Passive removal of residual heat

Loss of residual heat removal capability is a common cause of core melt.

SMRs are easer to design with passive means for residual heat removal by:

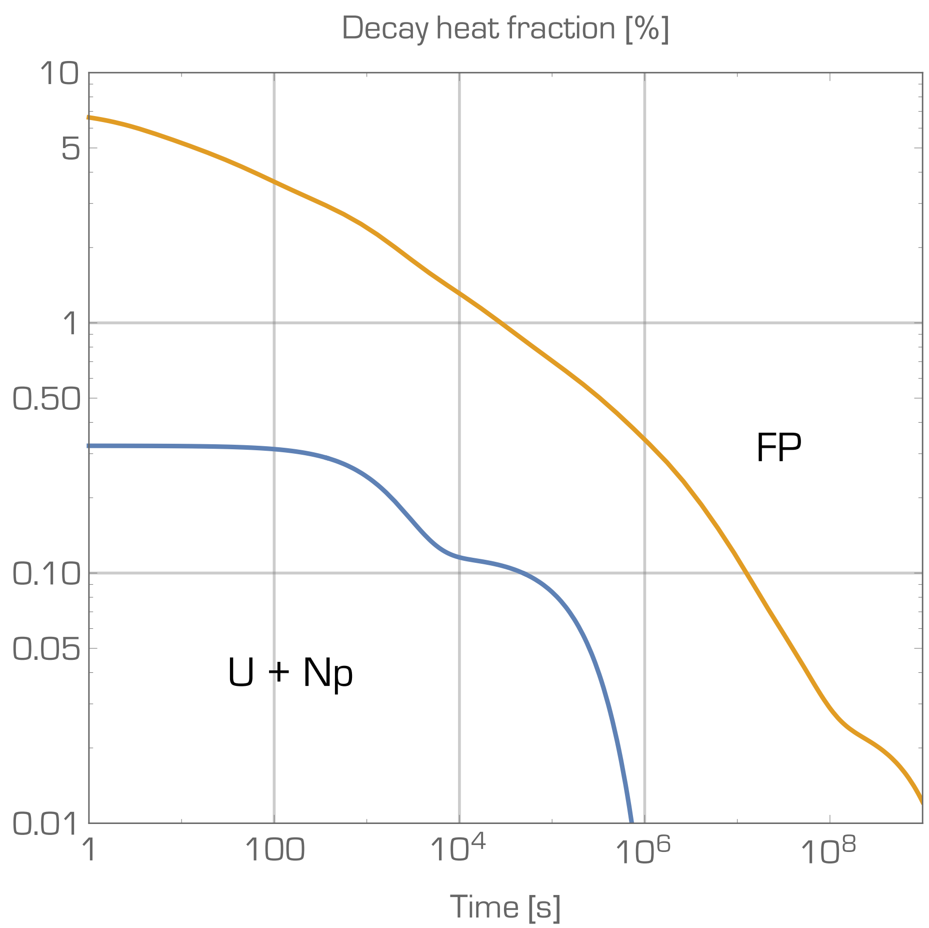
Full/residual heat removal from core by natural convection

Decay heat removal from vessel by radiation

After this lecture you will be able to:

- **Discuss the distinction between residual heat and decay heat**
- **Calculate natural convection heat removal rates**
- **Calculated heat removal rates by radiation**

