Thermal Hydraulic Considerations in Steady State Design

1. PWR Design
2. BWR Design

Course 22.39, Lecture 18
11/10/05
Professor Neil Todreas
PWR Design

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Components of Margin for MDNBR Overpower Transient

<table>
<thead>
<tr>
<th>MDNBR</th>
<th>Power Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>~2.17 (Rated)</td>
<td>Rated Power</td>
</tr>
<tr>
<td>~1.55</td>
<td>3800 MW&lt;sub&gt;th&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>Safety Analysis Limit</td>
</tr>
<tr>
<td></td>
<td>Design Limit</td>
</tr>
<tr>
<td></td>
<td>Process Parameters &amp;</td>
</tr>
<tr>
<td></td>
<td>Engineering Uncertainties</td>
</tr>
<tr>
<td></td>
<td>Correlation Limit</td>
</tr>
<tr>
<td></td>
<td>Correlation Uncertainties</td>
</tr>
<tr>
<td></td>
<td>Failure Limit</td>
</tr>
</tbody>
</table>

### Summary of Steady-State Thermal Hydraulic Design Constraints

<table>
<thead>
<tr>
<th>Design Constraints For:</th>
<th>Constrained Parameters</th>
<th>Design Limit</th>
<th>Reference Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vortex-Shedding Lock-in</td>
<td>$VSM_{\text{lift}}$, $VSM_{\text{drag}}$</td>
<td>$&gt; 0.3$</td>
<td>(3.18), (3.19)</td>
</tr>
<tr>
<td>Fluid-Elastic Instability</td>
<td>$FIM$</td>
<td>$&lt; 1$</td>
<td>(3.21)</td>
</tr>
<tr>
<td>Fretting Wear</td>
<td>$\frac{\dot{W}<em>{\text{fretting, new}}}{\dot{W}</em>{\text{fretting, ref}}}$</td>
<td>$\leq \frac{T_{c,\text{ref}}}{T_{c,\text{new}}}$</td>
<td>(3.39)</td>
</tr>
<tr>
<td>Sliding Wear</td>
<td>$\frac{\dot{W}<em>{\text{sliding, new}}}{\dot{W}</em>{\text{sliding, ref}}}$</td>
<td>$\leq \frac{T_{c,\text{ref}}}{T_{c,\text{new}}}$</td>
<td>(3.44)</td>
</tr>
<tr>
<td>DNBR</td>
<td>$\text{MDNBR}$</td>
<td>$&gt; 2.17$</td>
<td></td>
</tr>
<tr>
<td>Pressure Drop</td>
<td>$\Delta P_{\text{rod bundle}}$</td>
<td>$&lt; 29$ psia, 60 psia</td>
<td></td>
</tr>
<tr>
<td>Fuel Temperature</td>
<td>$T_{\text{centerline, UZrH}<em>{1.6}}$, $T</em>{\text{average, UO}_2}$</td>
<td>$&lt; 750$ C, $&lt; 1400$ C</td>
<td></td>
</tr>
</tbody>
</table>
MDNBR vs Power

Flow-Induced Vibration Mechanisms

<table>
<thead>
<tr>
<th>Flow-Induced Mechanism</th>
<th>Design Concern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vortex-Induced Vibration</td>
<td>• Large amplitude vibrations occur when vortex shedding frequencies lock-in to the structural frequency of the rod</td>
</tr>
<tr>
<td>Fluid-Elastic Instability</td>
<td>• Large amplitude vibrations occur when cross-flows exceed the critical velocity for the rod bundle configuration</td>
</tr>
<tr>
<td>Turbulence-Induced Vibration in Cross and Axial Flow</td>
<td>• Small amplitude rod vibrations from turbulence generated pressure fields cause excessive fretting and sliding wear at the cladding/rod support interface</td>
</tr>
</tbody>
</table>
Vibrations Analysis Assumptions

- The fuel rod is modeled as a linear structure
- Changes to the fuel assembly structure over time are not considered
- Only the cladding structure is considered in the fuel rod model
- Only the first vibration mode is considered
- Core power is the only operating parameter affecting the vibrations performance of new designs
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</tr>
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</tr>
<tr>
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<td>(3.44)</td>
</tr>
<tr>
<td>DNB R</td>
<td>$\text{MDNBR}$</td>
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<td></td>
</tr>
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<td>Fuel Temperature</td>
<td>$T_{\text{centerline}} - \text{UZfH}_{1,6}$</td>
<td>$&lt; 750 \text{ C}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$T_{\text{average}} - \text{UO}_2$</td>
<td>$&lt; 1400 \text{ C}$</td>
<td></td>
</tr>
</tbody>
</table>
Vortex Shedding

