SH2702
Nuclear Reactor Technology

Project work Task 6

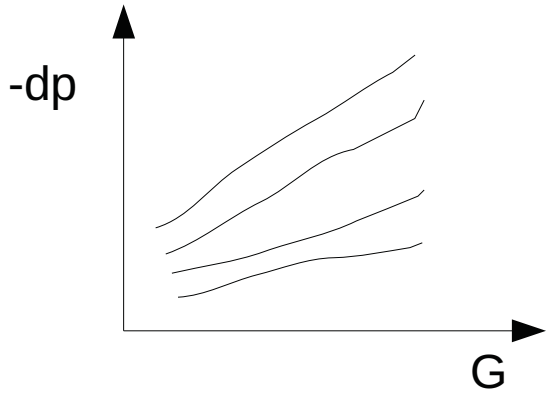
Project work

Topic numbers	Topics
1	Design, operation and safety features of NuSCALE
2	Design, operation and safety features of ABWR
3	Design, operation and safety features of ESBWR
4	Design, operation and safety features of EPR
5	Design, operation and safety features of AP1000

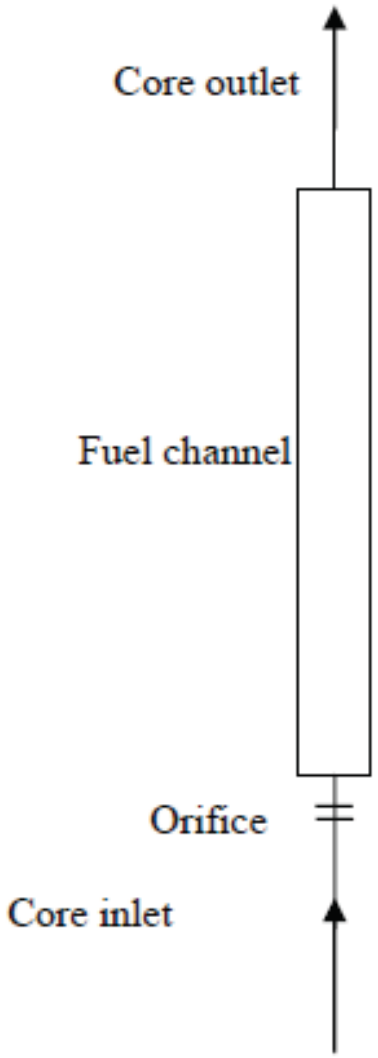
- Task 1 – General design specification of the nuclear power plant with selected reactor type
- Task 2 – Operational principles of the power plant
- Task 3 – Safety features of the power plant
- Task 4 – Calculation of selected core parameters
- Task 5 – Calculation of CHF margins in a hot channel
- Task 6 – Calculation of the maximum cladding and fuel pellet Temperature

Task 4

- 1. Data collection
  - Tables are recommended
- 2. core-averaged thermal-hydraulic calculations
  - Axial enthalpy/temperature distribution
  - Axial void fraction distribution
    - BWRs, from subcooled to saturated
  - Axial pressure distribution
    - Inlet orifices pressure loss, BWRs (50%), PWRs (25%)
  - Flow characteristic of the core (-dp)=f(G)
    - 0%, 50%, 100%, 150% power
    - 1% to 150% flow



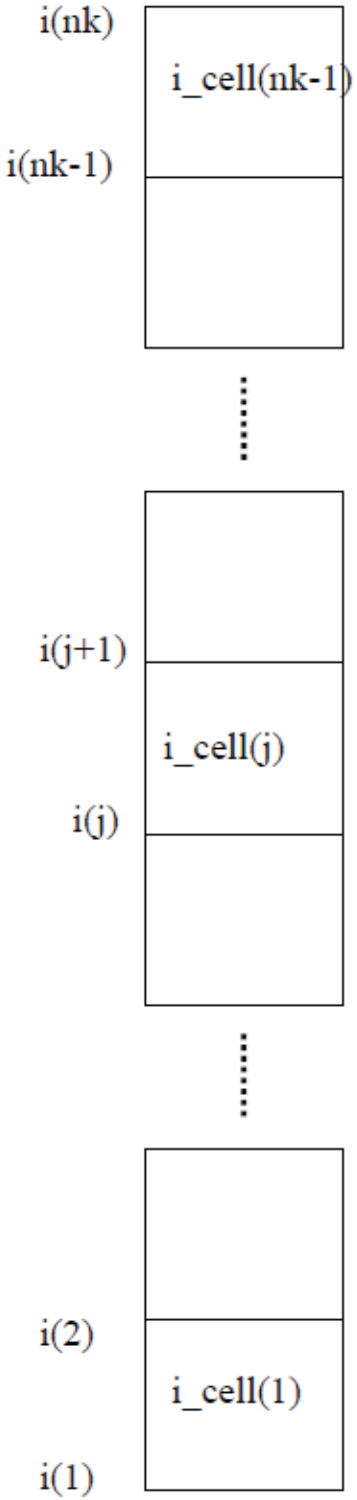
Task 4



- Inlet orifices pressure loss
  - BWRs (50% at nominal operating conditions)
  - PWRs (25% at nominal operating conditions)

$$\Delta p = p_{out} - p_{in} = \Delta p_{FuelChannel} + \Delta p_{Orifice}$$

$$\left|\Delta p_{Orifice}\right| = \xi_{Orifice}\frac{\rho U^2}{2} = \xi_{Orifice}\frac{G^2}{2\rho}$$



