SH2702
Nuclear Reactor Technology

Exercise Session 03

Emergency Core Cooling System (ECCS) in BWR

- BWR has a core spray system to provide water to the core in case the coolant level in the vessel is so low that there is a high risk that the core will be uncovered.
- The spray system will then prevent over-heating of the core by spraying water over fuel elements and eventually refill the core with water.
- The water is pumped from the suppression pools to a water box with nozzles placed just above the core.
- The system has usually at least two completely independent pumping loops, with connected fittings and instrumentation.

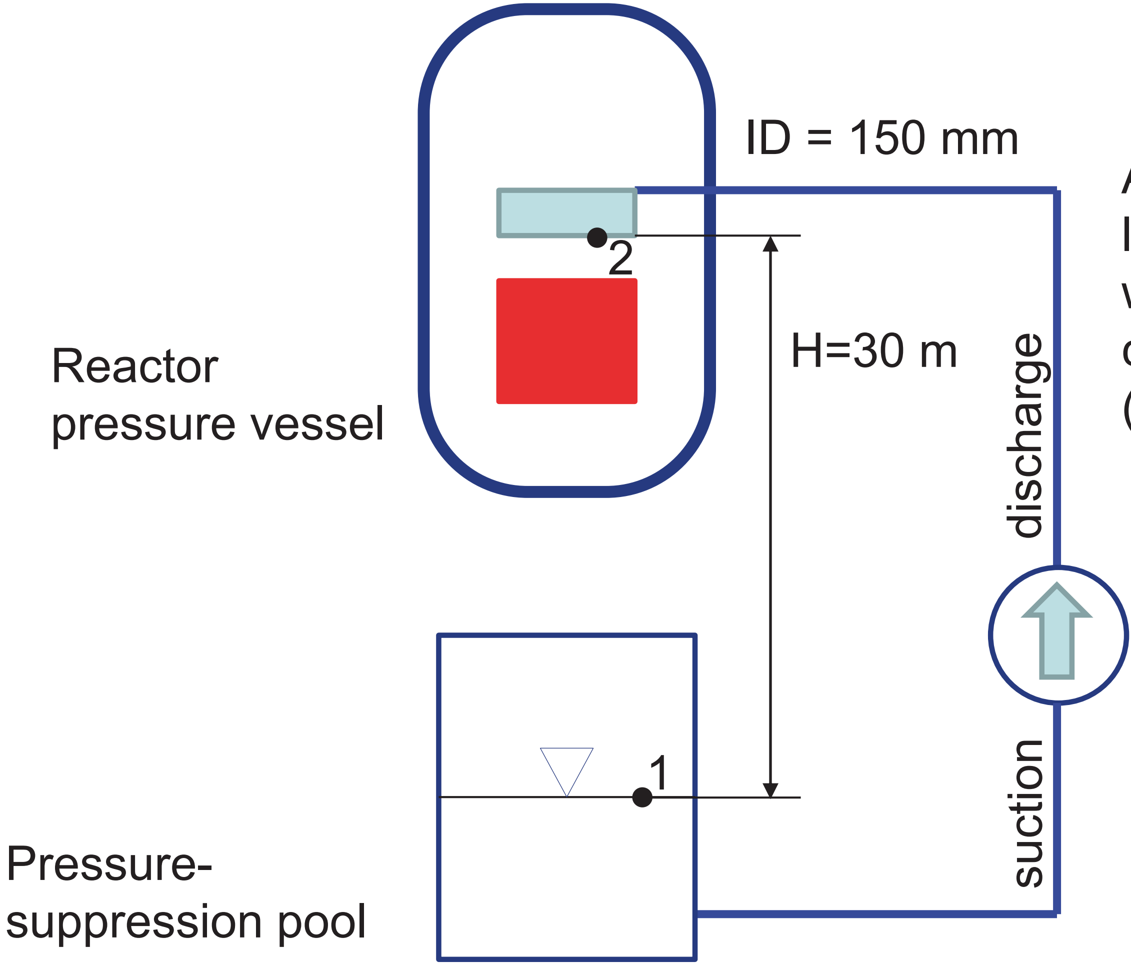
ECCS in BWR - Exercise

- Each of the loops has 100% capacity needed to provide safe cooling of the core.
- **EXERCISE:** Assume that one line of the Emergency Core Cooling System (ECCS) provides 150 kg/s of water from pressure suppression pool to the reactor pressure vessel (RPV). The pressure in RPV is 10 bars (abs). Assume atmospheric pressure and temperature T = 25 °C in the pressure-suppression pool. Calculate:

(a) the required (mechanical) pumping power

(b) the specific enthalpy of water leaving the reactor at steady-state (long operation of ECCS with all parameters constant)

ECCS in BWR - Exercise



Assume discharge pipeline length 35 m, ID = 150 mm, wall roughness 50 µm, total coefficient of local losses ξ = 2 (including spray nozzles)

Pump efficiency (internal 87% mechanical 97.7%) = ~85 %

Assume suction pipeline length 15 m, ID = 150 mm, wall roughness 50 µm, total coefficient of local losses ξ = 1.5

ECCS in BWR - Exercise

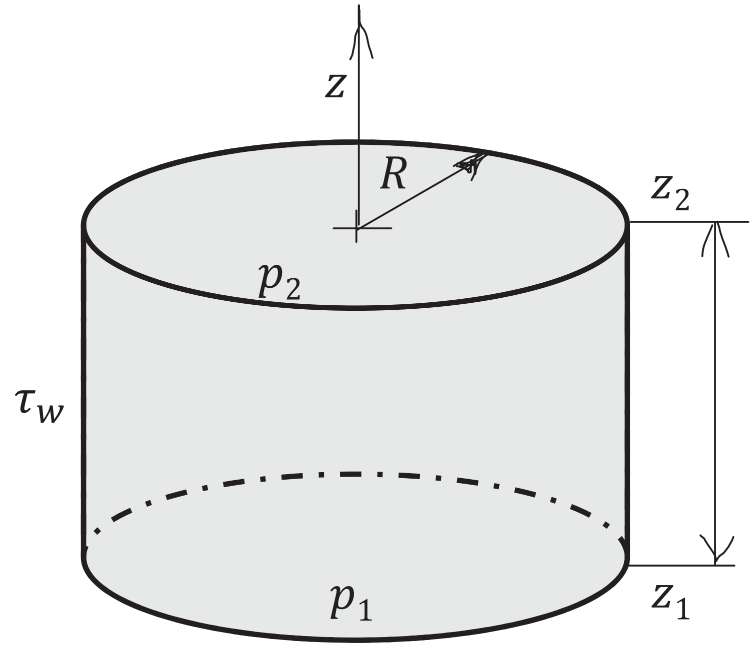
- **Assume:**
  - in the whole system, the same liquid properties as in the suppression pool; discharge spec. enthalpy=i(p=1 MPa,T=25°C)
  - 500 nozzles with diameter 15 mm placed above the core
  - infinitely large water surface area in the suppression pool
  - core thermal power after shutdown (decay heat) 60 MW
- **Hint:** use the following equation to find the total pressure change from point 1 to 2 ($\Delta p_{pump} = p_{dis} - p_{suc}$)

$$\underbrace{p_1 - p_2}_{total\ pressure\ drop} = \frac{W^2}{2\rho}\left[\underbrace{\left(\frac{1}{A_2^2} - \frac{1}{A_1^2}\right)}_{reversible\ velocity\ head} + \underbrace{\sum_k \left(\frac{4L_k}{D_{h,k}} C_{f,k}\right)\frac{1}{A_k^2}}_{irreversible\ friction\ loss} + \underbrace{\sum_j \xi_j \frac{1}{A_{j,\min}^2}}_{irreversible\ local\ loss}\right] + \underbrace{\rho g \left(H_2 - H_1\right)}_{reversible\ gravity\ head} - \Delta p_{pump}$$

W – mass flow rate, *A* – cross-section area, D_h – hydraulic diameter, *H* – vertical height, *L* – pipe length, C_f – fanning friction factor, ρ – density, *p* - pressure

Friction Factors

- For turbulent flows, τ_w, can be obtained only from correlations
- The correlations are frequently expressed in terms of friction factors
- Two different definitions for friction factors are used:



$$C_f \equiv \frac{\tau_w}{\frac{1}{2}\rho U^2}$$

Fanning friction factor

$$\lambda \equiv \frac{4\tau_w}{\frac{1}{2}\rho U^2}$$

Darcy-Weisbach friction factor

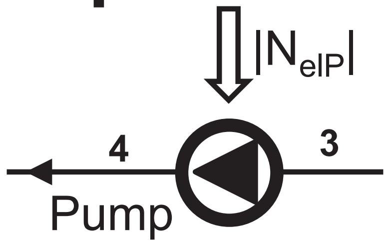
Haaland's Correlation

- To avoid iteration, Haaland proposed the following **explicit** correlation for the Darcy-Weisbach friction factor

$$\frac{1}{\sqrt{\lambda}} = -1.8\log_{10}\left[\left(\frac{k/D}{3.7}\right)^{1.11} + \frac{6.9}{\mathrm{Re}}\right]$$