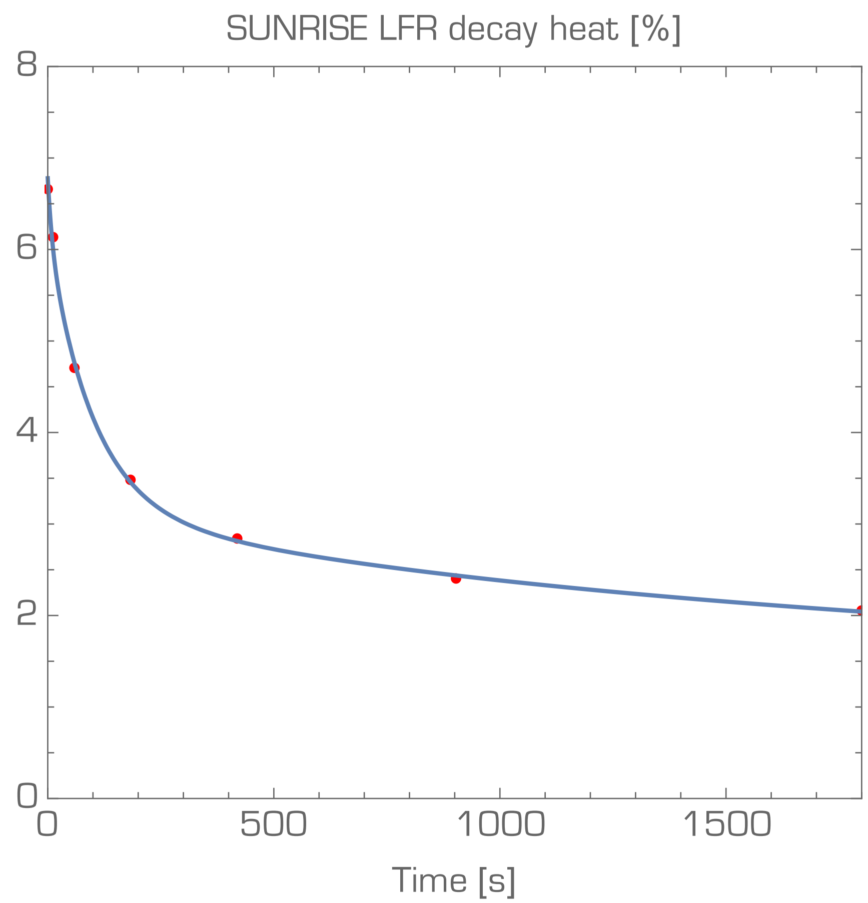
Fission product & actinide decay



> 100 fission products contribute to decay heat

- Three of these have a half-life longer than 1 year (^{90}Sr, ^{134}Cs & ^{137}Cs)
- Decay heat fraction of nominal power ≈ 6.7%.
- 1.7 % residual decay heat after 1 h.
- In a uranium fuelled fast reactor with 80% ^{238}U, decay of ^{239}U and ^{239}Np contribute with 0.3% of nominal power
- After 3 hours, actinide decay is 10% of total decay heat.

Short term evolution of decay heat



- During 1st hour, the decay heat is well described by a sum of four exponentials

$$\dot{Q}_{dec}(t) = 0.62 \times e^{-\frac{t}{10}} + 2.99 \times e^{-\frac{t}{100}} + 0.90 \times e^{-\frac{t}{1000}} + 2.27 \times e^{-\frac{t}{10000}}$$

Delayed neutrons

- Delayed neutrons are emitted by a limited set of neutron rich fission products

Br	$t_{1/2}$ [s]	Kr	$t_{1/2}$ [s]	Rb	$t_{1/2}$ [s]	I	$t_{1/2}$ [s]	Xe	$t_{1/2}$ [s]	Cs	$t_{1/2}$ [s]
^{86}Br	55.1	^{92}Kr	1.8	^{92}Rb	4.5	^{136m}I	46.9	^{141}Xe	1.7	^{141}Cs	24.5
^{87}Br	55.6	^{93}Kr	1.3	^{93}Rb	5.8	^{137}I	24.5	^{142}Xe	1.2	^{142}Cs	1.7
^{88}Br	16.3	^{94}Kr	0.2	^{94}Rb	2.7	^{138}I	6.5	^{145}Xe	0.9	^{143}Cs	1.8
^{89}Br	4.4			^{96}Rb	0.2	^{139}I	2.3			^{144}Cs	1.0
^{90}Br	1.9					^{140}I	0.9			^{145}Cs	0.6
^{91}Br	0.5					^{141}I	0.4			^{146}Cs	0.3
^{92}Br	0.3									^{147}Cs	0.2

- These precursors are binned in 8 groups with similar decay rates λ_i and yield β_i

i	1	2	3	4	5	6	7	8
$t_{1/2}$ [s]	55.5	24.5	16.3	5.2	2.4	1.0	0.4	0.2
λ_i [s^{-1}]	0.0125	0.0283	0.0425	0.133	0.292	0.666	1.63	3.55
β_i [pcm]	18	100	58	132	225	92	73	34

Fast fission in ^{235}U

Delayed neutron precursor population

Point kinetics equation:

$$\frac{dn(t)}{dt} = \frac{\rho(t) - \beta_{eff}}{\Lambda_{eff}} n(t) + \sum_{i=1}^{8} \lambda_i C_i(t)$$