Task 4 Nodalization and numerical solution

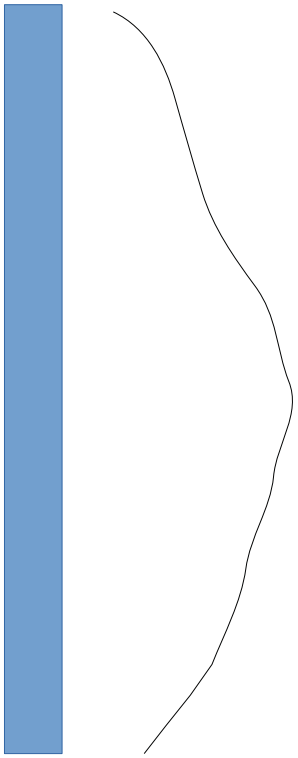
- for j = 2 to nk
  - i(j) = i(j-1) + q_cell(j-1) / W (energy balance)
- end for
- while p not converged
  - p(1) = pin + dpInletOrifice
  - for j = 2 to nk
    - xe(j), xa(j), alpha(j) (void fraction model)
    - dpf_cell(j-1), dpg_cell(j-1), dpa_cell(j-1), dpl_cell(j-1)
    - dp_cell(j-1) (pressure drop calculation)
    - p(j) = p(j-1) + dp_cell(j-1)
  - end for
- end while p
- T(j)
  - f(p(j), i(j)) for subcooled water
  - Tsat(j) for saturated water
- Inlet orifices pressure loss coefficient (designed for nominal condition)
- Flow characteristic of the core (-dp)=f(G)

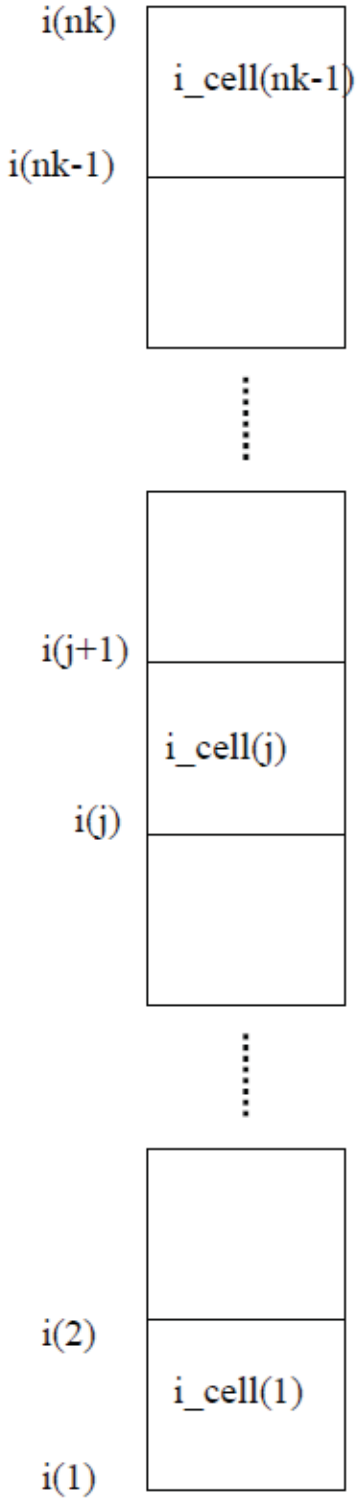
Task 5

- 1. Hot channel
  - Find data on power distribution, otherwise use the simplified shape

$$q''(r,z) = q_0'' J_0\left(\frac{2.405r}{\tilde{R}}\right)\cos\left(\frac{\pi z}{\tilde{H}}\right)$$

  - Find peaking factor in radial direction
- 2. CHF
  - Find CHF, DNB for PWRs, Dryout for BWRs
  - Calculate thermal margin parameters
    - MDNBR, MCPR
- 3. Hot channel result
  - Axial enthalpy/temperature distribution
  - Axial void fraction distribution
    - BWRs, from subcooled to saturated
  - Axial pressure distribution
  - *Axial distribution of DNBR and location of MDNBR, for PWRs*





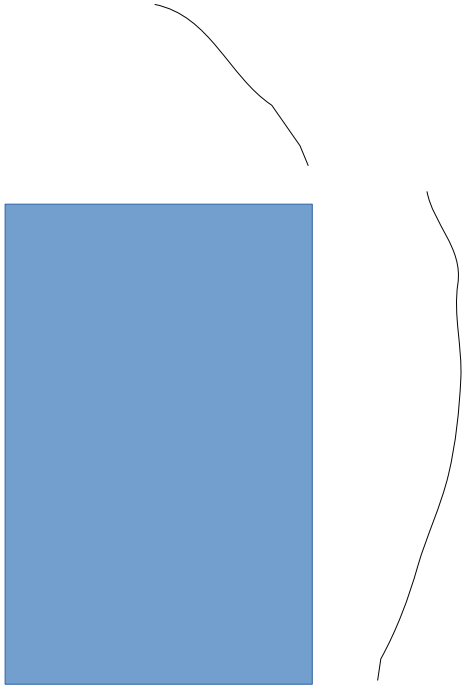
Task 5 Nodalization and numerical solution

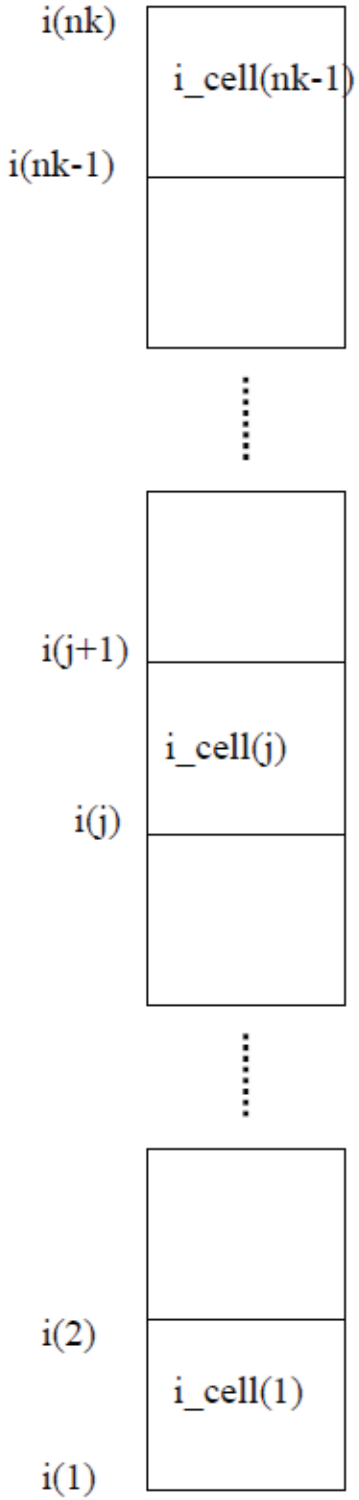
- for j = 2 to nk
  - q_cell = q_cell * fR
  - i(j) = i(j-1) + q_cell(j-1) / W (energy balance)
- end for
- while p not converged
  - p(1) = pin + dpInletOrifice
  - for j = 2 to nk
    - xe(j), xa(j), alpha(j) (void fraction model)
    - dpf_cell(j-1), dpg_cell(j-1), dpa_cell(j-1), dpl_cell(j-1)
    - dp_cell(j-1) (pressure drop calculation)
    - p(j) = p(j-1) + dp_cell(j-1)
  - end for
- end while p
- T(j)
  - f(p(j), i(j)) for subcooled water
  - Tsat(j) for saturated water
- q2cr(j), xcr(j), DNBR, CPR

