# SH2702
# Nuclear Reactor Technology

## Project work Task 5

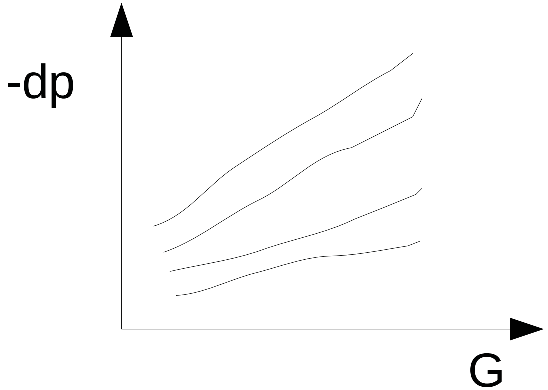
# Project work

| 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 |

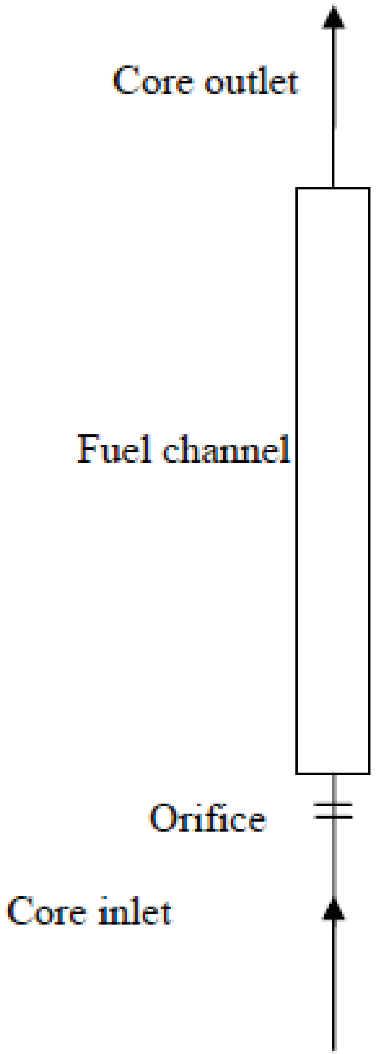
- Task 1 – General design specification of the nuclear power plant with selected reactor type
- Task 2 – Operational principles of the power plant
- Task 3 – Safety features of the power plant
- Task 4 – Calculation of selected core parameters
- Task 5 – Calculation of CHF margins in a hot channel
-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

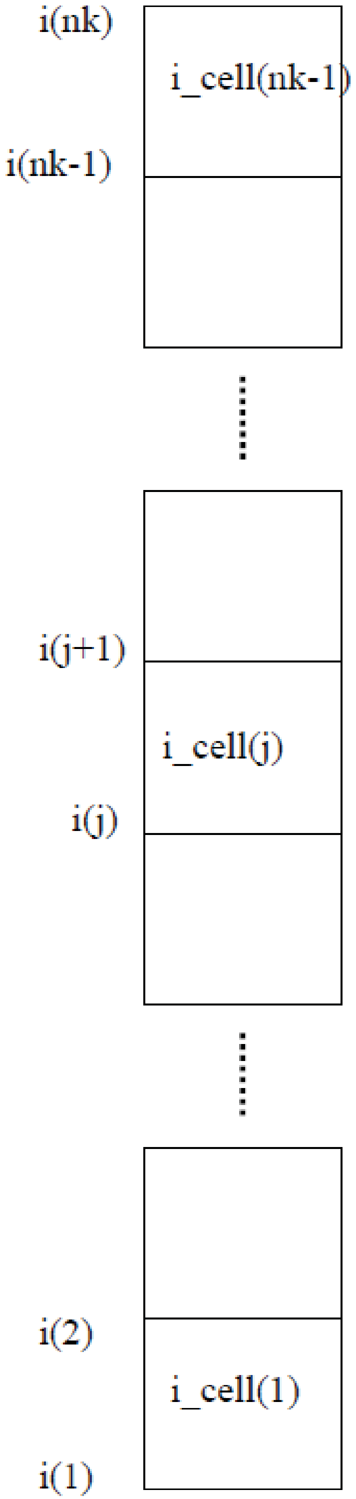



- Inlet orifices pressure loss
  - BWRs (50% at nominal operating conditions)
  - PWRs (25% at nominal operating conditions)

