Design for passive safety

Historically, nuclear power reactors were designed to optimize performance

Today, reactors are designed to achieve passive safety

Numerical simulation of limiting transients are applied for this purpose.

KTH is developing an analytical approach within the SUNRISE project.

After this lecture you will be able to:

- **Design a passively safe small reactor using an analytical approach**

Passive safety approach

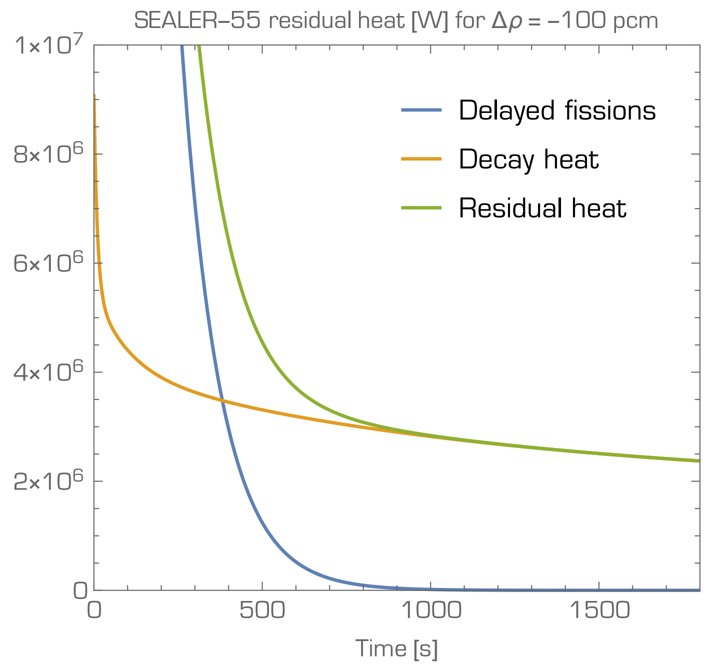
- Safety goal: protect the public from radiological exposure.
- Passive safety systems rely on natural phenomena such as gravity, buoyancy, temperature and radiation.

IAEA passive safety system categories

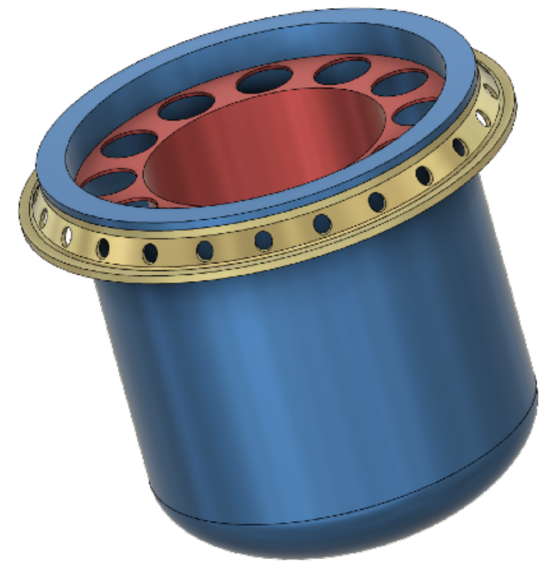
Category	A	B	C	D
Moving working fluids		X	X	X
Moving mechanical parts			X	X
Signal inputs				X
External power				

- Examples of category A: Fuel cladding tube, fuel Doppler feedback

Removal of residual heat from primary system by radiation from vessel



- Solve a simplified system of differential equation for the primary system temperature as function of vessel area, coolant mass (i.e. vessel volume), reactor power and residual heating during a **loss of heat sink event**:



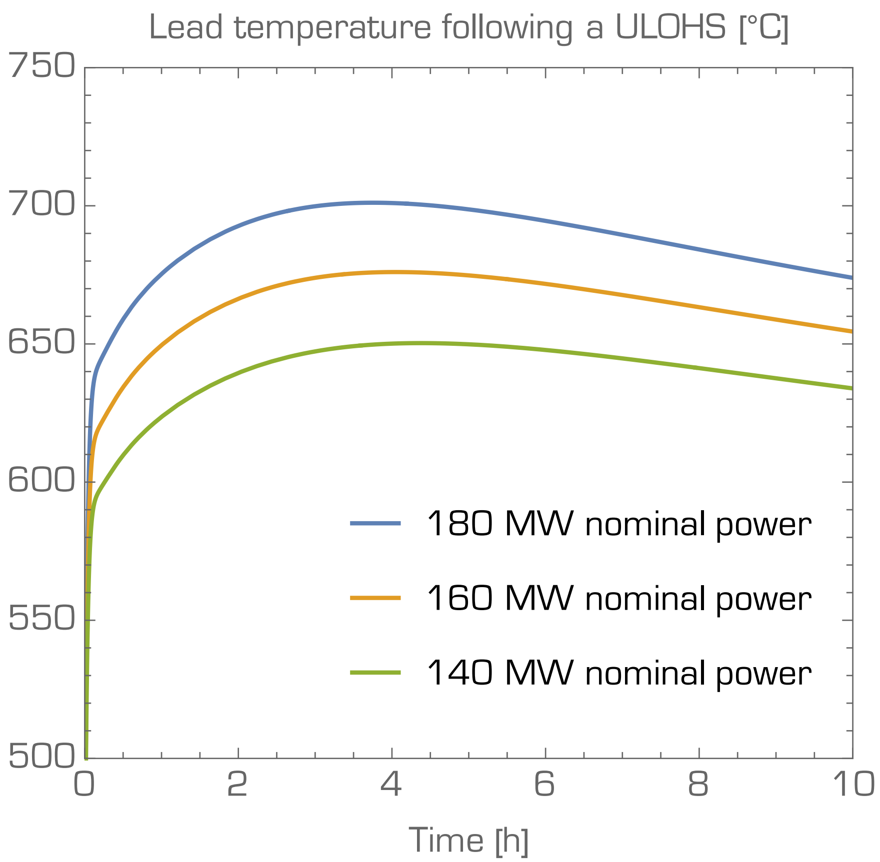
$$\frac{dT_{Pb}}{dt} = \frac{1}{m_{Pb} c_P^{Pb}(T)} \left(\dot{Q}_{res}(t) - A_{vessel} \times h_{Pb \to steel} \times (T_{Pb} - T_{steel}) \right)$$

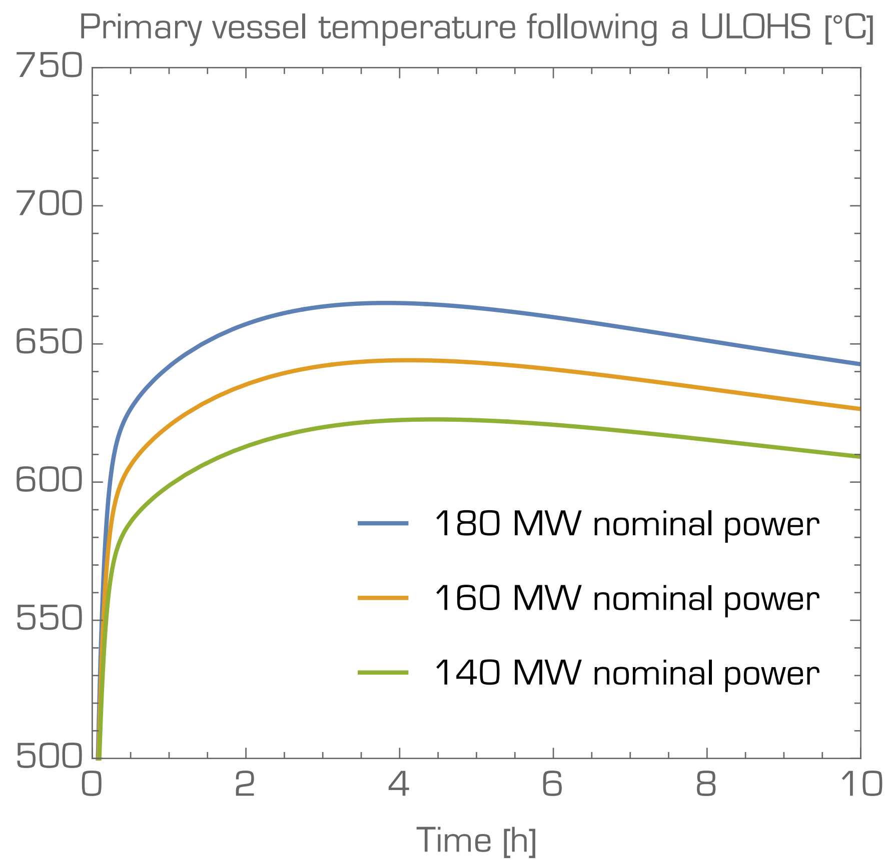
$$\frac{dT_{vessel}}{dt} = \frac{1}{m_{steel} \times c_P^{steel}(T)} \left(A_{vessel} \times h_{Pb \to steel} \times (T_{Pb} - T_{steel}) - \dot{Q}_{rad}(T_{vessel}) \right)$$