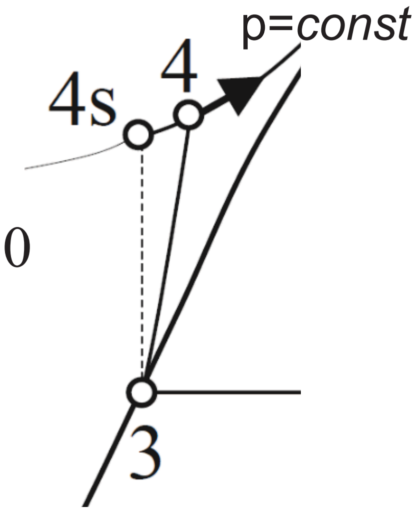
- This correlation agrees within 1% with the Colebrook's correlation
  - *k*, *D* and Re have the same meaning as in the Colebrok's correlation

ECCS in BWR - Pump



- To increase pressure from 3 to 4 (see fig.) pumping power $|N_{iP}|$ has to be supplied
- From the energy conservation principle for steady-state ($dE_T/dt=0$) we have

$$\frac{dE_T}{dt} = q - N_{iP} + W_3\left(i_3 + e_{P3} + e_{K3}\right) - W_4\left(i_4 + e_{P4} + e_{K4}\right) = 0$$

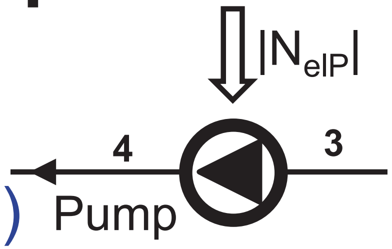


  - here we have to supply power to the system thus $N_{iP} < 0$; no heat is added thus q = 0; we also neglect kinetic and potential energy changes and from mass conservation we have $W_3=W_4=W$

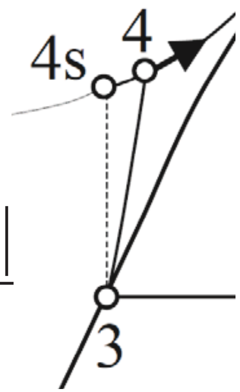
$$\left|N_{iP}\right| = W\left(i_4 - i_3\right) = W\left(\underbrace{e_{I4} - e_{I3}}_{\text{internal energy increase}} + \frac{p_4 - p_3}{\rho_e}\right) = \underbrace{W\frac{p_4 - p_3}{\rho_e}}_{N_{uP}=\text{useful pumping power}} + \underbrace{W\Delta e_I}_{\text{internal energy increase}}$$

Here ρ_e is an equivalent fluid density for process 3-4. Typically we assume $\rho_e \approx \rho_3 \approx \rho_4$ (incompressible)

ECCS in BWR - Pump



- The pumping power $|N_{thP}|$ is a theoretical pumping power (used in ideal cycle analyses)
- For real process 3-4, we obtain the pumping power $|N_{iP}|$ from energy conservation as $\left|N_{iP}\right| \equiv W\left(i_4 - i_3\right)$ and call this **internal power**



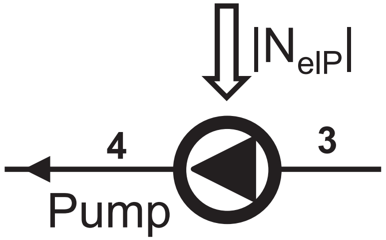
- Due to internal losses, internal power is: $\left|N_{iP}\right| = \dfrac{\left|N_{uP}\right|}{\eta_{iP}}$
- We also define an effective (or mechanical) pumping power, N_{effP}, due to pump mechanical efficiency η_{mP}: $\left|N_{effP}\right| = \dfrac{\left|N_{iP}\right|}{\eta_{mP}}$

