POLITECNICO DI MILANO
DIPARTIMENTO DI ENERGIA

HOMEWORK 2024-25

PRELIMINARY DESIGN AND VERIFICATION OF A FUEL PIN

POLITECNICO DI MILANO

DEPARTMENT OF ENERGY - NUCLEAR ENGINEERING DIVISION

Nuclear Design and Technology

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The aim of this project is to perform the preliminary design of a fuel pin intended for a testing channel within a sodium-cooled fast reactor (see Fig. 1 and Fig. 2). The fuel pin specifications are given in Table 1. The fuel pin consists of fissile (full) pellets made of homogeneous mixed oxide (MOX) wrapped in a cladding of austenitic stainless steel, and the initial fuel-cladding gap is filled with helium. The compositions of the fuel, cladding and gap are given in Table 2.

The irradiation scenario to be considered involves a single stationary irradiation cycle at a linear power of 38.7 kW/m for a duration of 360 days. Axial peak factors for both neutron flux and linear power are provided in Table 3, together with the position of the peak power node. Throughout the irradiation, axial profiles for both neutron flux and linear power are assumed to remain constant.

The material properties for fuel, cladding, and coolant are outlined in Table 4. The equivalent stress leading to thermal creep failure for the selected cladding material is plotted against the Larson-Miller Parameter (LMP) in Fig. 3. The design limits of the fuel pin are specified in Table 5.

If any additional data is required to complete the design process, you are encouraged to make consistent and well-justified assumptions.

You are asked to complete the **preliminary sizing** of the fuel pin, by determining:

1. The <u>thickness of the cladding</u>
2. The <u>size of the fuel-cladding gap</u>
3. The <u>height of the plenum</u>

Based on the sizing step, you are asked to **verify** (referring to the indicative design limits shown in Table 5) the preliminary pin design in terms of:

1. <u>Margin to melting</u> of the fuel
2. <u>Temperature</u> of the cladding
3. <u>Yielding</u> of the cladding
4. <u>Time to rupture</u> for thermal creep of the cladding
5. <u>Potential issues</u>, e.g, due to void swelling and helium embrittlement of the cladding, plutonium redistribution in the fuel.

Besides, identify the critical aspects to be considered in the proposed design if the irradiation time, for the same linear power and neutron flux, is doubled.

The project activity is to be performed in groups.

A mid-term review is planned for November 2024.
For the mid-term review, you are asked to deliver the preliminary assessment of the cladding temperature and the margin to fuel melting.

This review is solely for self-evaluation and does not contribute to the final evaluation of the project.

Deliverables:

Please, send to lelio.luzzi@polimi.it:
- A technical report in .pdf (**max. 5/6 pages**) detailing the project results and conclusions. Please, specify and discuss in the .pdf report the main assumptions and approximations made throughout the sizing and verification steps.
- A zip folder with all the files used to perform the calculations.

Please, include your group number and all your surnames in the name of each file.

Due date: 13/01/2025

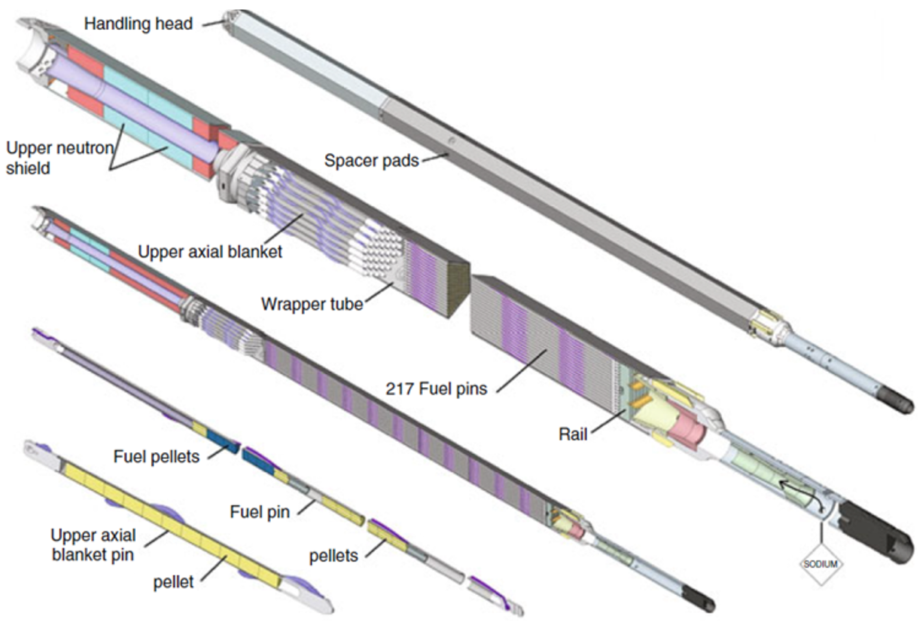

Figure 1: Illustration of the fuel assembly.