$$\dot{Q}_{rad} = \sigma_{SB} \frac{T_{vessel}^4 - T_{guard}^4}{\frac{1}{A_v \epsilon_v} + \frac{1}{A_g \epsilon_g} - \frac{1}{A_g}}$$

$$h_{Pb \to steel} = \frac{k_{steel}}{\delta_{steel}}$$

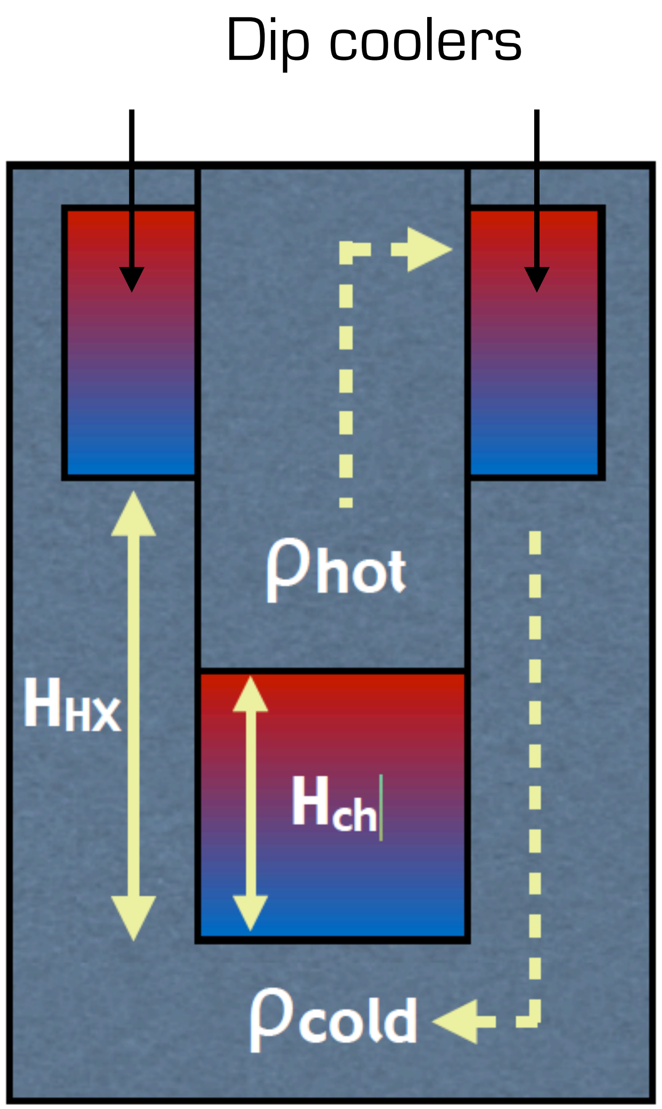
Peak temperature as function of power, vessel area & volume





- $\Delta\rho$ = -100 pcm
- A_{vessel} = 80 m^2
- m_{Pb} = 875 ton
- m_{steel} = 25 ton

Removal of residual heat from core by natural convection of primary coolant.



- Core geometry and vessel height are determined by requesting capability to remove residual heat by natural convection. The buoyancy head may be approximated by

$$P_b \approx g \times \left(\rho_{Pb}(T_{inlet}) - \rho_{Pb}(T_{outlet})\right) \times H_{DC}$$

$$\rho_{Pb}(T) = 11441 - 1.2798 \times T \rightarrow$$

$$\boxed{P_b \approx 1.28 \times g \times \Delta T_{nat} \times H_{DC}}$$

Pressure drop

- Since pressure drop is proportional to mass flow square, we approximate the total pressure drop by a factor K = 1.5 multiplying the channel pressure drop:

$$P_b \approx f_{nat} \frac{H_{ch} \rho_{Pb} v_{nat}^2}{2D_h} \times K \qquad f_{nat} = \frac{a}{Re_{nat}^b} = \boxed{a \times \left(\frac{\rho_{Pb} v_{nat} D_h}{\mu} \right)^{-b}}$$