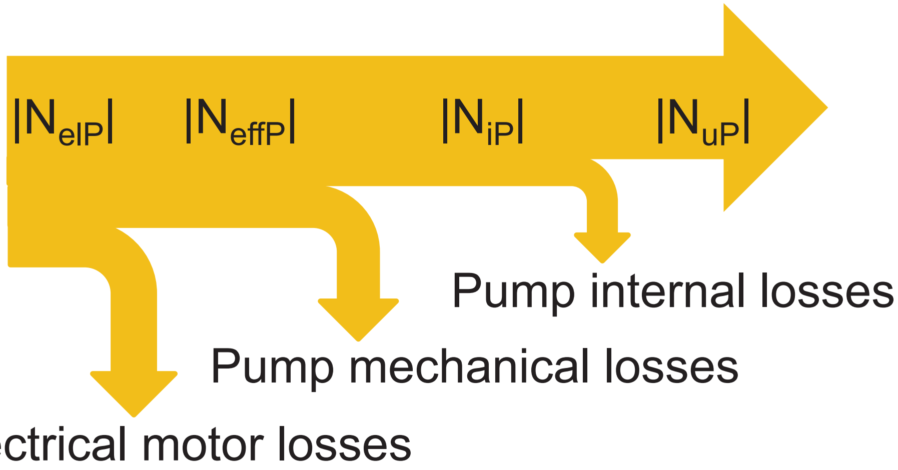
N_{uP} – useful pumping power

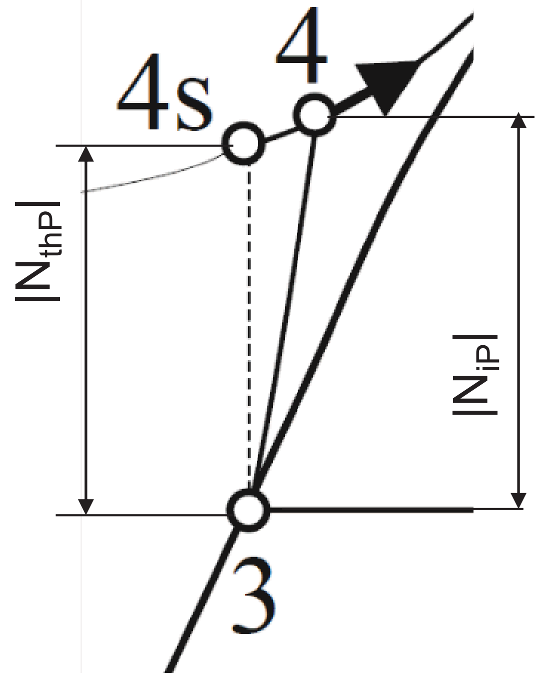
- Finally, the electric motor power for pumping is found as: $\left|N_{elP}\right| = \dfrac{\left|N_{effP}\right|}{\eta_{EM}}$

Here η_{EM}: is the electrical motor efficiency

ECCS in BWR - Pump







1) $$|N_{elP}| = W\frac{p_4 - p_3}{\eta_{iP}\eta_{mP}\eta_{EM}\rho_e}$$

2) $$i_4 - i_3 = \frac{\eta_{mP}\eta_{EM}|N_{elP}|}{W}$$

3) $$i_4 - i_3 = \frac{p_4 - p_3}{\rho_e \eta_{iP}}$$

Typical tasks: (**1**) calculate required electrical power to produce given pressure difference; (**2**) calculate specific enthalpy at pump discharge for given electrical power; (**3**) the same as in (2) for given pressure drop

ECCS in BWR - Exercise

- **Hint (cont.)** Here we have case 1, but we rather have to find the effective (mechanical power) that is needed:

$$\left|N_{effP}\right| = \eta_{EM}\left|N_{elP}\right| = W\frac{\Delta p}{\eta_{iP}\eta_{mP}\rho_e}$$

we can note that this mechanical power is related to torque and angular speed of the pump as:

$$\left|N_{effP}\right| = \omega T$$

T – torque,
ω – angular speed

ECCS in BWR - Exercise

Solution: we find water density and dynamic viscosity:

- density ρ = f(p=1.01 bar, T=25 °C) = 997.05 kg/m^3
- viscosity μ = f(p=1.01 bar, T=25 °C) = 8.9 10^{-4} Pa s

We find Reynolds number in pipes:

$Re = W*D_h/(A*\mu) = 150*0.15/(\pi*0.15^2/4*\ 8.9\ 10^{-4}) =$

$1.43\ x10^6$

Now we can find the Fanning friction factor C_f from the Haaland correlation as $C_f = 0.004$.

