Politecnico di Milano
Energy Department – Nuclear Engineering Division (CeSNEF)
Nuclear Design and Technology 2025/2026
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Please, send to lelio.luzzi@polimi.it (within January 15, 2026) the following deliverables, with the names of the group students:
- *A technical report in .pdf (max. 10 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.*

Homework

In Fig. 1, some components of an *innovative* PWR layout are sketched.

The primary fluid (liquid water at the pressure of 75 bar) enters the vessel from the top, flowing downstream in the annular zone between the barrel and the vessel. The vessel is protected by a thermal insulating layer, and is surrounded by an innovative containment system (CPP - Containment for Primary system Protection). The CPP is filled with still water, at the temperature of 70°C, and at the same pressure of the primary fluid.

In Table 1, reference data of the reactor are reported. Table 2 shows the values prescribed by ASME III for the stress intensity and for the yield stress of the vessel and the thermal shield material (for simplicity, the same steel). The thermal shield is placed between the barrel and the vessel, in order to limit the thermal stresses in the vessel itself.

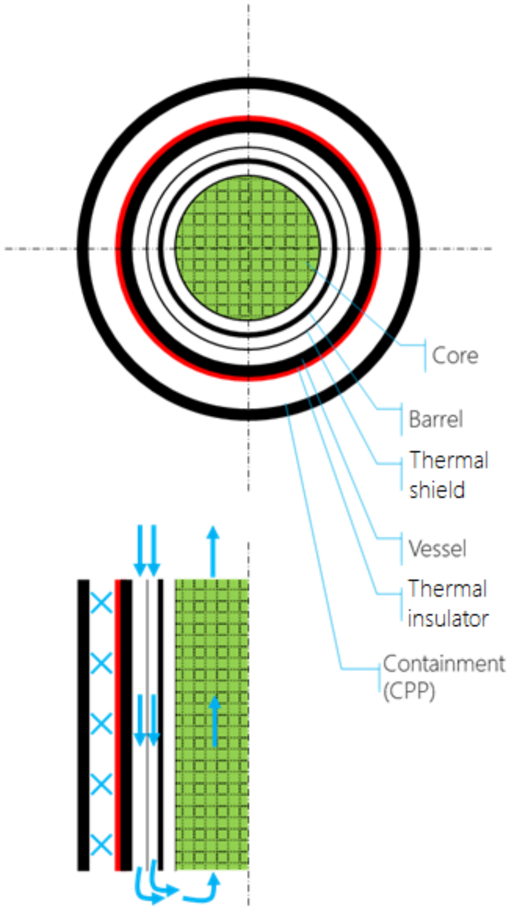

Figure 1. Sketch of the reactor components (not in scale), and of the primary fluid flow.

Table 1. Reference data.

Geometrical data		
Barrel external diameter	m	2.5
Vessel internal diameter	m	3.0
Thermal insulation thickness (thermal conductivity of 1.4 W m^{-1} K^{-1})	cm	5.0
Primary fluid		
Core inlet temperature	°C	214
Average core outlet temperature	°C	254
Maximum core outlet temperature (hot channel)	°C	270
Pressure	bar	75
Mass flow rate	kg s^{-1}	3227
Average specific heat	J kg^{-1} K^{-1}	4534
Average density	kg m^{-3}	852.5
Average dynamic viscosity	Pa s	1.259 10^{-4}
Average thermal conductivity	W m^{-1} K^{-1}	0.658
Containment (CPP) water		
Temperature	°C	70
Pressure	bar	75
Average specific heat	J kg^{-1} K^{-1}	4172.5
Average density	kg m^{-3}	981.2
Average dynamic viscosity	Pa s	4.06 10^{-4}
Average thermal conductivity	W m^{-1} K^{-1}	0.666
Thermal expansion coefficient	K^{-1}	5.57 10^{-4}
Steel (analysis and verification data)		
Young's modulus	GPa	177
Poisson coefficient	-	0.3
Linear thermal expansion coefficient	K^{-1}	1.7 10^{-5}
Thermal conductivity	W m^{-1} K^{-1}	48.1
Effective linear attenuation coefficient of gamma radiation	m^{-1}	24
Radiation source		
Gamma radiation flux[#]	photons cm^{-2} s^{-1}	1.5 10^{13}
Average gamma energy	MeV	6.0
Build-up factor	-	1.4

[#] Assume that this flux impacts the internal surface of the thermal shield, and the internal surface of the vessel in absence of the thermal shield.

Table 2. ASME III data for the considered steel.