$$\frac{dC_i}{dt} = \frac{\beta_i}{\Lambda_{eff}} n(t) - \lambda_i C_i(t)$$

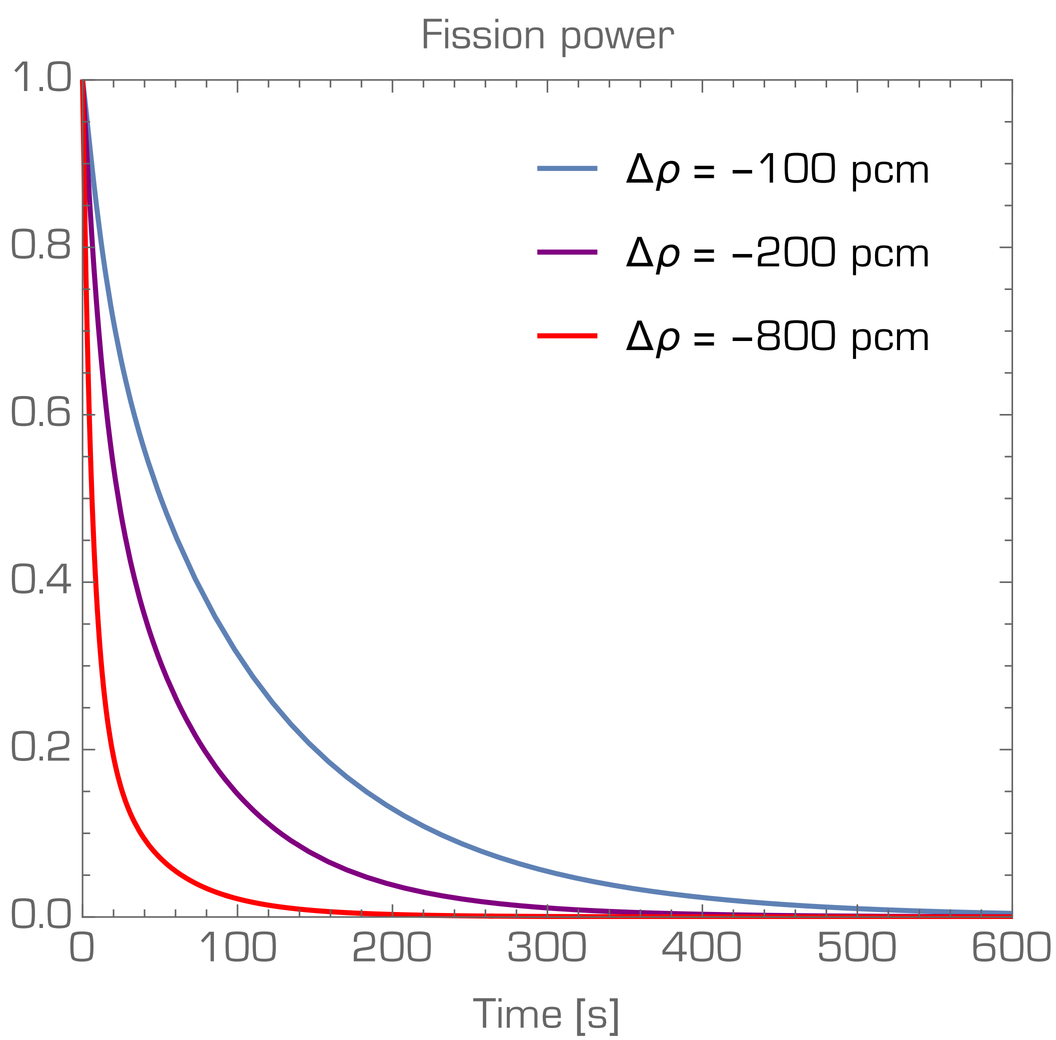
$$\beta_{eff} = \sum_{i=1}^{8} \beta_i$$

During nominal operation: $\frac{dn(t)}{dt} = 0,\ \rho(t) = 0,\ \frac{dC_i}{dt} = 0 \rightarrow C_i = \frac{\beta_i}{\Lambda_{eff}\lambda_i} n(t)$

In fast reactors: $\Lambda_{eff} \simeq 10\ \mu s$

i	1	2	3	4	5	6	7	8	Σ
$t_{1/2}$ [s]	55.5	24.5	16.3	5.2	2.4	1.0	0.4	0.2	
λ_i [s^{-1}]	0,0125	0,0283	0,0425	0,133	0,292	0,666	1,63	3,55	
β_i [pcm]	18	100	58	132	225	92	73	34	732
$C_i/n[t]$	1 440	3 534	1 365	992	771	138	45	10	8 294

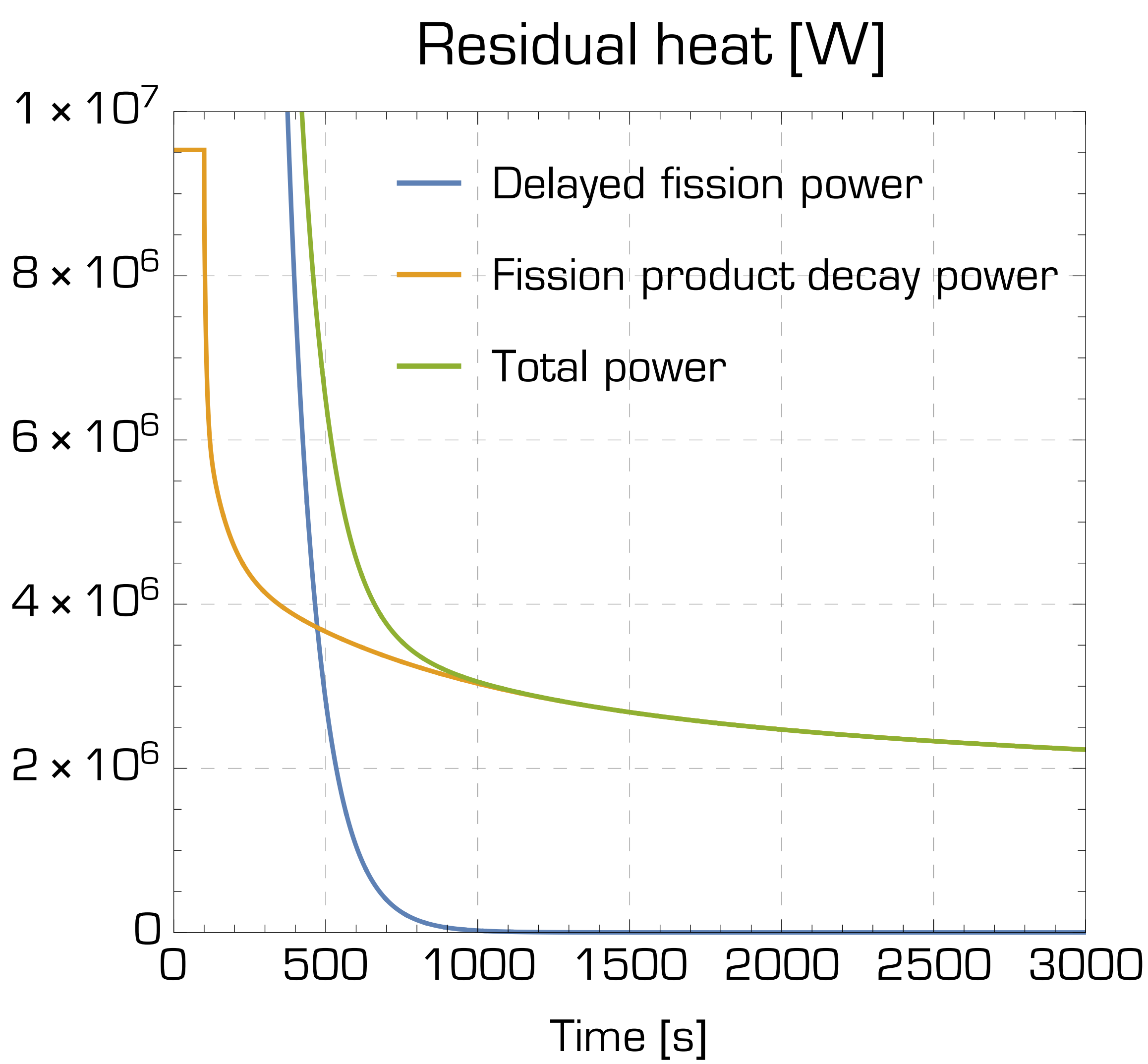
Delayed neutron induced fissions after passive shutdown



