Preliminary Design and Verification of a Fuel Pin

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1. Introduction

This report outlines the preliminary design and verification of a fuel pin intended for a testing channel within a sodium-cooled fast reactor. Based on following preliminary sizing of the:

- Thickness of the cladding
- Size of the gap between fuel and cladding
- Height of the plenum

The study evaluates the following key aspects:

- Margin to melting of the fuel.
- Temperature of the cladding.
- Yielding of the cladding.
- Time to rupture for thermal creep of the cladding.
- Potential issues such as void swelling, helium embrittlement, and plutonium redistribution in the fuel.
- Key concern if irradiation time is doubled (2 years)

2. Main assumptions

- Thickness variation due to thermal expansion is neglected (to simplify the evaluation), since smaller than the cladding/fuel one;
- Equiaxial region formation neglected in order to simplify the computation;
- Neglecting the beneficial and higher fuel thermal conductivity of the equiaxial (although quite small) and columnar region, in order to simplify evaluation and to be conservative;
- A 100% fission gas released taken into account (conservative assumption) and initial temperature of coolant used to perform pressure evaluation (simplifying hypothesis);
- Not considering axial thermal expansion, then plenum length size computed as not expanding with temperature increase (but diameter does);
- Temperature of columnar region considered: 1800 K (high then more conservative)

3. Preliminary sizing

Point A: Thickness of the cladding

Assuming firstly an average contact pressure due to fuel swelling $\approx 25\ [MPa]$, total inner pressure $\approx 30\ [MPa]$. Using Mariotte's solution for Tresca's criterion:

Minimum cladding thickness: $0.36\ [mm]$

Later, according to the thermal computing result, another (larger) value has been estimated and then verified *a posteriori* in the mechanical assessment:

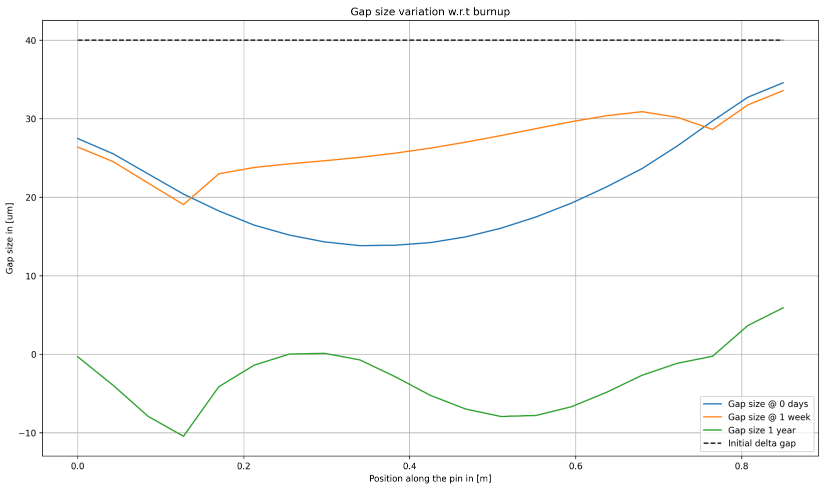
Estimated cladding thickness: $0.525\ [mm]$

From the point of view of the thermal analysis, this value was estimated considering that a bigger thickness is beneficial in order to reduce the gap size (because it leads to lower fuel temperature) and a proper contact between the fuel and the cladding after one year (since the conductivity of the gas becomes not so good as it was initially, then conduction thermal transfer is fundamental to avoid an excessive increase of the temperatures); on the other hand a smaller thickness would lead to a lower pressure contact and then lower mechanical-deriving stresses. Then the value estimated depicts a successful optimization problem result where both mechanical and thermal aspects have been considered.

Point B: Size of the gap

Simply computed as the difference of the internal cladding radius (this one depending on the thickness chosen above) and the external fuel radius:

Gap size: 40 [um]



Point C: Height of the plenum

For sizing the plenum, the pressure should not exceed 5 [MPa] at the highest gap temperature, considering the added moles of gaseous fission products after 360 days of irradiation:

Minimum plenum height: $1.0\ [m]$

However, after running the code considering the assumption written above, it can be seen that the plenum can be safely downsized:

Estimated plenum height: $0.7\ [m]$

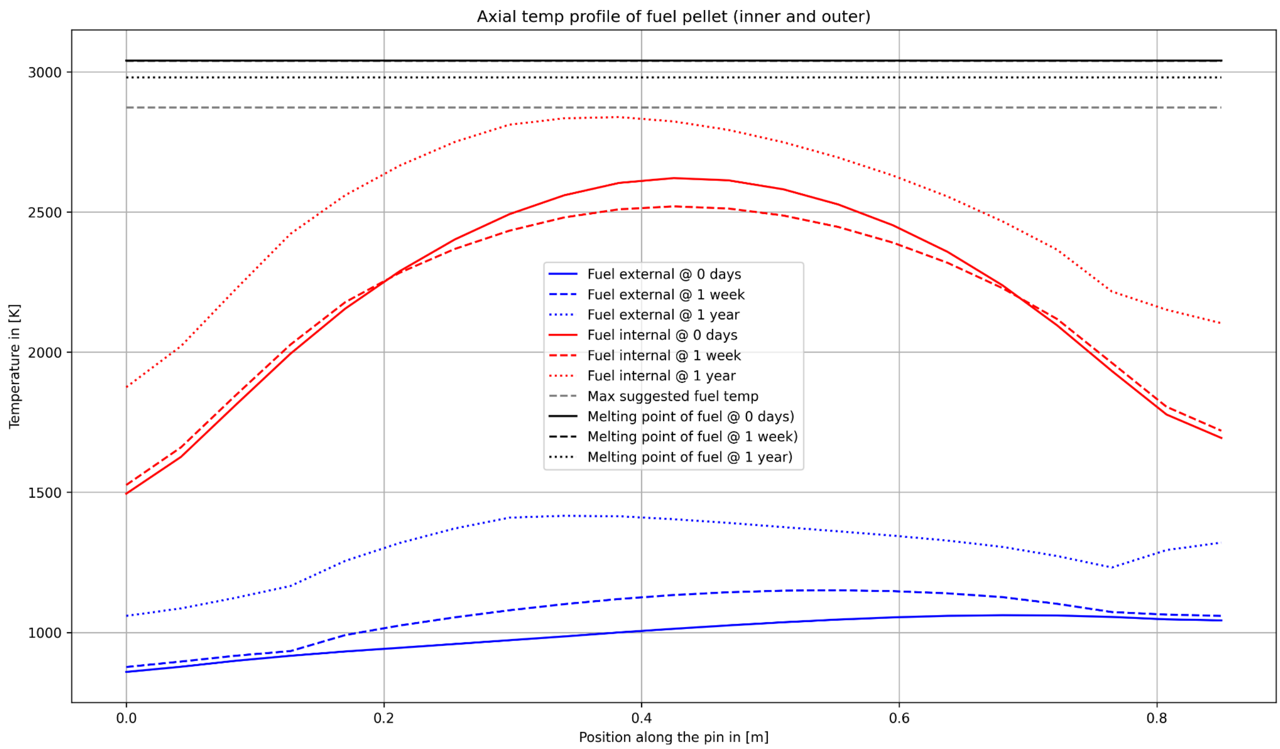
4. Verification

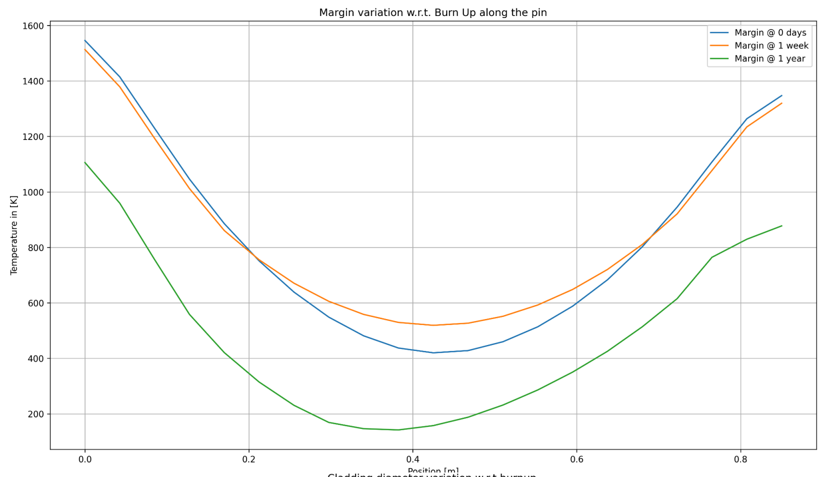
Point D: Margin to melting of the fuel

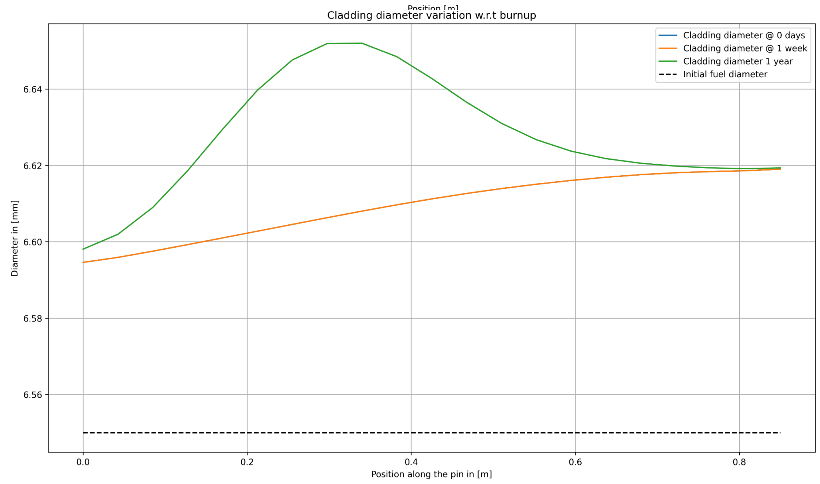
The margin to melting evaluates the maximum temperature reached by the fuel compared to its melting point. For the MOX fuel used, the melting temperature is described by a correlation dependent on burnup and plutonium content. Key assumptions and calculated parameters:

- **Fuel temperature axial profile (for different burn-up levels)**: see plot below
- **Maximum observed temperature**: $2797\ K$ at $Bu = 64\ [GWd/t]$.
- **Safety margin**: about 140 K after one year, see second plot below

The design limit for the maximum fuel temperature is 2600 °C (Table 5). Simulation results confirm that the fuel temperature remains below this threshold under nominal conditions (see plot below)