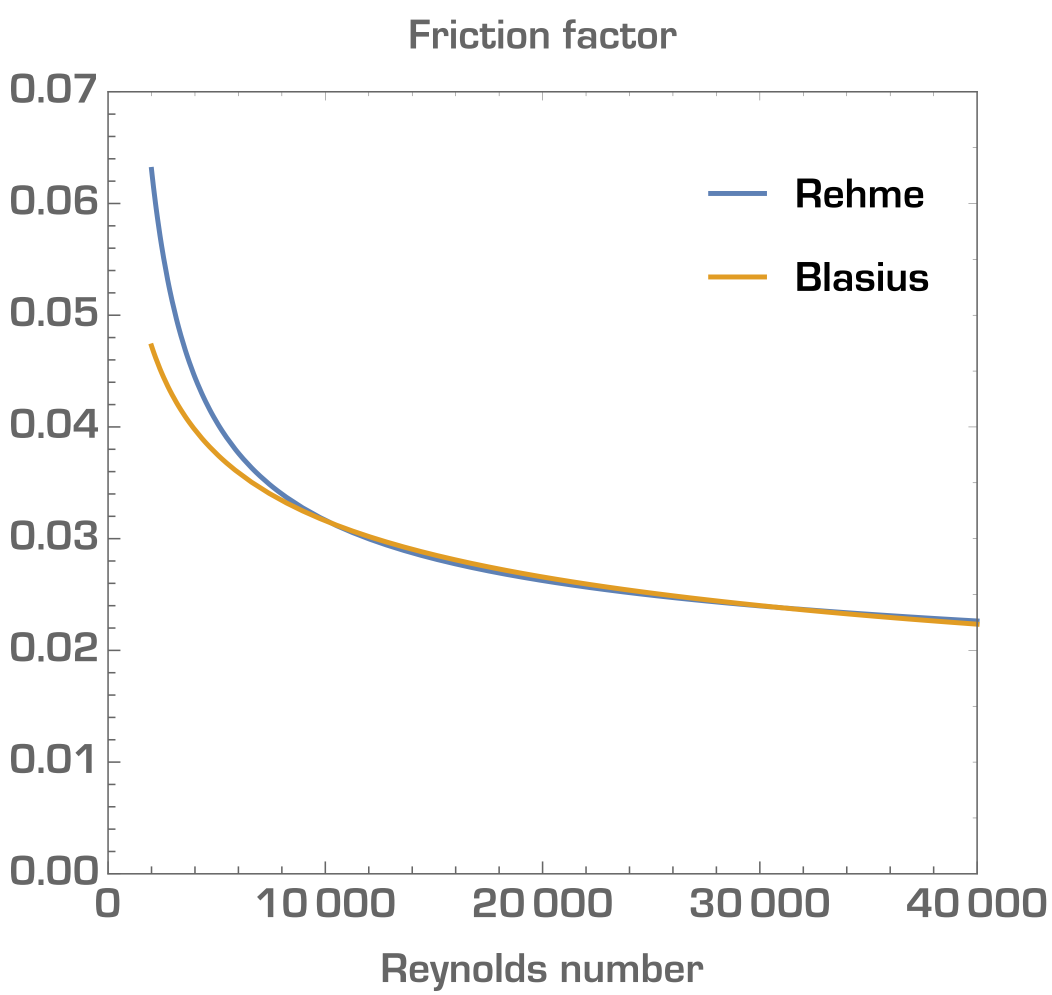
- Equating expressions for the hydraulic diameter under nominal and natural flow conditions, we get an expression for the nominal system pressure drop:

$$D_h = f_{nat} \frac{H_{ch} \rho_{Pb} v_{nat}^2}{2P_b} \times K = f_{nom} \frac{H_{ch} \rho_{Pb} v_{nom}^2}{2\Delta P_{nom}} \times K \quad \rightarrow$$

$$\left(\frac{v_{nat}}{v_{nom}} \right)^2 = \frac{f_{nom}}{f_{nat}} \frac{P_b}{\Delta P_{nom}} = \left(\frac{v_{nat}}{v_{nom}} \right)^b \frac{P_b}{\Delta P_{nom}} \quad \rightarrow$$

$$\Delta P_{nom} = P_b \left(\frac{v_{nom}}{v_{nat}} \right)^{2-b} = \boxed{1.28 \times g \times \Delta T \times H_{DC} \times \left(\frac{Q_{nom}}{Q_{res}} \right)^{2-b}}$$

Friction factor



- At lower velocities, the friction factor measured by Rehme in a wire spaced rod bundle differs from that given by the Blasius relation.