- Point kinetics equation solved for reactivity insertions with a time constant of 10 seconds, representative of loss of flow event.
- When $\Delta\rho < 1\$$, delayed fission power exceeds decay heat for several minutes.
- Reactivity feedbacks after passive shutdown are of the order of -100 pcm.

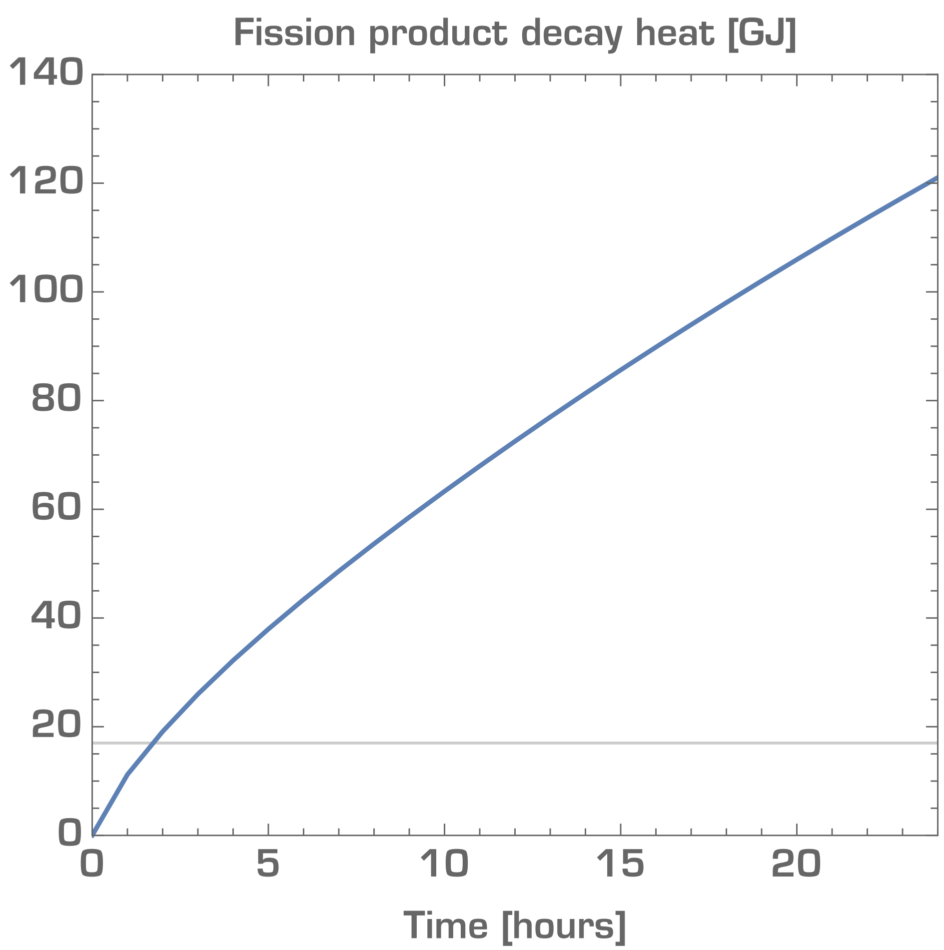
Residual heat =
Delayed fission power + decay heat

Residual power in SEALER-55 (140 MW_{th})



- Delayed fissions dominate power production during 6 minutes after loss of heat sink accident.
- 15 minutes into the transient, the residual heat mainly constitutes of decay heat and equals 3 MW (2.1% of nominal power)

