FUEL PIN PRELIMINARY DESIGN

Nuclear Engineering - Politecnico di Milano

Simone Pagliuca, Tommaso Pirola, Lisa Raffuzzi, Riccardo Ronchi, Darien Shabi

simone1.pagliuca@mail.polimi.it,
tommaso1.pirola@mail.polimi.it,
lisa.raffuzzi@mail.polimi.it,
riccardo3.ronchi@mail.polimi.it,
darien.shabi@mail.polimi.it

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ABSTRACT: This report presents the preliminary design and verification of a fuel pin for a sodium-cooled fast reactor. The analysis focuses on determining cladding thickness, the size of the fuel-cladding gap, and the plenum height while ensuring compliance with design limits and safety margins. The main assumptions, approximations, and conclusions are discussed.

Key-words: Fuel Pin, Lead Cooled, Plenum, Cladding Thickness

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1 INTRODUCTION

The fuel pin design process involves:

- Determining the cladding thickness, the fuel-cladding gap size, and the plenum height.
- Verifying the design against limits for fuel melting, cladding temperature, yielding, and thermal creep.
- Identifying critical aspects if the irradiation time is doubled.

Most design specifications were provided. Missing data were sourced from literature or handouts.

2 ASSUMPTIONS AND METHODOLOGY

2.1 Material and Thermal Assumptions

- Axial profiles for power and neutron flux were assumed constant in time.
- Initial helium pressure and temperature in the fuel-cladding gap were taken as specified.

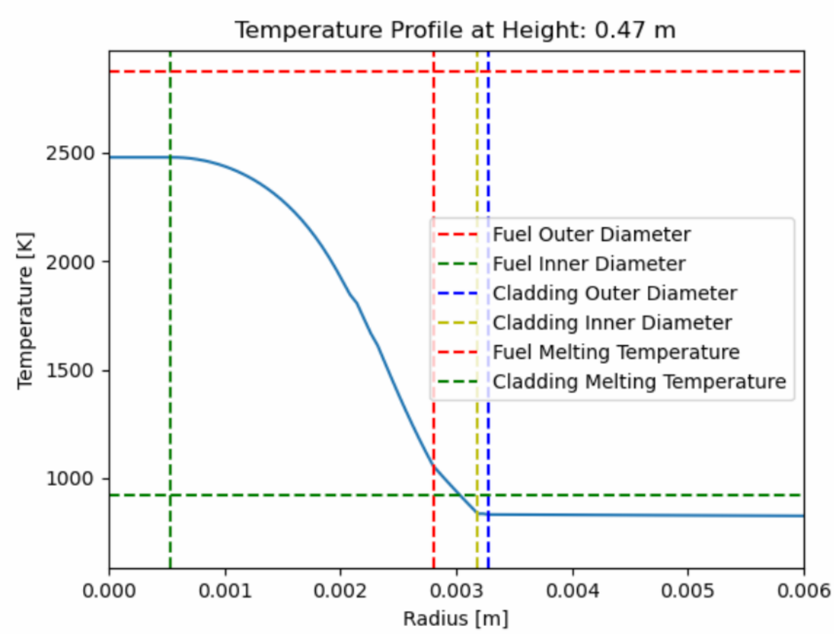

Figure 1: Radial temperature profile within the fuel pin. The profile shows the temperature distribution at the middle node.

2.2 Fission Gas Release Model

- **Domain size:** Grain size $d_g = 10\,\mu$m.
- **Diffusivity model:** Based on Matzke (1980):

$$D_{\text{eff}}[\text{m}^2/\text{s}] = D_0 \cdot \exp\left(-\frac{Q}{T}\right), \quad \text{where } D_0 = 5 \cdot 10^{-8}\ \text{m}^2/\text{s},\ Q = 40262, \text{ and } T \text{ is in Kelvin.}$$

- **Reference temperature:** Average of axial temperatures at three key positions (first slice, mid-plane, last slice).
- **Fission yield:** Combined yield for Xe and Kr, $y = 30\%$.
- **Fission rate:** $\dot{F} = \Sigma_f \cdot \phi_{\text{avg}}$, where Σ_f is the macroscopic fission cross section and ϕ_{avg} is the average neutron flux.
- **Initial conditions:** $P(0) = 0$ and $G_M(0) = 0$.
- **Boundary conditions (Booth, 1957):**
  - Surface: Perfect sink, $G_M(a) = 0$.
  - Center: Symmetry, $\frac{dG_M(0)}{dr} = 0$.
- **Steady-state assumption:** Due to the short timescale of the phenomenon, time derivatives are neglected in the equations for the steady-state solution.