ECCS in BWR - Exercise

We calculate the required pressure head that should be provided by the pump:

$$\Delta p_{pump} = \underbrace{p_2 - p_1}_{\text{pressure drop}} + \frac{W^2}{2\rho}\left[\frac{1}{A_2^2} + \underbrace{\frac{4L_s C_{f,s}}{D_s A_s^2} + \frac{\xi_s}{A_s^2}}_{\text{suction}} + \underbrace{\frac{4L_d C_{f,d}}{D_d A_d^2} + \frac{\xi_d}{A_d^2}}_{\text{discharge}}\right] + \underbrace{\rho g H}_{\text{gravity head}} =$$

$$1\times10^6 - 1.01\times10^5 + \frac{150^2}{2\times997.05}\left[\frac{1}{0.088^2} + \underbrace{\frac{4\times15\times0.004}{0.15\times0.018^2} + \frac{1.5}{0.018^2}}_{\text{suction}} + \underbrace{\frac{4\times35\times0.004}{0.15\times0.018^2} + \frac{2}{0.018^2}}_{\text{discharge}}\right] +$$

$$997.05\times9.81\times30 = 1.51\times10^6 \text{ Pa}$$

Thus, the pressure change Δp = 1.51 MPa

ECCS in BWR - Exercise

The useful (hydraulic) pumping power is

$$\left|N_{uP}\right| = \frac{W\Delta p}{\rho} = \frac{150 \times 1.51 \cdot 10^6}{997.05} = 2.27 \cdot 10^5 \quad \mathrm{W}$$

Note: as specified, we used the density of water the same as in the suppression pool

The mechanical pumping power (85% total pump efficiency):

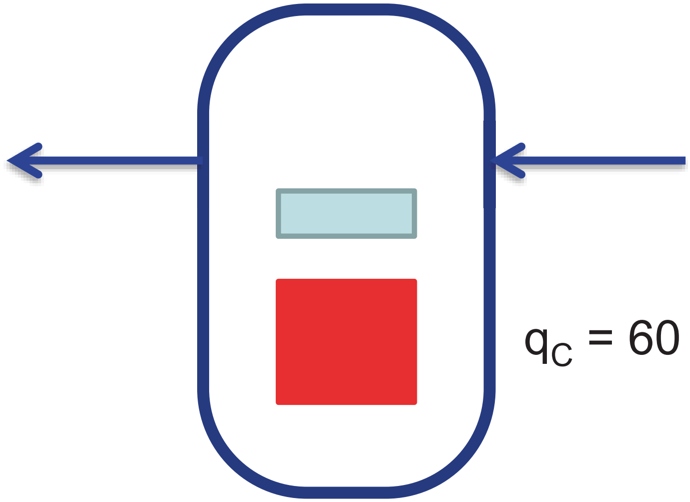
$$\left|N_{effP}\right| = \frac{\left|N_{uP}\right|}{\eta_p} = \frac{2.27 \cdot 10^5}{0.85} = 2.67 \cdot 10^5 \quad \mathrm{W}$$

$$\eta_p = \eta_{iP}\eta_{mP}$$

Answer: the mechanical pumping power that has to be supplied is 267 kW

ECCS in BWR - Exercise

The exit enthalpy of the water is found from the energy balance:



Energy balance:

$$W\left(i_{ex} - i_{in}\right) = q_C \quad \Rightarrow \quad i_{ex} = i_{in} + \frac{q_C}{W}$$

i_{in} = f(p=10 bar, T = 25 °C) = 105.8 kJ/kg

ECCS in BWR - Exercise

- We find the specific enthalpy of water at exit as:

$$i_{ex} = i_{in} + \frac{q_C}{W} = 105800 + \frac{60 \cdot 10^6 \text{ J/s}}{150 \text{ kg/s}} = 505.8 \frac{\text{kJ}}{\text{kg}}$$