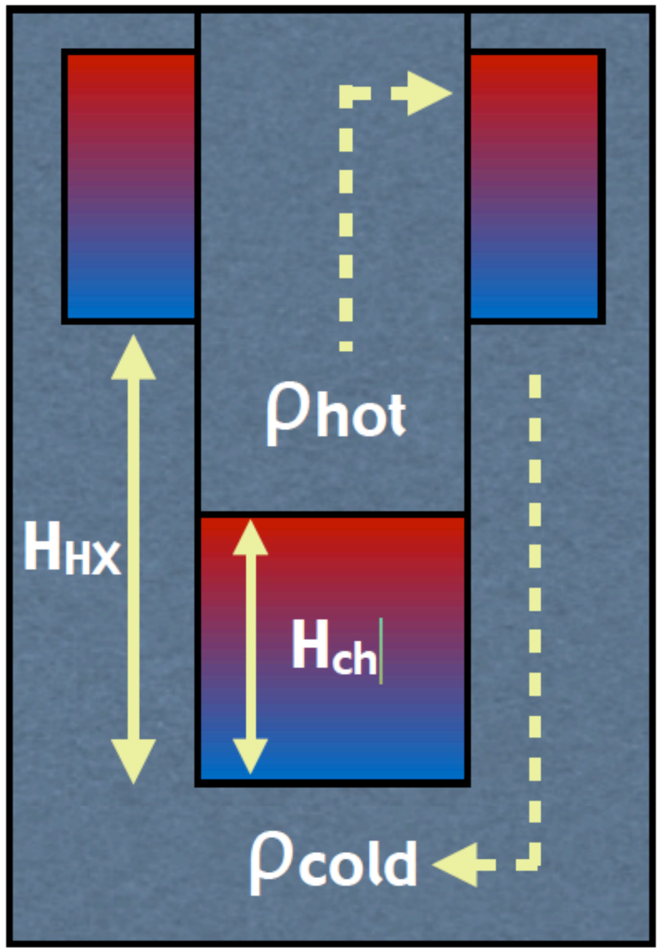
Accumulated post-shutdown heat



Post shut-down heat in SEALER-55

- 17 GJ = 4.7 MWh of residual heat is dissipated in first 15 minutes.
- Fission product decay heat accumulates to 120 GJ = 33 MWh within 24 hours.

Natural convection & pressure drop



$$P_b = g(\rho_{cold} - \rho_{hot})\Delta H_{HX}$$

- For fully established natural convection, buoyancy head equals pressure losses in core and heat exchanger/steam generator.

- Pressure drop is proportional to the square of the coolant velocity. E.g. one has for the rod channel friction pressure drop:

$$\Delta P_{ch} = f\frac{H_{ch}\rho v^2}{2D_h} = f\frac{H_{ch}\dot{m}^2}{2D_h\rho A_{flow}^2}$$

- At the inlet/outlet of a rod bundle the pressure drops due to flow area change are

$$\Delta P_{inlet} = \frac{1}{2}\left(1 - \frac{A_{small}}{A_{large}}\right)\frac{\dot{m}^2}{2\rho A_{small}^2}$$

$$\Delta P_{outlet} = \left(1 - \frac{A_{small}}{A_{large}}\right)^2\frac{\dot{m}^2}{2\rho A_{small}^2}$$

Friction factors

- Channel friction pressure drop:

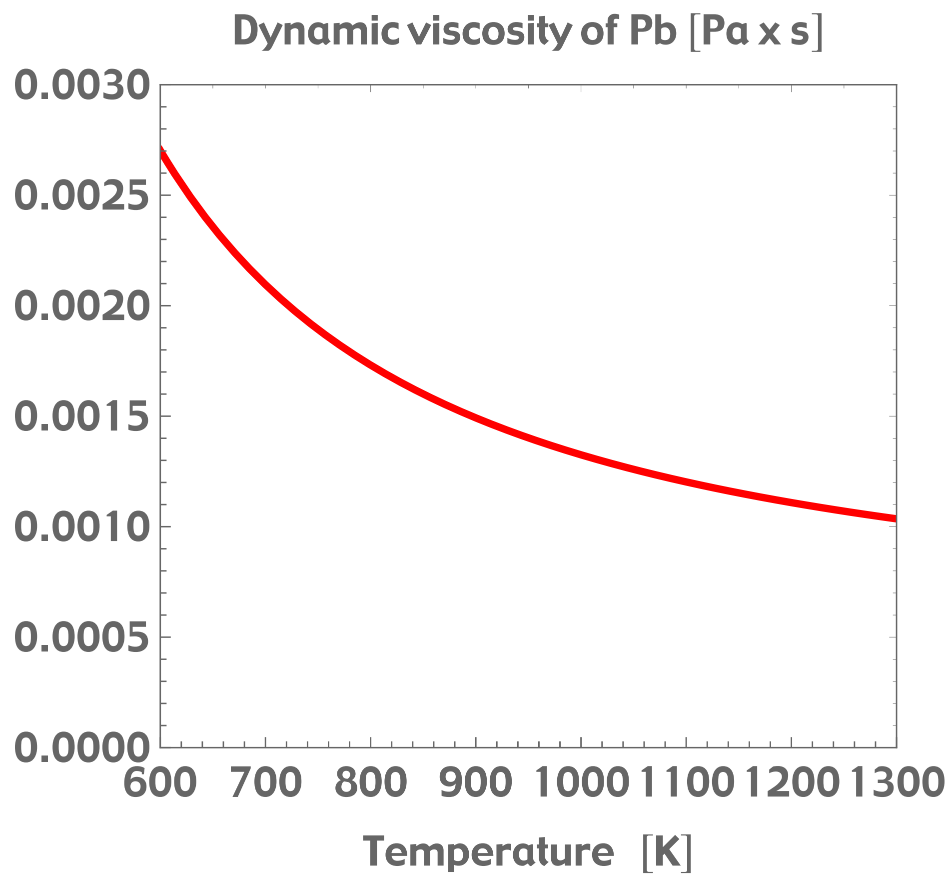
$$\Delta P_{ch} = f \frac{H_{ch} \dot{m}^2}{2 D_h \rho A_{flow}^2}$$