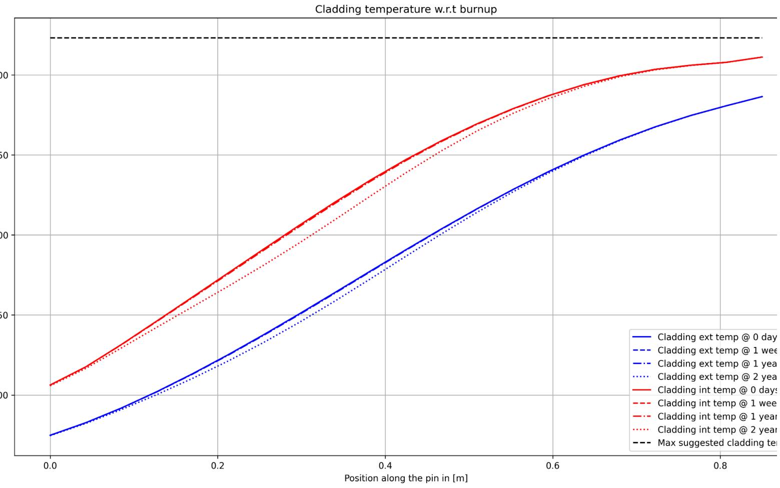


The first plot depicts the axial temperature profile of the fuel pellets, where the maximum (varying with the burn-up) shifts towards the bottom of the pin and increases in value if compared to the ones for lower burn-up, due to the fact that swelling of the cladding is increased in this region and so, even with closed gap, the contact pressure will be lower and so will the heat exchange. Moreover, after the first week it is clearly visible the effect of restructuring.

The second plot depicts the margin (variating with the burn-up) to fuel melting: it’s clear that for higher time of irradiation the value tends to decrease, then we can infer that a melting can occur even before reaching the second year.

The third one depicts the cladding diameter variation with respect to the initial cold geometry and we can clearly notice the swelling effect.