2.3 Stress Analysis on the Cladding

The stress distribution in the cladding was calculated using pipe equations for cylindrical geometries, under the assumptions of orthocylindricity and axial symmetry.

2.3.1 Mariotte Stresses

Given the hypotesis we can assume the radial, hoop and axial stresses are the principal stresses. We also verified that the simplified Mariotte approach is consistent with the more complex Lamé solution. For the design process we used Mariotte to optimize computational effort.

2.3.2 Stress Checks

- The Tresca criterion is used to evaluate plastic strain and failure within the cladding.
- No significant plastic strain nor failure was observed.
- The minimum cladding thickness was verified.

2.3.3 Thermal Creep (Time to Rupture)

- The rupture time due to thermal creep was evaluated using the Larson-Miller Parameter (LMP), based on operating stresses and temperatures.
- Even under conservative assumptions, the calculated time to rupture showed sufficient margins, indicating minimal risk of creep-related failure.

2.4 Computational Methods and Findings

The design utilized a genetic algorithm for optimization.

During the dimensioning process, it was observed that cladding thickness is strongly influenced by the operational time in the fitness function. For short cycles, such as one year, the algorithm recommends thinner cladding, unsuitable for long-term operation. To address this, the design was based on an expected four-year fuel cycle, which is representative of typical fast reactor operation.

This conservative approach ensures reliability and provides additional safety margins over the fuel pin lifecycle.

Key Observations:

- The time to rupture decreases significantly with lower plenum height due to lower internal pressure.
- The thermal stresses and mechanical stresses have opposite trends with respect to cladding thickness, the algorithm takes both into account by design.
- The optimization process tends to converge toward maximum plenum height and minimum cladding thickness.

Given these trends, additional considerations were taken into account:

- **Manufacturability and robustness:** Thin cladding is challenging to produce and more prone to mechanical failure, the minimum required thickness to withstand the inner pressure is $\sim 83\mu m$
- **Economic implications:** Increasing plenum height raises reactor vessel production costs, exisiting fast reactor designs have been taken as a reference.

Final Constraints:

- **Cladding thickness:** 80 to 120 micrometers.
- **Plenum height:** 80 to 100 cm (approximately the same as the active fuel length).

3 DESIGN RESULTS AND VERIFICATION

3.1 Preliminary Sizing

The genetic algorithm produced optimal dimensions:

– **Cladding Thickness:** 100 μm.
– **Plenum Height:** 90 cm.

3.2 Verification Results

Thermal Performance:

– **Maximum Fuel Temperature:** 2480 K (below melting point).
– **Maximum Cladding Temperature:** 912 K (below design limit).

Mechanical Performance:

– **Plenum Pressure:** 2.79 MPa (within limits).
– **Maximum Volumetric Swelling:** 2.9% (acceptable).
– **Time to Rupture:** 51.98 years (sufficient safety margin).

Key Findings:

– The design provides adequate safety margins for all key parameters.
– Fission gas release (FGR) was contained within acceptable limits.
– The fuel-cladding gap remained open throughout the operational cycle.

3.3 Plutonium Redistribution

Plutonium redistribution occurs due to fuel restructuring during operation, leading to the formation of distinct zones within the fuel element:

– **Central void**: Pores migrate outward, creating a void region and redistributing material (Computed by mass balance).
– **Columnar grains**: Formed by density changes and pore migration, resulting in localized Plutonium enrichment ($T > 1800°C$).
– **Equiaxed grains**: Developed at high temperatures, with a reduction in Plutonium concentration due to grain growth ($T > 1600°C$).
– **As-fabricated zone**: A stable region with minimal changes due to low temperatures.

This phenomenon results in variations in Plutonium concentration, initially uniform at 29%. The central zone becomes enriched, the equiaxed zone is depleted, and the outer as-fabricated zone stabilizes at the original concentration. This redistribution, driven by thermal and structural effects, increases power density in the central region, potentially raising local fuel temperatures.

Graphical results illustrate these phenomena: Figure 2 highlights the radial distribution of Plutonium concentration.