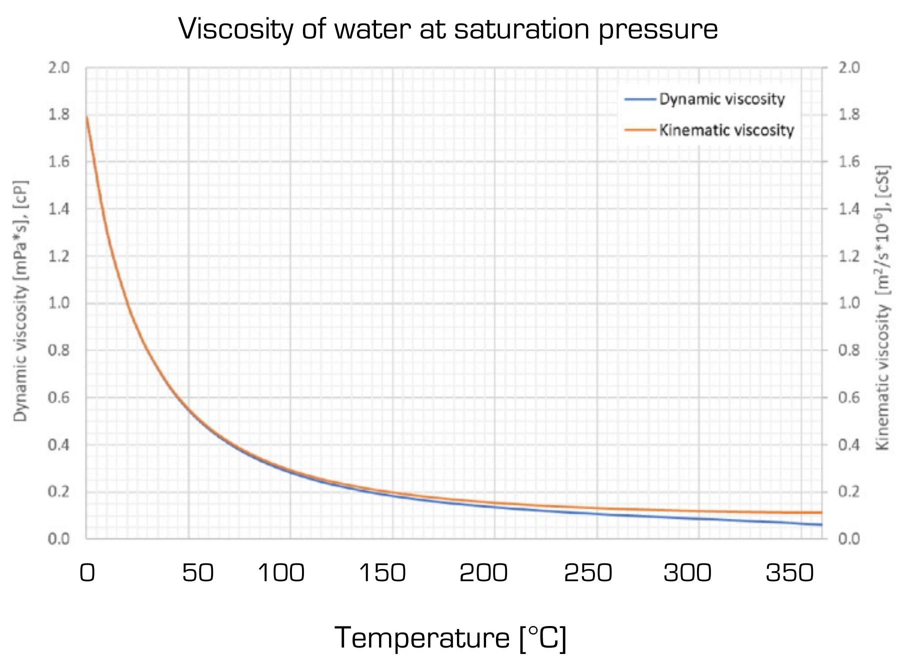
- Blasius friction factor:

$$f = \frac{0.316}{Re^{0.25}}$$

- Reynolds number:

$$Re = \frac{\rho v D_h}{\mu}$$





Mass flow, channel geometry and pressure drops in NuScales iPWR and LeadCold's SEALER

$$\dot{m} = \frac{\dot{Q}}{c_p \Delta T_{core}}$$

$$\Delta P_{ch} = f \frac{H_{ch}\dot{m}^2}{2D_h \rho A_{flow}^2} = f \frac{H_{ch}\rho v^2}{2D_h}$$

$$f = \frac{0.316}{Re^{0.25}}$$

$$Re = \frac{\rho v D_h}{\mu}$$

Nominal flow conditions

Property	Unit	iPWR	LFR
c_p	[J/kg/K]	4 300	140
ΔT_{core}	[K]	55	130
$\dot{m}/\dot{Q}$	[kg/s/MW$_{th}$]	4	55
ρ	[kg/m^3]	700	10 400
D_h	mm	10	10
v	m/s	5	1.5
μ	mPa s	0.1	2
Re	-	350 000	50 000
f	-	0.01	0.02
H_{ch}	m	2.0	2.0
ΔP_{ch}	Pa	17 500	43 000

Exercise: Full power removal

- Calculate ΔH_{HX} required for an iPWR to remove full power by natural convection (NuScale case)