Point E: Temperature of the cladding

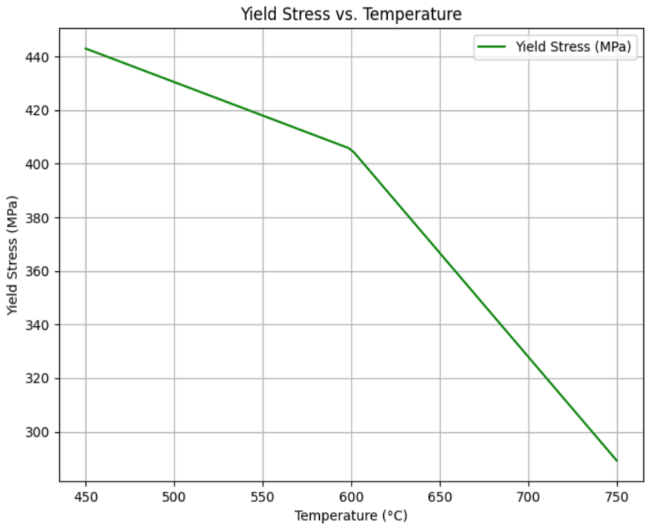


Cladding temperature is critical to ensure structural integrity and to prevent creep. Calculations based on heat transfer simulations show:

- **Maximum cladding temperature**: 898.9 K.
- **Design limit**: 650 °C.
- **Margin**: 24.25 K.

The cladding temperature is analyzed at the midwall, where heat conduction through the cladding material is critical.

Point F: Yielding of the cladding



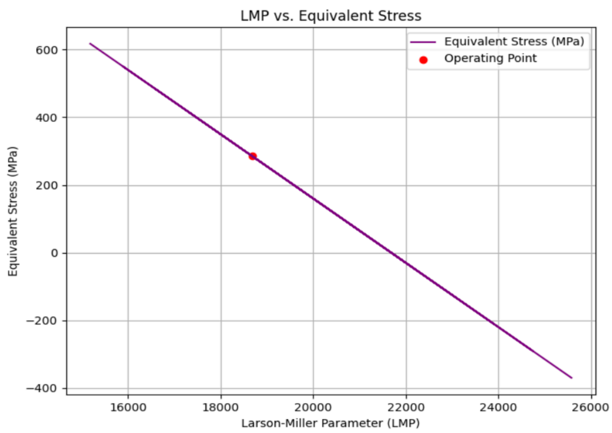
Yielding is assessed at Bu=64 [GWd/t] since at this stage the contact pressure between fuel and cladding is substantial. Key findings:

- **Yield stress**: 555, 49÷405 MPa, depending on axial discretization.

- **UTS** :700.5 MPa
- **Critical stress (Mariotte/Tresca)**: 370 MPa.
- **Thermal stress** : 68 MPa

The dependence of the yield stress on temperature shows a large jump. This may be due to the discretization of the domain. As a consequence, the equivalent stress (thermal + mechanical) may exceed the yield stress. In any case, we are well below the point of failure of the cladding. Yield stress decreases with increasing temperature, as shown by the material properties in Table 4.

Point G: Time to rupture for the thermal creep of the cladding



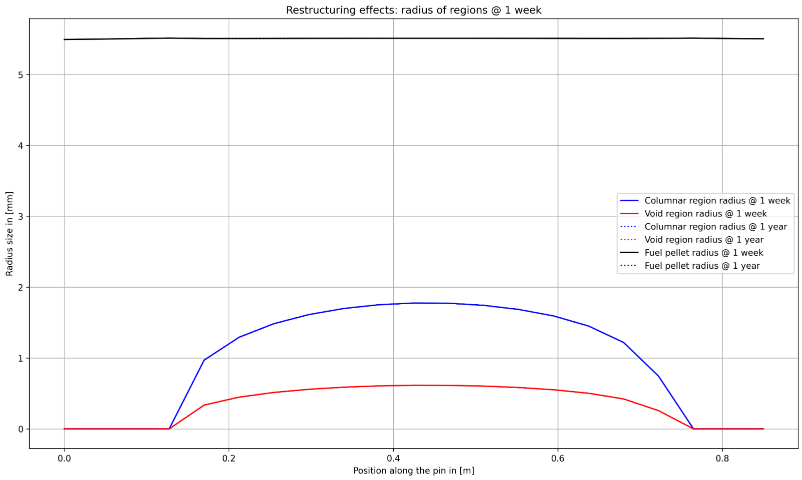
Evaluated using the Larson-Miller Parameter (LMP). Observations:

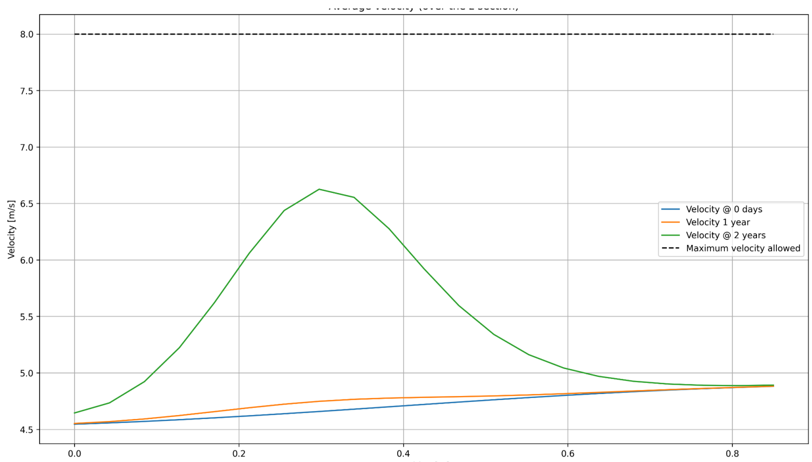
- **LMP correlation**: Provided as σ(MPa) = 2060 - 0.095 × LMP.
- **Predicted time to rupture**: 1100 days.
- **Irradiation duration**: 360 days (~8640 hours).

The time to rupture under thermal creep conditions exceeds the irradiation period, confirming the design's robustness.

Point G: Potential issues

Key potential challenges include:

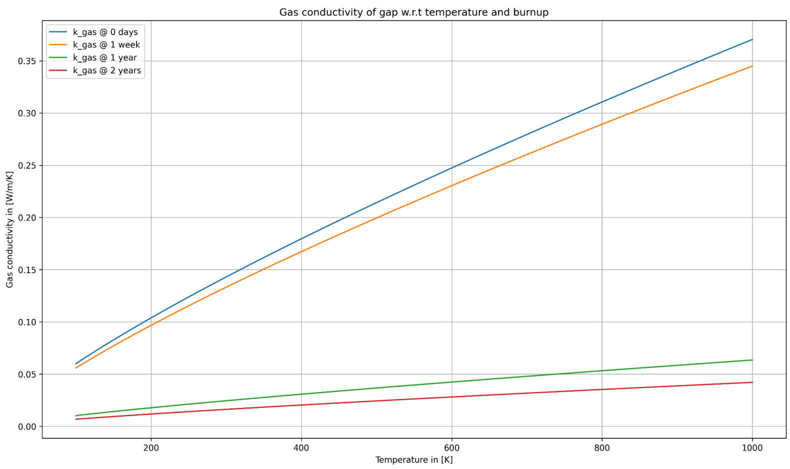




- **Void swelling**: as shown in the plot above, swelling of both fuel and cladding leads to a decrease in the temperature profile due to the closure of the gap, however this also results in additional stress on the cladding due to the contact with the fuel pellets when it occurs;
- **Helium embrittlement**: He production in the cladding leads to a (slight) lower strength of the latter;
- **Plutonium redistribution**: since our safety margins are sufficiently high, the effect of Pu redistribution on thermal conductivity and melting temperature of the fuel can be neglected;
- **Restructuring effects:** from the graph, it's possible to see that the void region radius does not extend for the entire length of the fuel pin, and the same thing applies to the columnar grains region;
- **Coolant velocity:** its increase is beneficial but it must always be kept under 8 *m/s*;
- **Fabrication uncertainties of cladding thickness:** a larger or smaller value of thickness than the one estimated may lead to melting prior the safety verified period of one year or excessive contact pressure, then we can infer the cladding thickness is quite sensitive to variation.