The vortex shedding margins in the lift and drag directions are defined as:

\[
VSM_{\text{lift}} = \frac{|f_1 - f_s|}{f_s} \quad (3.18)
\]

\[
VSM_{\text{drag}} = \frac{|f_1 - 2f_s|}{2f_s} \quad \text{where, } f_1: \text{fundamental frequency of the rod} \quad (3.19)
\]

The vortex shedding frequency is given by:

\[
f_s = S \cdot \frac{V_{\text{cross}}}{D} \quad (3.15)
\]

where the Strouhal number, S, was found by Weaver and Fitzpatrick to depend on the P/D ratio and channel shape. For square arrays,

\[
S = \frac{1}{2(P/D - 1)} \quad (3.16)
\]

and for hexagonal arrays,

\[
S = \frac{1}{1.73(P/D - 1)} \quad (3.17)
\]
Fluid Elastic Instability

The ratio of the maximum effective cross-flow velocity in the hot assembly, $V_{\text{eff}}$, to the critical velocity for the bundle geometry $V_{\text{critical}}$:

$$\frac{V_{\text{eff}}}{V_{\text{critical}}} = \text{FIM}$$ (3.21)

The most widely accepted correlation for estimating the critical velocity for a tube bundle is Connor’s equation:

$$\epsilon \quad V_{\text{critical}} = \beta \cdot f_n \sqrt{\frac{2 \cdot \pi \cdot \zeta \cdot m_f}{\rho_f}}$$ (3.23)

where Pettigrew suggested a P/D effect on Connors’ constant:

$$\epsilon \quad \beta = 4.76 \cdot \left(\frac{P}{D} - 1\right) + 0.76$$ (3.24)

The critical velocity is constant for a fixed geometry and, with the exception of small changes in coolant density, does not depend on the power and flow conditions in the core.

\[\epsilon\]
Fretting Wear

\[
\frac{\dot{W}_{\text{fretting,new}}}{\dot{W}_{\text{fretting,ref}}} = \frac{\left( f_1^3 \cdot m_t \cdot y_{\text{rms}}^2 \right)_{\text{new}}}{\left( f_1^3 \cdot m_t \cdot y_{\text{rms}}^2 \right)_{\text{ref}}} \leq \frac{T_{c,\text{ref}}}{T_{c,\text{new}}} \tag{3.39}
\]

where \( y_{\text{rms}} \) is turbulence induced vibration from axial and cross flow, \( m_t \) is total linear mass, and \( f_1 \) is fundamental frequency of fuel rod.

The wear rate ratio is the constrained parameter, and the ratio of the cycle lengths is the design limit.

If a new design has a shorter cycle length than the reference core, then it can safely accommodate a higher rate of wear.

The wear rate limit, due to its dependence on cycle length, will depend on both the power and the fuel burnup. The power, however, depends on the wear rate limit, and the burnup, when limited by fuel performance constraints, depends on the power.
Sliding Wear

\[
\frac{\dot{W}_{sliding, new}}{\dot{W}_{sliding, ref}} = \frac{(D \cdot y_{rms} \cdot f_1)_{new} \cdot \left( \frac{1}{A_{cl}} + \frac{D^2}{4I_{cl}} \right)_{ref}}{(D \cdot y_{rms} \cdot f_1)_{ref} \cdot \left( \frac{1}{A_{cl}} + \frac{D^2}{4I_{cl}} \right)_{new}} \leq \frac{T_{c, ref}}{T_{c, new}} \tag{3.44}
\]

where \( A_{cl} \) is cladding cross-sectional area,
\( I_{cl} \) is cladding moment of inertia,
\( D \) is cladding outside diameter
P/D vs H/HM for Square and Hexagonal arrays of UZrH_{1.6} and UO_{2}
Maximum Achievable Power for Square

Core Power (x10^6 kWth)

Ref. Geom. 3669 MWh
Max. Power. 4245 MWh


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Maximum Achievable Power for Square Arrays of UO$_2$ at 60 psia

Core Power ($\times 10^6$ kW$_{th}$)

Ref. Geom: 3787 MWth

Max. Power: 5458 MWth

D$_{red}$ (mm)

P/D

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Maximum Achievable Power at 29 psia
Accounting for Fuel Rod Vibration and Wear
Maximum Achievable Power at 60 psia
Accounting for Fuel Rod Vibration and Wear

Core Power ($x10^6$ kW$_{th}$)