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

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

# Task 4 Nodalization and numerical solution



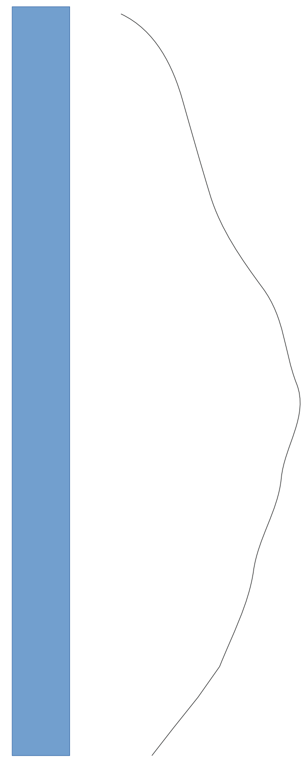

- for j = 2 to nk
  - i(j) = i(j-1) + q_cell(j-1) / W (energy balance)
- end for
- while p not converged
  - p(1) = pin + dpInletOrifice
  - for j = 2 to nk
    - xe(j), xa(j), alpha(j) (void fraction model)
    - dpf_cell(j-1), dpg_cell(j-1), dpa_cell(j-1), dpl_cell(j-1)
    - dp_cell(j-1) (pressure 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)

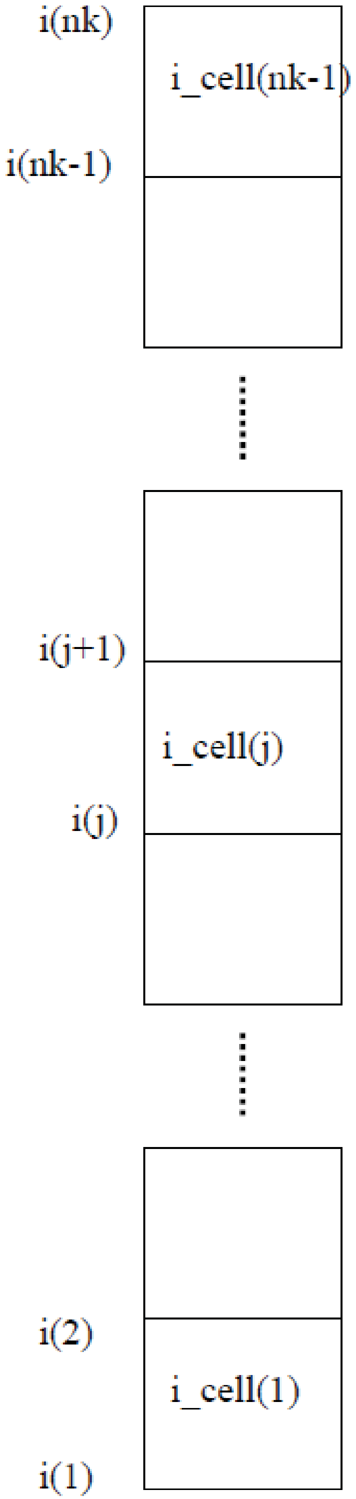
# Task 5

- 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*

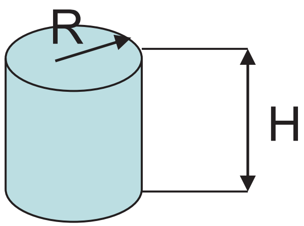
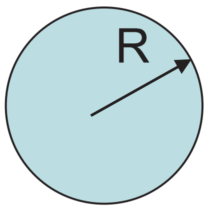
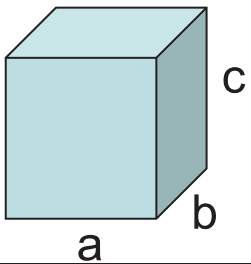





# Task 5 Nodalization and numerical solution

- 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

# Power Distribution

| | Volume | Power density distribution | Mean power density |
|---|---|---|---|
|   | $V = \pi R^2 H$ | $q'''(r,z) = q_0''' J_0\left(\frac{2.405 r}{\tilde{R}}\right)\cos\left(\frac{\pi z}{\tilde{H}}\right)$ | $\bar{q}''' = q_0''' \frac{2\tilde{R}}{2.405R} J_1\left(\frac{2.405R}{\tilde{R}}\right)\frac{2\tilde{H}}{H\pi}\sin\left(\frac{\pi H}{2\tilde{H}}\right)$ |
|   | $V = \frac{4}{3}\pi R^3$ | $q'''(r) = q_0'''\left(\frac{\tilde{R}}{\pi}\right)\frac{\sin\frac{\pi r}{\tilde{R}}}{r}$ | $\bar{q}''' = 3q_0'''\left(\frac{\tilde{R}}{\pi R}\right)^2\left[\frac{\tilde{R}}{\pi R}\sin\left(\frac{\pi R}{\tilde{R}}\right) - \cos\left(\frac{\pi R}{\tilde{R}}\right)\right]$ |
|   | $V = a \cdot b \cdot c$ | $q'''(x,y,z) = q_0''' \cos\left(\frac{\pi x}{\tilde{a}}\right)\cos\left(\frac{\pi y}{\tilde{b}}\right)\cos\left(\frac{\pi z}{\tilde{c}}\right)$ | $\bar{q}''' = q_0''' \frac{\tilde{a}\tilde{b}\tilde{c}}{abc}\left(\frac{2}{\pi}\right)^3 \sin\left(\frac{\pi a}{2\tilde{a}}\right)\sin\left(\frac{\pi b}{2\tilde{b}}\right) \cdot \sin\left(\frac{\pi c}{2\tilde{c}}\right)$ |