Point H: Considerations for double irradiation time

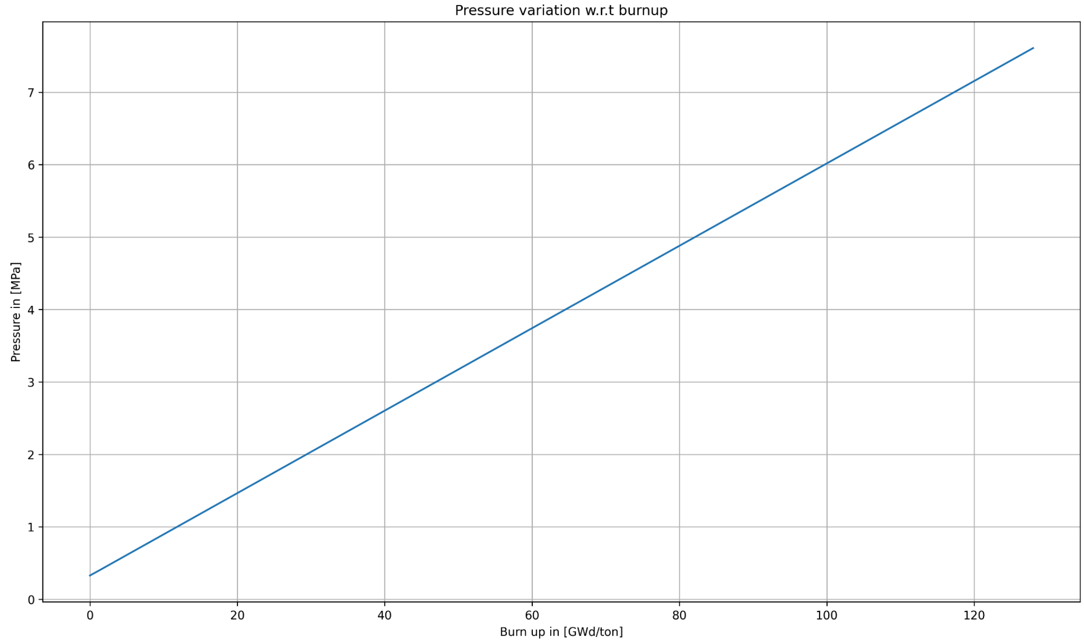
When the irradiation time doubles, critical aspects to consider include:

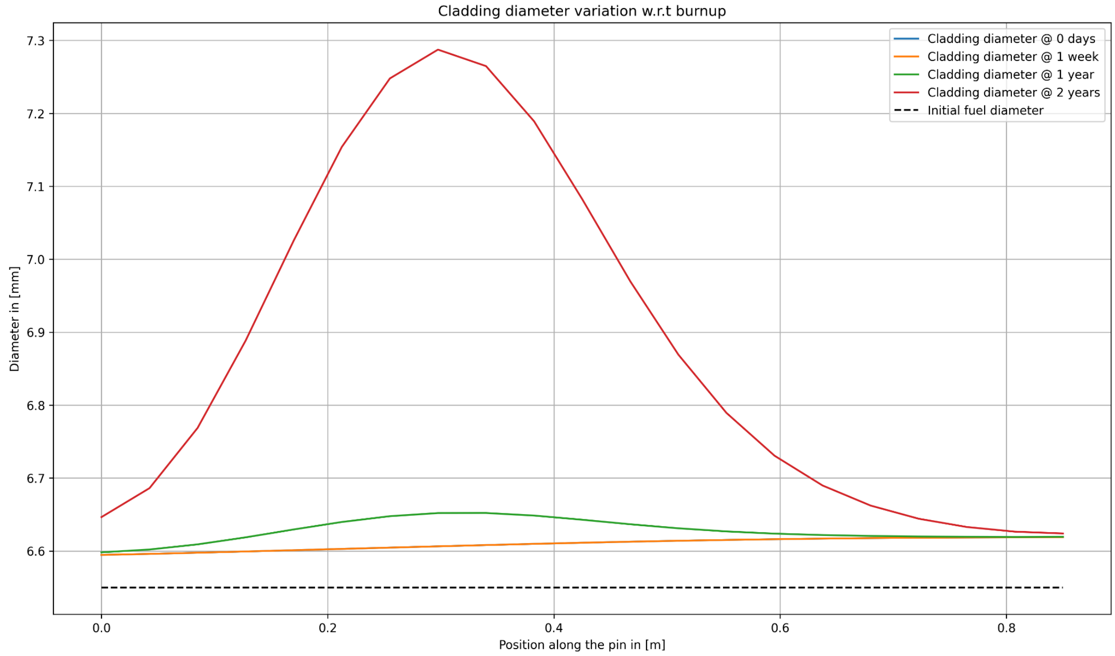


- Increased creep deformation and embrittlement of the cladding.
- The temperatures are very high due to the lower conductivity of the gas in the gap and reopening of the gap (although occurring in specific axial positions), leading to the melting of the fuel. Note that at this stage the code is very inaccurate and the iterative

computation of the temperature profile may even diverge.

- Increase of gas pressure and of contact pressure (due to fuel swelling)
- Void swelling of the cladding, that leads probably to fuel melting in some axial position (see plot)





5. Conclusions

The study successfully identifies the critical performance metrics and potential issues for the proposed fuel pin design. All parameters are within design limits for the base irradiation scenario. For extended irradiation times, additional safeguards are required.

Attachments: Detailed calculations and plots, refer to ‘readme.txt’.