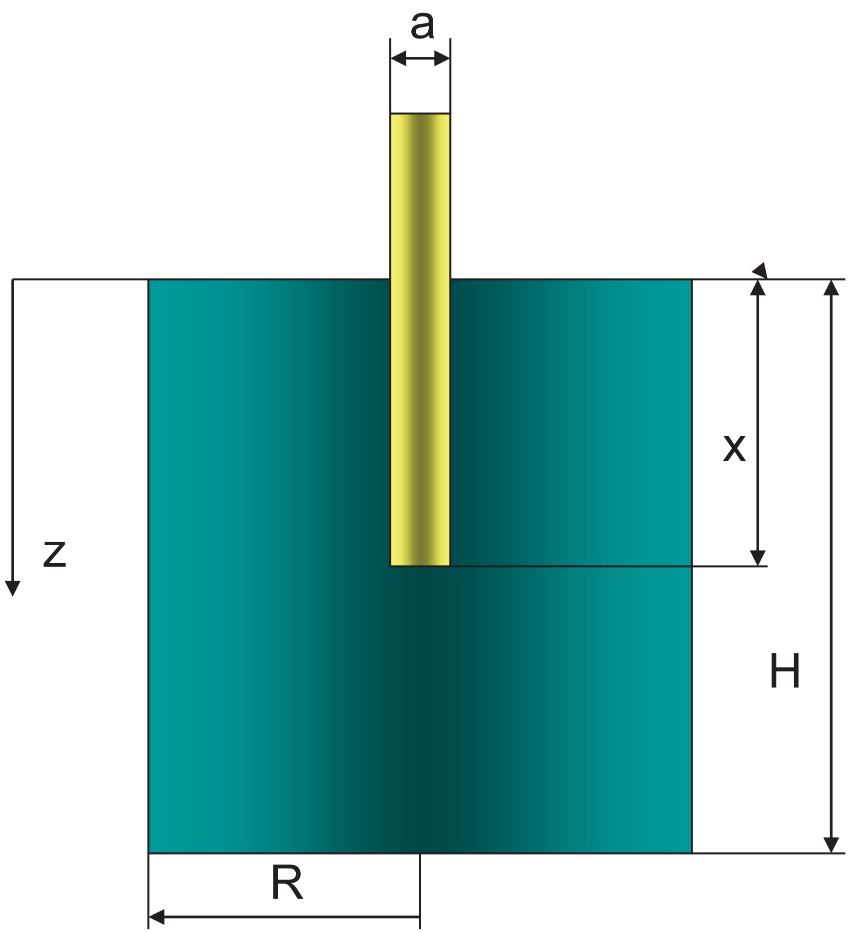
- We can check, that this is a subcooled liquid, since the saturated liquid enthalpy at 10 bars is i_f(10 bars) = 762.7 kJ/kg. We find its temperature T = 120.3 °C < T_f(10 bar) = 179.9 °C.
- However, when this water escapes to open atmosphere with atmospheric pressure, it will evaporate (flashing).

Control Rod Worth

- Consider a reactor with a <u>central partially inserted control rod</u>
- Applying a one-group diffusion approximation and using the perturbation theory it can be shown that the reactivity change *Δρ(x)* depends on the insertion length as follows:

$$\boxed{\Delta\rho(x) = \Delta\rho(H)\left(\frac{x}{H} - \frac{1}{2\pi}\sin\frac{2\pi x}{H}\right)}$$

Where *Δρ(H)* is the reactivity change due to full insertion of the control rod

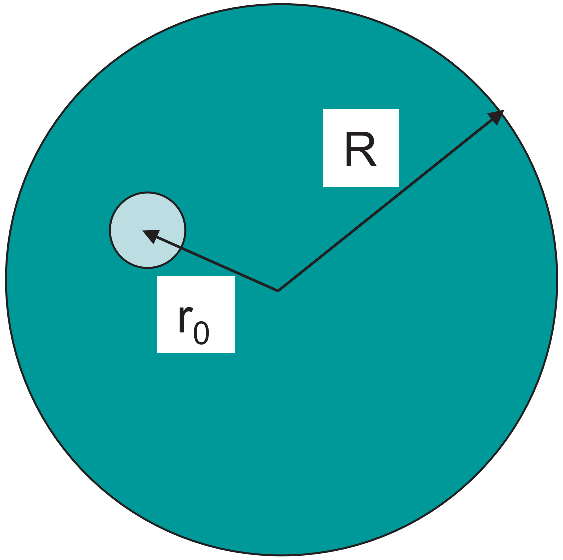


Control Rod Worth

- When the control rod is placed at $r = r_0$ distance from the centerline of the reactor, the reactivity change for such a rod can be estimated as

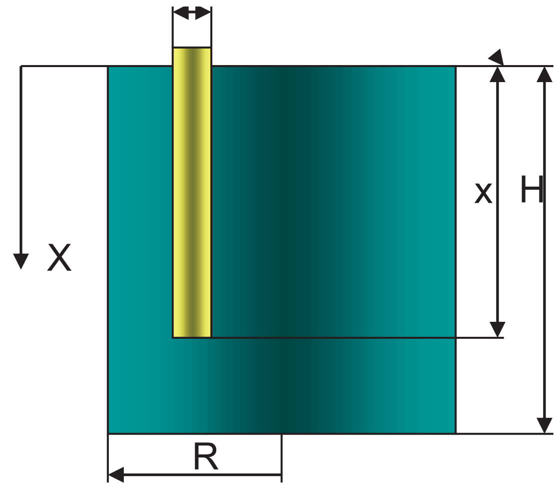
$$\boxed{\Delta\rho(r_0) = J_0^2\left(\frac{2.4048 r_0}{R}\right)\Delta\rho(0)}$$