$$P_b = g(\rho_{cold} - \rho_{hot})\Delta H_{HX}$$

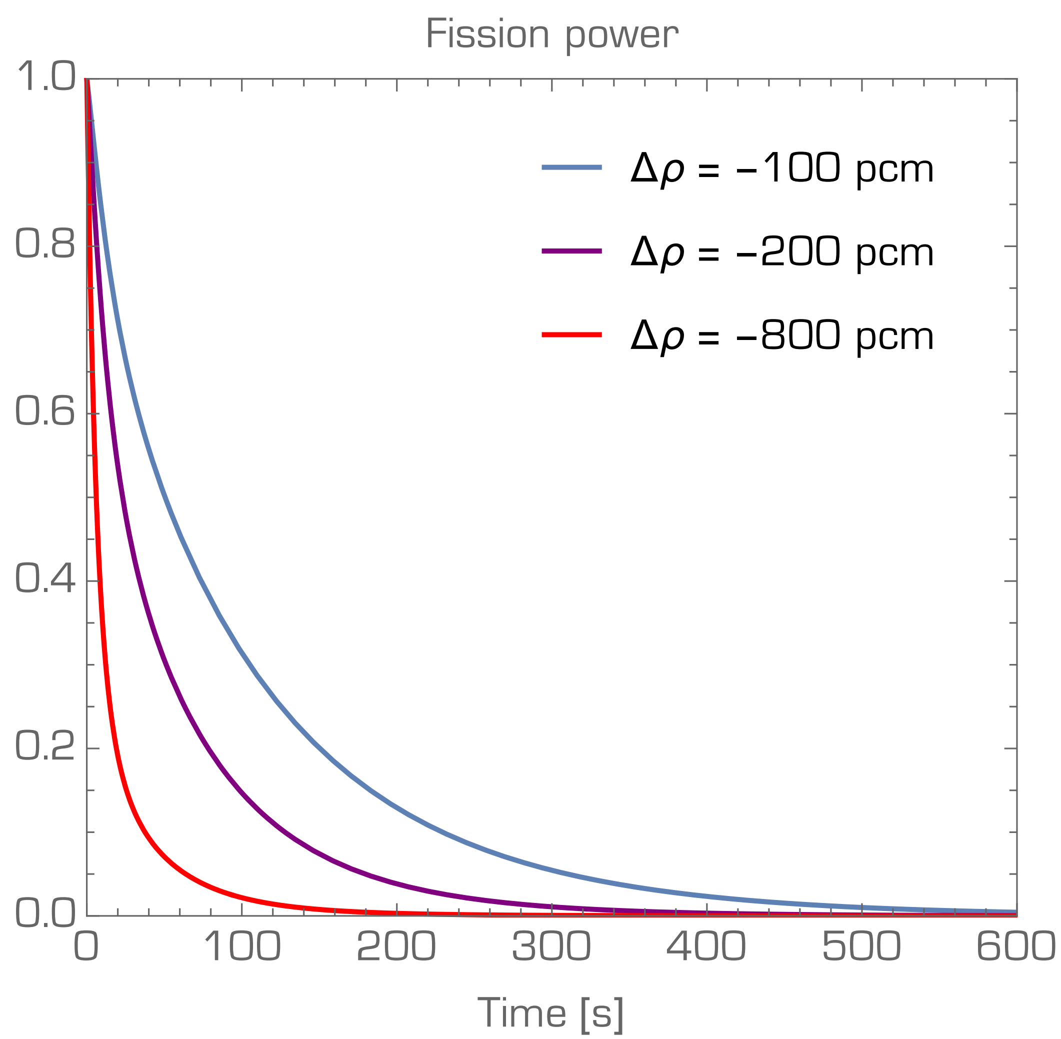
$$\Delta P_{ch} = f\frac{H_{ch}\dot{m}^2}{2D_h\rho A_{flow}^2} = 17.5\ kPa$$

$$P_{H_2O} = 13.8\ MPa$$

$$T_{in} = 538K$$

$$T_{out} = 593K$$

Exercise: Residual heat removal conditions



- Calculate ΔH_{HX} for an LFR necessary to remove 20 % of full power by natural convection.
- Assume $\Delta T_{nat} = \Delta T_{nom}$ = 130 K
- $\rho_{Pb}(T) = 11400 - 1.27 \times T$
- Does flow remain turbulent?

$$P_b = g(\rho_{cold} - \rho_{hot})\Delta H_{HX}$$

$$\Delta P_{ch} = f\frac{H_{ch}\dot{m}^2}{2D_h\rho A_{flow}^2} = f\frac{H_{ch}\rho v^2}{2D_h}$$

Loss of heat sink

- If the secondary system is lost, the primary coolant heats up
- Heat capacity of lead: 140 J/kg/K
- SEALER-55 lead inventory ≈ 700 ton
- Average coolant temperature increase: 10 K/GJ
- ULOHS: after 900 seconds, total heat dissipation ≈ 20 GJ
- At this time, what is the increase in temperature of the lead-coolant?

Radiative heat transport from primary vessel

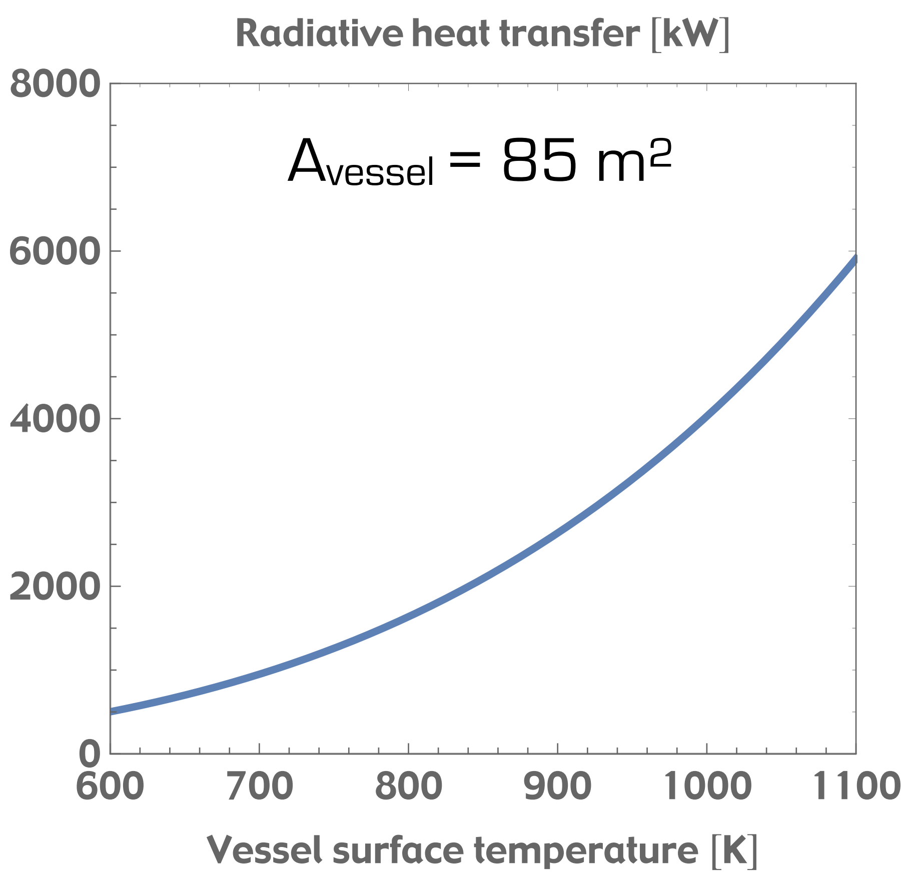
- Heat is alway transported by radiation from a hotter surface to a colder
- Net heat transfer from area A_1 to area A_2, having emissivities ϵ_1 and ϵ_2:

$$\dot{Q} = \frac{\sigma_{SB}(T_1^4 - T_2^4)}{\frac{1-\epsilon_1}{A_1\epsilon_1} + \frac{1}{A_1 F_{1\to 2}} + \frac{1-\epsilon_2}{A_2\epsilon_2}}$$

- For heat transfer between primary and guard vessel, the view factor $F_{1->2} \approx 1$, and $A_1 \approx A_2 = A$. One obtains

$$\dot{Q} \simeq \frac{\sigma_{SB} A(T_1^4 - T_2^4)}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1}$$

Passive heat removal from vessel

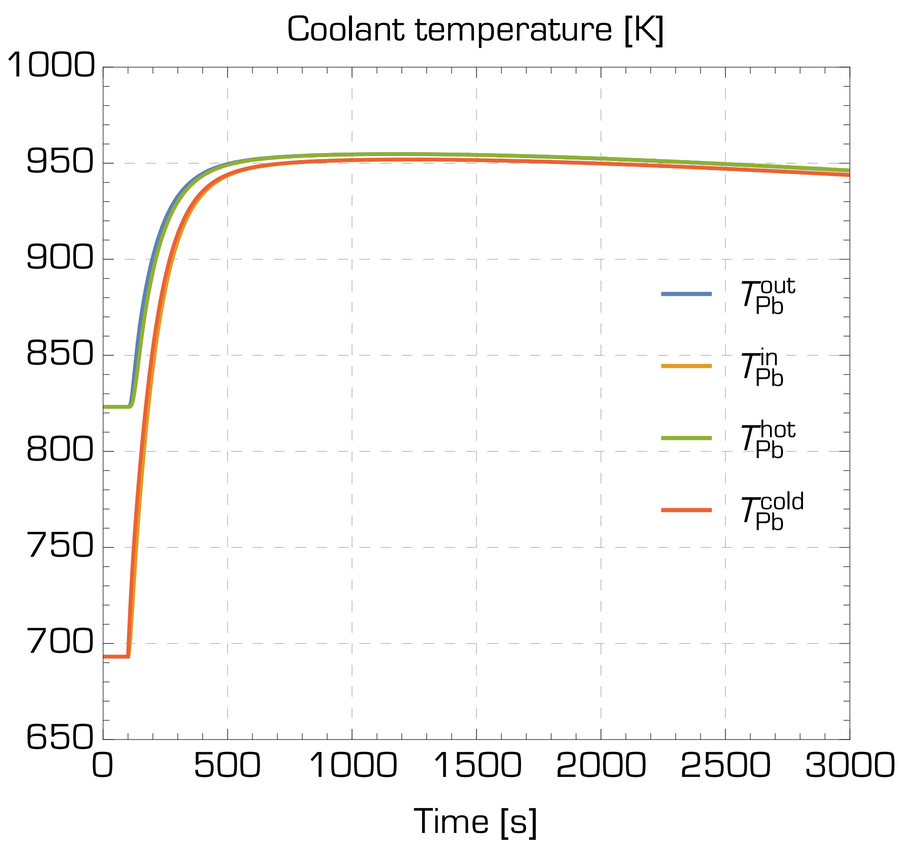


- Assuming loss of secondary system (ULOHS), post-shutdown heat is removed passively by radiation from vessel to a guard vessel.

$$\dot{Q}_{rad} = \frac{\sigma_{SB}(T_1^4 - T_2^4)}{1/A_1\epsilon_1 + 1/A_2\epsilon_2 - 1/A_2}$$

- Emissivity of oxidised steel surface: 0.85
- Temperature limit for reactor vessel: 700°C (970 K)
- Maximum radiative heat transfer capability from SEALER-55 vessel: 3.5 MW (!)

Loss of heat sink: SEALER-55



- Decay heat is passively transported by radiation from primary vessel to guard vessel.
- Maximum temperature in primary system < 700°C
- How can one evacuate the heat from the guard vessel?