$$f_{Blasius} = \frac{0.316}{Re^{0.25}}$$

- For our analytical model, we fit at nominal and natural convection point to obtain:

$$f_{Rehme-fit} \simeq \frac{0.485}{Re^{0.29}}$$

Hydraulic diameter

- Now, we may obtain an expression for the hydraulic diameter from the system pressure drop under nominal conditions:

$$\Delta P_{nom} \approx f_{nom} \frac{H_{ch} \rho_{Pb} v_{nom}^2}{2D_h} \times K, \; f_{nom} = \frac{a}{Re_{nom}^b}$$

$$\Delta P_{nom} = a \times K \left(\frac{\mu}{\rho_{Pb} v_{nom} D_h} \right)^b \frac{H_{ch} \rho_{Pb} v_{nom}^2}{2D_h} = \frac{a \times K}{2} \times \frac{\mu^b \; \rho_{Pb}^{1-b} \; v_{nom}^{2-b}}{D_h^{1+b}} \times H_{ch}$$

$$\boxed{D_h \approx \left(\frac{a \times K}{2} \frac{H_{ch}}{\Delta P_{nom}} \right)^{1/(1+b)} \left(\rho_{Pb}^{1-b} \; v_{nom}^{2-b} \; \mu^b \right)^{1/(1+b)}}$$

unknown

Coolant velocities

- For heat transfer, we require turbulent flow under natural convection

$$Re_{nat} = \frac{\rho_{Pb} v_{nat} D_h}{\mu} > 4000$$

- Inserting the expression previously derived for the hydraulic diameter and the relation between nominal and natural convection flow velocities, one arrives at:

$$v_{nat} > \left(4000^{1+b} \frac{2}{a \times K} \frac{P_b}{H_{ch}} \frac{\mu}{\rho_{Pb}^2} \right)^{1/3} = \boxed{\left(4000^{1+b} \frac{2.56}{a \times K} \frac{g \times \Delta T \times H_{DC}}{H_{ch}} \frac{\mu}{\rho_{Pb}^2} \right)^{1/3}}$$

$$v_{nom} = v_{nat} \frac{Q_{nom}}{Q_{res}}$$

Rod radius and pitch

- Knowing the hydraulic diameter and the flow velocity, we can calculate the flow area and the wetted perimeter in a wire spaced hexagonal flow channel:

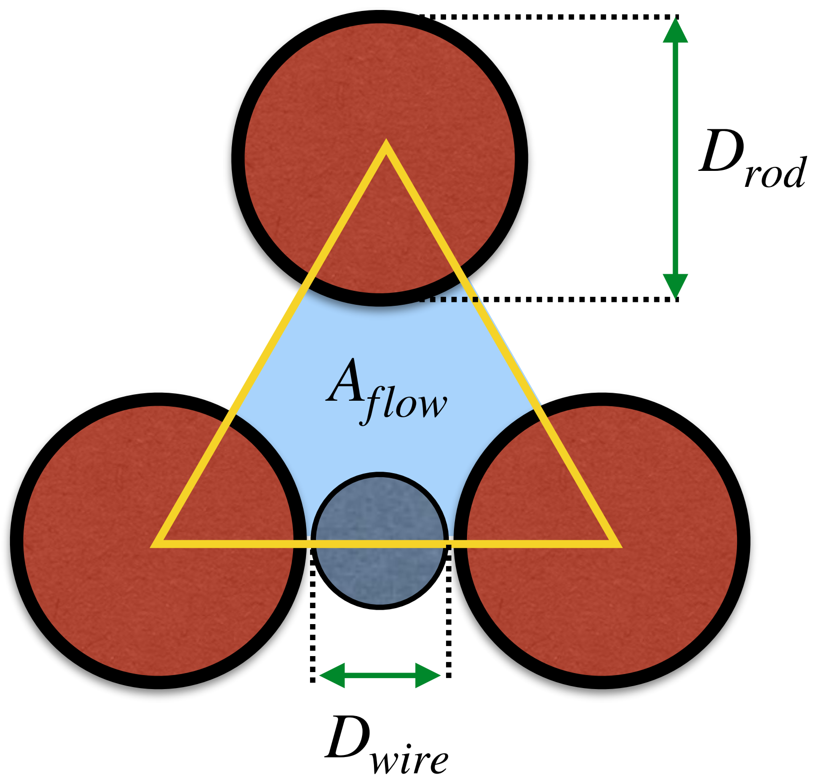
$$A_{flow} = \frac{\sqrt{3}}{4}(D_{rod} + D_{wire})^2 - \frac{\pi}{2}(r_{rod}^2 + r_{wire}^2) = \frac{Q_{ch}}{\rho_{Pb} v_{nom} c_p \Delta T}$$

$$P_{wet} = \frac{4A_{flow}}{D_h} = \pi r_{rod} + \pi r_{wire}$$

- From these expressions we may determine rod and wire radii:

$$r_{rod} = \frac{2}{\pi}\left(\frac{A_{flow}}{D_h} + \sqrt{\left(\frac{A_{flow}}{D_h}\right)^2 (\frac{4\sqrt{3}}{\pi} - 1) - \frac{\pi}{4} A_{flow}}\right)$$