Task 6

- 1. Find design and regulatory limit of fuel/clad temperatures

- 2. Identify hot spots (usually in hot channel)
  - Fuel temperature
    - Fuel material properties (temperature dependent)
    - Peak temperature and location
  - Clad temperature
    - Clad material properties (temperature dependent)
    - Peak temperature and location





Task 6 Nodalization and numerical solution

- for j = 2 to nk
  - q_cell = q_cell * fR
  - i(j) = i(j-1) + q_cell(j-1) / W (energy balance)
- end for
- while p not converged
  - p(1) = pin + dpInletOrifice
  - for j = 2 to nk
    - xe(j), xa(j), alpha(j) (void fraction model)
    - dpf_cell(j-1), dpg_cell(j-1), dpa_cell(j-1), dpl_cell(j-1)
    - dp_cell(j-1) (pressure drop calculation)
    - p(j) = p(j-1) + dp_cell(j-1)
  - end for
- end while p
- T(j)
- Re(j), Pr(j), Nu(j), HTC(j), Tw(j)
- Tco(j), Tci(j), Tfo(j), Tfc(j)
- TciMax, TfcMax

Clad-Coolant Heat Transfer in Channels with Single Phase Flows (1)

- In Light Water Reactors, coolant is sub-cooled at the inlet to the reactor core

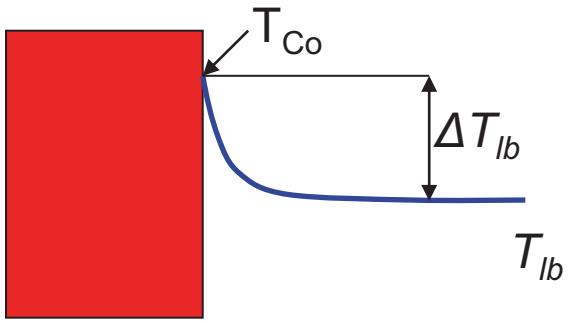
- The subcooling is defined as the difference between the saturation temperature and the actual coolant bulk temperature: $\Delta T_{sub} = T_f - T_{lb}$

- For example, if the inlet temperature and pressure of the water coolant are 549 K and 7 MPa, respectively, then the inlet subcooling is equal to 559 K – 549 K = 10 K, since the saturation temperature of water at 7 MPa pressure is equal to 559 K

Clad-Coolant Heat Transfer in Channels with Single Phase Flows (2)

- In the single-phase region, when $z_{in} < z < z_{ONB}$,*) the clad surface temperature T_{Co} of the heated wall and the liquid bulk temperature T_{lb} are related to each other as follows,

$$T_{Co} - T_{lb} \equiv \Delta T_{lb} = q''/h$$



- where h is the heat transfer coefficient and ΔT_{lb} is the temperature difference between the surface of the heated wall and the bulk liquid

*) z_{in} – inlet coordinate; ONB – Onset of Nucleate Boiling

Clad-Coolant Heat Transfer in Channels with Single Phase Flows (3)

- The heat transfer coefficient *h* is evaluated from correlations, which, in turn, are based on experimental data and are using the principles of the dimensionless analysis

- The following general relationships are employed

Nu = *f* (Re, Pr, …), where: $\mathrm{Nu} = \frac{hD_h}{\lambda}$ Nusselt number

$\mathrm{Re} = \frac{GD_h}{\mu}$ Reynolds number

, $\mathrm{Pr} = \frac{c_p \mu}{\lambda}$, $\mathrm{Pr}_w = \left.\frac{c_p \mu}{\lambda}\right|_{T=T_w}$ Prandtl number

Clad-Coolant Heat Transfer in Channels with Single Phase Flows (4)

- For flows in pipes, rectangular channel and annuli, and with $10^4 < Re$, $0.7 < Pr < 160$ and $L/D_h > 60$, the following correlation can be used (Colburn):

$$Nu = 0.023 \cdot Re^{0.8} \, Pr^{0.33}$$

- Another correlation frequently used for heat transfer calculations in pipes was given by Dittus&Boelter:

$$Nu = 0.023 \cdot Re^{0.8} \, Pr^{n}$$

n=0.4 for heating
n=0.3 for cooling

valid for $L/D_h > 60$, $Re > 10^4$ and $0.7 < Pr < 100$

Heat Transfer in Rod Bundles (1)

Heat transfer in the entire bundle is calculated from a single correlation including effects of:

- flow conditions
- fluid properties
- geometry

Typically the correlation is of the form:

$$Nu = F(Re, Pr, D_h/d_r, p/d_r, ...)$$

Heat Transfer in Rod Bundles (2)

The influence of flow/fluid conditions and geometry factors can be separated:

$Nu = F_1(Re, Pr,...) \times F_2(D_h/d_r, p/d_r,...)$

p – lattice pitch
d_r – rod diameter

Example: the Weisman (1959) correlation:

$$\mathrm{Nu} = A \cdot \mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3}$$

$$A = \begin{cases} 0.026\,p/d_r - 0.006 & \text{triangular } 1.1 < p/d_r < 1.5 \\ 0.042\,p/d_r - 0.024 & \text{square } 1.1 < p/d_r < 1.3 \end{cases}$$

Heat Transfer in Rod Bundles (3)

- Subotin et al. (1975) recommended for heat transfer to liquids in bundles

$$Nu = A \cdot \mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \qquad A = 0.0165 + 0.02\left[1 - \frac{0.91}{\left(p/d_r\right)^2}\right]\left(\frac{p}{d_r}\right)^{0.15}$$