# Peaking Factors (1)

- Peaking factor is a ratio of the maximum to average power densities in a reactor core
- Peaking factor can be calculated for the whole core volume: $$f_V = \frac{q_0'''}{\overline{q}'''} = \frac{q'''(0,0)}{\frac{1}{V}\int_V q''' dV}$$
- In a cylindrical core, we have in addition radial and axial peaking factors: $$f_R(z_P) = \frac{q'''(0, z_P)}{\frac{1}{\pi R^2}\int_0^R q'''(r, z_P) 2\pi r dr} \qquad f_A(r_P) = \frac{q'''(r_P, 0)}{\frac{1}{H}\int_{-H/2}^{H/2} q'''(r_P, z) dz}$$
- Here $z_P$ and $r_P$ are fixed values of the axial and radial coordinates at which peaking factors are defined

# Peaking Factors (2)

- For example for a fuel rod located at $r=r_P$ distance from the centreline, the axial peaking factor is found as:

$$f_A(r_P) = \frac{q_0''' J_0\left(\frac{2.405 r_P}{\tilde{R}}\right)\cos(0)}{\frac{1}{H}\int_{-H/2}^{H/2} q_0''' J_0\left(\frac{2.405 r_P}{\tilde{R}}\right)\cos\left(\frac{\pi z}{\tilde{H}}\right)dz} =$$

$$\frac{1}{\frac{1}{H}\int_{-H/2}^{H/2}\cos\left(\frac{\pi z}{\tilde{H}}\right)dz} = \frac{\pi H}{2\tilde{H}\sin\left(\frac{\pi}{2}\cdot\frac{H}{\tilde{H}}\right)}$$

- As can be seen the axial peaking factor does not depend on $r_P$

# Peaking Factors (3)

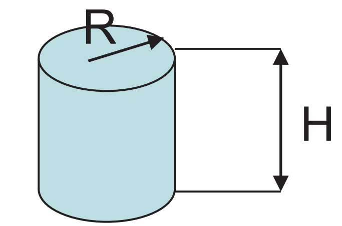
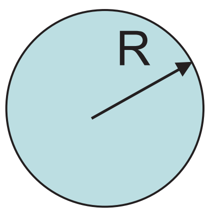
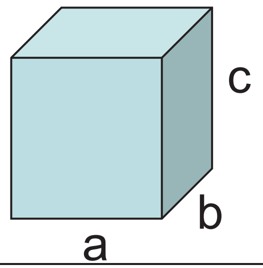
- Similarly for a core cross-section located at $z=z_P$, the radial peaking factor is found as:

$$f_R\left(z_P\right)=\frac{q_0'''J_0\left(0\right)\cos\left(\frac{\pi z_P}{\tilde{H}}\right)}{\frac{1}{\pi R^2}\int_0^R q_0'''J_0\left(\frac{2.405r}{\tilde{R}}\right)2\pi r\cos\left(\frac{\pi z_P}{\tilde{H}}\right)dr}=$$

$$\frac{1}{\frac{1}{\pi R^2}\int_0^R J_0\left(\frac{2.405r}{\tilde{R}}\right)2\pi r dr}=\frac{2.405\cdot R}{2\tilde{R}\cdot J_1\left(\frac{2.405R}{\tilde{R}}\right)}$$

- As can be seen the radial peaking factor does not depend on $z_P$

# Power Distribution – Peaking Factors

| | Mean power density | Assuming extrapolation length equal to zero |
|---|---|---|
|   | $\bar{q}''' = q_0''' \frac{2\tilde{R}}{2.405R} J_1\left(\frac{2.405R}{\tilde{R}}\right)\frac{2\tilde{H}}{H\pi}\sin\left(\frac{\pi H}{2\tilde{H}}\right)$ | $\bar{q}''' = 0.274824 q_0'''$<br>$q_0''' = 3.63869\bar{q}'''$ |
|   | $\bar{q}''' = 3q_0'''\left(\frac{\tilde{R}}{\pi R}\right)^2\left[\frac{\tilde{R}}{\pi R}\sin\left(\frac{\pi R}{\tilde{R}}\right) - \cos\left(\frac{\pi R}{\tilde{R}}\right)\right]$ | $\bar{q}''' = \frac{3q_0'''}{\pi^2} \approx 0.303964 q'''$<br>$q_0''' = 3.28986\bar{q}'''$ |
|   | $\bar{q}''' = q_0''' \frac{\tilde{a}\tilde{b}\tilde{c}}{abc}\left(\frac{2}{\pi}\right)^3 \sin\left(\frac{\pi a}{2\tilde{a}}\right)\sin\left(\frac{\pi b}{2\tilde{b}}\right)\sin\left(\frac{\pi c}{2\tilde{c}}\right)$ | $\bar{q}''' = \frac{8q_0'''}{\pi^3} \approx 0.258012 q'''$<br>$q_0''' = 3.87579\bar{q}'''$ |