Ref. Geom: 3821 MWth

Max. Power = 5045 MWth

Maximum Permissible Cycle Length. 29 psia

Maximum Permissible Cycle Length. 60 psia

Illustration of Porosity in a Wire-Wrapped Bundle

Porosity = A - B  Porosity / Ring = (A - B) / R
A : Distance between two wrapper tube walls
B = 2(R - 1)(D + d_w) cos 30° + D + 2d_w
D : Fuel pin diameter
D_w : Spacer wire diameter
THV-Induced Wear Data with Otsubo’s Wear Constraint

where $P_i$ is the pitch, $P$ is the porosity, $d_w$ is the wire diameter, $R$ is the number of rings in the bundle, $\Delta T$ is the temperature drop across the bundle in °C, $H$ is the axial pitch, and $L$ is the length of the assembly.

The region above this line (labeled wear mark region) is the region where Otsubo’s constraint predicts that wear will occur. In the region below the dotted line, Otsubo’s constraint predicts that no significant wear will occur. The points marked with a • represent reactors in which no wear has been observed, while the points marked with a * represent reactors in which wear marks occurred. The horizontal lines identify the range over which the subject fuel tests were conducted. The red dots, •, used for BN-350, BN-600, and BOR-60, represent Russian fast reactor data not used by Otsubo.
BWR Core Design
GE9_9 Fuel Bundle

# Thermal-Hydraulic Constraints

<table>
<thead>
<tr>
<th>Case</th>
<th>MCPR</th>
<th>Fuel centerline T (°C)</th>
<th>Fuel average T (°C)</th>
<th>Clad surface T (°C)</th>
<th>Core pres. drop (psi)</th>
<th>Vibration ratio</th>
<th>Q/m&lt;sub&gt;dot&lt;/sub&gt; (kW/(lbm/s))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 1a (UO&lt;sub&gt;2&lt;/sub&gt;)</td>
<td>1.123</td>
<td>2805</td>
<td>1400</td>
<td>349</td>
<td>38</td>
<td>0.021</td>
<td>110.26</td>
</tr>
<tr>
<td>2, 2a, 3 (UZrH&lt;sub&gt;1.6&lt;/sub&gt;)</td>
<td>1.123</td>
<td>750</td>
<td>Not applicable</td>
<td>349</td>
<td>38</td>
<td>0.021</td>
<td>110.26</td>
</tr>
</tbody>
</table>
The Hench-Gillis correlation has the general form:

\[ x_C = \frac{AZ}{B + Z} (2 - J) + F_P \]
Pin-by-Pin Power-to-Average Power Ratio at BOL for a BWR GE 9_9 Single Bundle – Without Gadolinia

<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.91</td>
<td>1.03</td>
<td>1.08</td>
<td>1.10</td>
<td>1.09</td>
<td>1.11</td>
<td>1.08</td>
<td>1.04</td>
</tr>
<tr>
<td>1.02</td>
<td>1.18</td>
<td>0.98</td>
<td>0.80</td>
<td>1.09</td>
<td>0.81</td>
<td>1.01</td>
<td>1.20</td>
</tr>
<tr>
<td>1.07</td>
<td>0.97</td>
<td>0.76</td>
<td>0.92</td>
<td>0.99</td>
<td>0.98</td>
<td>0.79</td>
<td>0.99</td>
</tr>
<tr>
<td>1.09</td>
<td>0.79</td>
<td>0.92</td>
<td>1.06</td>
<td></td>
<td>0.98</td>
<td>0.80</td>
<td>1.11</td>
</tr>
<tr>
<td>1.07</td>
<td>1.08</td>
<td>0.98</td>
<td></td>
<td></td>
<td>0.99</td>
<td>1.08</td>
<td>1.08</td>
</tr>
<tr>
<td>1.09</td>
<td>0.79</td>
<td>0.98</td>
<td></td>
<td>1.07</td>
<td>0.92</td>
<td>0.78</td>
<td>1.10</td>
</tr>
<tr>
<td>1.07</td>
<td>0.99</td>
<td>0.79</td>
<td>0.98</td>
<td>0.99</td>
<td>0.91</td>
<td>0.74</td>
<td>0.97</td>
</tr>
<tr>
<td>1.03</td>
<td>1.18</td>
<td>1.00</td>
<td>0.80</td>
<td>1.09</td>
<td>0.78</td>
<td>0.97</td>
<td>1.17</td>
</tr>
<tr>
<td>0.92</td>
<td>1.04</td>
<td>1.07</td>
<td>1.10</td>
<td>1.08</td>
<td>1.11</td>
<td>1.07</td>
<td>1.03</td>
</tr>
</tbody>
</table>