Triangular lattice with $1.1 < p/d_r < 1.8$; $1.0 < Pr < 20$; $5\ 10^3 < Re < 5\ 10^5$

- For gas flow in tight rod bundles Ajn and Putjkov (1964) give

$$\frac{Nu_{bundle}}{Nu_{DB}} = 1.184 + 0.351 \cdot \log_{10}\left(p/d_r - 1\right) \qquad 1.03 < p/d_r < 2.4$$

Nu_{DB} – Dittus-Boelter correlation

p – lattice pitch
d_r – rod diameter

Heat Transfer in Rod Bundles (4)

- In the cited correlations it is assumed that the flow/fluid conditions and the geometry effect are separable
- This, however, seems not to be valid based on an extensive study done by Markoczy (1972)
- He suggested the following form of the correlation

$$Nu_{bundle} = Nu_{pipe} \times F_{geom}(p/d_r, Re, Pr)$$

In other words, the geometry effect is flow/property-dependent

Heat Transfer in Rod Bundles (5)

Markoczy (1972) performed study of experimental data (over 63 bundles of different geometry)

He proposed the following correlation:

$$\frac{\mathrm{Nu}_{bundle}}{\mathrm{Nu}_{DB}} = 1 + 0.91\,\mathrm{Re}^{-0.1}\,\mathrm{Pr}^{0.4}\left(1 - 2e^{-B}\right) \qquad B = \begin{cases} \dfrac{2\sqrt{3}}{\pi}\left(\dfrac{p}{d_r}\right)^2 - 1 & \text{triangular} \\ \dfrac{4}{\pi}\left(\dfrac{p}{d_r}\right)^2 - 1 & \text{square} \end{cases}$$

Validity region: $3\,10^3 < \mathrm{Re} < 10^6$; $0.66 < \mathrm{Pr} < 5$; $1.02 < p/d_r < 2.5$

Heat Transfer in Rod Bundles (6)

- In summary, the bundle-wide approach is based on:
  - base correlation, which typically takes into account dependence of the heat transfer coefficient on flow/property conditions
  - geometry factor, which takes into account the dependence on pitch/rod-diameter

$$Nu_{bundle} = F_{geo}(p/d_r,...) \times Nu_{base}(Re, Pr, ..)$$

Heat Transfer in Rod Bundles (7)

- Occasionally another approach can be encountered in the literature:

- Osmachkin (1974) recommended to use a correlation valid for pipes (e.g. Dittus-Boelter), replacing the hydraulic diameter with the “effective” one:

$$D_{eff} = \frac{2}{(1-\varepsilon)^2}\left(\frac{\varepsilon - 3}{2} - \frac{\ln \varepsilon}{1-\varepsilon}\right) D_h$$

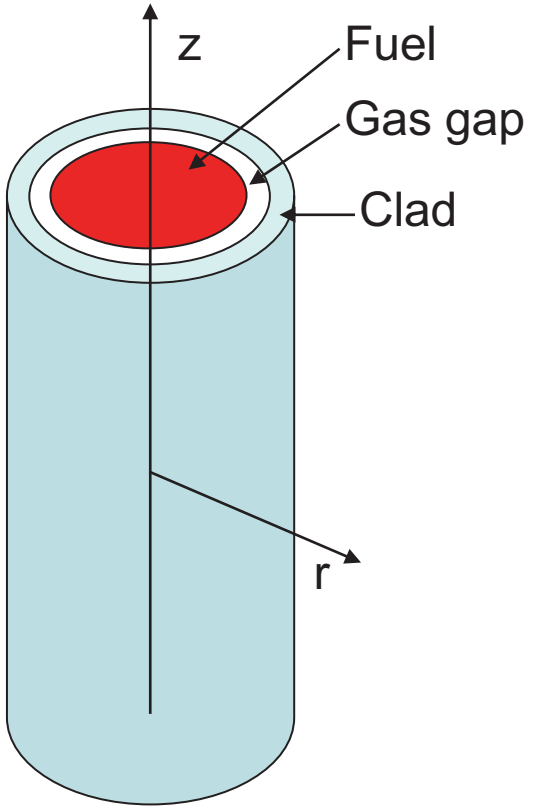
ε – fraction of the bundle cross-section occupied by rods:
$\varepsilon = A_r/A_{tot}$; A_r – rod cross-section area, A_{tot} – total (rod+coolant) cross section area

Heat conduction in reactor fuel elements (1)

- In the cylindrical coordinate system, for a fuel rod as shown in figure, the conduction equation can be written as

$$\nabla \cdot \lambda \nabla T = -q'''(\mathbf{r})$$

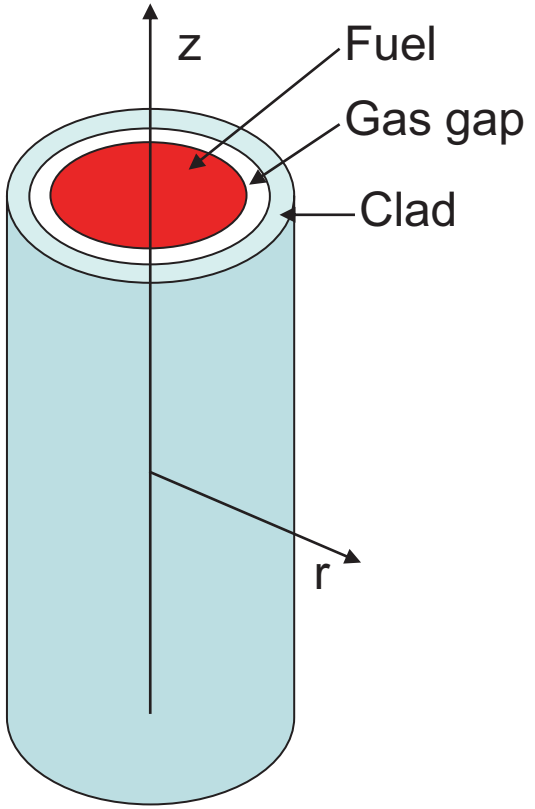
$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda\frac{\partial T(r,z)}{\partial r}\right)+\frac{\partial}{\partial z}\left[\lambda\frac{\partial T(r,z)}{\partial z}\right]=-q'''(r,z)$$



Fuel element

Heat conduction in reactor fuel elements (2)