# Example

- Calculate the total peaking factor in a cylindrical core assuming

$$\frac{R}{\tilde{R}} \cong \frac{H}{\tilde{H}} \cong \frac{5}{6}$$

# Example

•Solution:

$$f_A = \frac{\pi H}{2\tilde{H}\sin\left(\frac{\pi}{2}\cdot\frac{H}{\tilde{H}}\right)} = \frac{\pi}{2}\frac{5}{6}\frac{1}{\sin\left(\frac{\pi}{2}\frac{5}{6}\right)} \simeq 1.355$$

$$f_R = \frac{2.405\cdot R}{2\tilde{R}\cdot J_1\left(\frac{2.405R}{\tilde{R}}\right)} = \frac{2.405}{2}\frac{5}{6}\frac{1}{J_1\left(2.405\frac{5}{6}\right)} \simeq 1.738$$

• Answer: the total peaking factor is $f_A$*$f_R$ = 2.35578

# DNB Correlations

- Correlations are derived from experimental data obtained in rod bundles

- Typical DNB correlation has a form:

$$q''_{cr} = q''_{cr}\left(G, p, x, D_h, L, \ldots\right)$$

*G* – mass flux
*p*- pressure
*x* – quality $=(i-i_f)/i_{fg}$
$D_h$ – hydraulic diameter
*L* – heated length

- That is, the correlation predicts the value of the critical heat flux (when DNB occurs) as a function of local parameters and channel geometry
- DNB occurs at location where $q'' > q''_{cr}$

# Bowring Correlation

$$q''_{cr} = \frac{A + D \cdot G \cdot \Delta i_{subi} / 4}{C + L}$$

$$A = \frac{0.579 F_{B1} D \cdot G \cdot i_{fg}}{1 + 0.0143 F_{B2} D^{1/2} G}$$

$$C = \frac{0.077 F_{B3} D \cdot G}{1 + 0.347 F_{B4} (G/1356)^n}$$

$$n = 2.0 - 0.5 p_R$$

$$p_R = \frac{p}{6.895 \cdot 10^6}$$

$$F_{B1} = \begin{cases} \dfrac{p_R^{18.942} \exp[20.8(1 - p_R)] + 0.917}{1.917} & p_R \le 1 \\ p_R^{-0.368} \exp[0.648(1 - p_R)] & p_R > 1 \end{cases}$$

$$\frac{F_{B1}}{F_{B2}} = \begin{cases} \dfrac{p_R^{1.316} \exp[2.444(1 - p_R)] + 0.309}{1.309} & p_R \le 1 \\ p_R^{-0.448} \exp[0.245(1 - p_R)] & p_R > 1 \end{cases}$$

$$F_{B3} = \begin{cases} \dfrac{p_R^{17.023} \exp[16.658(1 - p_R)] + 0.667}{1.667} & p_R \le 1 \\ p_R^{-0.219} & p_R > 1 \end{cases}$$

$$\frac{F_{B4}}{F_{B3}} = p_R^{1.649}$$

$136 < G < 18600$ kg/m$^2$s – mass flux
$2 \cdot 10^5 < p < 190 \cdot 10^5$ Pa – pressure
$2 < D < 45$ mm – diameter
$0.15 < L < 3.7$ m – heated length
$\Delta i_{sub} = i_f - i_{in}$, J/kg – inlet subcooling

# GE Correlation for Uniform q”

## (Jansen & Levy)

$$q''_{cr} = q''_{cr70} + 6.2 \cdot 10^3 (70 - p)$$

$$q''_{cr70} = \begin{cases} 10^6 \left(2.24 + 0.55 \cdot 10^{-3} G\right) & if \quad x < x_1 \\ 10^6 \left(5.16 - 0.63 \cdot 10^{-3} G - 14.85x\right) & if \quad x_1 \le x < x_2 \\ 10^6 \left(1.91 - 0.383 \cdot 10^{-3} G - 2.06x\right) & if \quad x_2 \le x \end{cases}$$

$$x_1 = 0.197 - 0.08 \cdot 10^{-3} G \qquad x_2 = 0.254 - 0.019 \cdot 10^{-3} G$$

$q''_{cr}$ - critical quality, [W/m$^2$]
G – mass flux, [kg/m$^2$ s]
x – equilibrium quality
p – pressure [bar]