Temperature (°C)	S_m (MPa)	S_y (MPa)
< 40	160	240
< 65	155	232.5
< 100	148	222
< 125	144	216
< 150	140	210
< 175	136	204
< 200	133	199.5
< 225	130	195
< 250	127	190.5
< 275	124	186
< 300	121	181.5
< 325	118	177
< 350	114	171
< 375	110	165
< 400	105	157.5
< 425	98	147

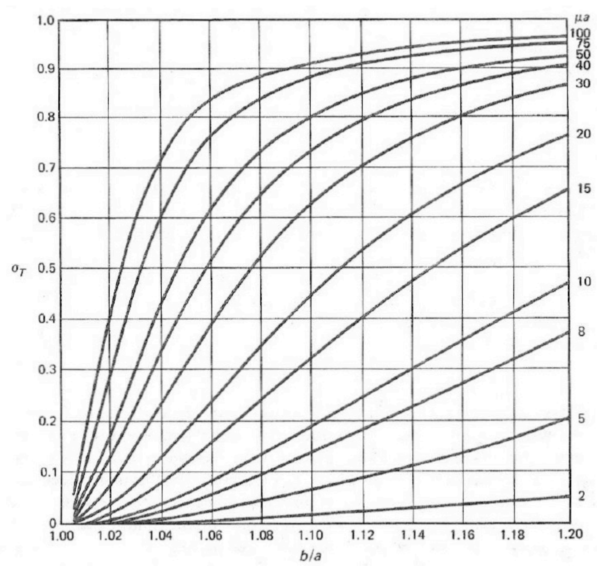

Figure 2. Design curve.

Vessel

Design-by-analysis. Perform a preliminary thickness sizing of the reactor vessel cylindrical shell (away from gross and local structural discontinuities), and its stress verification under static load for the design and the operating conditions of the *service level A*.

In detail, without and (secondly) with the thermal shield:

1. Select the *Quality Group*, the *Safety Class* and the *Seismic Category* of the vessel.
2. Select the *design conditions* for the vessel in terms of temperature (design temperature) and pressure (design pressure).
3. Find the thickness t of the vessel cylindrical shell (away from structural discontinuities and under the *design conditions* defined above).
4. Evaluate the convective heat exchange coefficient h_1 between the inner surface of the vessel and the primary fluid, the convective heat exchange coefficient h_2 between the outer thermal insulation surface and the still water inside the containment (natural convection), and the global heat exchange coefficient U_2 between the vessel outer surface and the water in the containment. For the evaluation of h_1, the Dittus-Boelter correlation is recommended: $Nu = 0.023\, Re^{0.8} Pr^{0.4}$. For h_2, the Mc Adams correlation is suggested: $Nu = 0.13\,(Gr\, Pr\,)^{1/3}$. For the calculation of the Grashof number Gr, a temperature difference of 30°C can be assumed. In the evaluation of U_2, refer to the outer surface of the vessel, setting a proper boundary condition at the interface between the vessel and the thermal insulating layer.
5. Evaluate the volumetric heat source (MW m^{-3}) at the inner surface of the vessel, and at the interface between the vessel and the thermal insulation, drawing its radial profile across the vessel thickness.
6. Draw the temperature profile $T(x)$ across the vessel thickness in stationary conditions, reporting the temperature at the inner surface ($x = 0$), the temperature at the outer surface ($x = t$), as well as the position and the value of the maximum temperature. For simplicity, assume a slab geometry, with reference to the following heat equation:

   $$\frac{d^2T}{dx^2} = -\frac{q_0'''}{k}\exp\left(-\mu x\right)$$

   where k and μ are the steel thermal conductivity and the effective linear attenuation coefficient of gamma radiation, respectively, and q_0''' represents the volumetric heat source at $x = 0$.
7. Find the thermal power flux (kW m^{-2}) on the inner and outer vessel surface without considering the radiation heat source ($q_0''' = 0$), and compare the temperature profile under this hypothesis with the one calculated at item (6).

8. Perform the resistance verification of the vessel cylindrical shell for static load conditions, in a section far from structural discontinuities, considering the operating conditions of the *service level A*. Justify the assumptions made. For a very preliminary evaluation of the maximum thermal stress, may use the following relation:

$$\sigma = \sigma_T \frac{\alpha\, E\, q_0'''}{k\,(1-\nu)\,\mu^2}$$

where α is the linear thermal expansion coefficient, E is the Young's modulus, ν is the Poisson coefficient, k is the thermal conductivity, μ is the gamma effective linear attenuation coefficient of the steel, and q_0''' is the radiation heat source at the vessel inner radius. The quantity σ_T can be derived from Fig. 2 (referring to the case of an outside adiabatic wall), in which a and b are the inner and outer radius of the cylindrical shell, respectively.

Thermal shield

To reduce the temperature gradient induced in the vessel by the radiation absorption (for simplicity, assume just the gamma component), a thermal shield is set coaxially between the barrel and the vessel. The function of this shield is limiting the thermal stresses in the vessel.

In detail:

1. Identify the criteria for the selection of the thermal shield material, with reference to its functional requirements.
2. Select the *Quality Group*, the *Safety Class* and the *Seismic Category* of the thermal shield.
3. Select the *design conditions* for the thermal shield in terms of temperature (design temperature), pressure (design pressure), and maximum allowable stress (remember that the sum of primary and secondary stresses has to be less than $3\,S_m$, with the primary stresses below S_m).
4. Find the thickness s of the thermal shield. Assume the same steel used for the vessel, and reduce the intensity of the gamma flux in order to assure allowable thermal stresses in the vessel.
5. Draw the radial temperature profile across the thickness s in stationary conditions, specifying the position and the value of the maximum temperature, as well as the temperatures at the inner and at the outer surfaces. Assume a slab geometry, and use the heat exchange coefficient h_1 on both sides.
6. With reference to the operating conditions of the *service level A*, evaluate if the stresses in the thermal shield are allowable. Justify the assumptions made.
7. Having determined the thickness s, discuss qualitatively the effects related to the choice of the thermal shield inner radius.