### J1 Factors

<table>
<thead>
<tr>
<th>J1 factors. BOL for a BWR GE 9_9, without Gadolinia</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.899</td>
</tr>
<tr>
<td>0.994</td>
</tr>
<tr>
<td>1.025</td>
</tr>
<tr>
<td>1.032</td>
</tr>
<tr>
<td>1.026</td>
</tr>
<tr>
<td>1.033</td>
</tr>
<tr>
<td>1.027</td>
</tr>
<tr>
<td>1.003</td>
</tr>
<tr>
<td>0.908</td>
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</table>
# Bundle Loss Coefficients

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Ax. location (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central region orificing coefficient, (reference core), ( C^{\text{ref}}_{\text{central}} )</td>
<td>10.12</td>
<td>0</td>
</tr>
<tr>
<td>Peripheral region orificing coefficient, (reference core), ( C^{\text{ref}}_{\text{periphery}} )</td>
<td>87.36</td>
<td>0</td>
</tr>
<tr>
<td>Lower tie plate form loss coefficient, (reference core), ( C^{\text{ref}}_{\text{ltp}} )</td>
<td>4.54</td>
<td>7.3^1</td>
</tr>
<tr>
<td>Grid spacers loss coefficient, ( C_{\text{grid}} )</td>
<td>using In’s correlation</td>
<td>19.008; 39.02; 59.039; 79.488; 99.504; 119.52; 139.469</td>
</tr>
<tr>
<td>Upper tie plate form loss coefficient, (reference core), ( C^{\text{ref}}_{\text{utp}} )</td>
<td>0.18</td>
<td>160.748</td>
</tr>
</tbody>
</table>

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### Coefficients for Frictional Pressure Drop Correlations

<table>
<thead>
<tr>
<th>Channel type</th>
<th>(a_L)</th>
<th>(b_L)</th>
<th>(a_T)</th>
<th>(b_T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bundles (Cheng&amp;Todreas)</td>
<td>(35.55 + 263.7 \cdot \left( \frac{P}{d} - 1 \right) - 190.2 \cdot \left( \frac{P}{d} - 1 \right)^2)</td>
<td>-1</td>
<td>(0.1339 + 0.09059 \cdot \left( \frac{P}{d} - 1 \right) - 0.09926 \cdot \left( \frac{P}{d} - 1 \right)^2)</td>
<td>-0.18</td>
</tr>
<tr>
<td>Bypass channels</td>
<td>64</td>
<td>-1</td>
<td>0.184</td>
<td>-0.2</td>
</tr>
</tbody>
</table>
Vibration Ratio Dependence on Quality and Mass Flux, Païdoussis Correlation

Païdoussis - Tsukuda Vibration Ratio Comparison (Restricted G Range)

Final Vibration Ratio Comparison

\[ y/d \text{ vs mass flux, various correlations} \]

- Tsukuda exp. max. peaks, \( x=15\% \)
- Paid. \( x=30\% \)
- Tsukuda \( x=30\% \)
- Paid. corrected \( x=30\% \)
- Limit value

\[ G (\text{kg/s m}^2) \]

Locations of the Assembly Configurations Examined for / Ratio Investigation

Comparison between “Relative” Maximum Power and “Overall” Maximum Power

<table>
<thead>
<tr>
<th>Assembly configuration</th>
<th>$\dot{\mathcal{Q}}_{5\text{-max}}$ (MW)</th>
<th>$\dot{\mathcal{Q}}_{\text{max}}$ (MW)</th>
<th>$n_{i\text{,max}}$ (kW/(lbm/s))</th>
<th>$gg$ (%)</th>
<th>$pp$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3336</td>
<td>3406</td>
<td>101</td>
<td>+2.1</td>
<td>+16.9</td>
</tr>
<tr>
<td>B</td>
<td>3828</td>
<td>3828</td>
<td>112</td>
<td>0.0</td>
<td>-2.3</td>
</tr>
<tr>
<td>C</td>
<td>3758</td>
<td>3828</td>
<td>104</td>
<td>+1.9</td>
<td>+12.4</td>
</tr>
<tr>
<td>D</td>
<td>3705</td>
<td>3793</td>
<td>115</td>
<td>+2.4</td>
<td>-2.1</td>
</tr>
<tr>
<td>E</td>
<td>3547</td>
<td>3547</td>
<td>110.26</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>F</td>
<td>3406</td>
<td>3441</td>
<td>95</td>
<td>+1.0</td>
<td>+27.0</td>
</tr>
<tr>
<td>G</td>
<td>2984</td>
<td>3055</td>
<td>101</td>
<td>+2.4</td>
<td>+17.7</td>
</tr>
</tbody>
</table>