Applicability range:
42 < p < 102 bar
540 < G < 8100 kg/m$^2$s
0.0 < x 0.45
6.2 < $D_h$ < 32 mm
0.74 < L < 2.8 m

# Westinghouse Correlation for Uniform q'': W-3

$$q''_{cr,U}(z) = A\left\{(2.022 - 0.0004302\,p_R) + (0.1722 - 0.0000984\,p_R)e^{[(18.177-0.004129\,p_R)x]}\right\}\times$$
$$\left[(0.1484 - 1.596x + 0.1729x|x|)G_R + 1.037\right](1.157 - 0.869x)\times$$
$$\left(0.2664 + 0.8357e^{-3.151D_e}\right)(0.8258 + 0.000794\Delta i_R)$$ in MW/m²

$$p_R = \frac{p(z)}{6.8947\cdot 10^3}$$ *p(z)* – pressure at location *z*, Pa

$$G_R = \frac{G(z)}{1.3562\cdot 10^3}$$ *G(z)* - mass flux at location *z*, kg/m²s

$$A = 3.1544$$

$$D_e = \frac{D_h}{0.0254}$$ $D_h$ - hydraulic diameter, m

$$\Delta i_R = \frac{i_f - i_{in}}{2326}$$

$i_f$ – specific enthalpy at saturation, J/kg
$i_{in}$ – specific enthalpy at inlet, J/kg

Validity range:
$5.5 < p < 16$ MPa
$1356 < G < 6800$ kg/m²s
$5 < D_h < 18$ mm, $0.254 < L < 3.7$ m
$-0.15 < x < 0.15$

# Effect of Non-Uniform Power Distribution

- GE correlation by Jansen and Levy is commonly used for PWR conditions with uniform heat distribution along the channel

- For non-uniform power distribution the W-3 correlation is applicable, where the following correction factor has to be applied:

$$F_c(z) \equiv \frac{q''_{cr,U}(z)}{q''_{cr,NU}(z)} = \frac{C}{q''(z)\left(1-e^{-C\cdot z}\right)} \int_0^z q''(z') e^{-C(z-z')} dz'$$

$q''_{cr,U}(z)$ - critical heat flux found with uniform power distribution, MW/m$^2$

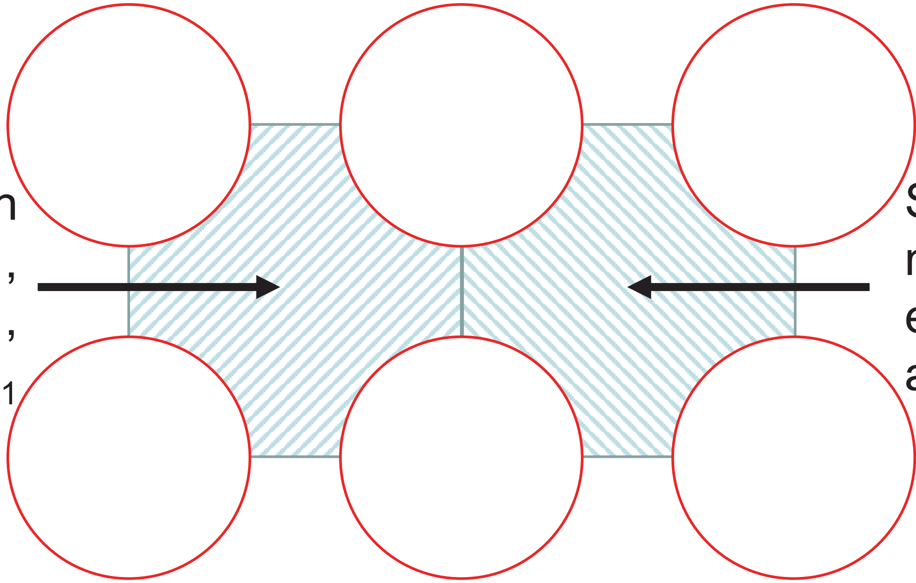
$$C = 185.6 \frac{\left(1-x_{cr,NU}\right)^{4.31}}{G^{0.478}}$$

$x_{cr,NU}$ – equilibrium quality at DNB location found with non-uniform power distribution
$G$ – mass flux, kg/m$^2$s

# Subchannel DNB

- The DNB correlations discussed so far are applicable to whole bundle
- Sometime a more detailed approach is required, in which conditions in individual subchannels are considered

Subchannel $S_1$, with mass flux $G_1$, equilibrium quality $x_1$, and mean heat flux $q''_1$



Subchannel $S_2$, with mass flux $G_2$, equilibrium quality $x_2$, and mean heat flux $q''_2$