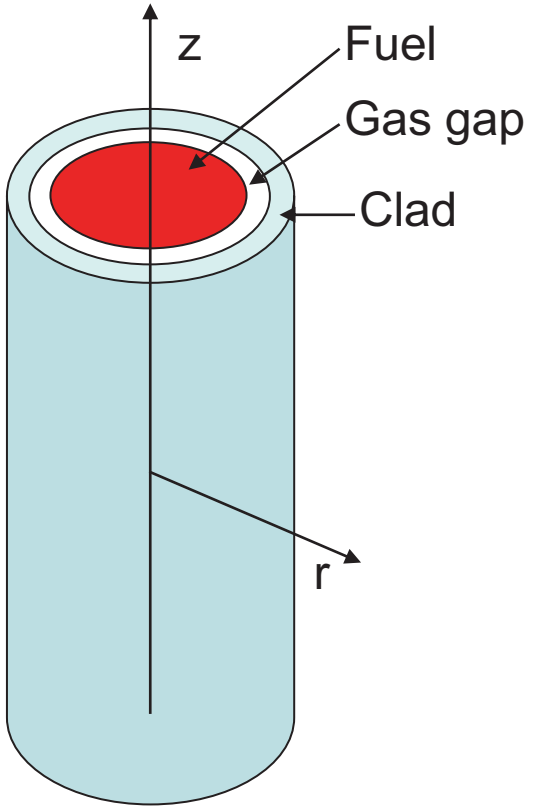
- The conduction equation can be further simplified:
  - Heat conduction in the *z*-direction can be neglected, since temperature gradient *dT/dz* is much lower than *dT/dr*
  - In fuel region $q''' = q'''(z)$
  - In gas gap and clad regions $q'''=0$



Fuel element

Heat conduction in reactor fuel elements (3)

- The conduction equation can be thus written for each region separately as:
  - Fuel $$\frac{1}{r}\frac{d}{dr}\left(r\lambda_F\frac{dT_F(r)}{dr}\right)=-q'''(z)$$
  - Gap $$\frac{1}{r}\frac{d}{dr}\left(r\lambda_G\frac{dT_G(r)}{dr}\right)=0$$
  - Clad $$\frac{1}{r}\frac{d}{dr}\left(r\lambda_C\frac{dT_C(r)}{dr}\right)=0$$



Fuel element

Heat conduction in reactor fuel elements (4)

- To solve the ordinary differential equations we need boundary conditions:
  - Finite temperature at r = 0
  - 4th kind b.c. at r = r_{Fo}

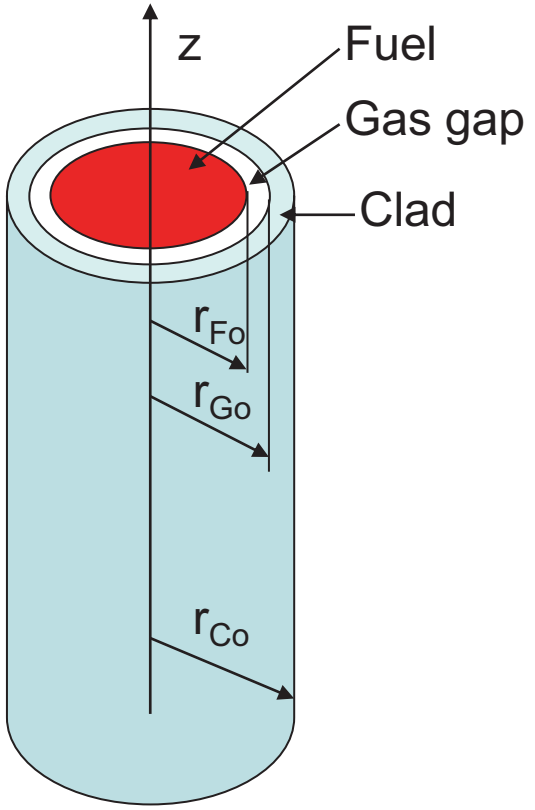
$$T_F\big|_{r=r_{Fo}} = T_G\big|_{r=r_{Fo}} \qquad \lambda_F \left.\frac{dT_F}{dr}\right|_{r=r_{Fo}} = \lambda_G \left.\frac{dT_G}{dr}\right|_{r=r_{Fo}}$$

  - 4th kind b.c. at r = r_{Go}

$$T_G\big|_{r=r_{Go}} = T_C\big|_{r=r_{Go}} \qquad \lambda_G \left.\frac{dT_G}{dr}\right|_{r=r_{Go}} = \lambda_C \left.\frac{dT_C}{dr}\right|_{r=r_{Go}}$$

  - 3rd kind b.c. at r = r_{Co}

$$-\lambda_C \left.\frac{dT_C}{dr}\right|_{r=r_{Co}} = h\left(T_{Co} - T_{lb}\right)$$



Fuel element

Heat conduction in reactor fuel elements (5)

- Solution in the fuel region

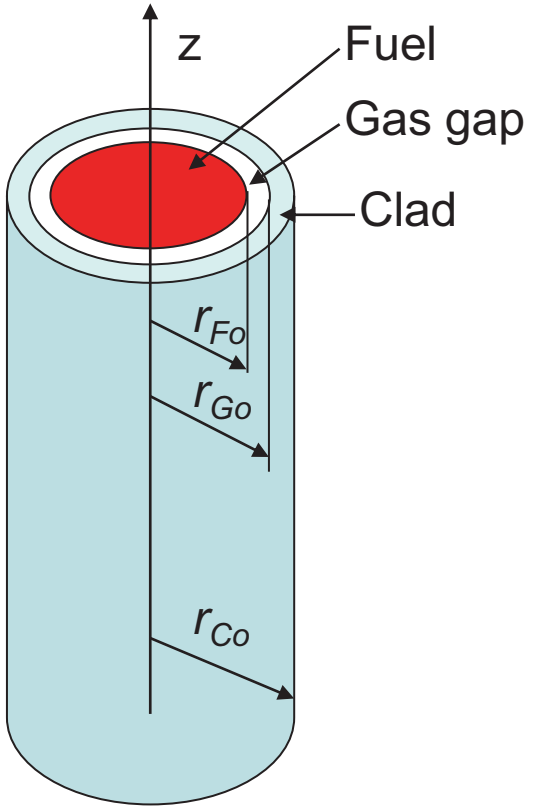
$$\frac{1}{r}\frac{d}{dr}\left(r\lambda_F\frac{dT_F(r)}{dr}\right)=-q'''(z)$$

$$\Downarrow$$

$$\lambda_F\frac{dT_F(r)}{dr}=-\frac{1}{r}\int q'''(z)\cdot r\cdot dr=-\frac{q'''(z)\cdot r}{2}+\frac{C}{r}$$