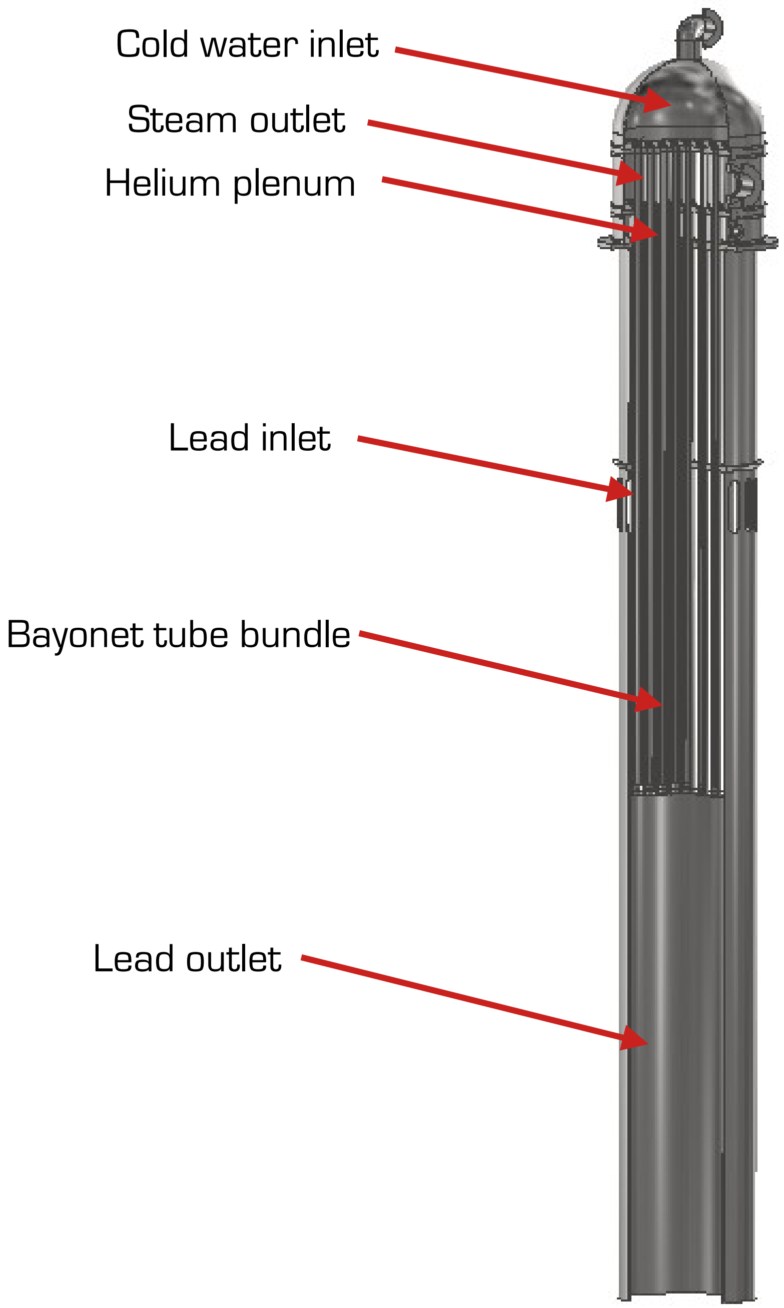
$$r_{wire} = \frac{2}{\pi}\left(\frac{A_{flow}}{D_h} - \sqrt{\left(\frac{A_{flow}}{D_h}\right)^2 (\frac{4\sqrt{3}}{\pi} - 1) - \frac{\pi}{4} A_{flow}}\right)$$



Analytical design process

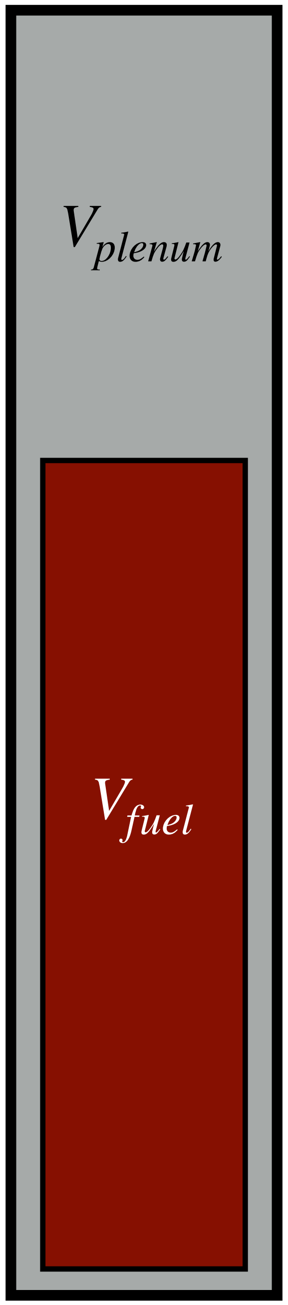
- Determine area and volume of vessel, based on nominal power and passive reactivity insertion and peak permitted vessel temperature
- Postulate the ΔT of the coolant from inlet to outlet of the core
- Postulate the fraction of nominal power to be removed by natural convection
- Assess the highest elevation of dip-coolers that is compatible with manufacturing and seismic constraints
- Postulate the minimum permitted Reynolds number during natural convection
- Determine the height of the fuel rod channel, considering fission gas release from the fuel.
- Determine the number of fuel rods from the permitted linear rating of the fuel.
- Calculate the rod diameter and pitch

