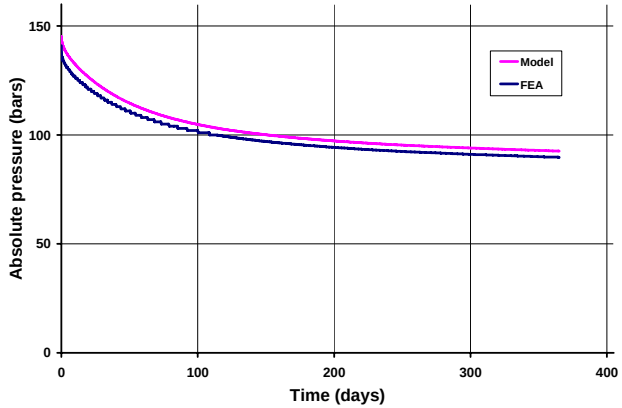
Temperature profiles for 450° C

FEA vs. Simplified Model: Calculation Parameters

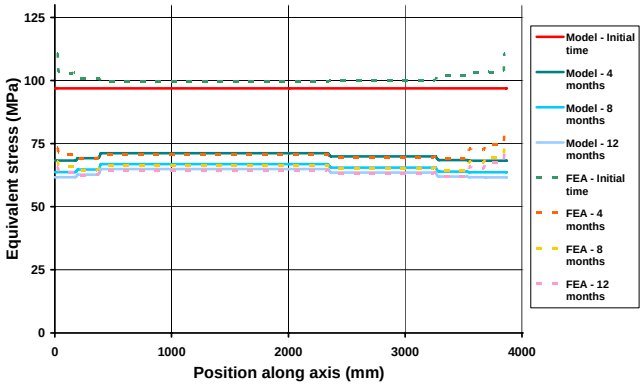
- **Pressure, stress and equivalent deformation for 450 °C**



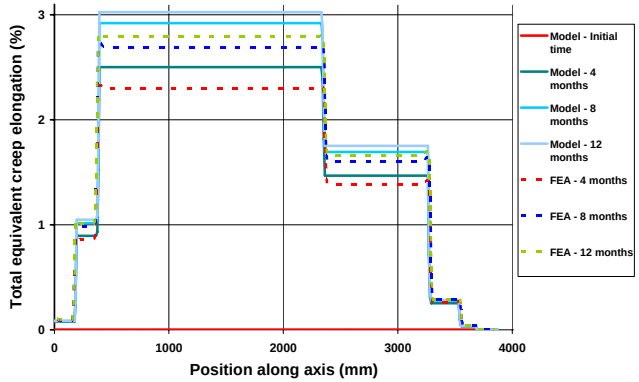
Time step



Internal pressure



Equivalent stress

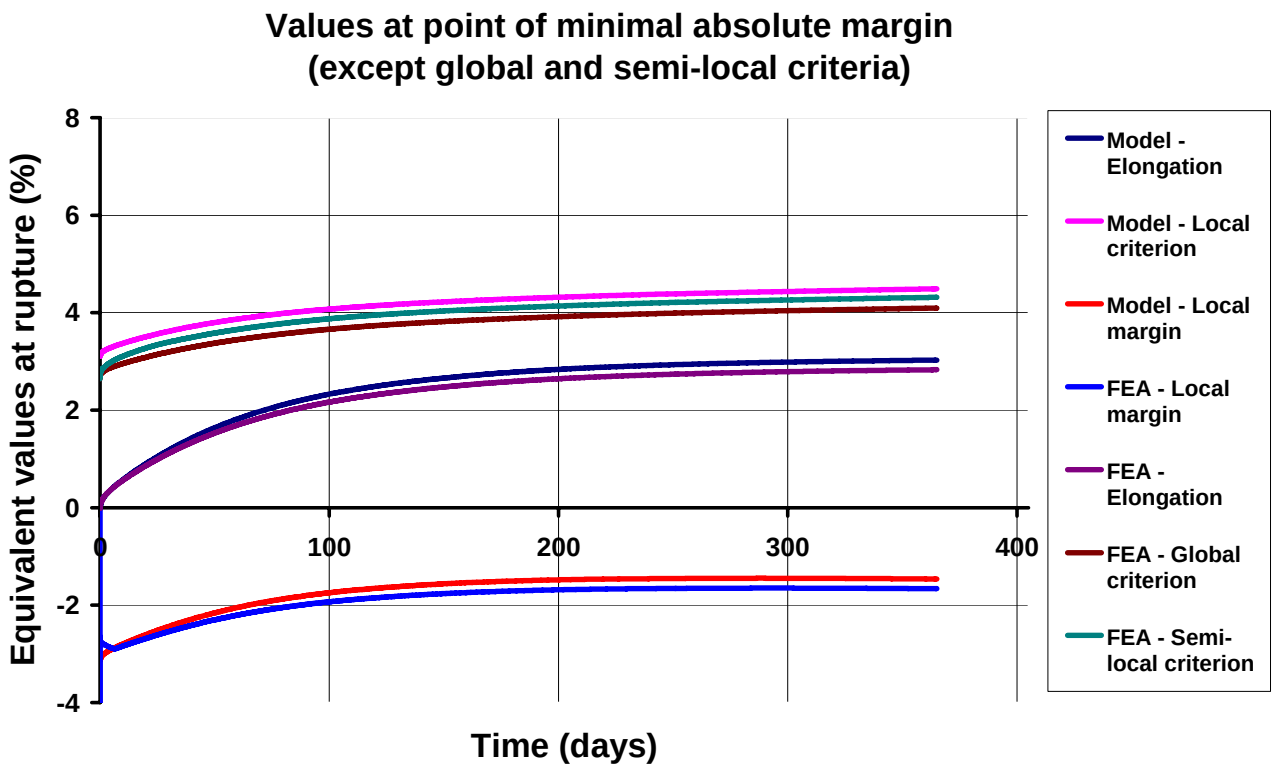


Cumulated equivalent deformation

(Results within cladding thickness: average for TNI program and maximum radial for FEA)

FEA vs. Simplified Model: Rupture Parameters

- **Deformation, criterion and margin to rupture for 450°C**



Minimum deformation margin until rupture is still 1.7 % at end of the year (typical transport lasts about a week)

Conclusion: Simplified Model Advantages

- **The FORTRAN simplified model:**
  - **Already has a good accuracy although not yet fully validated**
  - **Runs with important time and means benefits**
  - **Is adapted to a daily use and is open to further developments**
- **The FEA calculations are more pertinent for:**
  - **Indirect validation of the FORTRAN program (when there is no convenient test result)**
  - **Independent comparative calculations that may be required in some projects**
- **After validation, the FORTRAN simplified program will allow, in the framework of safety studies, reliable calculation of:**
  - **Routine conditions of transport (duration from a week to a year)**
  - **Cask vacuum drying**
  - **Half-hour fire test**
  - **Interim storage conditions**