  - To limit $T_{Fc}=T_F(0)$, the constant C must be equal to zero: C = 0, thus

$$\lambda_F\frac{dT_F(r)}{dr}=-\frac{q'''(z)\cdot r}{2}$$



Fuel element

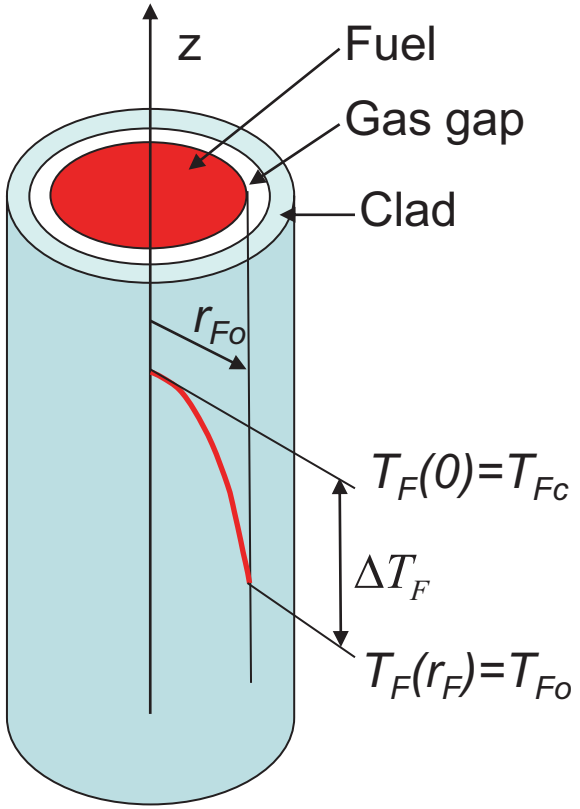
Heat conduction in reactor fuel elements (6)

- If the conductivity of the fuel material is assumed constant, the integration is straightforward as

$$T_F(r_F) - T_F(0) \equiv -\Delta T_F = -\int_0^{r_{Fo}} \frac{q'''(z)\cdot r}{2\cdot\lambda_F}\, dr$$

or, after integration the temperature rise in fuel region is as follows

$$\Delta T_F(z) \equiv T_F(0) - T_F(r_F) = T_{Fc} - T_{Fo} = \frac{q'''(z)\cdot r_{Fo}^2}{4\cdot\lambda_F}$$



Fuel element

Heat conduction in reactor fuel elements (7)

- Solution in the gas gap

$$\frac{1}{r}\frac{d}{dr}\left(r\lambda_G\frac{dT_G(r)}{dr}\right)=0$$

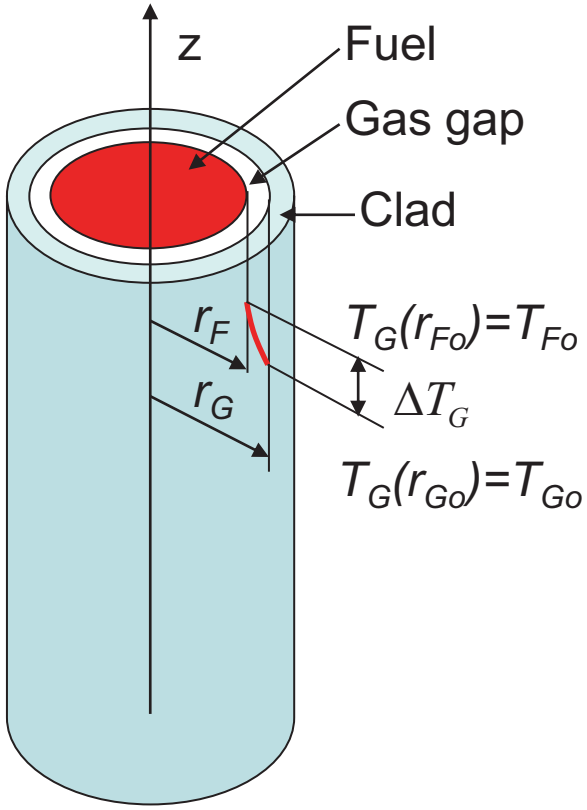
$$\Downarrow$$

$$\lambda_G\frac{dT_G(r)}{dr}=\frac{C'}{r}\Rightarrow T_G(r)=\frac{C'}{\lambda_G}\ln(r)+C''$$

  - Where C' and C'' are constants

- Temperature drop in gap is

$$\Delta T_G\equiv T_G(r_{Fo})-T_G(r_{Go})=-\frac{C'}{\lambda_G}\ln\left(\frac{r_{Go}}{r_{Fo}}\right)$$



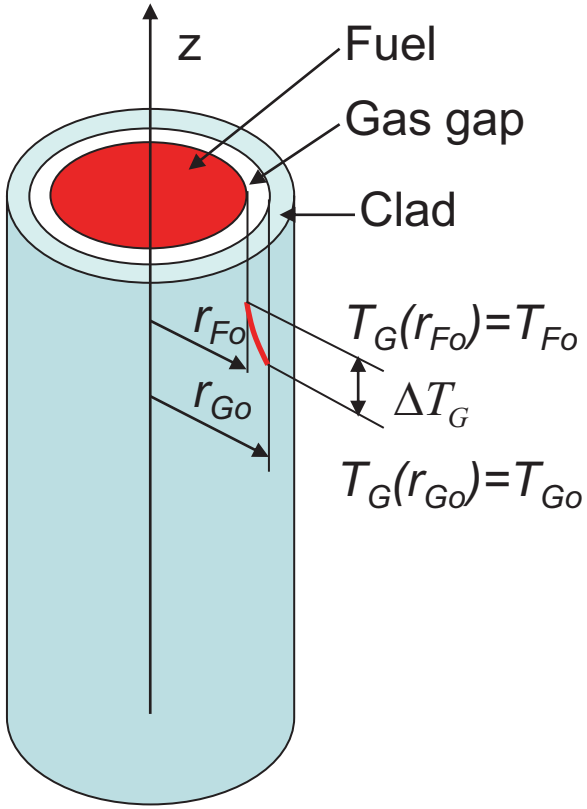
Fuel element

Heat conduction in reactor fuel elements (8)