# Subchannel CHF Correlation

- Reddy and Fighetti developed a generalized subchannel CHF correlation for both PWR and BWR fuel assemblies (both DNB and dryout)

$$q''_{cr}(\mathbf{r}) = B\frac{A - x_{in}}{C + \dfrac{x(\mathbf{r}) - x_{in}}{q''_R(\mathbf{r})}}$$

$$A = a_1 p_R^{a_2} G_R^{(a_3 + a_4 p_R)} \qquad G_R = G/1356.23$$

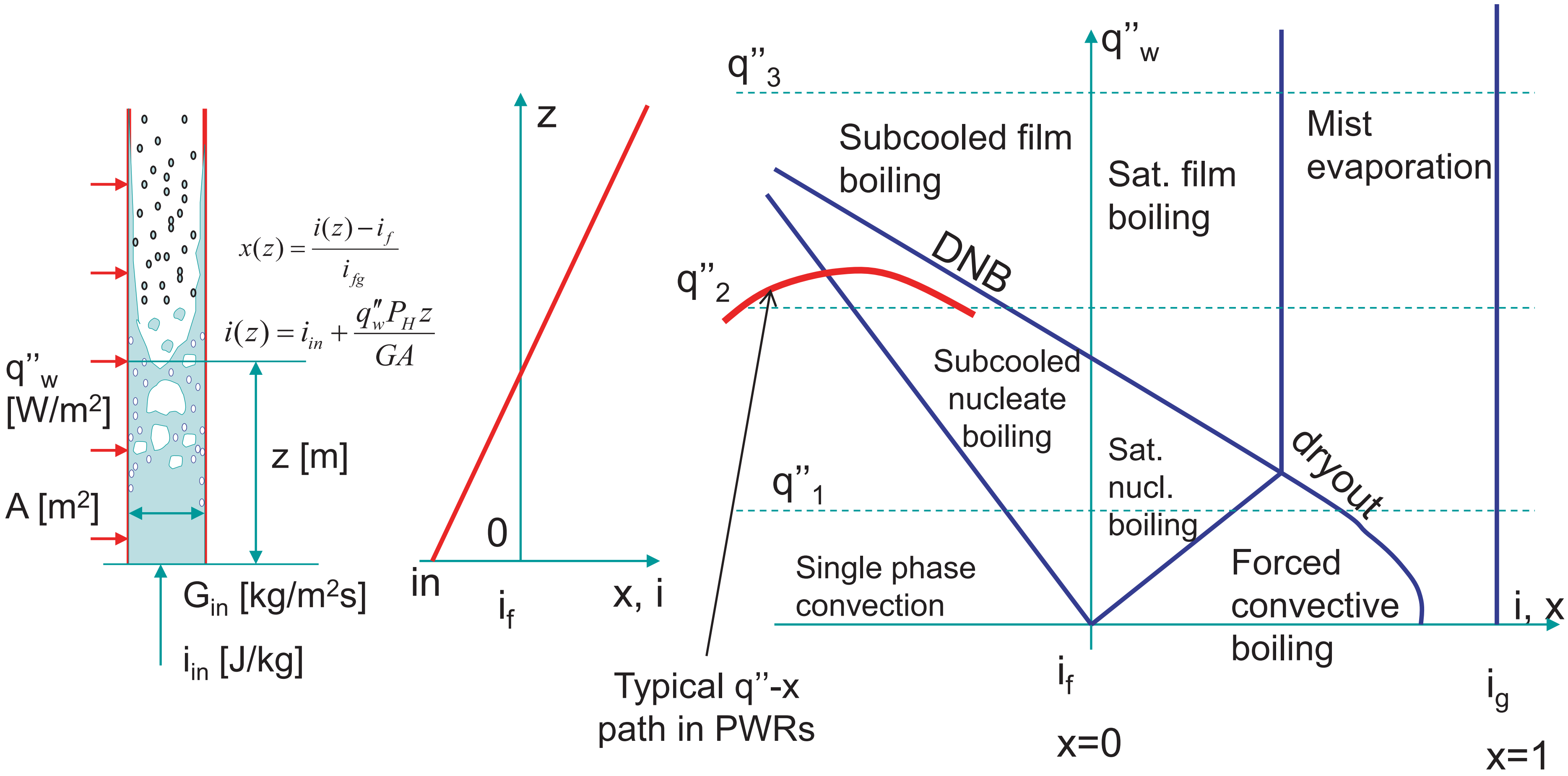
$$B = 3.1544 \times 10^6 \qquad p_R = p/p_{cr}$$

$$C = c_1 p_R^{c_2} G_R^{(c_3 + c_4 p_R)} \qquad q''_R(\mathbf{r}) = q''(\mathbf{r})/3.1544e6$$