Power distribution assumptions

The non-uniform radial power distribution is accounted for by means of four radial peaking factors, which reflect typical average BWR values

- Hot assembly: 1.45
- Mid-hot assemblies: 1.3
- Mid-cold assemblies: 1.0
- Cold assemblies: 0.6
3 core types are considered*:

1) Oxide Backfit Core: existing BWR 5 vessel fueled with UO$_2$ (core radius = 3.2 m). Cruciform CRs, WRs, constant fuel channel size.

2) Hydride Backfit Core: existing BWR5 vessel fueled with UZrH$_{1.6}$ (core radius = 3.2 m). Variable fuel channel size.

3) Hydride New Core: ESBWR vessel fueled with UZrH$_{1.6}$ (core radius = 3.55 m). Variable fuel channel size.

* Each core type has been modeled 400 times, i.e. each time with a different assembly configuration.
Core structural changes resulting from the implementation of UZrH$_{1.6}$…
The greater design freedom for the hydride cores is limited by the application of 2 Structural Constraints:

<table>
<thead>
<tr>
<th>Structural Constraints</th>
<th>Maximum Number of Assemblies*</th>
<th>Maximum Assembly Weight**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydride Backfit Core</td>
<td>$1.6N_{\text{ref}}$ (1222)</td>
<td>$1.4M_{\text{ref}}$ (361kg)</td>
</tr>
<tr>
<td>Hydride New Core</td>
<td>$1.6N_{\text{ref}}$ (1222)</td>
<td>Not Applied</td>
</tr>
</tbody>
</table>

* to limit the refueling time.
** due to the limited load capacity of the crane in an existing plant. Not applied to the Hydride New Core since a reactor designed specifically to utilize UZrH$_{1.6}$ is assumed to be provided with a crane of sufficient load capacity.
Oxide Core Powermap

Core Power ($10^6$ kW$_{th}$)

Ref. assembly
3.3008 GW$_{th}$

Maximum Power
3.8281 GW$_{th}$

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Power, LHGR and Number of Rods Ratios Between the Examined Oxide Core Configuration and the Reference Core (the lines represent unity ratios)

Whole Core Flow Rate (Oxide Core)

Some observations about the powermaps: What are the limiting parameters and where do they apply

The size of this area increases significantly (especially for Hydride fuel) if the fuel-clad gap is modeled as a He-filled gap*. However, for all the three core types the overall max power is not affected by the choice of the gap filling.

Very tight lattice assemblies.

Small d rods: significantly more subject to vibrations.

NOTE: Fuel Centerline T, Clad Surface T and Decay Ratio are never limiting.

* Through the whole analysis, the fuel-clad gap is assumed to be filled by a liquid-metal eutectic.

NOTE: Fuel Centerline T, Clad Surface T and Decay Ratio are never limiting.
Limiting Effect Exerted by Constraints (Oxide Core)

Core Average Exit Quality and Hot Bundle Exit Quality (Oxide Core)

Core Average Exit Quality (deforming line: 17%)

Hot Bundle Exit Quality (deforming line: 36%)

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Bypass Flow Percentage (Oxide Core)

Oxide Core Fuel Matrix \((n_n)\) Size

(the colored scale indicates the matrix index \(n\); black upper line: \(n=7\), black lower line: \(n=12\); green line: high power region)
1) Oxide Backfit Core
2) Hydride Backfit Core

Although the core size is the same, the Hydride Core delivers 10-25% more power! (depending on the assembly configuration considered)

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Power, LHGR and Rod Ratios Between Hydride Backfit Core and Oxide Ref. Core (continuous lines represent unity ratios)
Limiting Effect Exerted by Constraints (Hydride Backfit Core)

Hench-Gillis MCPR, (lim=1.123)

Fuel centerline temperature (°C), (lim=750°C)

P/D

Avg dp (psia), (lim=38 psia)

Max clad surface T (°C), (lim=349°C)

Maximum vibration ratio, (lim=0.021)
3) Hydride New Core

The benefits derived from the implementation of Hydride fuel are coupled with those (predictable) resulting from having a larger core size (ESBWR core size).

For the sake of comparison, the ESBWR fueled with oxide delivers about 4500 MW$_{th}$

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Course 22.39, Lecture 18
Professor Neil Todreas