- The constant C' can be found from the energy balance at the fuel-gap interface:

$$\left.\begin{aligned} q''\big|_{r_{Fo}} &= -\lambda_G \left.\frac{dT_G(r)}{dr}\right|_{r_{Fo}} = -\frac{C'}{r_{Fo}} \\ q''\big|_{r_{Fo}} \cdot 2\pi r_{Fo} \cdot dz &= q''' \cdot \pi r_{Fo}^2 \cdot dz \end{aligned}\right\} \Rightarrow C' = -\frac{q''' r_{Fo}^2}{2}$$

$$\Delta T_G = \frac{q''' r_{Fo}^2}{2\lambda_G} \ln\left(\frac{r_{Go}}{r_{Fo}}\right)$$



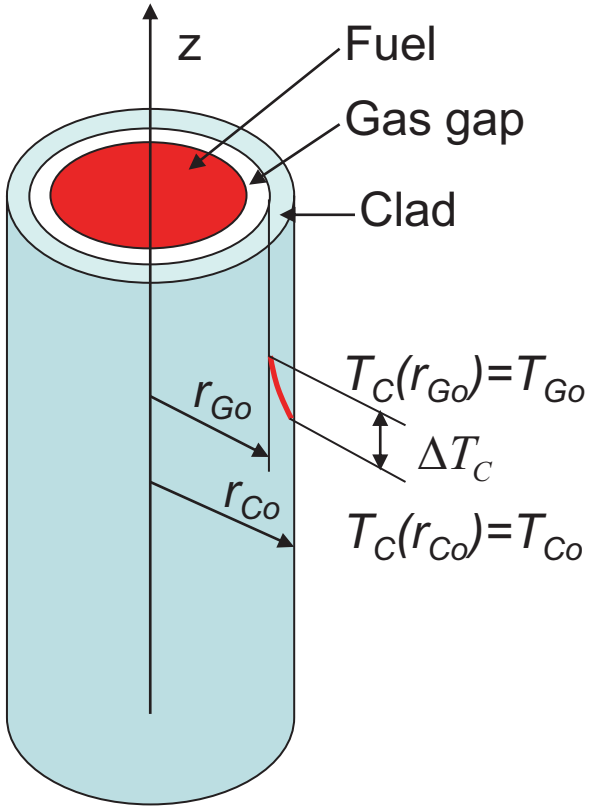
Fuel element

Heat conduction in reactor fuel elements (9)

- Since the conduction equation is the same in the clad region, the temperature rise in the clad is found as

$$\left.\begin{aligned} q''\big|_{r_{Go}} &= -\lambda_C \left.\frac{dT_C(r)}{dr}\right|_{r_{Go}} = -\frac{C'}{r_{Go}} \\ q''\big|_{r_{Go}} \cdot 2\pi r_{Go} \cdot dz &= q''' \cdot \pi r_{Fo}^2 \cdot dz \end{aligned}\right\} \Rightarrow C' = -\frac{q''' r_{Fo}^2}{2}$$

$$\Delta T_C = \frac{q''' r_{Fo}^2}{2\lambda_C} \ln\left(\frac{r_{Co}}{r_{Go}}\right)$$



Fuel element

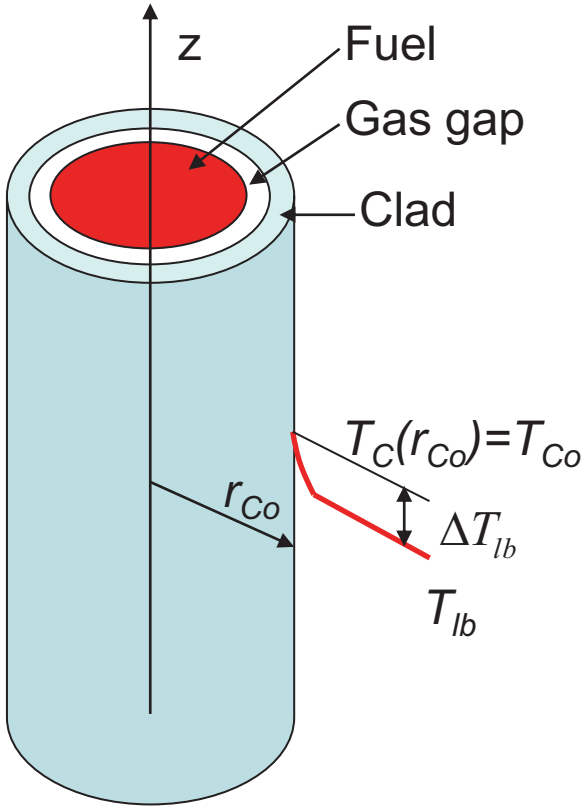
Heat conduction in reactor fuel elements (10)

- Finally, the temperature rise in the thermal boundary layer in coolant can be found from the Newton equation for the convective heat transfer:

$$q''\big|_{r_{Co}} = h\cdot\left(T_{Co}-T_{lb}\right)=h\cdot\Delta T_{lb}$$

since $$q''\big|_{r_{Co}}\cdot 2\pi r_{Co}\cdot dz = q'''\cdot\pi r_{Fo}^2\cdot dz \Rightarrow q''\big|_{r_{Co}} = \frac{q'''r_{Fo}^2}{2r_{Co}}$$

thus $$\Delta T_{lb} = \frac{q'''r_{Fo}^2}{2r_{Co}h}$$



Fuel element

Heat conduction in reactor fuel elements (11)