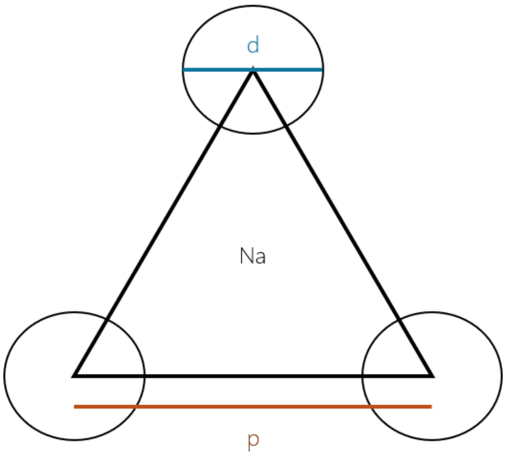

Figure 2: Sketch of the triangular channel to be considered, *d* being the cladding outer diameter and *p* the pin pitch.

Table 1: Design specifications of the channel and fuel pin.

Neutronic specifications	**Values**
Neutron flux (> 100 keV) (10^{15} n cm^{-2} s^{-1}) at peak power node	6.1
Thermo-hydraulic specifications	
Pin pitch (mm)	8.275
Coolant inlet temperature (°C)	395
Coolant inlet pressure (MPa)	0.1
Coolant mass flow rate (kg s^{-1}) with reference to the channel in Fig. 2	0.049
Fuel pin specifications	
Fuel material	Homogeneus MOX
Fuel column height (mm)	850
Fuel pellet outer diameter (mm)	5.42
Fuel pellet heigth (mm)	7
Fuel theoretical density (TD) (g cm^{-3})	11.31
Fuel density (%TD)	94.5
Fuel grain diameter (μm)	10
Oxygen-to-metal ratio (O/M)	1.957
Cladding material	15-15, Ti stabilized, cold worked stainless steel
Cladding outer diameter (mm)	6.55
Filling gas	He
Initial pressure of filling gas (MPa)	0.1
Initial temperature of filling gas (°C)	20

Table 2: Material composition.

Fuel composition	
Uranium	Natural composition
Plutonium content (wt./)	0.29
Cladding composition	
(Cr, Ni, Mo, Mn, Si, Ti, C) (wt.%)	(15.0, 15.0, 1.5, 1.5, 0.9, 0.4, 0.09)
B (ppm)	60
Filling gas	
He (%)	100

Table 3: Axial nodalization of the fuel pin.

Node number	**Height of the slice centre from bottom of fuel column (mm)**	**Peak factors (/)**
1	42.5	0.572
2	127.5	0.737
3	212.5	0.868
4	297.5	0.958
(peak power node) 5	382.5	1
6	467.5	0.983
7	552.5	0.912
8	637.5	0.802
9	722.5	0.658
10	807.5	0.498

Table 4: Material properties.