$q_{cr}$ – critical heat flux, W/m$^2$, xin – inlet equilibrium quality, $G$ – mass flux, kg/m$^2$s, $p$ – pressure, Pa, $p_{cr}$ – critical pressure, Pa, $a_1$ = 0.5328, $a_2$ = 0.1212, $a_3$ = -0.3040, $a_4$ = 0.3285, $c_1$ = 1.6151, $c_2$ = 1.4066, $c_3$ = 0.4843, $c_4$ = -2.0749, **r** - location

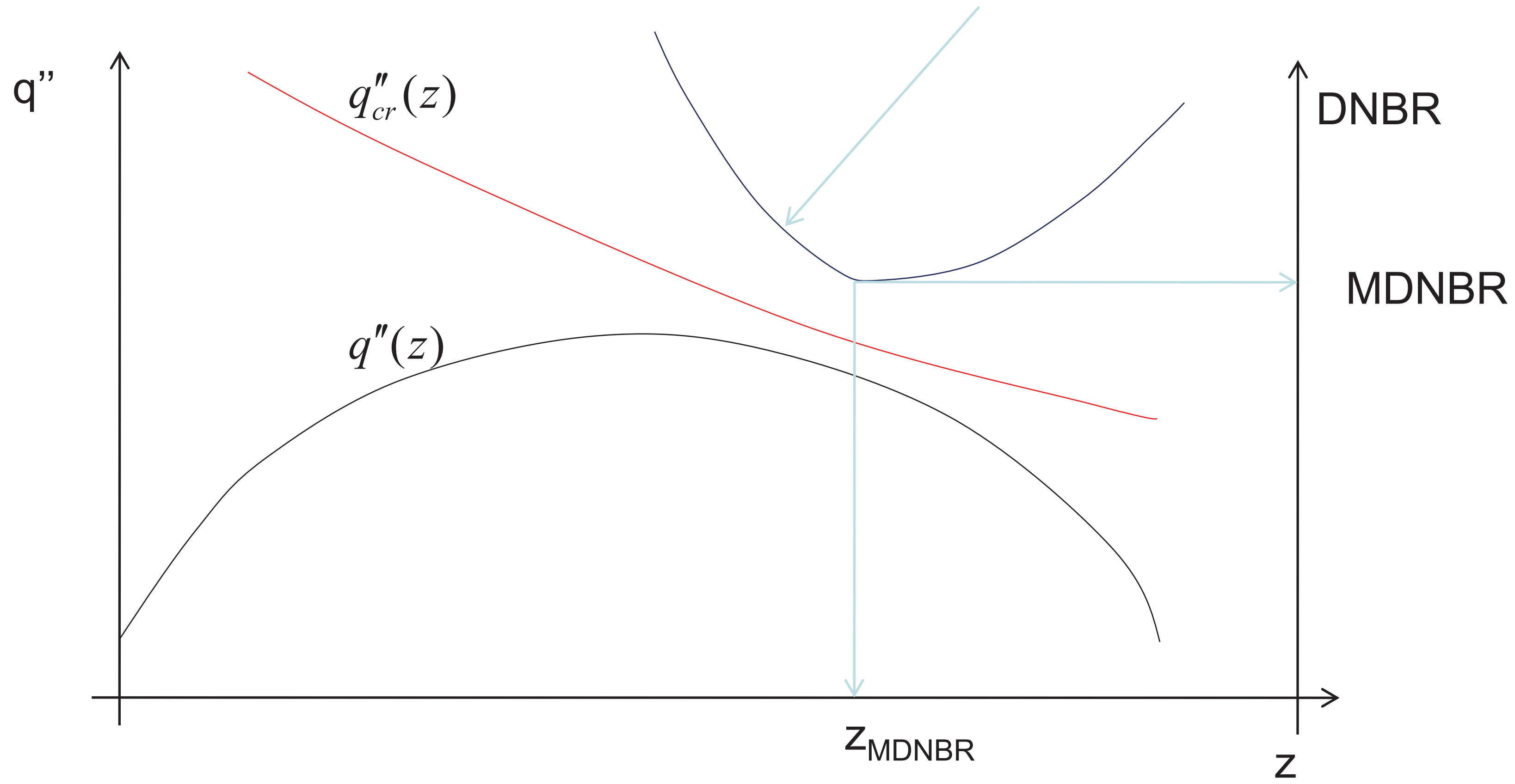
Applicability range: $147 < G < 3023$ kg/m$^2$s, $13.8 < p < 169.9$ bar, $8.9<D_h<13.9$ mm, $6.3<D_H<13.9$ mm, $-0.25 <x<0.75$, $-1.10<x_{in}<=0.0$, $0.762<L<4.267$ m