- The total temperature rise in the fuel element is thus

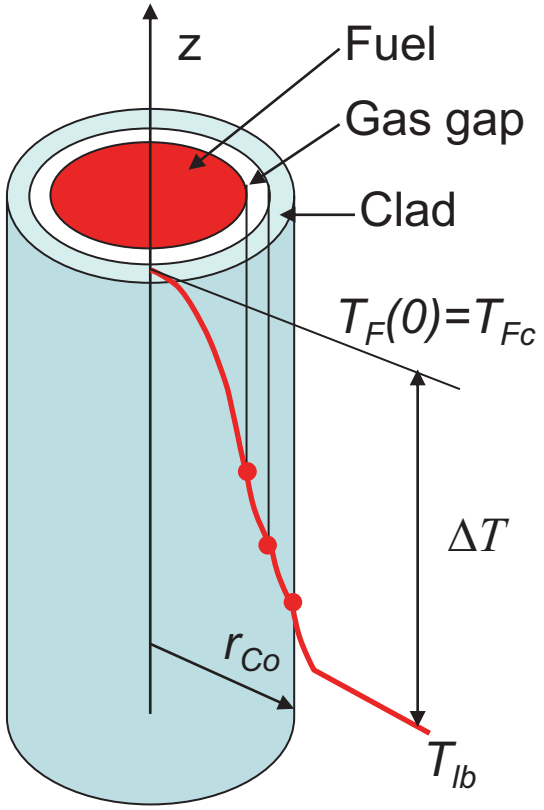
$$\Delta T = \Delta T_F + \Delta T_G + \Delta T_C + \Delta T_{lb} = T_{Fc} - T_{lb}$$

$$\Delta T = \frac{q''' r_{Fo}^2}{4\lambda_F} + \frac{q''' r_{Fo}^2}{2\lambda_G}\ln\left(\frac{r_{Go}}{r_{Fo}}\right) + \frac{q''' r_{Fo}^2}{2\lambda_C}\ln\left(\frac{r_{Co}}{r_{Go}}\right) + \frac{q''' r_{Fo}^2}{2 r_{Co} h} =$$

$$\frac{q''' r_{Fo}^2}{4}\left[\frac{1}{\lambda_F} + \frac{2}{\lambda_G}\ln\left(\frac{r_{Go}}{r_{Fo}}\right) + \frac{2}{\lambda_C}\ln\left(\frac{r_{Co}}{r_{Go}}\right) + \frac{2}{r_{Co} h}\right]$$

Since $q''' \pi r_{Fo}^2 = q'$ (linear power density)

$$\Delta T = \frac{q'}{4\pi}\left[\frac{1}{\lambda_F} + \frac{2}{\lambda_G}\ln\left(\frac{r_{Go}}{r_{Fo}}\right) + \frac{2}{\lambda_C}\ln\left(\frac{r_{Co}}{r_{Go}}\right) + \frac{2}{r_{Co} h}\right]$$



Fuel element

Fuel Thermal Analysis

- For solid UO_2 with 95% density the recommended equation for the thermal conductivity is

$$\lambda_F(T) = \frac{100}{7.5408 + 17.692t + 3.6142t^2} + \frac{6400}{t^{5/2}} \exp\left(-\frac{16.35}{t}\right)$$

- where λ_F is in W/m·K , t = T/1000 and T is temperature in K. For porosity different from 5%, the thermal conductivity is found as:

$$\lambda_0 = \frac{\lambda_p}{1-(2.6-0.5t)p}$$

Here λ_0 is the thermal conductivity of fully dense UO_2 (that is p = 0) and λ_p is the thermal conductivity of UO_2 with porosity p.

$$\lambda_p = \lambda_0\left[1-(2.6-0.5t)\,p\right] = \lambda_F(T)\frac{1-(2.6-0.5t)\,p}{1-(2.6-0.5t)0.05}$$

Fuel Thermal Analysis

- For mixed oxide fuel (80% U, 20% Pu) at 95% theoretical density and O/M (oxigen/metal)=2.0, the fuel thermal conductivity can be given as (Washington, 1973)

$$\lambda_F(T) = \left(0.042 + 2.71\times10^{-4}T\right)^{-1} + 6.9\times10^{-11}T^3$$

where λ_F is in W/m·K and T in K. For porosity different from 5%, the thermal conductivity is found as:

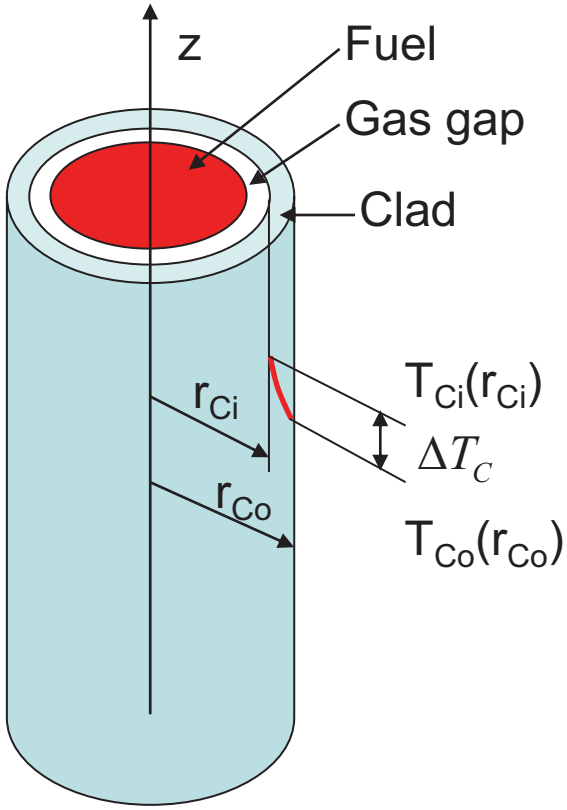
$$\lambda_{Fp}(T) = \begin{cases} \lambda_F(T)\dfrac{1-2.5p}{0.875} & p \le 0.1 \\ \lambda_F(T)\dfrac{1-p}{0.875(1+2p)} & p > 0.1 \end{cases}$$

Cladding Thermal Analysis

- For Zircaloy-2 and Zircaloy-4 (α-phase), the thermal conductivity can be found as

$$\lambda_C = 12.6 + 0.0118T$$

  - here: T [°C] – temperature, λ_C [W/mK] – thermal conductivity
  - valid for 20 < T < 800 °C
  - uncertainty ±1.01 W/mK



Fuel element