Fuel properties	**Correlations**
Melting temperature (MOX) Concentrations [ ] in (wt./) Deviation from stoichiometry x (/)	$T_m(K) =$ $2964.92 + [(3147 - 364.85\,[Pu] - 1014.15\,x) - 2964.92]\exp\left(-\frac{\beta(GWd/t_{HM})}{41.01}\right)$
Thermal conductivity (MOX) Concentrations [ ] in (wt./) Deviation from stoichiometry x (/) Porosity p (/)	$k(W\,m^{-1}\,K^{-1}) = 1.755 + (k_0 - 1.755)\exp\left(-\frac{\beta(GWd/t_{HM})}{128.75}\right)$ $k_0 = \left(\frac{1}{A + B\,T(K)} + \frac{D}{T(K)^2}\exp\left(-\frac{E}{T(K)}\right)\right)(1-p)^{2.5}$ $A = 0.01926 + 1.06\,10^{-6}x + 2.63\,10^{-8}[Pu]$, $B = 2.39\,10^{-4} + 1.37\,10^{-13}\,[Pu]$, $D = 5.27\,10^{9}$, $E = 17109.5$
Linear thermal expansion coefficient (reference: 25°C)	$\alpha_L = 1.2\,10^{-5}\,°C^{-1}$
Young's modulus	$E(MPa) = (22.43\,10^4 - 31.19\,T(°C))(1 - 2.6\,p)$
Poisson's ratio	$\nu = 0.32$
Swelling strain	$\varepsilon_{swe,tot}(\%) = 0.07\,\beta(GWd\,t_{HM}^{-1})$
Cladding properties	
Melting temperature	$T_m = 1673\,K$
Linear thermal expansion	$\varepsilon_{th}\,(/) = -3.101\,10^{-4} + 1.545\,10^{-5}\,T(°C) + 2.75\,10^{-9}\,T(°C)^2$
Density	$\rho\,(kg\,m^{-3}) = 7900\,(1 + \varepsilon_{th})^{-3}$
Thermal conductivity	$k(W\,m^{-1}\,K^{-1}) = 13.95 + 0.01163\,T(°C)$
Young's modulus	$E(GPa) = 202.7 - 0.08167\,T(°C)$
Poisson's ratio	$\nu(/) = 0.277 + 6\,10^{-5}\,T(°C)$
Yield stress at 0.2% strain	$\sigma_{Y,0.2\%}(MPa)\begin{cases} 555.5 - 0.25\,T(°C) & \text{if } T < 600°C \\ 405.5 - 0.775\,(T(°C) - 600) & \text{if } 600°C < T < 1000°C \\ 345.5 - 0.25\,T(°C) & \text{if } T > 1000°C \end{cases}$
Ultimate tensile strength (UTS)	$\sigma_{UTS}(MPa)\begin{cases} 700 - 0.3125\,T(°C) & \text{if } T < 600°C \\ 512.5 - 0.969\,(T(°C) - 600) & \text{if } 600°C < T < 1000°C \\ 437.5 - 0.3125\,T(°C) & \text{if } T > 1000°C \end{cases}$
Rupture strain	$\varepsilon_{rupt}(\%) = 8 + 4.74\,10^{-3}\,(T(°C) - 500) + 6.2\,10^{-5}(T(°C) - 500)^2$
Void swelling	$\frac{\Delta V}{V}(\%) = 1.5\,10^{-3}\exp\left[-2.5\left(\frac{T(°C) - 450}{100}\right)^2\right]\left(\frac{\varphi(n\,cm^{-2})}{10^{22}}\right)^{2.75}$
Coolant properties	
Melting temperature at atmospheric pressure	$T_m = 98°C$
Boiling temperature at atmospheric pressure	$T_b = 882°C$
Isobaric specific heat	$c_p\,(J\,kg^{-1}\,K^{-1}) = 1608 - 0.7481\,T(K) + 3.929\,10^{-4}\,T(K)^2$
Density	$\rho\,(kg\,m^{-3}) = 954.1579 + T(°F)\,(T(°F)\,(T(°F)\,0.9667\,10^{-9} - 0.46\,10^{-5}) - 0.1273534)$
Dynamic viscosity	$\eta(mPa\,s) = \exp\left(\frac{813.9}{T(K)} - 2.530\right)$
Thermal conductivity	$k(W\,m^{-1}\,K^{-1}) = 110 - 0.0648\,T(K) + 1.16\,10^{-5}\,T(K)^2$
Nusselt number	$Nu = 7 + 0.025\,Pe^{0.8}$
Filling gas, Thermal conductivity	$k_{He}\,(W\,m^{-1}\,K^{-1}) = 15.8\,10^{-4}\,T(K)^{0.79}$

Variables: β = burnup (GWd/t_{HM}). p: porosity (/). R = gas constant = 1.986 cal $mol^{-1}\,K^{-1}$. T temperature (°C, K or °F).

x = 2.00-O/M: deviation from stoichiometry (/). φ = neutron fluence ($n\,cm^{-2}$). σ_{eq} = Von Mises equivalent stress (MPa).

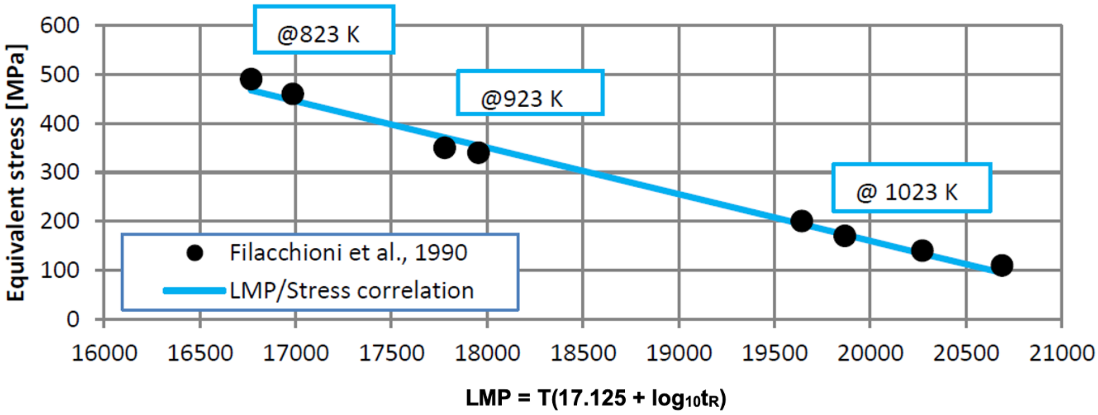

Figure 3: Equivalent stress leading to creep failure vs. Larson-Miller parameter (LMP) for the considered cladding steel (T: temperature in K, t_R: time-to-rupture in hours). The LMP/Stress correlation is expressed by $\sigma_{eq}(\text{MPa}) = 2060 - 0.095\ \text{LMP}$.

Table 5: Indicative design limits.

Quantity	**Design limits**
Maximum fuel temperature	< 2600°C
Maximum cladding temperature	< 650°C (at cladding midwall)
Maximum plenum pressure	< 5 MPa
Instantaneous cladding plastic strain	< 0.5%
Cladding volumetric swelling	< 3 %
Maximum coolant velocity	< 8 m/s