- Where $\Delta\rho(r_0)$ is the reactivity change for off-centerline rod and $\Delta\rho(0)$ is the reactivity change for a rod inserted at the centerline



Control Rod Worth - Exercise

- A control rod is placed at r_0 = 0.75 m distance from the centerline of a cylindrical reactor with radius R=1.85 m and height H=3.66 m. Calculate the reactivity change caused by a withdrawal of the rod by 2.5 cm, if the rod was initially inserted into the core with 2/3 of its height. The integral worth of the <u>central rod</u> in fully-inserted position is known and equal to 2% (2000 pcm)



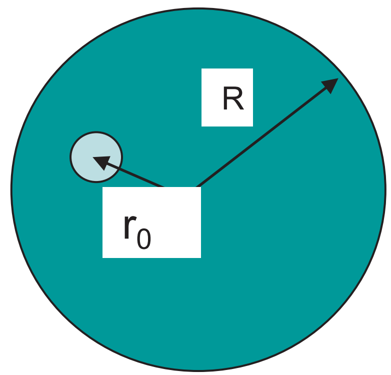
x = 2/3H, dx = -2.5 cm

r_0 = 0.75 m

R = 1.85 m, H = 3.66 m

$$\boxed{\Delta\rho(x) = \Delta\rho(H)\left(\frac{x}{H} - \frac{1}{2\pi}\sin\frac{2\pi x}{H}\right)}$$

$$\boxed{\Delta\rho(r_0, x) = J_0^2\left(\frac{2.4048 r_0}{R}\right)\Delta\rho(x)}$$



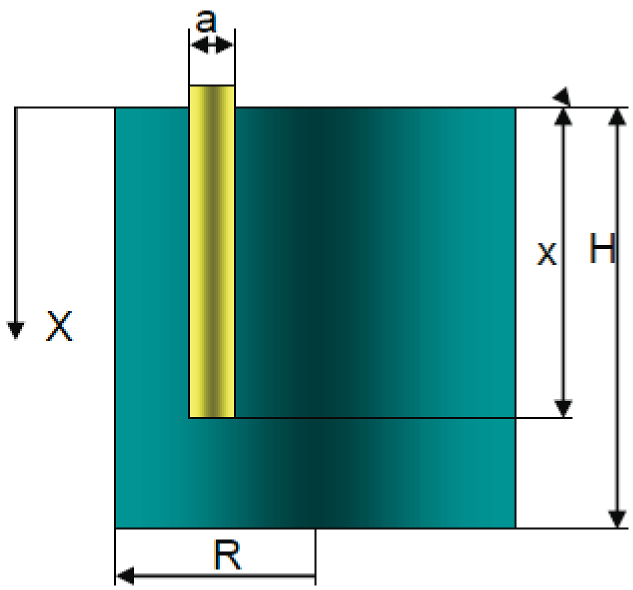
- Solution

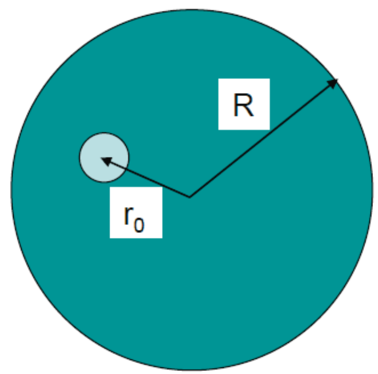
$$\Delta\rho(x) = \Delta\rho(H)\left(\frac{x}{H} - \frac{1}{2\pi}\sin\frac{2\pi x}{H}\right)$$

  - drhoH = -2000 pcm
  - drho0 = drhoH * (x0/H - sin(2*pi*x0/H)/(2*pi))
  - drho1 = drhoH * (x1/H - sin(2*pi*x1/H)/(2*pi))