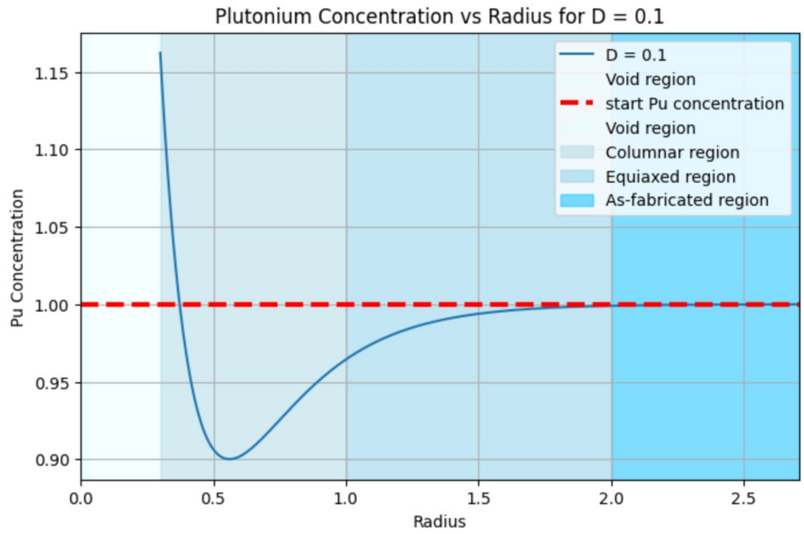

Figure 2: Radial distribution of Plutonium concentration (relative to the starting concentration) within the fuel structure.

Impact on Design and Operation

Plutonium enrichment in the central zone increases power density, leading to higher local temperatures. This effect must be managed to ensure the fuel remains below its melting point, particularly during extended operation. Redistribution can also worsen fuel swelling and impact cladding integrity, requiring careful consideration in the design phase.

3.4 Helium Embrittlement

Helium embrittlement occurs due to the accumulation of helium at grain boundaries in the cladding material, primarily produced by neutron-induced reactions such as ^{58}Ni(n,α)^{55}Fe. This leads to:

- **Loss of ductility**: Making the material more brittle.
- **Crack formation**: Making the cladding more likely to crack.
- **Increased swelling**: Causing the material to expand under stress.

Helium concentrations after 1 and 2 years of operation are 67 ppm and 122 ppm, respectively. These values match those reported in the literature (*Olander - Fundamentals Aspects of Nuclear Reactor Fuel Elements*). A more accurate evaluation would require calculating helium per displacements-per-atom (ppm/DPA).

4 CRITICAL ISSUES FOR EXTENDED OPERATION

With the selected dimensions, we extended the computation to simulate an uptime of 2 years instead of the initial 1-year design. The results demonstrate the performance and safety of the fuel pin under prolonged operational conditions:

- ✓ **Maximum Fuel Temperature:** 2553.260 K (increased from 2480.096 K).
- **Maximum Cladding Temperature:** 912.696 K (unchanged).
- × **Plenum Pressure:** 5.409 MPa (limit exceeded, increased from 2.792 MPa).
- **Maximum Instantaneous Cladding Plastic Strain:** 0.000% (unchanged).
- **Maximum Cladding Volumetric Swelling:** 20.118% (limit exceeded, increased significantly from 2.900%).
- **Maximum Coolant Velocity:** 5.558 m/s (increased from 4.779 m/s).
- **Minimum Gap Thickness:** 367.927 microns (decreased from 386.495 microns).
- **Burnup:** 128.268 GWd/tHM (increased from 64.134 GWd/tHM).
- **Fuel Yielding Due to Swelling:** 8.979% (increased from 4.489%).
- **Time to Rupture:** 4.23 years (decreased significantly from 51.98 years).

Comparison and Observations:

- The maximum fuel temperature increased slightly, indicating a higher thermal load on the fuel, likely due to increased burnup.
- The plenum pressure and cladding volumetric swelling both exceeded design limits, indicating that the fuel pin design is insufficient for extended irradiation cycles without adjustments.
- The burnup doubled, as expected
- The time to rupture decreased drastically from 51.98 years to 4.23 years, showing that thermal creep becomes a significant concern under these conditions.
- While the coolant velocity increased, it remained within acceptable operational ranges, highlighting that the thermal-hydraulic design is not a limiting factor in this scenario.
- The gap thickness decreased but the gap is still open, which guarantees no pellet-cladding interaction.

In summary, the significant rise in cladding swelling, plenum pressure, and reduced time to rupture indicate that this design requires further optimization to handle extended operation cycles safely.

5 CONCLUSIONS

The finalized design meets all specified requirements for one year operation, ensuring safety and reliability. Conservative assumptions and thorough validation steps provided additional safety margins. The design demonstrates robustness under normal operating conditions but shows criticalities in extended operational conditions.

APPENDIX

All supporting code is available in the following repository: NDT-Homeworks Repository.

- The final computation can be run from the Dimensioning.ipynb Jupyter notebook, which calls functions from loop.py.
- In-depth analysis and verification are found within Verification.ipynb, which calls functions from functions.py.
- genetic_algorithm.py contains the implementation of the genetic algorithm.
- Useful Data.xlsx contains cross-section data from the JANIS database.
- nuclei_func.py contains a collection of functions to calculate nuclear properties.