# Boiling Regimes on q”-x Plain



# DNB Ratio - DNBR

- DNB Ratio (DNBR) is defined as: $DNBR(z) = \dfrac{q''_{cr}(z)}{q''(z)}$



# DNBR, MNDBR and $z_{MNDBR}$

- DNBR is a local parameter function
- DNBR(z) has to be calculated along the whole assembly
- The minimum value of DNBR is called Minimum DNBR (MDNBR)
- Both MDNBR and its location $z_{MNDBR}$ need to be determined for a bundle or subchannel when predicting thermal margins

# Dryout (1)

- Dryout occurs in channels with high quality
- This type of CHF is a concern in BWRs
- Typical dryout correlation has a form

$$x_{cr} = x_{cr}\left(G, p, D_h, L_B, \ldots\right)$$

- That is, the correlation predicts the quality at which dryout occurs

# Dryout (2)

- Example of a dryout correlation – Levitan-Lantsman

$$x_{cr}\Big|_{8mm} = \left[0.39 + 1.57\frac{p}{98} - 2.04\left(\frac{p}{98}\right)^2 + 0.68\left(\frac{p}{98}\right)^3\right]\left(\frac{G}{1000}\right)^{-0.5} \qquad x_{cr} = x_{cr}\Big|_{8mm} \cdot \left(\frac{8}{D_h}\right)^{0.15}$$

  *p* – pressure (bar), *G* mass flux (kg/m$^2$.s), $D_h$ – hydraulic diameter, mm

- To predict the dryout it is thus necessary to find quality in a channel and compare it with the critical value

- Dryout will occur if at any point: $x(z) >= x_{cr}(z)$

# CISE Correlation

- Original CISE correlation was developed for tubes
- General Electric extended the correlation to rod bundles based on their experimental data

$$x_{cr} = \frac{A \cdot L_B^*}{B + L_B^*}\left(\frac{1.24}{R_f}\right)$$

$$L_B^* = L_B / 0.0254$$

$L_B$ – boiling length in [m]

$R_f$ – radial peaking factor, [-]

$$A = 1.055 - 0.013\left(\frac{p_R - 600}{400}\right)^2 - 1.233 G_R + 0.907 G_R^2 - 0.285 G_R^3$$

$$G_R = G/1356.23$$

$$p_R = p/6894.757$$

$$B = 17.98 + 78.873 G_R - 35.464 G_R^2$$

G [kg/m$^2$.s]; p [Pa]

Valid for 7x7 bundle; B=B/1.12 for 8x8 bundle

# Hench and Gillis Correlation

$$x_{cr} = \frac{0.50 \cdot G_R^{-0.43} \cdot Z}{165 + 115 \cdot G_R^{2.3} + Z} \times \left[ 2 - J_1 + \frac{0.19}{G_R}(J_1 - 1)^2 + J_3 \right] + 0.006 - 0.0157 p_R - 0.0714 p_R^2$$

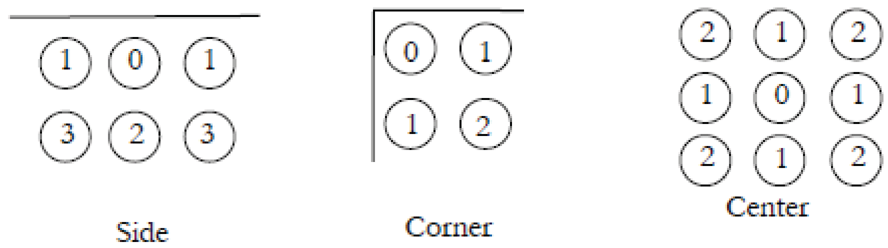
$G_R = G/1356.23$    $G$ – mass flux, kg/m$^2$s

$Z = n\pi d_r L_B / A$    $n$ – number of rods, $d_r$ – rod diameter, m; $L_B$ – boiling length, m

$p_R = (p/6894.7 - 800)/1000$    $A$ – bundle flow area, m$^2$, $p$ – pressure, Pa

$$J_1 = \begin{cases} \frac{1}{32}\left(25R_{f0} + 3\sum R_{f1} + R_{f2}\right) & \text{for corner rods} \\ \frac{1}{32}\left(22R_{f0} + 3\sum R_{f1} + 2R_{f2} + \sum R_{f3}\right) & \text{for side rods} \\ \frac{1}{32}\left(20R_{f0} + 2\sum R_{f1} + \sum R_{f2}\right) & \text{for central rods} \end{cases}$$

$$J_3 = \begin{cases} 0 & \text{for corner rods} \\ \frac{0.07}{G_R + 0.25} - 0.05 & \text{for side rods} \\ \frac{0.14}{G_R + 0.25} - 0.10 & \text{for central rods} \end{cases}$$



# Critical Power Ratio - CPR

- CPR (Critical Power Ratio) for a fuel assembly is defined as:

$$CPR = q_{cr}/q_{ac}$$

here: $q_{cr}$ [W] is the total power of a bundle at which dryout occurs

$q_{ac}$ [W] is the actual power of the bundle