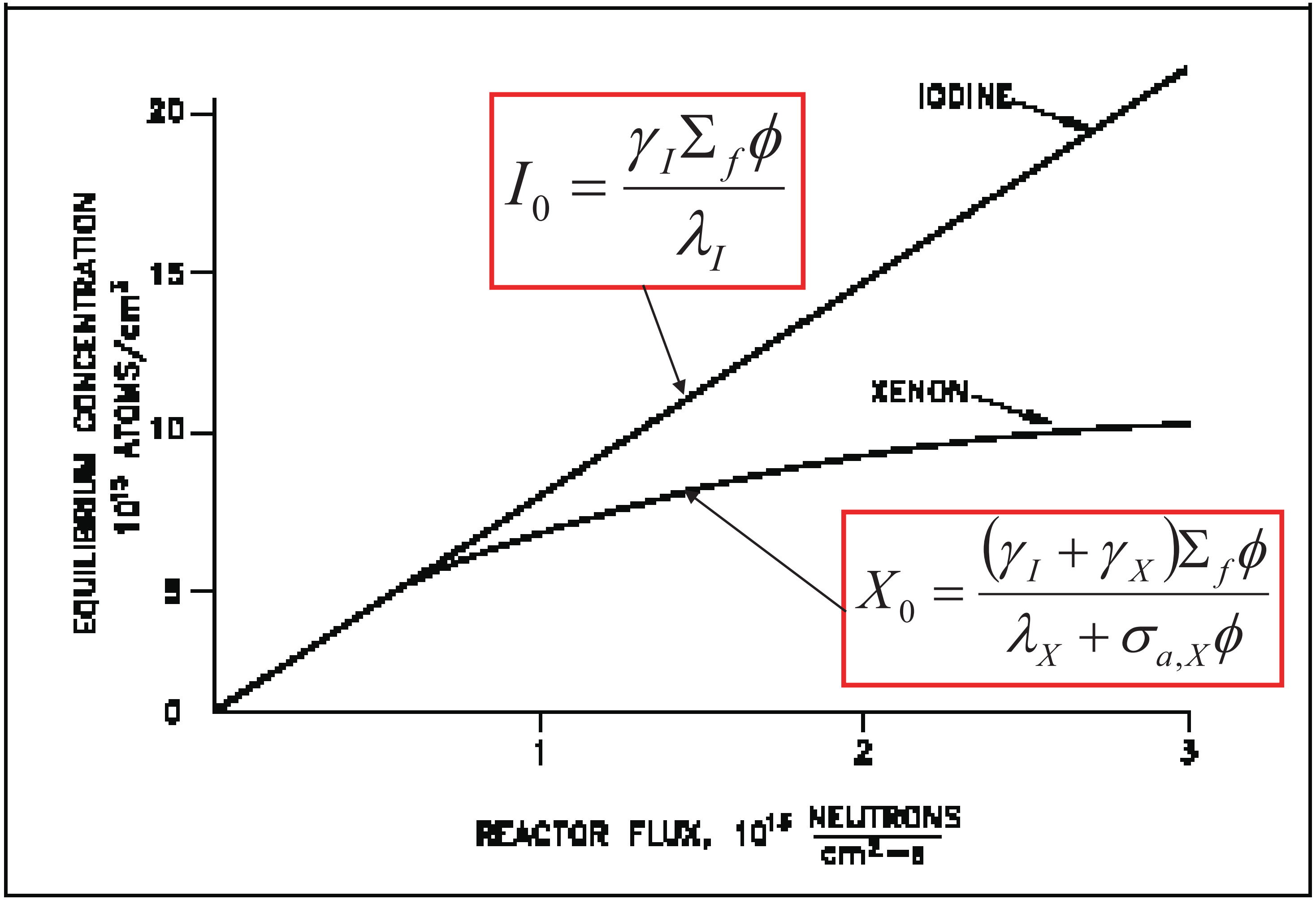
$$\Delta\rho(r_0, x) = J_0^2\left(\frac{2.4048 r_0}{R}\right)\Delta\rho(x)$$

  - RadialFactor = besselj(0,2.4048*r/R)^2
  - drho = (drho1-drho0)*RadialFactor = 12.5 pcm





Production and Removal of Xenon-135



Production and Removal of Xenon-135 - Exercise

- EXERCISE: A thermal nuclear reactor was loaded with fresh fuel and started. Assume that the thermal neutron flux step changed from 0 to $2 \cdot 10^{18}$ [m^{-2} s^{-1}] at t = 0.

  Plot the concentration of iodine and xenon as a function of time and calculate the equilibrium concentrations of the two isotopes in the reactor. Given:

$$\lambda_I = 2.9\times10^{-5}\left[s^{-1}\right], \lambda_X = 2.1\times10^{-5}\left[s^{-1}\right], \gamma_I = 0.061, \gamma_X = 0.003,$$
$$\Sigma_f = 1.8\cdot10^{-1}\,[m^{-1}], \sigma_{a,X} = 2.6\times10^{6}\,[b]$$

- Solution

  - I0 = gammaI * Sigmaf * phi / lambda = 7.57x10^{20} m^{-3}
  - X0 = (gammaI + gammaX) * Sigmaf * phi / (lambdaX + sigmaaX * phi) = 4.26x10^{19} m^{-3}