Elevation of dip-coolers



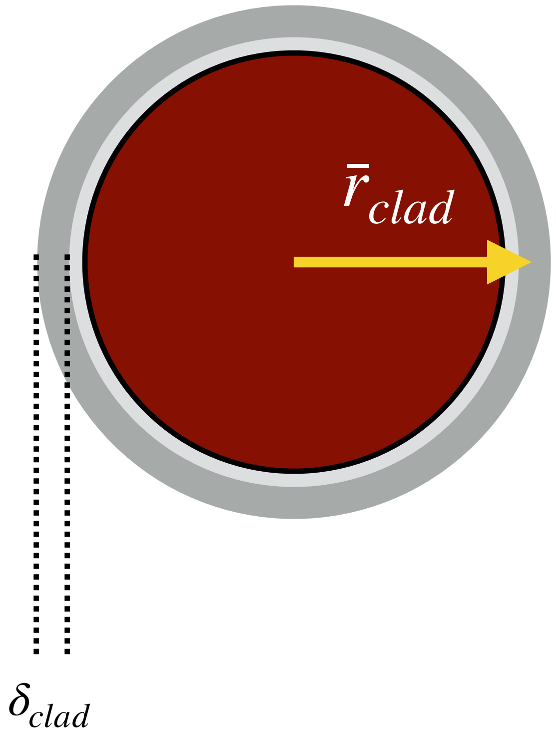
- Dip-coolers are actuated by opening of a valve.
- Their tubes are filled with water from a pool at room temperature and pressure, relying on gravitation.
- Flash steam provide efficient heat removal
- The elevation of the thermal centre of the dip-cooler with respect to the thermal centre of the core determines the buoyancy head.
- The height of the primary vessel may be limited by seismic constraints (LFRs) or by manufacturing considerations (iPWRs and LFRs).
- Widest rolled steel plate that is manufactured: 4.0 m. A taller cylindrical section requires the introduction of 1-2 circumferential welds, known to constitute issues in operation of LWRs.

Fuel rod internal gas pressure



- During transients, oxide fuel may release its entire inventory of fission gases (FG) to the gas plenum of the rod.
- In solid UO_2, the number density of U atoms is $n_U / V_{UO_2} = \rho_{UO_2} / M_{UO_2}$
- Xenon and Krypton atom production: Y_{FG} = 25% per fission
- The number of fission gas atoms: $n_{FG} = n_U \times Y_{FG} \times BU_{FIMA}$
- Pressure of fission gas: $p_{FG} = \dfrac{n_{FG} \times R_{gas} \times T_{FG}}{V_{plenum}}$
- $$P_{FG} = \frac{\rho_{UO_2}}{M_{UO_2}} \times R_{gas} \times T_{FG} \times BU_{FIMA} \times Y_{FG} \times \frac{V_{fuel}}{V_{plenum}}$$

Fuel clad Hoop stress due to fission gas release



- The released fission gas causes a Hoop stress on the cladding tube:

$$\sigma_{Hoop} \simeq \frac{\bar{r}_{clad}}{\delta_{clad}} P_{FG}$$

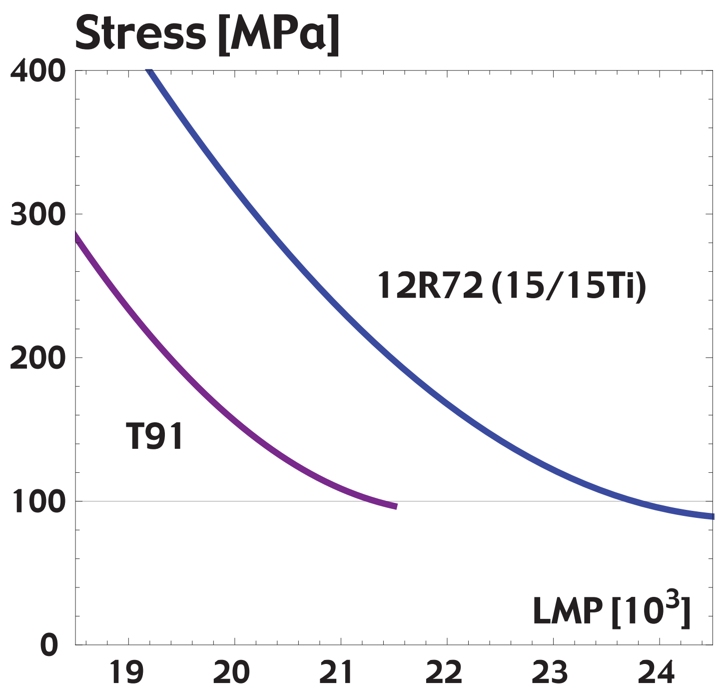
- For a fuel cladding tube: $r_{clad}/\delta_{clad} \simeq 10$

$$V_{plenum} = \frac{\rho_{UO_2}}{M_{UO_2}} \times R_{gas} \times T_{FG} \times BU_{FIMA} \times Y_{FG} \times \frac{V_{fuel}}{P_{FG}}$$

$$= \frac{\rho_{UO_2}}{M_{UO_2}} \times R_{gas} \times T_{FG} \times BU_{FIMA} \times Y_{FG} \times \frac{V_{fuel}}{\sigma_{Hoop}^{max}} \frac{\delta_{clad}}{\bar{r}_{clad}}$$

$$H_{plenum} = \frac{\rho_{UO_2}}{M_{UO_2}} \times R_{gas} \times T_{FG} \times BU_{FIMA} \times Y_{FG} \times \frac{H_{fuel}}{\sigma_{Hoop}^{max}} \frac{\delta_{clad}}{\bar{r}_{clad}}$$

Creep rupture life due to Hoop stress



Experimental creep rupture data

- The time to creep rupture of a cladding tube can be derived from the Larson-Miller parameter:

$$P = T\left(20 + {}^{10}log(t_r)\right) \rightarrow t_r = 10^{P/T-20}$$

- Time for rupture t_r is expressed in hours, temperature T in Kelvin

- For the reference fast reactor cladding material, 15-15Ti:

$$\sigma_{Hoop}^{max} = 200\ MPa \rightarrow P = 21500$$

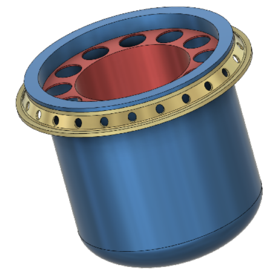
- What is the time to rupture at T = 973 K?

Example: 80 MW LFR

- $\dot{Q}_{nom} = 80\ MW_{th}$
- $\Delta\rho$ = -100 pcm

$A_{vessel} = 40\ m^2$

$m_{Pb} = 260\ t$



- a = 0.485, b = 0.29
- ΔT = 130 K
- $\dot{Q}_{nat}/\dot{Q}_{nom} = 0.14$
- H_{DC} = 2.5 m
- Re_{min} = 4000
- H_{ch} = 1.5 m

$D_{rod} = 12.6\ mm$

$D_{wire} = 1.5\ mm$

Home assignment 2

- Estimate the primary vessel area and mass of lead required to maintain coolant temperatures below 973 K during a loss of heat-sink accident in a small LFR, for a power equal to:

- Q = 100 + 10 x GroupNumber

- Assume that the cylindrical section of the vessel has a height of 4.0 m and that the bottom head of the vessel has a spherical shape. The entire volume of the vessel up to 0.5 m below the lid is filled with lead. Neglect the volume occupied by internal structures. The initial average lead temperature is 720 K.

- The expression for decay heat fraction following shut-down is:

$$\dot{Q}_{dec}(t) = (0.410 \times e^{-\frac{t}{10}} + 0.133 \times e^{-\frac{t}{10^2}} + 0.218 \times e^{-\frac{t}{10^3}} + 0.114 \times e^{-\frac{t}{10^4}} + 0.453 \times e^{-\frac{t}{10^5}} + 0.076 \times e^{-\frac{t}{10^6}})\frac{6.54}{100}$$

- The expression for delayed fission power fraction following shut-down is:

$$\dot{Q}_{del}(t) = 0.22 \times e^{-0.020t} + 0.67 \times e^{-0.0087t}$$